UNIVERSITY OF SOUTHAMPTON

FACULTY OF HEALTH SCIENCES

Ultrasound Imaging of the Abdominal Muscles and Bladder: Implications for the Clinical Assessment of Individuals with Lumbopelvic Pain

by

Jacqueline Lee Whittaker

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ABSTRACT

Doctor of Philosophy

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Lumbopelvic pain (LPP) is associated with altered abdominal muscle function yet few tools exist that enable physiotherapists to identify these changes in a clinical setting. Ultrasound imaging (USI) has potential however its ability to detect altered abdominal muscle function and associated changes in bladder base (BB) position during tests common to a physiotherapy assessment of LPP, has yet to be established. The aims of this research were to determine the validity and reliability of USI technique in a clinical setting, investigate the relationship between changes in abdominal muscle thickness and electrical activity, and compare sonographic characteristics of the abdominal wall, and BB position, between persons with and without LPP. Validity results indicate that 5^{o}-10^{o} of angular, and 8mm of inward/outward transducer motion don't produce measurement error, and that transducer motion can be kept within these thresholds during two commonly used clinical tests; the Active Straight Leg Raise (ASLR) test and Abdominal Drawing in Manoeuvre (ADIM). Regarding reliability, measurements of abdominal muscle thickness, inter-recti distance (IRD) and BB position (healthy and LPP cohorts) during the ASLR and ADIM were good to excellent (within day ICC; 0.84-0.99, between day; 0.80-0.99). Cross-correlation functions examining the relationship between changes in abdominal muscle thickness and activity during an ASLR and ADIM were low (r=0.22-0.40), and associated time lags large (-0.44-1.15s), suggesting that changes in muscle thickness represent more than changes in electrical activity. On comparing sonographic features between cohorts a series of features were identified that differed between the groups. Specifically, the LPP cohort had a thinner rectus abdominis ($p<0.001$), thicker perimuscular connective tissue ($p=0.007$), a wider IRD ($p=0.005$) and demonstrated smaller increases in TrA thickness ($p\leq0.00$-0.05), and greater BB descent ($p=0.02$-0.03) during the ASLR. To determine if these sonographic features assist in discriminating LPP a statistical classification technique was piloted. Preliminary results identified a set of 14 sonographic features that classified LPP participants with 84% accuracy. These findings support an argument regarding the clinical value of USI and serve as the basis for future investigations aimed at determining if USI enhances the assessment, and ultimately treatment, of individuals with LPP.

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AUTHOR'S DECLARATION

Declaration of authorship

I Jacqueline Lee Whittaker

Declare that the thesis entitled:

Ultrasound Imaging of the Abdominal Muscles and Bladder: Implications for the Clinical Assessment of Individuals with Lumbopelvic Pain

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at the University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the sources is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published as:

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Whittaker JL, Warner MB and Stokes M (2009d) Ultrasound imaging transducer motion during clinical lumbopelvic manoeuvres. *Canadian Physiotherapy Annual Conference*. Calgary, AB, Canada.

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Signed:

Date:

Things are not what they appear to be: nor are they otherwise.
Surangama Sutra

For Jodi and Traven

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LIST OF ABBREVIATIONS

A

ADIM – Abdominal Drawing in Manoeuvre
ANOVA - Analyses of Variance
ANCOVA – Analysis of Covariance
AP – Anterior / Posterior
ASIS – Anterior Superior Iliac Spine
ASLR – Active Straight Leg Raise Test
ARA – Anorectal Angle

B

B-Mode – Brightness Mode
BMI – Body Mass Index
bpm – Breaths per Minute

C

CC – Cranial / Caudal
CI – 95% Confidence Interval
cm – Centimetres
cm^2 – Squared Centimetres
CSA – Cross-sectional Area
CW – Clockwise
CCW – Counter Clockwise
CO_2 – Carbon Dioxide

E

ECG – Electrocardiogram
EMG - Electromyography
EO – External Oblique
$ETCO_2$ – End Tidal Carbon Dioxide

F

FABQ – Fear Avoidance Beliefs Questionnaire
FABQPA - Fear Avoidance Beliefs Questionnaire Physical Activity sub-scale
FABQW – Fear Avoidance Beliefs Questionnaire Work sub-scale

G

GB – Global Bladder Position
GBB – Global Bladder Base Position

H

Hz – Hertz

I

IAP – Intra-abdominal Pressure
ICC – Interclass Correlation Coefficient
IIQ - Incontinence Impact Questionnaire
IO – Internal Oblique
IRD – Inter-recti Distance

J

JW – Jacqueline (Jackie) Whittaker

K

kg – kilograms
kHz = kiloHertz

L

LA – Linea Alba
LAW – Lateral Abdominal Wall
LBP – Low Back Pain
LDA – Linear Discriminant Analysis
LOA – Limits of Agreement
LPP – Lumbopelvic Pain

M

m – Metres

m^2 – Squared Metres

MATLAB - Matrix Laboratory

MDC – Minimum Detectable Change

MHz – Mega (million) hertz

ml – Millilitres

mm – Millimetres

mmHG – Millimetres of Mercury

MRI – Magnetic Resonance Imaging

ms – Millisecond

MVC – Maximum Voluntary Contraction

N

EMG – Electromyography

NPRS - Numerical Pain Rating Scale

O

ODQ - Oswestry Disability Questionnaire

OLS – One Leg Standing test

P

PFM – Pelvic Floor Muscles

PGP – Pelvic Girdle Pain

PMCT – Perimuscular Connective Tissue

PSIS – Posterior Superior Iliac Spine

R

RA – Rectus Abdominis

RBB – Relative Bladder Base Position

RUSI – Rehabilitative Ultrasound Imaging

S

s – seconds

SBB – Sagittal Bladder Base

SD – Standard Deviation

SEM – Standard Error of the Measurement

SPSS –Statistical Package for the Social Sciences

T

TrA – Transversus Abdominis

2D – Two Dimensional

U

UDI - Urogenital Distress Inventory

UI – Urinary Incontinence

USI – Ultrasound Imaging

W

WPC – Whittaker Physiotherapy Consulting

Y

yrs - Years

CHAPTER 1 - INTRODUCTION

This chapter will provide a brief introduction to the motivation and rationale for investigating the sonographic characteristics of the abdominal wall and bladder base in persons with lumpopelvic pain (LPP) in a clinical setting. This will be followed by an overview of the thesis layout.

1.1. Ultrasound Imaging of the Abdominal Wall and Bladder during Physiotherapy Assessment of Lumbopelvic Pain.

Lumbopelvic pain (low back; LBP and pelvic girdle pain; PGP) constitutes a significant health concern in western societies with lifetime prevalence rates ranging between 49-80% (Loney & Stratford 1999; Maniadakis & Gray 2000; Wu et al. 2004). As such, LPP is a leading cause for physician visits, hospitalisations and other health care service utilisation. In a cost-of-illness study published in 2000 Maniadakis and Gray (2000) reported that over £9 billion are spent on LPP in the UK per annum, and that this figure was expected to increase. Likewise, Deyo et al (2009) reported that although there has been an enormous increase in the health care resources spent on managing disorders of the lumbopelvic region in the USA (i.e. a 629% increase in expenditures for epidural steroid injections; a 423% increase in expenditures for opioids; a 307% increase in the number of lumbar magnetic resonance images; and a 220% increase in spinal fusion surgery rates) the disability relating to them continues to increase. Based on this growing trend of economic impact there are increasing calls for a change in the management of LPP. Specifically, a call to shift the model of care away from one based solely upon identifying and treating, patho-anatomical mechanisms, to one that adopts a more broad based ‘bio-psycho-social’ approach (Andersson 1999; Deyo et al. 2009; O'Sullivan 2011). Consequently, the role of altered muscle function in the development and perpetuation of LPP has received considerable attention due to an accumulation of evidence: suggesting that these changes reflect alterations in ‘bio’, ‘psycho’ and ‘social’ factors (i.e. tissue injury, pain attitudes, and fear; Moseley 2004; Hodges 2011; O'Sullivan 2011), identifying altered patterns of muscle control in persons with lasting and reoccurring pain (see Hodges & Moseley 2003 and; Hodges & Tucker 2011 for a summary), and based on the fact that it is potentially modifiable with non-invasive treatment approaches such as physiotherapy (Tsao & Hodges 2008).

The most contemporary theory behind the mechanisms of altered patterns of control seen with LPP is that pain and injury (actual, or the threat of) lead to adaptations in muscle control aimed at protecting the region from further harm. Although this response is initially adaptive, and has short term benefit, it appears that in some individuals these changes persist (Hides et al. 1996; MacDonald et al. 2009; Hodges 2011), and may have

detrimental long term consequences (Geisser et al. 2004; Moseley & Hodges 2006; Hodges 2011; Hodges & Tucker 2011). Further, the literature would suggest that the motor control changes, and protective strategy employed, is unique to each individual based upon the interplay of multiple factors (O'Sullivan & Beales 2007c). Although the evidence is sound and has resulted in changes in how LPP is rehabilitated, there is still a significant gap between the basic scientific discoveries and their application in clinical practice. Hence, there has not been a significant reduction in the prevalence and reoccurrence of LPP (Andersson 1999; Pengel et al. 2003; Deyo et al. 2009).

One plausible interpretation of the evidence is that rehabilitation must aim to modify these alterations in muscle function through an intervention rooted in motor learning (a process of improving the smoothness and accuracy of movement by ensuring proper function of the muscle and nervous system through error correction, augmented feedback and part-practice) that considers the unique presentation of each individual patient (Stuge et al. 2004; O'Sullivan & Beales 2007a; Tsao & Hodges 2008; Dankaerts & O'Sullivan 2011). Fundamental to this approach is the ability of a physiotherapist to detect changes in muscle function. To date, few objective tools exist that enable physiotherapists to detect these changes, particularly in the deeply located muscles, in a typical clinical setting.

Ultrasound imaging (USI) is a potential tool as it is safe, non-invasive, clinically accessible, and allows physiotherapists to monitor changes in muscle and connective tissue morphology (thickness, width, length, area, etc.), as well as bladder base position (which may be reflective of the interaction between pelvic floor muscle activity and intra-abdominal pressure) during a typical physiotherapy assessment (Stokes et al. 1997; Whittaker et al. 2007a; 2007b). However, the ability of USI to detect changes in the abdominal muscles, their associated connective tissue, and bladder base position at rest, and during clinical tests common to a typical physiotherapy assessment of LPP, has yet to be established. Accordingly, a series of five investigations were undertaken (Table 1.1). These studies can be categorized into those concerned with investigating the validity and reliability of USI technique in a clinical setting, those that intend to further investigate the relationship between changes in muscle thickness (measured with USI) and electrical activity (measured with electromyography; EMG), and those concerned with observing and analysing differences in the sonographic characteristics of the abdominal wall and bladder base position between persons with and without LPP.

1.2. Thesis Overview

The goal of this thesis is to inform an argument regarding the clinical value of USI in routine physiotherapy practice as it applies to detecting altered structure and function of the abdominal wall muscles, and changes bladder base position in persons with LPP. The

thesis begins (Chapter 2) with background information and a critique of the literature pertinent to the investigation of muscle function with USI in persons with LPP, followed by an overview of general methodological considerations for the five investigations (Table 1.1) conducted in this research (Chapter 3). Chapters 4 through 8 are experimental chapters and contain detailed descriptions of the measurements, results, discussion points and limitations of the aforementioned studies. Specifically, the first (Chapter 4) examines if a USI transducer can be held adequately stationary to gather accurate measurements of the transversus abdominis (TrA), and bladder base (BB), during two clinical tests typical of a physiotherapy exam, the Active Straight Leg Raise test (ASLR) and Abdominal Drawing in Manoeuvre (ADIM), while the second (Chapter 5) investigates the reproducibility of resting, contracted, and percent change measurements of abdominal muscle thickness, inter-recti distance (IRD) and BB position in healthy and LPP cohorts during the ASLR and ADIM. The third study (Chapter 6) investigates the relationship between muscle thickness and electrical activity by comparing changes in thickness (USI) of the four abdominal muscles, to changes in muscle activity (EMG), during the ASLR and ADIM, while the final two studies compare abdominal wall and BB sonographic features between healthy and LPP cohorts, at rest (Chapter 7), and during the ASLR and ADIM (Chapter 8). Chapter 9 introduces work that has been piloted on a secondary analyses of the data presented in Chapters 7 and 8 from the perspective of which clinical and sonographic variables are the most potent discriminates for classifying LPP and control cohorts, and what the added value of the sonographic parameters are to this classification model. Chapter 10 presents the main discussion points generated by the investigations and presents the limitation of this research. Finally, the conclusions, recommendations, and a summary of the main areas for future work are presented in Chapter 11.

Table 1.1: Categorization, Title, and Location of Experimental Studies

Category / Title		Location
Ultrasound Imaging Protocol Construct Validity and Reliability		
Study 1a – Chapter 4	Induced Transducer Orientation during Ultrasound Imaging: Effects on Abdominal Muscle Thickness and Bladder Position	Southampton, UK
Study 1b – Chapter 4	Ultrasound Imaging Transducer Motion during Clinical Manoeuvres: Respiration, Active Straight Leg Raise Test and Abdominal Drawing in.	
Study 2 – Chapter 5	Reliability of Developed Ultrasound Imaging Protocols of Abdominal Wall Muscle Thickness and Bladder Position.	Surrey, British Columbia, Canada
The Relationship Between Muscle Thickness and Electrical Activity		
Study 3 – Chapter 6	Comparison of Electromyography and Ultrasound Imaging Measures of the Abdominal Wall Muscles in Individuals with and without Lumbopelvic Pain	Kingston, Ontario, Canada
Sonographic Characteristics of Lumbopelvic Pain; Observational Studies		
Study 4 - Chapter 7	Resting Sonographic Characteristics of the Abdominal Wall in Persons with Lumbopelvic Pain: Muscles and Connective Tissues	Surrey, British Columbia, Canada
Study 5 – Chapter 8	Sonographic Characteristics of the Abdominal Wall and Bladder in Individuals with Lumbopelvic Pain during Dynamic Clinical Tests	

CHAPTER 2- BACKGROUND AND LITERATURE REVIEW

This chapter contains background information and a literature review pertinent to the investigation of muscle function with ultrasound imaging (USI) in persons with lumbopelvic pain (LPP). Specific emphasis is placed upon the information pertinent to the abdominal (rectus abdominis; RA, external oblique; EO, internal oblique; IO, and transversus abdominis; TrA) and pelvic floor muscles (PFM) as they are the primary focus of this project. The chapter begins with background information about the current understanding of neuromusculoskeletal dysfunction in the lumbopelvic region and the resulting implications for rehabilitation, as well as the most common methods used for assessing altered muscle control, namely electromyography (EMG), magnetic resonance imaging (MRI), and USI. This is followed by a critical appraisal of the current literature as it applies to the use of USI for measurement of the abdominal muscles and bladder base position. Validity and reliability of the measurements are discussed, as well as the findings specific to LPP. The chapter concludes with implications for methodology as well as the aims of this research.

BACKGROUND INFORMATION

2.1 Neuromusculoskeletal Dysfunction of the Lumbopelvic Region and Implications for Rehabilitation

Lumbopelvic pain (low back; LBP and pelvic girdle pain; PGP) is a prevalent and costly health concern in western society (Andersson 1999; Maniadakis & Gray 2000; Wu et al. 2004; Bagnall 2010). It appears to be linked to other disorders of the lumbopelvic region including urinary incontinence (UI), gastrointestinal difficulties and respiratory dysfunction (Smith et al. 2006b; 2008b; 2009; Mens et al. 2012). Lumbopelvic pain has a high incidence of reoccurrence, with up to 70% of persons with LBP reporting a recurrence within one year (Pengel et al. 2003), and a propensity for chronicity, with 7 to 10% of persons with PGP developing chronic symptoms (Wu et al. 2004; Rost et al. 2006).

In recent years there has been considerable growth in the knowledge base that serves as the foundation for neuromusculoskeletal rehabilitation of the lumbopelvic region as changes in neuromuscular control are known to reflect the biological, psychological and social factors (Moseley 2004; Hodges 2011; O'Sullivan 2011) associated with LPP. Further, as muscle function is modifiable with rehabilitation, extensive focus has been placed upon identifying the aspects of muscle control that are consistent with health and the specific alterations that underlie dysfunction. Namely, there has been an accumulation

of evidence from EMG, MRI and USI studies pointing to the importance of coordinated muscle function for health and altered patterns of muscle control in persons with persistent and reoccurring symptoms (Deindl et al. 1994; O'Sullivan et al. 2002; Barbic et al. 2003; Hodges & Moseley 2003; van Dieen et al. 2003b; Cholewicki et al. 2005; Dankaerts et al. 2006; Stuge et al. 2006b; Thomas et al. 2007; Beales et al. 2009a; MacDonald et al. 2009; Hodges & Tucker 2011; Tsao et al. 2011). Specifically, the literature reports that pain and injury (actual or the threat of) lead to an adaptation in muscle control that involves the redistribution of activity within and between muscles (resulting from changes in multiple levels of the motor control system), that modify movement and stiffness with the intent of protecting the region from further pain or injury. Although this initially adaptive response has short term benefit it appears that in some individuals these changes do not automatically recover when pain is eliminated (Hides et al. 1996; MacDonald et al. 2009; Hodges 2011), and are not always resolved with traditional exercise programs (Stuge et al. 2006a; Hall et al. 2007). The persistence of these changes may have long term consequences that are detrimental in that they increase load, decrease movement, and decrease variability (Moseley & Hodges 2006; Hodges 2011; Hodges & Tucker 2011). Further, the literature suggests that the motor control changes and protective strategy employed are likely to be unique to each individual based upon their history, anthropometrics, posture and the task at hand. Consequently, it is doubtful that these changes in muscle activity will be predictable or stereotypical. With that being said, Hodges and Moseley (2003) have synthesized the information, with respect to LPP, and report a trend within the evidence of diminished activity of the deep (Hides et al. 1994; Hodges & Richardson 1996; Moseley et al. 2002; Barbic et al. 2003; 2006a; Hodges et al. 2007a; MacDonald et al. 2009; Teyhen et al. 2009b), and augmented activity of the superficial muscles of the region (Shirado et al. 1995; Zedka et al. 1999; Ng et al. 2002a; van Dieen et al. 2003a; Gregory et al. 2008; Beales et al. 2009a; Masani et al. 2009). Further, although there is very limited evidence at this point, there is speculation that these changes in motor control may lead to adaptive changes in the perimuscular connective tissues (PMCT) associated with the muscles of the lumbopelvic region (Langevin et al. 2009).

2.1.1 The Deep Muscles of the Lumbopelvic Region

The most commonly investigated deep lumbopelvic muscles are the TrA (Hodges & Richardson 1996; 1997a; Hodges 2001; Cowan et al. 2004; Ferreira et al. 2004), the segmental fibres of lumbar multifidus (Hides et al. 1994; Moseley et al. 2002; MacDonald et al. 2004; 2006a; 2009), the diaphragm (Hodges et al. 1997; Hodges & Gandevia 2000b; 2000a; 2003a) and the PFM (Constantinou & Govan 1982; Sapsford & Hodges 2001; Sapsford et al. 2001; Barbic et al. 2003; 2006; Smith et al. 2006a; Thompson et al. 2006a;

2007; 2008; Lovegrove Jones et al. 2009; Sjodahl et al. 2009). These muscles have been shown to be anatomically (Figure 2.1) and neurophysiologically suited for a simultaneous role in respiration, continence and postural control (Goldman et al. 1987; Hodges & Gandevia 2000a; Hodges et al. 2003a; 2005; 2007b) which may explain the link between LPP, UI, gastrointestinal and respiratory disorders. Specifically, they exhibit non-direction specific, early, tonic co-activation to identifiable perturbations (Hodges et al. 1997; Hodges & Richardson 1997b; Moseley et al. 2002; Smith et al. 2007; Sjodahl et al. 2009) suggesting that their activity is increased in anticipation of a load regardless of its direction.

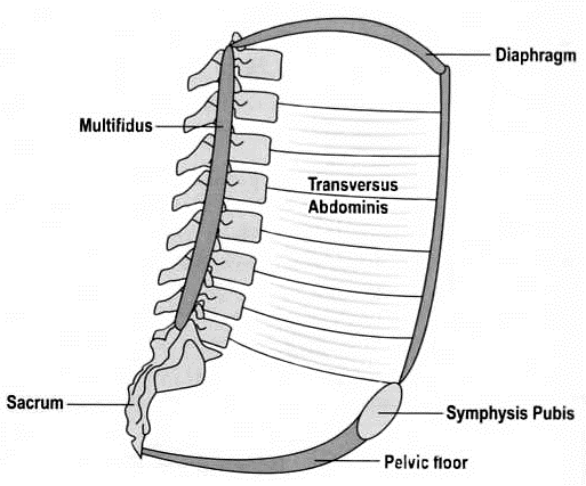


Figure 2.1: The deep muscles of the lumbopelvic region (reprinted with permission from *Ultrasound imaging for Rehabilitation of the Lumbopelvic Region: A Clinical Approach*, by Whittaker (2007).

The mechanism by which the deep muscles of the lumbopelvic region contribute to postural control has been investigated by Hodges et al (2003a). Using a porcine model they monitored intra-abdominal pressure (IAP), the relative intervertebral motion of the L3 and L4 vertebrae, and stiffness of the L4 vertebrae to displacement, during TrA and diaphragm contraction. They found an increase in IAP, a decrease in L3,4 motion, and increased stiffness of L4 to displacement. Further, they reported a significantly smaller change in motion and stiffness when either a hole was created in the abdominal wall (preventing an increase in IAP), or the fascial attachment of either muscle (diaphragm cura or the thoracolumbar fascia) was cut (preventing the mechanical transmission of muscle forces). These findings suggest that the TrA and diaphragm muscles provide a mechanical contribution to the control of intervertebral motion due both to their ability to influence IAP, and tension the ligamentous stocking which surrounds the vertebral column and pelvis (Figure 2.2).

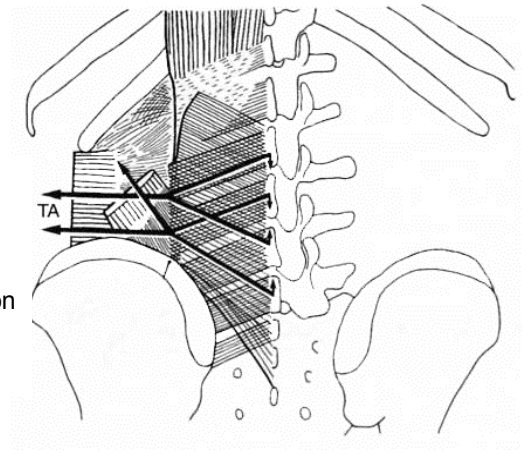


Figure 2.2: Illustration of how the transversus abdominis (TA) muscle contributes to spinal control through fascial attachements to the thoracolumbar fascia (reprinted with permission from (Bogduk & Twomey 1991).

Although there is evidence that the PFM contribute to postural control (Hodges et al. 2007b; Smith et al. 2007; Sjodahl et al. 2009) and are tonically active in standing and sitting (Deindl et al. 1994; Morgan et al. 2005), an investigation into the mechanism of this control has not been undertaken. However, as there is evidence that the PFM contribute to the control of IAP (Hemborg et al. 1985; Howard et al. 2000) and increase the stiffness of the sacroiliac joint (in vitro) in women (Pool-Goudzwaard et al. 2004) through their fascial attachments, one could argue that they may contribute to postural control via a mechanism similar to the diaphragm and TrA muscles (Hodges et al. 2007b). The segmental fibres of the lumbar multifidus, unlike the diaphragm, TrA or PFM, do not play a role in modulating IAP. However, there is in vitro evidence that these fibres increase intervertebral stiffness (Panjabi et al. 1989; Kaigle et al. 1995) and speculation, that this is the result of their ability to increase tension in the thoracolumbar fascia when they contract (Porterfield & DeRosa 1998).

With dysfunction, the neurophysiological characteristics of the deep muscles are altered and there is evidence of diminished (Hides et al. 2008; Kiesel et al. 2008; Beales et al. 2009a; Teyhen et al. 2009b) and delayed (Hodges & Richardson 1996; 1999; Cowan et al. 2004; Ferreira et al. 2004; MacDonald et al. 2004) contraction, atrophy (Hides et al. 1994; 2006a) and degeneration (Campbell et al. 1998; Danneels et al. 2000; Kader et al. 2000). With regards to the TrA muscle there is evidence of delayed and diminished contraction in LPP cohorts during postural perturbations and tasks such as supine leg raising and abdominal drawing in (Hodges & Richardson 1996; 1999; Cowan et al. 2004; Ferreira et al. 2004; Hides et al. 2008; Teyhen et al. 2009b). For instance, Hodges & Richardson (1996; 1999) used fine wire EMG to demonstrate a delay in the onset of TrA contraction in LBP participants in response to various speeds of postural perturbation (shoulder flexion and extension). Ferreira et al (2004) gathered simultaneous fine wire EMG and USI data from the TrA muscle in participants with and without LBP and found

that those with LBP have less TrA activity and significantly smaller increases in TrA thickness with an isometric knee flexion and extension task. Further, Teyhen et al (2009b) demonstrated that participants with unilateral LPP have smaller increases in TrA thickness (measured with USI) during an Active Straight Leg Raise test (ASLR; Mens et al. 2001; see Sections 2.3.3 and 3.2.3 for more information), and Hides et al (2008) concluded that elite cricketers with LBP have a reduced increase in TrA thickness (measured with MRI) when asked to perform an abdominal drawing in manoeuvre (ADIM; Richardson & Jull 1995; see Section 2.3.3 for more information).

With respect to the PFM there is evidence of deficient or delayed activity, and poorer endurance in participants with LPP or UI in response to coughing, sneezing, voluntary PFM contraction, postural perturbation and /or limb lifting tasks (Deindl et al. 1994; O'Sullivan et al. 2002; Barbic et al. 2003; Smith et al. 2006a; Thompson et al. 2006c; Peng et al. 2007b; Lovegrove Jones et al. 2009). For instance O'Sullivan et al (2002) monitored bladder base motion (transabdominal USI) during the ASLR test in participants with a clinical diagnosis of sacroiliac joint pain versus a healthy cohort. They found increased pelvic floor descent in the patient cohort and hypothesized that the greater pelvic floor depression was in response to a larger increase of IAP resulting from diaphragmatic splinting or a primary dysfunction of the PFM. Thompson et al (2006c) demonstrated that the PFM were less active (measured with surface EMG) during a PFM contraction in a cohort of women with UI than healthy participants. Further, Smith et al (2006a) gathered surface EMG data from the PFM in women with and without UI and found a delay in the response of the PFM to postural perturbations (shoulder flexion and extension).

2.1.2 The Superficial Muscles of the Lumbopelvic Region

The most commonly investigated superficial muscles of the lumbopelvic region include the oblique abdominal and paraspinal muscles (Shirado et al. 1995; Radebold et al. 2000; van Dieen et al. 2003a; Reeves et al. 2006a; Gregory et al. 2008; Ranson et al. 2008; Beales et al. 2009b; 2009a; Masani et al. 2009). However, there have been several studies that have reported on the rectus abdominis (RA; Ng et al. 2002b; Thomas et al. 2007; Coldron et al. 2008; Beales et al. 2009a; 2009b; Sjodahl et al. 2009) and quadratus lumborum (Engstrom et al. 2007; Hides et al. 2008; Ranson et al. 2008) muscles. As a rule the superficial muscle of the lumbopelvic region span from the thorax to the pelvis attaching at times to the lumbar vertebrae (Figure 2.3). They are located a distance from the instantaneous axis of rotation of the lumbar segments and are capable of producing sufficient torque, to directionally influence the spinal column (Bogduk et al. 1992; Masani et al. 2009). From a neurophysiological perspective, these muscles exhibit direction

specific, phasic activation to external loads (Masani et al. 2009). Consequently the superficial muscles of the lumbopelvic region are anatomically and neurophysiologically suited to for influencing spinal orientation and producing spinal motion. As such, they have a role to play in postural control in situations in which the body is exposed to directional loads, and spinal motion.

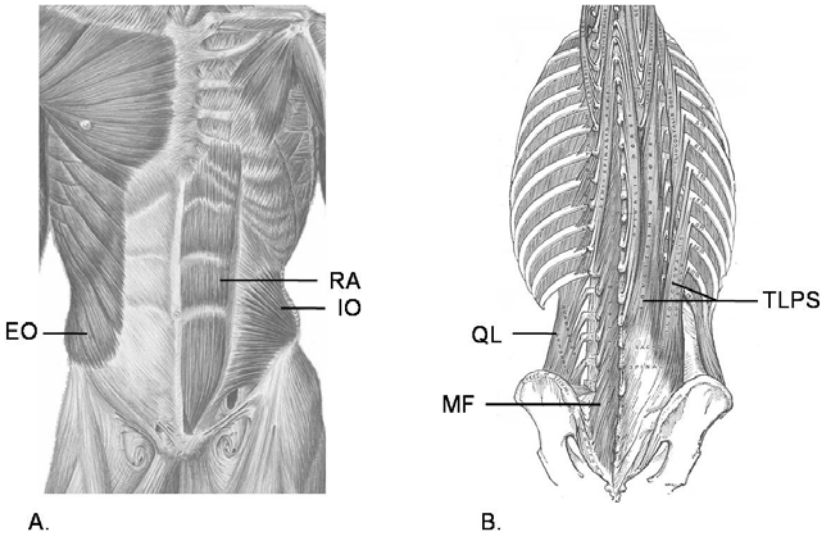


Figure 2.3: A. The anterior superficial muscles of the lumbopelvic region (EO = external oblique, IO = internal oblique, RA = rectus abdominis; reproduced from www.anatomyatlases.org), B. The posterior superficial muscles of the lumbopelvic region (QL = quadratus lumborum, MF = multifidus, TLPS = thoracolumbar paraspinal muscles; reproduced from www.theodora.com).

With dysfunction the neurophysiological characteristics of the superficial muscles of the lumbopelvic region become altered and there is evidence of increased muscle activity and augmented function (Radebold et al. 2000; van Dieen et al. 2003b; Moseley & Hodges 2005; Smith et al. 2007; Gregory et al. 2008). With regards to the EO muscle there is evidence of increased activity during postural perturbations (Moseley & Hodges 2005; Smith et al. 2007), prolonged standing (Gregory et al. 2008) or supine leg lifting (de Groot et al. 2008; Beales et al. 2009a), and a lack of relaxation following trunk loading in LPP (Radebold et al. 2000) and stress UI (Smith et al. 2007) cohorts. For instance, Moseley and Hodges (2005) demonstrated greater EO activity (surface EMG) during voluntary arm movements coupled with painful lumbar cutaneous stimulation versus arm movements without painful stimulation. DeGroot et al (2008) have demonstrated greater EO activity (surface EMG) in pregnant PGP participants versus pregnant controls during an ASLR test, while Beales et al (2009a) have shown the same findings in a cohort of female with PGP.

Gregory et al (2008), while investigating trunk muscle activity in response to a prolonged period of static standing combined with suddenly applied hand loads in persons with LBP found increased paraspinal and oblique abdominal responses (surface EMG) in the LBP cohort that developed discomfort during the task.

The evidence with respect to the IO and RA muscles is less cohesive. For instance investigators employing EMG and USI have found indicators of delayed (Hungerford et al. 2003; Moseley & Hodges 2005) and diminished (Teyhen et al. 2009b) function of the IO during functional tasks, while others have found indicators of augmented function (Beales et al. 2009a; Hides et al. 2009). However as surface EMG electrodes placed over the lower portion of the IO have been shown to represent activity of both the IO and underlying TrA muscle (McGill et al. 1996; Marshall & Murphy 2003) it is difficult to interpret the studies employing this tool. Perhaps this limitation serves as an argument for the use of USI or MRI as these two modalities allow for the evaluation of the TrA and IO muscles relatively independent from others in the region. However the puzzle persist as the evidence is inconclusive with Teyhen et al (2009b) showing a decreased, and Hides et al (2009) showing an increased, change in thickness (USI) of the IO in a LPP cohort versus a healthy one during an ASLR test, and a simulated weight bearing task, respectively. In regard to the RA muscle, Ng et al (2002b) found increased activity (surface EMG) during standing isometric rotation in a LPP cohort. However, Beales et al (2009b; 2009a) found similarities in the activation of the RA during an ASLR test in healthy and PGP cohorts. It is likely that the explanation of the discrepancies in the literature for these two muscles lies in the heterogeneous nature of LPP. In some instances the investigators have made an attempt to identify a homogenous subgroup of LPP based on clinical presentation (Beales et al. 2009b; 2009a; Teyhen et al. 2009b) while in others, the investigators have chosen to investigate a heterogeneous ‘non-specific’ LPP cohort (Ng et al. 2002b; Hides et al. 2009) making comparison of the findings impractical.

There are always potential methodological shortcomings with every investigation (i.e. cross talk from other muscles with EMG; see Section 2.2.1 for significance, limited real-time capacity with MRI, and transducer motion with USI) and those mentioned above are not immune. However, it seems to be clearly established that persons with LPP (and UI) exhibit different patterns of muscle control in response to perturbation, voluntary and postural tasks. As muscle control is modifiable through rehabilitation (O'Sullivan et al. 1998; O'Sullivan & Beales 2007b; Tsao & Hodges 2007) it seems logical that if physiotherapists were able to identify alterations in the resulting muscle function, a treatment strategy consistent with these changes could be developed. To date, few

objective tools exist to enable physiotherapists to detect specific changes in muscle function in a typical clinical setting.

2.1.3 The Perimuscular Connective Tissue of the Lumbopelvic Region

The non-specialized connective tissues that form the perimuscular, intramuscular, and fascial planes of the lumbopelvic region have received little attention in the literature as it pertains to LPP. However, it is known that connective tissues remodel in response to mechanical stress (Tillman & Cummings 1992), and it has been hypothesized that abnormal movement patterns resulting from altered motor control may contribute to physiological changes in these tissues (Langevin & Sherman 2007; Langevin et al. 2009). The foundation for this hypothesis are histology investigations showing that connective tissue fibrosis occurs as a result of micro-trauma and inflammation resulting from increased load (Ettema et al. 2004; Perry et al. 2005), or due to atrophy, architectural disorganization, and adhesions caused from an absence of load (Savolainen et al. 1987; Williams et al. 1988).

To date, only one quantitative evaluation of the non-specialized connective tissues of lumbopelvic region comparing persons with and without LBP has been reported. In that investigation, USI was used to measure the thickness and echogenicity of the subcutaneous and PMCT at the L2, 3 vertebral level, in a group of 47 controls and 60 participants with chronic LBP (Langevin et al. 2009). The authors reported the thickness and echogenicity of the PMCT were significantly greater in the LBP cohort and that these findings were not attributable to differences in age, sex, body mass index (BMI) or activity levels (Langevin et al. 2009). The rationale provided by the investigators was that these changes are secondary to chronic inflammation and associated fibrosis of these tissues.

2.2 Assessment of Neuromusculoskeletal Dysfunction in the Lumbopelvic Region

As outlined above, investigations to date have revealed altered amplitude and timing of muscle activity in both deep and superficial muscles in participants with LPP (and UI). Many of the muscles of interest during these investigations are located under other muscle layers and accordingly cannot be accessed directly from the body surface. The majority of these studies employed either surface or indwelling EMG as they are the most direct method of monitoring muscle activity (see van Dieen et al. 2003b for a summary). However, supporting information such as differences in muscle morphology (shape, size and structure), composition, and the motion resulting from muscle contraction, has come from studies employing MRI (Christensen et al. 1995; Fielding et al. 1998; Bo et al. 2001; Hides et al. 2006b) and USI (Hides et al. 1996; Thompson et al. 2006a; Peng et al. 2007a; Teyhen et al. 2009b; Hides et al. 2010).

In light of the evidence, and the idiosyncrasies of clinical practice, what is required from a clinical perspective is a tool that is safe, accessible, objective, reliable, relatively inexpensive, capable of assessing both superficial and deep musculature, and provide information about muscle function during both static and dynamic tasks. Both EMG and MRI are expensive, sophisticated tools requiring precise methodology. Hence they are best suited for the laboratory environment. In contrast, USI may have greater clinical efficacy. As all three modalities will be referred to throughout the thesis it is prudent to introduce them here.

2.2.1 Electromyography

Electromyography is considered the gold standard for measuring muscle activity. It detects myoelectric signals which are formed by variations in the physiological state of a muscle fibres membrane resulting from motor nerve excitation (Basmajian & De Luca 1985). These signals can be analysed with respect to their amplitude, timing or deconstructed into the different frequencies of which they are comprised. EMG signal analysis can provide information about a variety of aspects muscle activity and function (i.e. amplitude, activation intervals and rate of fatigue; Merletti & Parker 2004). For the purpose of this document and the literature reviewed, the primary parameters of interest are the on and off set (activation intervals) of muscle activity, as well as relative magnitude (amplitude).

The two most commonly reported limitations of EMG are related to cross talk (when activity from a muscle other that the one being investigated is detected and included in the EMG signal), and the calculation of absolute EMG amplitudes (Merletti & Parker 2004). EMG amplitudes depend on factors other than muscle activation, such as the thickness of tissues overlying the muscle, skin impedance and inter-electrode distance. EMG amplitudes are generally ‘normalised’ to the amplitude obtained during maximum voluntary contraction (MVC). This procedure is often considered unreliable for patients because they usually are unwilling, or unable to perform MVCs (van Dieen et al. 2003b). Further, the preparation, use, and analysis of EMG are time consuming and require considerable expertise. Additional drawbacks associated with needle or fine-wire EMG include the fact that information is only being sampled from a very small portion of the muscle of interest (Hodges et al. 2003b), and the discomfort and risks associated with needle insertion such as infection (Costa et al. 2009b).

2.2.2 Magnetic Resonance Imaging

Magnetic resonance imaging is considered the gold standard for musculoskeletal imaging and the quantification of muscle composition (Elliott et al. 2006; Mengiardi et al. 2006),

degeneration (Kader et al. 2000) and morphology (Hallgren et al. 1994; Andary et al. 1998; Campbell et al. 1998; Elliott et al. 2007; Hides et al. 2007a). In very basic terms MRI uses a powerful magnetic field to generate a radio frequency field which systematically alters the alignment of the protons of hydrogen atoms in the water molecules contained within the tissues. When the magnetic field is turned off the hydrogen atoms return to a state of equilibrium. Different tissues return to equilibrium at different rates and this information can be collected and used to construct an image of the body part of interest (Squire & Novelline 1997).

As MRI provides reliable measures of muscle morphology and composition it can be used to quantify atrophy (Hallgren et al. 1994; Andary et al. 1998; Campbell et al. 1998; Hides et al. 2007a) and fatty infiltration (Kader et al. 2000; Elliott et al. 2006; Mengiardi et al. 2006). The advantages of MRI are that it has multi-planar and multi-slice imaging capabilities. The drawbacks include; cost, accessibility, constraints in the number of muscles that can be investigated per session, limited real-time imaging capacity, and variable patient tolerance (i.e. claustrophobia, metallic implants, pacemaker, and pregnancy).

2.2.3 Ultrasound Imaging

Although less sophisticated in terms of resolution than MRI, USI has advantages as it is a safe, relatively inexpensive, portable, clinically accessible and well tolerated method for gathering information about muscle morphology. In contrast to MRI, an ultrasound image is constructed based upon how sound of a particular frequency interacts with the tissue of the body that it is directed at (Kremkau 2002). Specifically, a high frequency sound wave (2.5 – 15.0 MHz) is generated by passing an electrical current across transducers located along the face of the ultrasound probe. How far they travel and how they reflect depends upon the characteristics (frequency and intensity) of the sound wave, which are determined by the current transmitted from the ultrasound unit as well as the properties of the transducer crystals housed in the transducer assembly or ‘transducer’, and the impedance (resistance) of the tissues that they travel through. Specifically, the intensity of an USI wave, which is operator controlled, refers to the rate at which energy is delivered per unit area and is determined by the total power output (Watts) of an USI transducer divided by its area (centimetre squared; cm^2). As the intensity of an USI wave increases so does the depth it can penetrate and the strength of the echo that it can generate. The frequency of an USI wave is determined in the construction of the transducer assembly. Frequency has a direct relationship with resolution and an indirect one with penetration. Accordingly, the convention for determining what frequency setting to employ is to choose the highest frequency for the depth penetration required.

Generally speaking, at every tissue interface sound waves are absorbed, reflected and/or scattered. When sound reflects back to the ultrasound transducer the unit can determine where along the length of the transducer it arrived, how long it has taken to go out and come back, and its amplitude (Van Holsbeeck & Introcaso 2001). With brightness (B) mode imaging the ultrasound unit uses these three parameters to assign the echo from a particular structure a ‘pixel’ (picture element). The horizontal location of the pixel is determined by were along the length of the transducer the echo returns, while the vertical placement is determined by the length of time the sound took to go out and come back. For instance reflections that return quickly are assumed to be from superficial structures and are placed closer to the top of the image, while those that take a greater amount of time to return are from deeper structures and are placed at the bottom. The brightness of the pixel is dependent upon the strength of the returning echo. The stronger the echo the more white it will be within the image and the weaker, the darker. This process is repeated over and over until an image is built up over the entire screen (Figure 2.4). As ultrasound waves are continuously going out and coming back the image is continuous with most conventional grey scale USI units updating each pixel 20 – 40 times per second, depending on the frequency of the sound wave (Kremkau 2002).

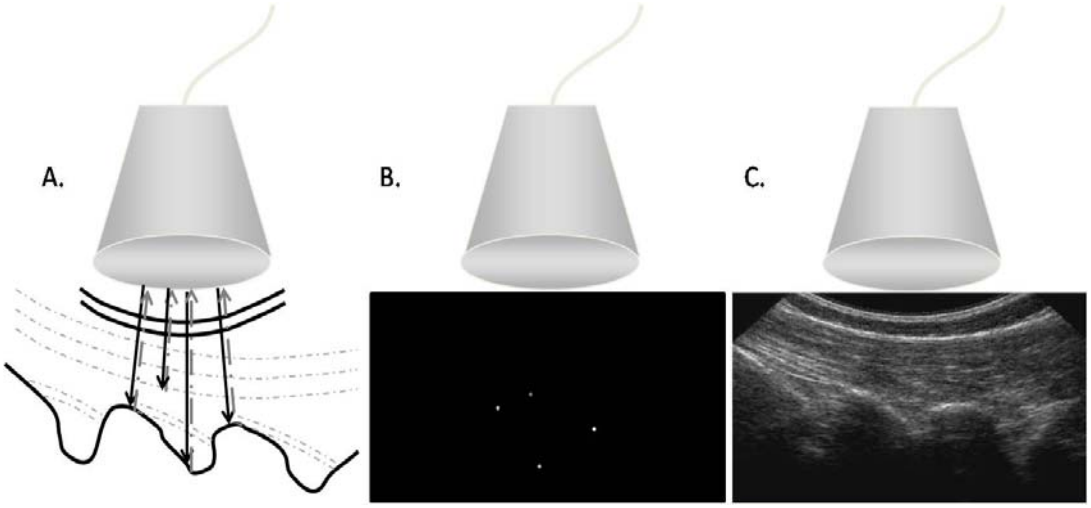


Figure 2.4: Illustration of brightness-mode ultrasound image generation. A. Sound waves penetrate tissues. At each interface a portion of the sound wave is reflected back to the transducer. B. The unit can determine were along the face of the transducer the echo returned, the length of time it was away and amplitude. These three parameters determine the vertical (time) and horizontal (transducer) location and brightness (amplitude) of a pixel representing the echo from a particular structure. C. This process is repeated until an image is generated. Reproduced with permission from Whittaker and Stokes (2011)

As with any imaging modality USI units generate images based upon several assumptions; sound only travels in straight lines, echoes only originate from objects

located within the two dimensions of the sound beam, and that sound travels through all tissues at the same speed (1540 meters per second; m/s). These assumptions are commonly violated and consequently artefact (incorrect representations of anatomy) is possible. However with proper equipment operation, imaging technique and expertise they can be avoided.

Features unique to USI are that it allows for dynamic study (real time images) of both superficial and deep muscles, as well as the influence that they have on the fascia system and adjacent organs. These features suggest that USI is superior to MRI for visualizing muscle contraction (Hides et al. 1995a; Stokes et al. 1997; Whittaker et al. 2007a). Further, it is feasible for physiotherapists to acquire the skills needed to incorporate USI into clinical practice. Consequently the use of USI to complement traditional assessment procedures has been advocated by various authors (Hides et al. 1995a; Dietz et al. 2001; Richardson et al. 2004; Whittaker 2007).

LITERATURE REVIEW

2.3 Rehabilitative Ultrasound Imaging of the Abdominal Wall:

The clinical use of USI by physiotherapists to measure muscle morphology during static and dynamic conditions falls within the scope of rehabilitative ultrasound imaging (RUSI). The term RUSI has been coined in an attempt to outline the scope of USI use by physiotherapists (Teyhen 2006). Specifically RUSI refers to USI procedures used by physiotherapists to; evaluate the morphology and behaviour of muscle and their related soft tissues, provide biofeedback about muscle behaviour during restoration of function, and to carry out research aimed at informing clinical practice (Teyhen 2006; Whittaker et al. 2007a). With respect to the abdominal wall, USI has been used to measure both the structure (morphology; Figures 3.2 and 3.4) and function (change in architecture) of the EO, IO, TrA and RA muscles (see Teyhen et al. 2007 for a summary). This section summarizes and critically reviews the literature evaluating the validity and reliability of these measurements, as well as the evidence that has explored these parameters in LPP cohorts.

2.3.1 Validity of Sonographic Measurements of the Abdominal Wall Muscles

Ultrasound imaging has been used to directly measure muscle morphology and indirectly muscle activity. This section will address these two issues separately.

2.3.1.i Muscle Morphology

Although MRI is the gold standard for measuring muscle morphology inaccessibility has led some investigators to turn to USI to provide this information. Several studies have looked at the agreement between measurements taken with MRI and USI. Muscles investigated include the masseter (Raadsheer et al. 1994), cervical (Lee et al. 2006) and lumbar (Hides et al. 1995b) multifidus, biceps, brachii, and rectus femoris (Bemben 2002), supraspinatus, infraspinatus (Juul-Kristensen et al. 2000) and the trapezius (O'Sullivan et al. 2009). A variety of parameters, ranging from measures of thickness, width, length and cross sectional area (CSA) at various anatomical locations have been considered. Correlation statistics (interclass correlation coefficient; ICC) reported range from 0.22 – 0.90 for thickness measurements (middle fibres of trapezius and CSA of the rectus femoris respectively). All of the studies reported good agreement for at least one of the measurements investigated and concluded that USI is an accurate method for measuring muscle size. In an attempt to explain lower agreement values several of the investigators were quick to point out that it was difficult at times to image the exact same portion of anatomy with the two modalities due to differences in positioning and imaging planes.

In regard to the abdominal wall, Hides et al (2006b) investigated the agreement between USI and MRI for measures of TrA and IO thickness (Figure 3.1), as well as the slide of the anterior fascial attachment of TrA (indicator of TrA length change) in thirteen healthy elite male cricket players (21.3 ± 2.1 years; yrs) during an Abdominal Drawing in Manoeuvre (ADIM). They found that USI measurements of all of the investigated parameters correlated well with measures obtained using MRI (ICC, 0.78 - 0.95) and concluded that USI can be used to measure changes in the TrA muscle during the ADIM.

It is important to point out that all of the studies that have compared measurement obtained with MRI and USI have been carried out on small numbers of young healthy participants. Further, they were done under static resting conditions with the exception of Raadsheer et al (1994) and Hides et al (2006b). Keeping in mind that muscle parameters are more difficult to measure during dynamic studies and in older or patient populations, future investigations are required to validate USI for these populations and in dynamic conditions. With that being said it is commonly stated that the validity of USI for measuring muscle morphology is adequate (Springer et al. 2006; Whittaker et al. 2007a; Mannion et al. 2008b; Hides et al. 2009; Teyhen et al. 2009b). If we concur, then the next point to consider is what does a change in muscle architecture tell us about muscle activity?

2.3.1.ii Muscle Activity

The gold standard for measuring muscle activity is EMG. There are five studies (see Table 2.1 for a summary) that have investigated the relationship between changes in

abdominal muscle thickness (measured by USI) and muscle activity (measured by EMG; Hodges et al. 2003b; McMeeken et al. 2004; John & Beith 2007a; Brown & McGill 2009; Ferreira et al. 2011). There are discrepancies in the findings with reported correlations ranging from poor to strong (EO, r = 0.22 – 0.23; IO, r = 0.14 – 0.84; and TrA, r = 0.40 - 0.90). Table 2.1 summarizes the varied methodologies which provide a possible explanation for the uncertainty in findings. For instance, three of the investigative teams collected data in a supine position while the other two used an upright position. As the length and thickness of the abdominal muscles differ between supine and upright positions due to a shift of the abdominal contents, differences in test positions will contribute to the variability in results. Similarly, as the relationship between changes in muscle thickness and EMG activity are task specific the different contraction strategies employed have likely added to the inconsistencies. Further, three of the investigative teams employed fine-wire EMG while two chose to use surface EMG for recordings from the EO and IO. Given the close proximity of muscles in the lower abdominal region EMG data recorded from these muscles using a surface electrode is likely contaminated by crosstalk from other nearby muscles (i.e. EO and TrA) which would impact any outcome (Merletti & Parker 2004). One other methodological variation that may provide explanation for the discrepancy in findings between the studies is that two of the investigations controlled for respiration (Hodges et al. 2003b; Ferreira et al. 2011), while the others did not (McMeeken et al. 2004; John & Beith 2007b; Brown & McGill 2010; see Section 2.3.3 for significance).

Table 2.1: Summary of Investigations; The Relationship between Muscle Thickness and Activity

METHOD	Hodges et al 2003	McMeeken et al 2004	John & Beith 2007	Brown & McGill 2009	Ferreira et al 2011
Muscles	- EO, IO, TrA	- TrA	- EO	- EO, IO	- EO, IO, TrA
Sample	- 3 healthy subjects	- 9 healthy subjects	- 24 healthy subjects	- 5 healthy subjects	- 10 healthy, 10 LBP
Subject position	- Reclined sitting	- Supine	- Supine	- Unsupported sitting	- Supine
Task	- Isometric contractions (10% increments from 0–100% MVC)	- Ramped ADIM (at baseline, 5%, 10%, 15%, 20%, 30%, 40%, 60%, 80% MVC)	- Isometric trunk rotation & ADIM (at baseline, 5%, 10%, 15%, 20%, 30%, 40%, 60%, 80% MVC)	- Ramped ADIM and abdominal bracing.	- Isometric low load knee flexion or extension with the limbs suspended.
USI	- 5.0 MHz linear - B-mode image	- 5.0 MHz curvilinear - M-mode image (5s)	- 5.0 MHz curvilinear - M-mode image (5s)	- 6.0–13.0 MHz linear (unspecified) - B-mode	- 5.0 MHz curvilinear - Mode unspecified
Sampling rate	- n/a (25Hz)	- Not provided	- Not provided	- Down sampled to 3 Hz	- Not Provided
Imaging site	- Parallel to TrA fibres - Mid-way between rib cage and iliac crest, 10cm from midline.	- Parallel to TrA fibres - Mid-way between rib cage and iliac crest, mid-axillary line.	- Parallel to TrA fibres - Mid-way between rib cage and iliac crest, mid-axillary line.	- 3 positions parallel to EO, IO & TrA fibres. - Level of umbilicus on left.	- Parallel to TrA fibres - Mid-way between rib cage and iliac crest, 10cm from midline.
Normalization	- Change from rest value	- % thickness Δ relative to maximal thickness.	- % thickness Δ relative to maximal thickness.	- % thickness Δ relative to rest value	- Change from rest value
EMG	- Fine wire EMG	- Bipolar needle EMG	- Surface EMG	- Surface EMG	- Fine wire EMG
Sampling rate	- 2000Hz	- 500Hz	- 1000Hz	- 2048Hz	- 2000Hz
Site	- Mid-way between rib cage & iliac crest, anterior axillary line.	- Mid-way between rib cage and iliac crest, mid-axillary line.	- On a line from inferior costal margin to contralateral pubic tubercle.	- EO (14cm lateral to midline) & IO (medio-inferior to ASIS)	- Mid-way between rib cage & iliac crest, anterior axillary line.
Normalization	- 50% MVC (3 repetitions)	- % of the largest EMG signal during testing.	- % of the largest EMG signal during testing.	- % of MVC	- % MVC
Synchronization Method	- Not provided	- "Tapping the abdomen"	- Not provided	- Not provided	- Trigger to mark, the EMG trace.
Data Reduction	- 1s epoch of EMG sampled for each USI image (rest and targeted contractions).	- 0.5s epoch of EMG sampled for each USI image (rest and targeted contractions).	- 0.5s epoch of EMG sampled for each USI image (rest and targeted contractions) - USI measured from one M-mode image 5s in duration	- EMG data reduction is not provided. - USI thickness was measured on three frames / s for the course of the ramped contraction.	- 1s epoch of EMG sampled for each USI image (rest and targeted contractions).

Data Analysis	- Nonlinear regression	- ANCOVA	- Regression Analysis - ANCOVA	- Bivariate correlation	- Pearson product moment correlation
Conclusions	- Non-linear increase in USI thickness between 0–20% MVC. - EO r=0.23, IO r=0.84, TrA r=0.93	- Linear relationship between EMG and USI thickness. - r^2 = 0.87	- Trunk Rotation = linear relationship between EMG and USI thickness (r^2=0.29-0.92). - ADIM = No relationship (r^2=0.03-0.74)	- No relationship between change in EO or IO thickness and EMG - IO r=0.14 (-0.09-0.35) - EO r=-0.22 (0.42-0.01)	- Strong correlation for TrA (r^2=0.74; 0.37-0.87) and IO (r^2=0.85; 0.76-0.96). - Poor correlation for EO (r^2=0.28;-0.16-0.66).

ADIM = abdominal drawing in manoeuvre, ANCOVA = analyses of co-variance, ASIS = anterior superior iliac spine, cm = centimetre, EMG = electromyography, EO = external oblique, IO = internal oblique, LBP = low back pain, MVC = maximum voluntary contraction, RA = rectus abdominis, s = second, TrA = transversus abdominis, USI = ultrasound imaging.

Beyond the methodological differences, there is a more fundamental reason underlying the lack of a consistent EMG-thickness relationship in the literature. Namely, that many factors, in addition to muscle activity, influence changes in muscle thickness (Hodges 2005; Whittaker & Stokes 2011). Such factors include; the resting state (activity and length) of a muscle, the extensibility (Ito et al. 1998) and structure (parallel versus pennate muscle fibre orientation) of a musculotendinous unit (Herbert & Gandevia 1995; Brown & McGill 2010), the contraction type (isometric, concentric, eccentric), the presence of external forces that an expanding muscle must compete against (i.e. increases in IAP or contraction of adjacent muscles; Cresswell & Thorstensson 1989; Delaney et al. 2010), consideration of out-of-plane changes (Boyett et al. 1991), and imaging technique (Klimstra et al. 2007; Whittaker et al. 2009). For example, when a muscle undergoes a concentric contraction it generally increases in thickness, and decreases in length (Figure 2.5a). If, however the muscle is hypertonic (i.e. hypertonic secondary to pain), the musculotendinous unit has been lengthened (i.e. a postpartum abdominal wall), or if there is any increase in activity or resistance of an adjacent muscle or fascial / body compartment which restrains the muscle from expanding, a similar contraction may result in a smaller degree of thickness change (Figures 2.5b - d) for the same amount of increase in muscle activity. In addition to factors associated with the myofascial unit, it is also important to consider those associated with interpreting 2 dimensional ultrasound images and the imaging technique itself. Specifically, that architectural change can occur outside of the plane of motion that is being imaged and that by simply changing the angle at which the ultrasound transducer is orientated to the skin, the thickness of a muscle can be altered (see Chapter 4 and Whittaker et al. 2009). If an investigative team has managed to control for the majority of these factors with their methodology then it is likely that the EMG-thickness relationship would be high. In situations where this is not the case, the relationship is likely to not be so clear.

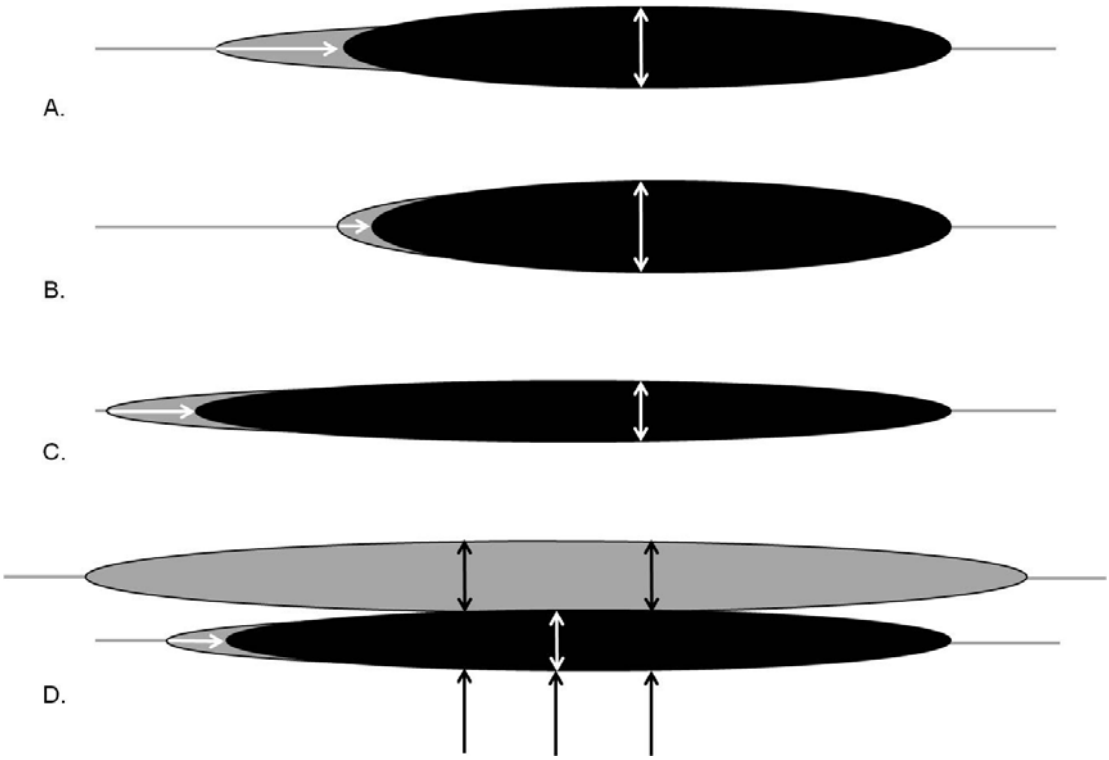


Figure 2.5 An illustration of factors that influence the change in thickness of a muscle. A. An increase in thickness and decrease in length of a 'normal' muscle (grey = pre-contraction, black = post-contraction) during a sub-maximal concentric contraction. A relatively smaller increase in thickness and decrease in length then seen with a normal muscle due to B. increased resting activity (i.e. secondary to pain), C. an increase in the extensibility of the myofascial unit (i.e. postpartum) and D. competing forces, specifically an increase in resistance from an adjacent muscle contracting (two headed black arrows) and an increase in intra-abdominal pressure (black upward pointing arrows). Reprinted with permission from Whittaker and Stokes (2011).

In addition to not establishing a relationship between USI and EMG measures, it is important to consider that like the MRI studies these investigations have been conducted predominantly on small numbers of young, healthy participants using nonclinical environments and tasks. Further they have ignored the RA muscle. Hence the confines of these investigations prevent extrapolation of the findings to patient populations, to dynamic tasks commonly employed in clinical practice, and to other muscles in the lumbopelvic region. This combined with the inconsistency in the EMG-thickness relationships reported suggest that, the validity or ability to use USI to quantify muscle activity are, at best, context dependent (Koppenhaver et al. 2009b). Consequently, the logical conclusion is that USI cannot be used to indiscriminately assess muscle activity.

In summary, although some authors conclude that USI can be used as a surrogate measure of muscle activity (McMeeken et al. 2004; Koppenhaver et al. 2009b; Ferreira et al. 2011) the literature reporting the relationship between increases in abdominal wall muscle activity (EMG) and thickness change (USI) is not conclusive. Until this relationship is better understood it may be premature for investigators to continue to employ USI as a surrogate tool for EMG. Furthermore, there is a lack of information upon which to interpret USI thickness changes of all four abdominal wall muscles in patients with LPP as compared to healthy control subjects, and during clinically relevant tests (i.e. ASLR and ADIM.)

2.3.2 Reliability of Ultrasound Imaging Measurements of the Abdominal Muscles

Costa et al (2009b) undertook a systematic review of the reproducibility of abdominal muscle measurement with USI. They identified 315 potentially relevant studies, but considered only 21 eligible for analysis. Nine of the studies investigated the EO, IO and TrA muscles, three the IO and TrA muscles, eight the TrA muscle alone, two the RA muscle, and one the EO muscle. As there was a considerable amount of heterogeneity detected in study design data pooling, and meta-analysis was not carried out (see Table 2.2 for a summary).The authors concluded that the investigations (ranging from 1997 – 2008) were of low quality (small sample sizes, did not include information about blinding or order of tests, and used poorly defined intervals) and provided information primarily about healthy cohorts (only five included participants with LBP). Reliability was assessed by some form of ICC in 18 of the studies however as different models were employed the authors urged caution in interpretation. Five studies provided confidence intervals, most used the standard error of measurement (SEM) as the agreement parameter, two used Bland and Altman plots and only one study calculated the minimum detectable change (MDC). The studies reported moderate to excellent (ICC, 0.62 - .092) reliability for single measures of thickness, and poor to good (ICC, 0.26 - 0.85) reliability for measure of thickness change. 80% of the ICC values for single measures were > 0.80 while most values for change in thickness were < 0.70. Further, the ICC values of the five studies that included participants with LBP were slightly lower that the sixteen studies that used a healthy cohort. The authors went on to point out that no investigations to date had reported on the reliability of measures of the difference in thickness changes between-day which they felt was important for determining improvement or deterioration in muscle function.

Since the review by Costa et al (2009b) three noteworthy studies looking at the reliability of the lateral abdominal wall muscles have been published (see Table 2.2 for a summary; Costa et al. 2009a; Koppenhaver et al. 2009a; Jhu et al. 2010). Koppenhaver et al

(2009a) used the mean of two measures to investigate intra and interrater reliability in participants with LBP reporting values for single within, and between day measures of thickness and thickness change (ASLR and ADIM) of the TrA muscle. Intrarater and interrater reliability ranged from ICC values of 0.96 – 0.99 and 0.88 – 0.94 respectively for same day, and 0.87 – 0.98 and 0.80 – 0.92 respectively for between day comparisons. Costa et al (2009a) used single measures to investigate intrarater reliability in participants with LBP reporting values for reproducibility of measurement of thickness, thickness change and thickness changes from single images before and after treatment of the EO, IO and TrA muscles. Intrarater reliability ICC values ranged from 0.96 – 0.97 for thickness measurements, 0.65 – 0.76 for thickness change and 0.33 – 0.58 for changes from single images before and after treatment. Finally, Jhu et al (2010) used the sonographic shadow created by a thin metal wire secured to the skin to control for medial and lateral motion of the ultrasound transducer to measure the reproducibility of resting, contracted and change in thickness, as well as change in length of the TrA muscle (by measuring the lateral slide of the anterior musculotendinous junction). Intra-rater reliability ICC values for all reliability estimates were found to be greater than 0.75.

The other parameter of the abdominal wall that has been investigated with USI is the inter-recti distance (IRD; Figure 3.3). In the only study published to date Liaw et al (2006) reported intrarater and interrater ICC values ranging from 0.78 – 0.89 and 0.85 – 0.95 respectively for resting measures at four imaging sites along the length of the linea alba in a young healthy cohort. Further, they reported SEM values associated with the intrarater condition ranging from 0.07 – 0.10cm.

In summary, there are a considerable number of studies that have been undertaken to establish the reproducibility of USI measurements of the abdominal wall. Some aspects of intra / interrater and within and between day reliability have been established however reliability has not been completely established (particularly for the RA muscle and IRD) and the generalizability of the findings to clinical settings are uncertain. Future investigations should include measures from all four abdominal muscles as well as the IRD, and focus on understanding the factors that are influencing the varied findings of the studies to date in an attempt to improve testing protocols. Further, reliability studies on LPP patients during clinical simulations are required.

Table 2.1: Summary of Reliability Studies of Abdominal Muscle Thickness (modified from Costa et al. 2009b)

Study	Sample	Muscles	Muscle Task	Reliability for Single Measures	Reliability for Changes in Thickness
Misuri et al (1997)	6 healthy	TrA, IO, EO, RA	1. Seated FRC 2. Seated RV 3. Seated TLC	CV: 0 - 15.7% Between subject variability: (F = 9.1-273, p = 0.003-0.00001) Intrasubject variability: (F = 0.54-3.2, p = 0.66-0.06)	No information
Bunce et al (2002)	22 healthy	TrA	1. Supine rest 2. Standing rest 3. Walking (3kmph)	Intrarater reliability ($ICC_{1,1}$: SEM [mm]) TrA Supine: 0.94; 0.35 TrA Standing: 0.88; 0.66 TrA Walking: 0.88; 0.56	$ICC_{1,1}$ TrA supine and standing: 0.78 TrA supine and walking: 0.48
Critchley and Coutts (2002)	10 unclear	TrA, IO, EO	1. Four point kneeling rest	Intrarater reliability ($ICC_{1,1}$; SEM [mm]) EO: .95; .66, IO: .98; .80, TrA: .94; .60	No information
Kidd et al (2002)	11 healthy	TrA	1. Seated rest 2. Standing rest	Same day ($ICC_{1,1}$; SEM [mm]; SEM [%]) TrA: 0.79 to 0.96; 029 to 0.57; 3.7 to 8.0 Between day ($ICC_{1,1}$; SEM [mm]; SEM [%]) TrA Sitting: 0.96; 0.18; 1.2 TrA Standing: 0.88; 0.33; 3.6	No information
McMeeken et al (2004)	13 healthy	TrA	1. Crook ly rest	$ICC_{?,?}$; 95% CI TrA B-mode: 0.99; 0.96- 0.99 TrA M-mode: 0.98; 0.94-0.99 Mean difference (mm); SD (mm); 95% LOA (mm); repeatability coefficient. TrA B mode: 0.03; 0.03; -0.17-0.24; 0.02 TrA M mode: 0.04; 0.04; -0.23-0.03; 0.04	No information
Teyhen et al (2005a)	30 LBP	TrA & EO+IO+TrA	1. Crook ly rest	$ICC_{3,1}$; 95% CI; SEM (cm); CV (%) TrA Intraimage: 0.98; 0.96-0.99; 0.013; 5 TrA Interimage: 0.93; 0.77-0.99; 0.031; 11 EO+IO+TrA Intraimage: 0.99; 0.99-1.0; 0.02; 5 EO+IO+TrA Interimage:0.97; 0.77-0.99; 0.09;14	No information
Ainscough-Potts et al	10 healthy	TrA, IO	1. Supine rest 2. Seated rest	Intrarater reliability ($ICC_{?,?}$) Inspiration 0.97	No information

(2006)			3. Ball sit 4. Ball sit with left leg lifted	Expiration 0.99 Images taken at the end of inspiration and expiration	
Beazell et al (2006)	19 healthy 20 LBP	TrA	Supine rest	Intrarater reliability ($ICC_{3,1}$) TrA; 0.94 to 0.99	No information
Rankin et al (2006)	10 healthy	TrA, IO, EO	1. Supine rest	Within day ($ICC_{1,1}$; 95% CI) 0.98 to 0.99; 0.91-1.00 Between days ($ICC_{1,2}$; 95% CI) 0.96-0.99; 0.85-1.00 " Bland and Altman tests produced mean differences close to zero and SD diff values were very low" 95% LOA (cm) EO: 0.12, IO: 0.22, TrA: 0.09	No information
Springer et al (2006)	32 healthy	TrA & EO+IO+ TrA	1. Crook ly rest 2. Crook ly ADIM	Single measure ($ICC_{2,1}$; 95% CI; SEM [mm]) TrA rest: 0.93; 0.86-0.96; 0.32 TrA ADIM:0.96; 0.92-0.98; 0.45 EO+IO+TrA rest: 0.98; 0.96-0.99; .80 EO+IO+TrA ADIM: 0.99; 0.98-1.00; 0.71 Ave. 3 measures ($ICC_{2,3}$; 95% CI; SEM[mm]) TrA rest: 0.98; 0.92-0.99; 0.13 TrA ADIM: 0.99; 0.98-0.99; 0.2 EO+IO+TrA rest:1.00; 0.99-1.00; 0.35 EO+IO+TrA ADIM: 1.00; 0.99-1.00; 0.34	Single measure ($ICC_{2,1}$; 95% CI; SEM [%]) TrA/total rest:0.91; 0.82-0.95; 2 TrA/total ADIM: 0.98; 0.96-0.99; 1.2 Ave. 3 measures: ($ICC_{2,3}$; 95% CI; SEM [%]) TrA/total rest: 0.99; 0.97-0.99; 0.5 TrA/total ADIM:0.99; 0.99-1.00; 0.7
Toma et al (2006)	16 healthy	TrA, IO, EO	1. Crook ly rest 2. Crook ly ADIM	ICC range from 0.70-0.94 SEM 0.44-0.7 mm; 8-15% mean thickness	ICC (TrA only); Left 0.44, Right 0.70
Hides et al (2007c)	19 healthy	TrA, IO	1. Crook ly rest 2. Crook ly ADIM	Intrarater reliability; Same Image($ICC_{3,1}$; 95% CI; SEM[mm]) TrA rest: 0.98;0.95-1.00; 0.01 TrA ADIM: 0.97; 0.98-1.99; 0.02 IO rest: 0.99; 0.97-1.00; .028 IO ADIM: 0.98; 0.95-1.00; 0.33 Across 3 images ($ICC_{3,4}$; 95% CI; SEM[mm]) TrA rest: 0.62 .032-0.85; 0.25 TrA ADIM: 0.80; 0.56-0.93; 0.22 IO rest: 0.82; 0.55-0.95; 0.16 IO ADIM: 0.66; 0.23-0.92; 0.39	No information

				Between day ($ICC_{3,6}$; 95% CI; SEM[mm]) TrA rest: 0.85; 0.42-0.98; 0.09 TrA ADIM: 0.84; 0.54-0.96; 0.18 IO rest: 0.69; 0.30-0.92; 0.30 IO ADIM: 0.63; 0.21-0.94; 0.43		
John and Beith (2007a)	24 healthy	EO	1. Crook ly rest	Intrarater reliability ($ICC_{?,?}$): 0.92		No Information
Kiesel et al (2007)	15 unclear	TrA	1. Crook ly rest 2. Crook ly ADIM	($ICC_{3,3}$; 95% CI; SEM[cm]; MDC[cm]) TrA rest: 0.98; 0 .91-0.99; 0.01; 0.03 TrA ADIM: 0.97; 0.91 -0.98;0.02; 0.06		($ICC_{3,3}$; 95% CI; SEM [%]; MDC [%]) TrA % change: 0.96; 0.91-0.99; 6.26; 17.34
Norasteh et al (2007)	27 healthy 12 LBP	TrA, IO, EO, RA	1. Supine rest 2. Seated rest 3. Standing rest	Healthy $ICC_{1,2}$; $ICC_{1,3}$, SEM TrA: 0.81; 0.80; 0.45 IO: 0.97; 0.91; 0.07 EO: 0.96; 0.72; 0.33 RA: n/a; 0.85; 0.84	LBP $ICC_{2,1}$; SEM TrA: 0.91; 0.30 IO: 0.87; 0.31 EO: 0.87; 0.35	No information
Roddey et al (2007)	70 healthy	TrA	1. Crook ly rest 2. Crook ly TrA	$ICC_{2,1}$; SEM(mm) TrA R rest: 0.83; 0.03 TrA R contracted 0.81; 0.09 TrA L relaxed 0.93; 0.02 TrA L contracted 0.92; 0.04		No information
Mannion et al (2008a)	14 healthy 14 LBP	TrA, IO, EO	1. Crook ly rest 2. Crook ly ADIM	Healthy $ICC_{3,1}$;SEM(mm);CV TrA rest R: 0.83; 0.40; 10.3 L: 0.86; 0.40; 10.7 TrA ADIM R: 0.78; 0.58; 10.7 L: 0.75; 0.65; 12.0 IO rest R: 0.92; 0.58; 8.8 L: 0.94; 0.72; 9.8 EO rest R: 0.26; 0.84; 17.0 L: 0.59; 1.03; 19.6	LBP $ICC_{3,1}$;SEM(mm); CV TrA rest R: 0.89; 0.27; 7.2 L; 0.63; 0.46; 11.5 TrA ADIM R:0.88; 0.41; 7.7 L: 0.41; 0.78; 14.3 IO rest R:0.73; 0.82; 10.8 L: 0.85; 0.68; 9.8 EO rest R: 0.42; 1.20; 19. L: 0.51; 0.84; 14.	Healthy ($ICC_{3,1}$;SEM[mm],CV) TrA contraction ratio R: 0.52; 0.16; 11.4 L: 0.50; 0.16; 10.9 EO contraction ratio R: 0.66; 0.04; 4.4 L: 0.60; 0.06; 5.8 IO/EO cont. ratio R: 0.72; 0.04; 3.9 L:0.61; 0.03; 3.2 TrA activation ratio R: 0.62; 0.02; 30.2 L:0.55; 0.02; 38.0	LBP $ICC_{3,1}$;SEM[mm];CV TrA contraction ratio R: 0.80; 0.09; 6.0 L: 0.28; 0.16; 11.6 EO contraction ratio R: 0.43; 0.05; 5.4 L:0.57; 0.05; 5.6 IO/EO cont.ratio R: 0.25; 0.05; 4.5 L: 0.39; 0.05; 5.6 TrA activation ratio R: 0.48; 0.02; 27.4 L: 0.32; 0.03; 49.5
Costa et al (2009a)	24 LBP	TrA, IO, EO	1. Crook ly rest 2. Crook ly	$ICC_{2,1}$; 95% CI; SEM(cm);SDC(cm)		$ICC_{2,1}$; 95% CI; SEM(%);SDC(%)

			knee flexion / extension leg suspended	0.97;0.96-0.97; 0,04; 0.11	0.72; 0.65-0.76; 15%; 41%
Koppenhaver et al (2009a)	30 LBP	TrA	1. Crook ly rest 2. Crook ly ADIM 3. Supine rest 4. Supine ASLR Images taken at the end of expiration	<u>Intrarater reliability</u> Withinday(ICC3,2;95%CI;SEM[mm];MDC[mm]) TrA crook ly rest: 0.96; 0.91-0.98; 0.2; 0.5 TrA ADIM:0.97; 0.94-0.99; 0.3; 0.7 TrA supine rest: 0.98; 0.95-0.99; 0.1; 0.4 TrA ASLR: 0.96; 0.92-0.98; 0.3; 0.8 Btw. day (ICC3,2;95% CI;SEM[mm];MDC[mm]) TrA crook ly rest: 0.93; 0.85-0.97; 0.2; 0.7 TrA ADIM: 0.87; 0.74-0.94; 0.5; 1.3 TrA supine rest: 0.94; 0.87-0.97; 0.2; 0.6 TrA ASLR:0.93; 0.86-0.97; 0.4; 1.1 <u>Interrater reliability</u> Withinday (ICC2,2;95%CI;SEM[mm];MDC[mm]) TrA crook ly rest: 0.94; 0.79-0.98; 0.2; 0.7 TrA ADIM: 0.89; 0.75-0.95; 0.5; 1.4 TrA supine rest: 0.89; 0.78-0.95; 0.3; 0.8 TrA ASLR:0.91; 0.79-0.96; 0.4; 1.1 Btw. day (ICC2,2;95%CI; SEM[mm]; MDC[mm]) TrA crook ly rest: 0.92; 0.83-0.96; 0.3; 0.7 TrA ADIM: 0.90; 0.80-0.95; 0.4; 1.2 TrA supine rest: 0.91; 0.82-0.96; 0.3; 0.7 TrA ASLR:0.80; 0.58-0.91; 0.6; 1.7	<u>Intrarater reliability</u> Within day (ICC3,2; 95% CI; SEM[%]; MDC[%]) ADIM % change: 0.94; 0.87-0.97; 9.8, 27.1 ASLR % change: 0.92; 0.84-0.96; 9.2; 25.4 Btw. day (ICC3,2; 95% CI; SEM[%]; MDC[%]) ADIM % change: 0.73; 0.43-0.87; 19.2, 53.3 ASLR % change: 0.89; 0.76-0.95; 12.3; 34.1 <u>Interrater reliability</u> Within day (ICC3,2; 95% CI; SEM[%]; MDC[%]) ADIM % change: 0.73; 0.42-0.87; 19.0, 52.7 ASLR % change: 0.91; 0.81-0.96; 8.7; 24.2 Btw. day (ICC[3,2]; 95% CI; SEM[%]; MDC[%]) ADIM % change: 0.55; 0.04-0.79; 22.8, 63.3 ASLR % change: 0.78; 0.53-0.89; 15.6; 43.2

ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg raise, Btw = between, CV = coefficient of variation, EO = external oblique, FRC = functional residual capacity, ICC = interclass correlation coefficient, IO = internal oblique, L = left, LBP = low back pain, MDC = minimal detectable change, mm = millimetres, R = right, RA = rectus abdominis, RV = residual volume, SDC = smallest detectable change, SEM = standard error of measurement, TLC = total lung capacity, TrA = transversus abdominis

2.3.3 Sonographic Characteristics of the Abdominal Muscles; Normal and Abnormal Patterns

In addition to the studies mentioned above, observational studies (as outlined below) employing USI have been used to measure the thickness, change in length and/or CSA of the lateral abdominal wall muscles (Figure 3.2) and the RA (Figure 3.4). Imaging has been performed in both static (resting) and dynamic (i.e. ASLR, ADIM, respiration, balance, upper limb and walking tasks etc.) conditions within various (LBP, LPP, PGP, amputees, athletes with groin pain and healthy) cohorts. In many cases the findings have been compared to the motor control literature in an attempt to speculate on the function of the muscle during the specific experimental set-up. These studies can be summarized as those that provide resting values, or describe patterns of architectural change resulting from respiration and tasks involving voluntary (ADIM), or automatic (i.e. ASLR, walking or running and leg or arm lifting tasks) activation.

2.3.3.i Sonographic characteristics of the abdominal muscles; resting state

Rankin et al (2006) were the first to report relative resting thickness values for the abdominal wall muscles. They imaged 123 healthy participants (55 men [21 – 72 yrs], 68 women [20 – 64 yrs]) with the goal of establishing normal reference ranges for abdominal muscle size, side-to-side symmetry, and determining the effect of age and gender. They reported that at rest the RA, EO, IO, and TrA muscles represent 35.0%, 22.8%, 28.4%, and 13.8% of the total abdominal muscle thickness respectively. Further, this pattern is independent of age, gender or side of measurement. Their findings were consistent with previously reported data by DeTroyer et al (1990) and Misuri et al (1997; Table 2.3).

As a general rule the literature suggests that males have significantly thicker lateral abdominal muscles than females (Bunce et al. 2002; Rankin et al. 2006; Springer et al. 2006) and that this gender difference persists, with the exception of TrA, when normalised for body mass (Rankin et al. 2006). Further, Springer et al (2006) have reported that the TrA muscle represents a greater proportion of the total lateral abdominal muscle thickness in healthy women than in men, while Rankin et al (2006) have found that the relative thickness of the IO muscle is greater in males.

Table 2.2: Summary of Healthy Resting Abdominal Muscle Thickness Measurements

STUDY	TrA*		IO*		EO*		RA*		Additional Information
	Female	Male	Female	Male	Female	Male	Female	Male	
DeTroyer et al (1990)		4.6		11.4		7.9			Seated, right side n = 6, 25-39 yrs.
Misuri et al (1997)		5.8±1.3		11.1±3.8		5.5±1.7		11±4.3	Seated, FRC, right side n = 6, 26- 36 yrs.
Bunce (2002)	2.7±0.33	3.3±0.33							Supine crook lying, side unspecified n = 10 males, 12 females, 18-44 yrs.
Rankin et al (2006)	3.7±1.0	4.9±1.3	8.3±2.3	11.8±2.8	7.4±1.8	9.7±2.2	10.2±1.6	12.5±2.3	Supine crook lying, mean of sides n = 55 males, 21-72 yrs. n = 68 females, 20-64 yrs.
Springer et al (2006)	4.2±0.7	5.0±0.9							Supine crook lying, mean of sides n = 17 males 18-44 yrs. n = 15 females 19-45 yrs.
Coldron et al (2008)							9.77±1.6		Supine crook lying, mean of sides n = 69, 27 (18-45) yrs.

*all values are expressed as mm (mean ± s.d.). EO = external oblique, FRC = functional residual capacity, IO = internal oblique, n= number of participants, RA = rectus abdominis, TrA = transversus abdominis, yrs. = years of age

In support of Rankin et al (2006), Springer et al (2006) found no difference associated with hand dominance in the side-to-side resting thickness of the TrA in a healthy cohort. There is however preliminary evidence to support side to-side asymmetry in the trunk rotators (EO, IO) of persons who perform repetitive asymmetric motions during occupational or recreational pursuits or have an underlying anatomical predisposition. For instance, Hides et al (2008) found large side to side differences in IO muscle thickness in a small sample of elite cricketers, while in a retrospective study of unilateral lower limb amputees (n = 70) Springer and Gill (2007) reported that the IO and EO muscles were significantly larger on the side of the amputated limb. It is interesting to note that in both of these studies investigators found no side-to-side differences in thickness of the TrA muscle further supporting its role in postural control as opposed to trunk motion. There are no studies that have reported on differences in the resting thickness of the abdominal wall muscles in persons with LBP or LPP however Jansen et al (2010) have reported a decreased resting thickness of the TrA in a cohort of athletes with longstanding adduction-related groin pain.

In an attempt to characterize changes in the RA muscle and provide reference ranges for the first year postpartum, Coldron et al (2008) reported on the thickness (Figure 3.4), length, CSA and IRD (Figure 3.3) in postnatal participants, versus age-matched nulliparous female controls, at day 1, and 2, 6 and 12 months postpartum. They found that the RA muscle was significantly thinner, wider and the IRD was significantly larger in the postnatal participants. Further, there was some recovery in these parameters over the first two months postpartum (i.e. the RA muscle became thicker and the RA width and IRD decreased) although none of the parameters returned to control values by the 12 month. The authors point out that the changes in RA and IRD morphology likely have implications with respect to the forces that can be generated within the muscle as well as the stiffness of the anterior abdominal wall, predisposing this population to a mechanical disadvantage in loading situations. This is an important consideration for two main reasons. Firstly, if these changes are consistently seen in a post-partum population then they must be factored into any analyses of abdominal wall function in this population. In other words, postpartum women represent a sub-classification that will confound the findings with respect to larger cohort, in which they may be grouped. Secondly, the majority of the USI studies of the abdominal wall muscles have reported only on the EO, IO and TrA without consideration of the status of the RA and IRD. As the PMCT of the lateral muscles is continuous with that of the RA and IRD it is critical that their status are taken into consideration when interpreting changes in these muscles.

2.3.3.ii Sonographic characteristics of the abdominal muscles; respiration

The imaging studies concerned with monitoring the abdominal wall muscles during respiration have primarily commented upon the TrA and IO muscles. Ainscough-Potts et al (2006) reported significantly greater TrA and IO thickness at the end of expiration versus inspiration in 30 healthy participants during quiet respiration in relaxed supine lying and sitting postures. These findings are in contrast to studies employing fine wire EMG which have found little to no activity of these muscles during quiet supine respiration in healthy participants (Strohl et al. 1981; Goldman et al. 1987; De Troyer et al. 1990). This apparent discrepancy points to a very important principle that must be considered when interpreting USI studies. Specifically, that all muscles have a constant volume, and that passive changes in muscle length are associated with inverse changes in thickness. In this case the modulation in TrA and IO thickness may be a result of passive lengthening and shortening resulting from motion of the abdominal contents with respiration versus muscle activity. Specifically, as the diaphragm descends during inspiration, or with a valsalva manoeuvre and the abdominal contents are displaced down and outward there is a resulting increase in length and apparent decrease in thickness of the TrA and IO muscles. Correspondingly, on expiration the reverse is seen and the TrA and IO muscles decrease in length and appear to shorten. This displacement and resulting modulation in the thickness of the TrA and IO is further confounded by subject position as some will facilitate abdominal expansion with respiration while others may inhibit it.

This rhythmic change in thickness of the lateral abdominal wall muscles, corresponding to respiration, has also been observed in persons with LBP (Critchley & Coutts 2002). Further, Whittaker (2008) showed a change in thickness of the TrA and IO muscles of 1.3% (+/- 5.8%) and 2% (+/- 7.2%) respectively, in a LPP cohort, during quiet respiration. More so, that in persons with LPP and a concurrent respiratory dysfunction (hypocapnia), these values can increase to 20.8% (± 7.6%) and 9.2% (±8.1%) respectively.

In regards to respiration during loading tasks McEvoy et al (2008) have demonstrated increases in TrA thickness associated with increased ventilatory demands during an unsupported upper limb exercise test in 26 healthy participants. This finding is supported by EMG studies suggesting that when respiration is challenged through either increased chemical drive (Hodges et al. 2001), elastic loading (Ninane et al. 1992), or as in this case, is voluntarily promoted (De Troyer et al. 1990; Abe et al. 1996; Misuri et al. 1997; McEvoy et al. 2008), the TrA muscle (followed by the IO and RA) is recruited to assist with expiration.

As the thickness of TrA (and potentially IO) has been shown to modulate with quiet respiration and tasks that load the trunk, in a variety of investigations involving both

healthy and LPP cohorts, it is important that this be taken into consideration during study design. Specifically, care must be taken to standardize subject position and the points in the respiratory cycle were measurements of these muscles are to be made. As many past investigations have not taken the respiration variable into consideration care must be taken in the interpretation of their findings. Thankfully however more recent investigators understand the importance of standardizing for respiration and have begun to do so (Stuge et al. 2006b; McEvoy et al. 2008; Koppenhaver et al. 2009a; Teyhen et al. 2009b).

2.3.3.iii Sonographic characteristics of the abdominal muscles; drawing-in

The most commonly investigated clinical muscle test of the abdominal wall is 'Abdominal Hollowing' or the 'Abdominal Drawing-in Manoeuvre' (ADIM; Richardson & Jull 1995; Beith et al. 2001; Critchley & Coutts 2002; Teyhen et al. 2005a; Hides et al. 2006b; Stuge et al. 2006b; Gill et al. 2007; Kiesel et al. 2007) as clinical trials that have focused on re-educating this drawing in action have been successful in decreasing LPP (O'Sullivan et al. 1998; Stuge et al. 2004; Goldby et al. 2006). Based on the principles of traditional muscle testing the ADIM is considered a muscle test for the TrA muscle as a voluntary contraction would result in a 'drawing-in' of the abdominal wall due its horizontal fibre orientation (Urquhart et al. 2005). An MRI investigation of the manoeuvre, on healthy participants, has demonstrated that during the ADIM the muscle bellies of the TrA muscle are seen to thicken and shorten, resulting in an associated reduction of the circumference of the trunk and flattening of the anterior abdominal wall (Hides et al. 2006b). This action of the TrA muscle can be viewed with USI and measurements of the thickness and length changes made with USI correlate well with measures obtained with MRI (Hides et al. 2006b).

There are several studies that have looked at the difference in thickness change of the TrA and IO muscles during the ADIM between various case cohorts and healthy participants. Critchley and Coutts (2002) compared the change in thickness of the TrA and IO muscles during a four-point kneeling ADIM between participants with and without chronic LBP (n=20) and controls (n=24), and demonstrated significantly smaller increase in TrA thickness muscle in the LBP cohort. These findings were supported by the work of Kiesel et al (2007) who performed a similar investigation during a supine crook lying ADIM and demonstrated significantly smaller increases in TrA thickness in several different categories (treatment-based classification system) of participants with LBP. In contrast, both Stuge et al (2006b) and Pulkovski et al (2011) measured the change in thickness of the TrA and IO muscles during a supine crook lying ADIM in participants with and without persisting PGP, and chronic LBP, respectively and found no statistical significant difference between the groups.

Perhaps the variation in the findings can be explained by better understanding the shortcomings of using the ADIM as a clinical test. The ADIM is a voluntary motor skill. Its performance depends upon a variety of factors, only one of which is function of the TrA muscle. Factors such as how the skill is taught, the participant's ability to learn the skill, and any previous exposure, will all impact performance. Further, the ADIM is an extremely difficult test to standardize, both in regards to the kinematics of the task, and the effort exerted. Although the goal of the ADIM is to be a clinical muscle test of the TrA muscle, MRI (Hides et al. 2006b), EMG (Beith et al. 2001), and USI (Teyhen et al. 2005a) studies have identified changes in the IO muscle during its performance suggesting that it is not as selective as other traditional muscle tests. Future studies employing the manoeuvre must find novel ways to standardize the manoeuvre across participants and data collection points.

2.3.3.iv Sonographic characteristics of the abdominal muscles; automatic tasks

In addition to the studies employing the ADIM several others have monitored and reported on the architectural changes of the abdominal wall muscles during different postures (Ainscough-Potts et al. 2006; Reeve & Dilley 2009) or limb lifting tasks (Ferreira et al. 2004; Hides et al. 2007c; McEvoy et al. 2008; 2009; Teyhen et al. 2009b). As with the ADIM most of these investigations have excluded the RA muscle and reported primarily on changes in thickness of the EO, IO and TrA muscles.

Two studies have measured the effect of supine lying, sitting and standing postures as well as different sitting surfaces on the thickness of the TrA and IO muscles (Ainscough-Potts et al. 2006; Reeve & Dilley 2009). Ainscough-Potts et al (2006) reported that the thickness of the TrA and IO did not differ between supine lying and relaxed sitting on a chair, or gym ball, in a cohort of 30 healthy participants. This was supported by Reeves and Dilley (2009) who monitored TrA thickness in 20 healthy participants during five postures; supine lying, erect sitting, slouched sitting, erect standing and sway-back standing. They too found no significant difference in TrA thickness during supine lying and slouched sitting. However, they reported greater TrA thickness during erect sitting vs. slouched sitting, and during erect standing vs. sway-back standing. Although there are many factors that could result in changes in thickness of these muscles between the various postures other than muscle activity (i.e. shift in the abdominal contents or alterations in breathing patterns) these findings are partially supported by the motor control literature. Specifically, Claus et al (2009) who found greater TrA activity (fine-wire EMG) in healthy male participants positioned in lumbar or thoracolumbar lordosis vs. a slump sitting position.

A commonly employed clinical test in the lumbopelvic region is the ASLR test (Mens et al. 2001; O'Sullivan et al. 2002; de Groot et al. 2008; Beales et al. 2009b; 2009a; 2009c; 2010). This test requires supine participants to raise one leg five cm off the supporting surface without bending their knee (see Section 3.2.3). Teyhen et al (2009b) monitored the thickness (USI) of the IO and TrA muscles in 15 participants with unilateral LPP and 15 sex-matched controls during the performance of the ASLR test. They reported a 23.7% and 11.2% increase in TrA and IO thickness respectively in the control group, and significantly smaller (6.4% and 5.7% respectively) increases in thickness in the LPP group. Further, they pointed out that the response of the two muscles appeared to be symmetrical regardless of the side of the leg lifted or the unilateral nature of the symptoms. To date no EMG studies have reported a difference in the relative magnitude of TrA and IO muscle activity during this task in a LPP cohort, however Cowan et al (2004) have demonstrated a delay (fine wire EMG) in the onset of the TrA during the ASLR in 10 participants with long standing groin pain versus asymptomatic controls.

In addition to the ASLR test several investigators have investigated lateral abdominal wall muscle thickness changes utilizing laboratory based leg loading tasks (Ferreira et al. 2004; Hides et al. 2007c; 2009). For instance Ferreira et al (2004) positioned healthy and recurrent LBP participants in a standardized crook lying supine position in which their legs were suspended by slings wrapped around the knees and ankles. Participants performed resisted isometric knee flexion and extension equivalent to 7.5% and 15% of their body weight while the thickness (USI) and activity (fine wire EMG) of the EO, IO and TrA muscles were monitored. They reported significantly smaller increases in TrA thickness and activity in the recurrent LBP group during the tasks, however no difference in the change of thickness or activity of the IO and EO muscles. Hides et al (2007b; 2009) used a novel sling system outfitted with a strain gauge to standardize (0%, 25% and 45% body weight) a simulated unilateral weight-bearing task, and monitored thickness changes of the TrA and IO muscles as well as TrA muscle shortening in healthy and LBP participants. They reported significantly less shortening of the TrA and great increases in IO thickness in the LBP than the healthy cohort. In contrast to Ferreira et al (2004), they found no statistical difference between the groups with respect to changes in TrA muscle thickness during the loading task.

In contrast to the leg loading tasks McEvoy et al (2008) described the pattern and consistency of TrA thickness during an incremental seated upper limb exercise test in 26 young healthy participants. Although the experimental set up was quite complicated the rationale for employing the chosen test was that it was more consistent with activity of daily living then the studies to date. They reported TrA thickness changed significantly during the course of the progressively more challenging test and that measures at later

points in the test (minutes 10, 11 and 12), which were associated with the largest loads, were significantly greater than at base line.

In summary, investigations to date have reported on the resting morphology or patterns of architectural change of the abdominal wall muscles in various cohorts during specific postures & tasks. Characteristic patterns are starting to emerge, patterns that for the most extent reinforce what has been seen in the motor control studies that have employed EMG. Specifically there is evidence of sustained tonic increases in thickness of the TrA during more erect postures and a variety of different tasks in healthy cohorts while there is evidence of diminished changes in thickness and length of the TrA muscle in LPP cohorts in comparison to controls. Further, there is contrasting findings in regard to changes in IO thickness with some studies reporting no change, while others report diminished or increased thickness in LPP cohorts. To date only one study was found that has included measures of the RA muscle or considered the length of the IRD.

2.4 Rehabilitative Ultrasound Imaging of the Bladder and Bladder Base

Conventional USI has been used to measure the morphology (Bernstein et al. 1991; Morkved et al. 2004) of the PFM and their impact on the bladder base (Thompson & O'Sullivan 2003; Sherburn et al. 2005; Thompson et al. 2005) bladder neck (Schaer et al. 1995; Reddy et al. 2001; Thompson et al. 2005; Thompson et al. 2006a) and anorectal angle (ARA; Peng et al. 2006; 2007a; Lovegrove Jones et al. 2009), during static and dynamic conditions (Figure 2.6; see Whittaker et al. 2007b for a summary). These imaging studies have been carried out from a variety of approaches (transperineal and transabdominal), planes (sagittal and transverse), and positions. This section discusses the pros and cons of the two approaches and outlines the decision to employ transabdominal techniques to monitor the bladder base throughout this project. It then goes on to evaluate the validity and reliability of bladder base measurements, as well as the literature in regard to this parameter in persons with LPP and UI.

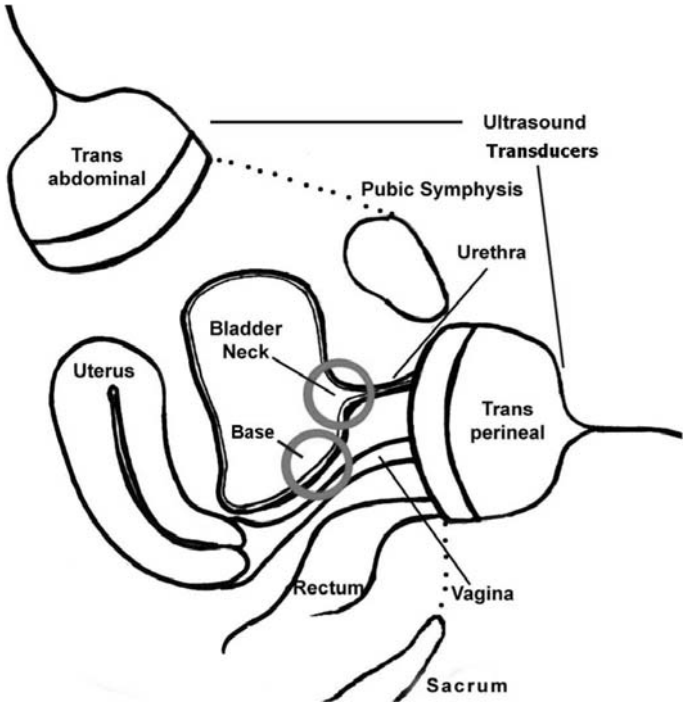


Figure 2.6: Comparison of transperineal and transabdominal USI in a supine position. Note the different transducer locations and regions of the bladder where movement is visualized.

2.4.1 Transabdominal vs. Transperineal Ultrasound Imaging of the Bladder

Transperineal USI involves placement of the transducer in a sagittal plane along the midline of the perineum. It is considered advantageous to the transabdominal approach as it provides a direct view of the levator ani muscles, facilitating study of their morphology, as well as the bony pubic symphysis, the bladder neck, and the ARA (Figure 2.7), which serve as standardized points of reference. Further, the techniques for evaluation of bladder neck and ARA motion during PFM contraction and straining are well established (Schaer et al. 1995; 1996; Peschers et al. 2001; Dietz 2004; Peng et al. 2006; 2007b). The disadvantages of the transperineal technique are that proficiency requires extensive training, measurements are complex, and transducer location is both invasive and may at times interfere with functional manoeuvres (Whittaker et al. 2007b).

In contrast, the transabdominal approach involves placement of the transducer on the midline of the abdomen just cephlad to the pubic symphysis (Figures 3.4 and 3.5). This technique was originally described by White et al (1980) for the investigation of women with stress UI, however was abandoned in favour of the transperineal approach, due to its inability to consistently provide a view of the bladder neck, which is a common point of investigation in this population. This approach has received renewed interest, as it is a

relatively non-invasive method to obtain information about the position of the bladder base (which serves as a marker of the interaction between the lifting action of the PFM and IAP), as well as serving as source of biofeedback when retraining the PFM (Dietz et al. 2001; O'Sullivan et al. 2002; Bo et al. 2003; Thompson & O'Sullivan 2003; Whittaker 2004a; Frawley et al. 2005; Sherburn et al. 2005; Thompson et al. 2005; 2006b; 2006c; 2006a; Beales et al. 2009b; 2009a).

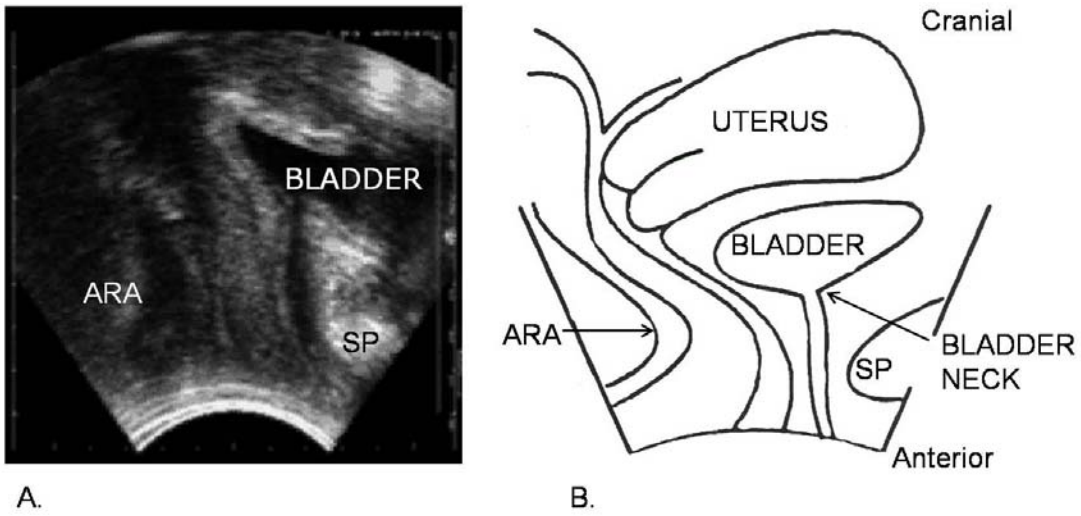


Figure 2.7: Transperineal ultrasound imaging. A. A transperineal ultrasound image (sagittal) showing the bladder, anorectal angle (ARA), symphysis pubis (SP). B. Labelled illustration of the transperineal ultrasound image in A.

Unlike the transperineal the transabdominal technique is relatively easy to learn, measurements and image interpretation are less complex, and transducer placement does not restrict movement of the lower extremities, which has been argued to be important for assessment of people with lumbopelvic pain (O'Sullivan et al. 2002). Furthermore, the transabdominal technique is totally non-invasive (i.e. the subject does not need to undress), which may be important in specific populations where invasive techniques may not be desirable (i.e. children, adolescents, men, and some ethnic groups). Ultimately the decision to employ the transabdominal techniques during this project are related to these arguments and the fact that it was likely to be seen as more acceptable to potential participants, ethic committees and to the populace of physiotherapists that treat LPP that are not comfortable with approaching the perineum directly.

2.4.2 Validity of Sonographic Measurements of the Bladder Base

As described earlier (Section 2.3.1), MRI has been used to establish the validity of USI as a tool for the measurement of muscle architecture and several investigations have been undertaken to describe the relationship between these architectural changes and EMG recordings of muscle activity. There are no studies that have compared measurements of bladder base position obtained with USI and MRI. With that being said several MRI studies have described changes in the position of the bladder base during voluntary contraction and straining in both continent and incontinent cohorts (Christensen et al. 1995; Fielding et al. 1998; Bo et al. 2001). For instance, using MRI to monitor bladder wall motion during a supine voluntary PFM contraction in continent females Christensen et al (1995) demonstrated that the greatest amount of motion (7.0 ± 2.8 millimetres; mm) occurs at the posteroinferior region of the bladder wall (bladder base) and that the displacement is most easily observed in a sagittal plane. BØ et al (2001) reconfirmed the elevating function of the PFM using dynamic MRI to measure the inward motion of the bladder base (10.8 ± 6.0mm) during a seated PFM contraction in both continent and incontinent women. Further, these authors demonstrated a mean outward motion of 19.1 ± 7.4mm associated with straining. Although these findings were not directly compared to values gathered with USI they are consistent with the ranges reported in similar experimental designs employing transabdominal USI (Bo et al. 2003; Sherburn et al. 2005).

Further, construct validity for the use of transabdominal USI to monitor bladder base motion to provide an indicator of PFM function comes from studies comparing the findings of bladder neck motion (obtained with transperineal USI) to bladder base motion (obtained from transabdominal USI). Thompson et al (2005; 2007) compared the findings of the two parameters / approaches during PFM contraction, straining, and an abdominal curl in a group of women with incontinence and continent controls. They demonstrated that, although a divergence in bladder base and bladder neck motion occurred in 15% of the participants, there was a significant correlation between measurements across the tasks.

To date, no studies have described the relationship between the amount of EMG activity of the PFM and bladder base elevation although many investigators state that movement of the bladder base is a marker for PFM activity (O'Sullivan et al. 2002; Bo et al. 2003; Thompson & O'Sullivan 2003; Sherburn et al. 2005). As the position of the bladder base is dependent on many factors it is likely that the relationship between PFM activity and bladder base motion would be affected by the complex interrelationship between elevating forces generated from PFM contraction, downward forces resulting from changes IAP, the start position of the bladder base, and any pre-existing myofascial laxity in the region (see

Whittaker et al. 2007b for more information). Until such inquiry is undertaken to clarify this relationship it may be prudent to assume that bladder base motion is indicative of more than PFM activity and to acknowledge this limitation.

2.4.3 Reliability of Sonographic Measurements of the Bladder Base

The reliability of measuring global bladder base (GBB) motion has been investigated during voluntary PFM contraction (Sherburn et al. 2005), straining, abdominal curl-up, and the ASLR test (O'Sullivan et al. 2002; Sherburn et al. 2005; Thompson et al. 2005; 2006a). Good intrarater and interrater reliability for measurement of GBB motion (transverse and sagittal views) during a PFM contraction (ICC, 0.81-0.88; Sherburn et al. 2005), as well as good to excellent intrarater reliability (transverse view) during the ASLR test (ICC, 0.98: O'Sullivan et al. 2002) have been reported. In contrast, Thompson et al (2005; 2006a) report only moderate reliability for the measurement of GBB motion (sagittal view) during an abdominal curl-up (ICC, 0.53) and straining (ICC, 0.51) likely due to difficulty in maintaining a consistent transducer position when the abdominal wall is displaced outward with the contraction of the abdominal muscles or increase in IAP. Consequently, transabdominal USI may have limited value for monitoring bladder base motion during these tasks. To date there are no studies looking at measures of GBB position or the reliability of measuring GBB displacement between days.

Measurements of bladder base displacement are influenced by a variety of factors including; bladder filling, subject and transducer position / motion, measurement sites, and verbal instructions (see Whittaker et al. 2007b for more information). As such it is critical that each of these factors are given due consideration during study design, and that the reliability of the entire ‘experimental system’ (including factors associated with the subject, the operator, the ultrasound imaging unit, the measurement site, the measurement method, and the rater) is established before an investigation proceeds.

2.4.4 Normal and Abnormal Patterns of Bladder Base Motion

In addition to the studies mentioned above, observational studies employing transabdominal USI have assessed bladder base motion during voluntary PFM contraction (Bo et al. 2003; Thompson & O'Sullivan 2003; Sherburn et al. 2005; Thompson et al. 2005; 2006a; O'Sullivan & Beales 2007b) straining, abdominal curl-up, and the ASLR test (O'Sullivan et al. 2002; Thompson et al. 2005; 2006a; O'Sullivan & Beales 2007b; Beales et al. 2009b; 2009a) in various cohorts (healthy, UI, PGP). In some cases the findings have been compared to the motor control literature in an attempt to speculate on the activity of the PFM as well as the abdominal wall muscles.

Bø et al (2003) measured bladder base motion during a supine PFM contraction in 20 healthy female participants. They reported that in all but one of the participants the bladder base elevated and that the mean displacement was 11.2 mm. Thompson and O'Sullivan (2003) carried out a similar measurement in 104 participants with incontinence (urge and stress UI) and prolapse. Three different patterns of bladder base motion were identified; with 38% elevating, 43% depressing and 19% having no displacement. Further, in the UI group there was a higher than expected number that elevated the bladder base, and in the urgency and prolapse groups a higher number that depressed the bladder base. This was followed by another investigation aimed at comparing bladder base displacement during a PFM contraction, straining and an abdominal curl-up in continent and incontinent women. They reported no difference between groups during a voluntary PFM contraction, however increased decent during straining in the incontinent cohort. Finally O'Sullivan and Beales (2007b) assessed the ability of eight participants with sacroiliac joint pain to elevate the bladder base during a voluntary PFM contraction prior to a motor learning intervention aimed at changing performance of the ASLR test. They reported that all eight participants exhibited descent of the bladder base (average magnitude of 11.5mm) prior to the intervention and that following the intervention the descent was eliminated

With respect to the ASLR test, O'Sullivan et al (2002) monitored bladder base displacement in participants with sacroiliac joint pain and matched controls. They reported that participants with sacroiliac pain demonstrate increased bladder base descent in comparison to the healthy cohort. They went on to speculate that these differences were part of a compensatory strategy of the neuromuscular system to control the pelvis while the load of the leg was transferred through the pelvis as there were indications of altered breathing patterns and decreased diaphragmatic excursion (abdominal bracing). This investigation was followed up by two others aimed at further investigating the motor control strategies associated with an ASLR test in healthy (Beales et al. 2009b) and PGP (Beales et al. 2009a) participants. In the first, surface EMG of the abdominal and chest wall muscles, IAP, respiratory rate and bladder base motion was monitored 14 pain-free nulli-parous women during an ASLR test. In the second, a similar methodology was employed with 12 female participants with chronic PGP. The findings support the earlier investigation with greater bladder base descent seen in the PGP cohort. Further, a pattern of bracing through the abdominal and chest wall muscles associated with an increase in IAP was detected in this cohort. They went on to suggest that perhaps the splinting activation of the diaphragm and oblique abdominals generated a significant increase in IAP that overcame the ability of the PFM to control the position of the bladder base.

In summary, investigations to date have reported on bladder base displacement in various cohorts during voluntary PFM contraction, straining, abdominal curl-up and the ASLR test. As with the abdominal wall muscles characteristic patterns are starting to emerge. Specifically, there is evidence of more frequent and greater descent of the bladder base during a voluntary PFM contraction in women with incontinence and prolapse, as well as increased bladder base descent in incontinence, prolapse and PGP cohorts in comparison to controls during an ASLR. Although the bladder base is a marker for the pelvic floor there are many factors that must be taken into consideration when determining the direction or degree of bladder base displacement, consequently no known studies have made an attempt to correlate bladder base displacement and PFM activity. As such the true clinical significance of this parameter is still unknown.

2.5 Conclusions

Persons with LPP exhibit variable patterns of altered muscle control. As muscle control is modifiable through rehabilitation it seems logical that if these alterations can be identified, a treatment strategy consistent with these changes could be developed. To date few objective tools exist to enable physiotherapists to detect specific changes in muscle function in a typical clinical setting. Ultrasound imaging appears to hold considerable promise in this regard, as seen in the investigations outlined in this chapter and as exemplified in one previously published case history (Whittaker 2007) and the two included in Appendix 13 (see Section 10.7). To date, some aspects of validity and reliability have been investigated, and many observational studies involving various cohorts and testing methodologies have been undertaken. Although these investigations have taken place primarily in laboratory settings, in which many variables can be controlled for, and do not necessarily address the clinical value of USI during routine physiotherapy practice, they serve as a rich source of information to inform future investigations. Specifically, they provide insight into the strengths and limitations of various USI parameters, cohorts and study designs. They also highlight topics for investigation.

2.5.1 Implications for Methodology

In the context of the research contained within this thesis there are five main implications that arise out of the information contained in this review of the literature.

1. *Lumbopelvic pain is heterogeneous* - Many authors have alluded to the heterogeneous nature of low back and pelvic girdle pain (Fourney et al. 2011; O'Sullivan 2011) and called for the need to sub-group based on movement behaviours (O'Sullivan 2005; Dankaerts et al. 2009), pain behaviours (Martel et al. 2010),

pathology (Borkan et al. 1998), or treatment that an individual is most likely to respond to (so called 'prediction rules'; Fritz et al. 2003; Delitto 2005). This is critical consideration as investigation of a heterogeneous group is unlikely to provide constructive information as findings in participants that may belong to one sub-group (postpartum women) may be washed out by those of another belonging to a different sub-group (central sensitization). Consequently care must be taken during study design to identify a homogenous subgroup of LPP participants for investigation.

2. *Reliability of USI measurements in a clinical setting* - Measurement properties are system specific. As such it is important to establish if USI can be used in a meaningful and reliable way for measuring the abdominal wall muscles, IRD and bladder base during various clinically relevant static and dynamic manoeuvres in a clinical setting before further investigations into the clinical value of USI in the assessment of LPP can be undertaken.

3. *Importance of employing clinically relevant testing manoeuvres* - Many of the studies reviewed have used either voluntary muscle testing (ADIM or PFM contraction) or tasks that result in automatic activation of the muscles of the lumbopelvic region. In many cases the automatic activation tasks have been laboratory based leg loading manoeuvres, involving apparatus that allow the kinematics and effort of the task to be easily standardized. Such tasks and apparatus are not feasible or relevant in a clinical environment. Studies aimed at determining the clinical value of USI should employ testing procedures that are capable of being standardized in clinical environment and hold clinical significance (i.e. the ADIM and the ASLR test).

4. *Importance of clarifying the relationship between a change in muscle morphology and electrical activity* - The relationship between a change in muscle size (USI) and muscle activity (EMG) has only been investigated in small numbers of young healthy participants in non-clinical environments. To better interpret USI studies in persons with LPP this relationship needs to be investigated further.

5. *The abdominal wall is a functional unit* - The majority of USI studies to date investigating persons with dysfunction in the lumbopelvic region report on only one or two parameters of the abdominal wall (i.e. TrA or IO thickness). Further, no investigators have collected sonographic parameters of the entire abdominal wall and bladder base during specific manoeuvres. To have a greater understanding of how the abdominal wall functions as a unit, and how its influence on intra-abdominal pressure interacts with pelvic floor muscle activity to impact the bladder, it seems prudent that all aspects of the abdominal wall (muscles and their associated connective tissues) and the bladder base are monitored.

2.5.2 Aims

As indicated in Section 1.2 the goal of this thesis is to inform an argument regarding the clinical value of USI in routine physiotherapy practice as it applies to detecting altered structure and function of the abdominal wall muscles, and changes in bladder base position in persons with LPP. Accordingly the specific aims of the research were to;

2.5.2.i Investigate the threshold of ultrasound transducer motion that is acceptable during USI studies before significant error is introduced into measurements of abdominal muscle thickness and bladder base position (Chapter 4)

2.5.2.ii Determine the amount of ultrasound transducer motion that occurs during commonly utilised clinical physiotherapy tests for LPP (respiration, ADIM and ASLR test; Chapter 4).

2.5.2.iii Evaluate the intrarater reliability of sonographic measurements of abdominal muscle thickness, IRD and bladder base position, at rest and during an ASLR test and ADIM, within a single session (within day), and between two sessions (between day), in healthy and LPP cohorts in a clinical setting (Chapter 5).

2.5.2.iv Investigate the correlation between the magnitude and timeline of EMG amplitude, and the thickness of the RA, EO, IO and TrA muscles over the course of an ADIM and an ASLR test in healthy and LPP cohorts (Chapter 6).

2.5.2.v Compare the sonographic features of the abdominal wall (muscle and PMCT thickness as well as IRD) and bladder (position) between healthy and LPP cohorts, at rest and during the ASLR and ADIM (Chapters 7 and 8).

2.5.2.vi Assess the feasibility of using linear discriminate analysis to determine the value of the sonographic features of the abdominal wall and bladder in the discrimination of participants with LPP (Chapter 9).

2.6 Summary

This chapter has provided background information and a review of the literature pertinent to the investigation of muscle structure and function with USI in persons with LPP in a clinical setting. The next chapter will describe the general methodologies used to carry out the five investigations that are the basis of this thesis.

CHAPTER 3 - METHODOLOGY

This chapter reports the general methodologies (descriptions and justifications) for the five studies that are the basis for this thesis. Specific aims, hypotheses and procedures used for individual studies are described in the relevant experimental chapters (4 - 8).

3.1 Ethical Considerations

Studies 1, 2, 4, 5 (Chapters 4, 5, 7 and 8) were granted ethical approval by the School of Health Professions and Rehabilitation Sciences Ethics Committee, University of Southampton, UK (Appendices 1a-c). Study 3 (Chapter 6) received ethical approval from Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board, Kingston, Canada, and underwent a peer review through the Research and Enterprise Services Office of the University of Southampton, UK (Appendices 1d, e). All participants gave written informed consent prior to data collection (see Appendices 2a-c).

3.2 Participants

A total of 69 participants (37 healthy controls; 28 female, nine male, aged 19 – 53, 34.0 ± 9.9 years; yrs: 32 lumbopelvic pain; LPP cases; 26 female, six male, aged 20 – 59, 42.8 ± 11.5 yrs) participated in the five investigations that constitute this thesis. A summary of the specific characteristics of the participant pool for each individual study are described in the experimental chapters and summarized in Appendices 3a-c.

3.2.1 Inclusion and Exclusion Criteria

The patient group consisted of participants with unabating (> six weeks) unilateral lumbopelvic pain (LPP) and a positive Active Straight Leg Raise test (ASLR; see Section 3.2.3.iii). For the purposes of this thesis, LPP is defined as a pain distribution that is not proximal to the iliac crests and not distal to the popliteal fossa (Fortin et al. 1994a; Fortin et al. 1994b). Exclusion criteria included; a musculoskeletal or neuromuscular disorder affecting the lumbopelvic region, a body mass index (BMI) > than 31 kilograms per square meter (kg/m^2), respiratory dysfunction (hypocapnia, see Section 3.2.3.iv for relevance), history of congenital lumbopelvic anomalies or surgery, neurological signs, lower limb pathology (i.e. fracture, surgery, neoplasm), skin disorder, an inability to follow instructions, pregnancy or an activity level consistent with a high level athlete. For the purposes of this study hypocapnia was defined as an end tidal carbon dioxide ($ETCO_2$) < 35 millimetres of Mercury (mmHg) and a Nijmegen questionnaire score > 24 (see Section 3.2.3).

Control participants were healthy adults between the ages of 18 and 60 yrs who, in addition to the exclusion criteria for the patient group, did not have a history of

lumbopelvic, hip or thigh pain that in the last year had interfered with work, recreation or required medical attention, or were unable to perform an ASLR test.

3.2.2 Participant Recruitment

Participants for study 1 (Chapter 4) were recruited at the University of Southampton, Southampton, UK. For studies 2, 4 and 5 (Chapters 5, 7 and 8) participants were recruited in Surrey, British Columbia, Canada while participants for study 3 (Chapter 6) were recruited in Kingston, Ontario, Canada.

In Southampton, UK (at the University of Southampton) and Kingston, Canada (Queen's University), participants were recruited by on-campus posters that provided information about the study and requirements for participation. Interested persons contacted the principal investigator (JW) who's contact details were included on the poster. After first contact potential participants were emailed a participant information sheet (Appendix 2c and 4 a,b). If required, an email, telephone converstation or meeting between the investigator and the subject took place to explain the details of the project and answer any questions. If the individual was keen to proceed, a data collection session was scheduled. Participants included university students, staff and colleagues of the primary investigator. It was made clear to all participants that their choice to participate would not effect their status, employment or any other relationship with the University or investigators.

In Surrey, Canada, participants with LPP were recruited from the general case load of a private physiotherapy practice (WPC) following an in-clinic advertisement (poster) that provided information about the study and requirements for participation. In addition, a convience sample of healthy controls was recruited from regional fitness and educational facilities. Participants were either patients of the researcher, or if recruited from regional fitness and educational facilities, were unknown to the researcher. All potential participants learned of the study through general advertisement and then approached the researcher if interested. A process similar to that described above was used to inform and identify participants for data collection. It was be made clear to all participants that their choice to participate would not effect their access to future treatment.

3.2.3 Participant Demographics and Clinical Characteristics

At the time of data collection participants completed a standard screening form which served as a preliminary screening tool and provided demographic details (age, gender), information related to the distribution and duration of symptoms, as well as medical and parity history (Appendices 5a-c). Further, all participants underwent a standardized clinical examination, which served as a screening mechanism and provided a basic clinical profile. The examination included; measures of body mass and height, tests of lower

extremity neural conductivity and mobility, lumbopelvic load transfer, as well as capnography testing and visual inspection of their breathing pattern.

3.2.3.i Body mass and height

Participants for study 1 were weighed and their height measured using a mechanical column scale with a Seca 220 telescopic measuring rod (Seca, Hamburg, Germany). Participants for studies 2, 3 4 and 5 were weighed using a mechanical floor scale (Model 158CWP, Health o Meter®, Pelstar LCC, USA) and their height was determined by using a tape measure to measure the height of a mark on the wall corresponding to a line horizontal (construction level) to the top of their head. In both instances participants wore light clothing, shoes were removed and they were instructed to stand as straight as possible. Mass was recorded in kilogrammes to one decimal place. Height was recorded in centimetres (cm) to one decimal place.

3.2.3.ii Neural conductivity and mobility

The conductivity of the L2 through S1 spinal levels were assessed by observing the tendon reflex of the quadriceps (L2, 3) and Achilles (S1) tendons and the tibialis anterior (L4, 5) muscle belly with a reflex hammer. In addition, participants underwent key muscle testing for hip flexion (L2, 3), knee extension (L3, 4) ankle dorsiflexion (L5) ankle plantar flexion (S1), and great toe extension (L5). The mobility of the sciatic and femoral nerves was tested with the 'Slump' and 'Prone Knee Flexion' tests respectively (Butler 2000).

3.2.3.iii Lumbopelvic load transfer tests

The One Leg Standing (OLS) and ASLR tests are clinical tests for assessing the ability of the lumbopelvic region to effectively transfer load (Mens et al. 1999; Hungerford et al. 2004). The OLS test developed from an investigation undertaken by Hungerford et al (2004). Using a six-camera motion analysis system to monitor the angular and translational motion of the pelvic bones during OLS, the investigators identified an altered pattern of intrapelvic (innominate versus sacrum) motion in LPP participants. Specifically, they reported anterior rotation of the innominate (and the associated cranial motion of the posterior superior ischial spine; PSIS) of the weight bearing leg in the LPP cohort. This was in contrast to the pattern in a healthy cohort, in which no relative innominate motion was seen. They concluded that consistent cranial motion of the PSIS during OLS should be considered a positive test. The OLS test has been shown to have good intrarater reliability (kappa, 0.67 and 0.77, left and right respectively) and percentage agreement (89.9% - 91.9%; Hungerford et al. 2007). In regards to the ASLR test, Mens et al (1999) demonstrated a significant association between an impaired ASLR test and radiographic measures of increased pelvic joint motion. The ASLR test has been shown to have both good sensitivity (0.87) and specificity (0.94) for detecting LPP, and good (ICC, 0.87) test re-test reliability (Mens et al. 2001). The OLS and ASLR tests have been used by previous

investigators (O'Sullivan et al. 2002; Beales et al. 2009b; 2009a; Teyhen et al. 2009b) and are commonly employed in clinical practice (Lee 2004) for the purpose of assessing the ability of the lumbopelvic region to effectively transfer load. Consequently a combination of these two tests was employed to the same end during the investigations included here.

During the OLS test participants were instructed to stand on one leg and to flex the contralateral hip and knee towards the waist. The ability to effectively perform the test, and any consistent cranial motion of the PSIS (palpated or observed) of the innominate during the support (weight bearing) phase was assessed by the primary investigator (JW). The OLS test was repeated three times for both legs and the most consistent pattern of innominate motion was recorded (i.e. no rotation vs. anterior rotation).

The ASLR test was performed with participants in a supine lying position with their legs straight and their feet approximately 20cm apart. Participants were instructed to raise one leg five cm off the plinth without bending their knee. To standardize the height of the leg lift a ruler attached to a tripod was set five cm above the height the plinth. After holding the leg in the raised position for five seconds, they were asked to lower the leg to the resting position and repeat the test on the opposite leg. This process was repeated three times before participants reported any perceived asymmetry in weight of the two legs which was recorded as a positive score. The test was then repeated as general, anterior and posterior pelvic compression was applied in a random order to the pelvis while participants lifted the leg that they perceived was heavier. If the effort required to perform the leg lift was normalised by any of the three locations of compression it was noted.

3.2.3.iv Capnography testing and breathing pattern

A previous investigation (Whittaker 2008) has identified that participants with LPP and hypocapnia demonstrate significant modulation in the thickness of the transversus abdominis (TrA) muscle during resting respiration (see section 2.3.2.ii). As this would confound the current investigation, the $ETCO_2$ levels of participants was screened and those whose levels fell below normal (<35mmHg), and who demonstrated clinical symptoms of hypocapnia, (Nijmegen score > 24) were excluded.

Although the gold standard for determining physiological CO_2 levels is arterial blood gas analysis, the use of capnography to monitor real-time CO_2 levels is accepted common practice (Gardner 1996; Meuret et al. 2001; Roth 2005) as the $ETCO_2$ in exhaled air has been found to be similar to arterial levels (Hoffmann et al. 1990; Barton & Wang 1994). Accordingly, a portable, capnometry device (CapnoTrainer®, Better Physiology Ltd. Boulder CO, USA) was used to assess the $ETCO_2$ levels of all participants involved in the studies included within this thesis. Prior to each data collection session the CO_2 zero level of the instrument was calibrated by attaching a syringe filled with CO_2 absorbent which

created a CO_2 deficient environment. Further, prior to the first participants data collection the ability of the instrument to accurately analyse CO_2 content was calibrated with a solution of 5% CO_2, and the agreement of the device to a capnography system (BCI Capnocheck 9004, Smith's Medical, Graseby Medical Ltd. Watford, Herts, UK) at the University of Southampton was confirmed.

For the testing procedure, nasal cannulae were inserted into both nostrils and secured into place with micropore. Participants were seated comfortably and instructed to refrain from talking, laughing, chewing or breathing through their mouth during the data collection period. Expired air was collected every 30 seconds for six minutes, during which participants were distracted from their respiration by a standardized travel slide presentation. The capnography data were captured, stored and then exported to a personal laptop (Windows Excel), for further analysis. The average $ETCO_2$ level and breaths per minute (bpm), for the middle four minute period were recorded for all participants. In addition to these respiratory parameters, a visual assessment of each participant was made while they were in a supine lying position as to whether they had a breathing pattern that was predominately, apical, lateral costal, abdominal or more global.

3.3 Ultrasound Imaging

All imaging procedures were performed by one operator, the principle investigator (JW) who is an experienced physiotherapist (qualified 16 years) and has 10 years of RUSI experience. Prior to data collection the investigator had completed course work in USI with the Burwin Institute of Diagnostic Medical Ultrasound in Canada, authored several peer reviewed publications, printed both before, and during this post-graduate program (Whittaker 2004a; Teyhen et al. 2007; Whittaker et al. 2007a; 2007b; Whittaker 2008; Teyhen et al. 2009a; 2009b), as well as one text chapter (Whittaker 2004b), and the first textbook devoted to the topic of RUSI (Whittaker 2007).

3.3.1 Equipment

All imaging studies for the investigations contained within this document were carried out with the same imaging equipment which was transported from Surrey, Canada to Southampton, UK, and Kingston, Canada, as needed. Specifically, a MyLab 25, USI unit (Figure 3.1a; Biosound Esaote Inc, Indianapolis IL, USA) with a 5.0 MHz (40mm footprint) curvilinear transducer (Figure 3.1b; lateral and axial resolution of 0.95 and 0.90mm respectively) was employed to generate B – mode ultrasound images and / or clips (at a frame rate of 24 – 40 Hz) from the four abdominal imaging sites.

Figure.3.1: A. A MyLab 25 ultrasound imaging unit (Biosound Esaote Inc, Indianapolis IL, USA) and, B. A 5.0 MHz (40mm footprint) curvilinear transducer similar to the equipment used during data collection.

3.3.2 Experimental Set-up

This section contains detailed information regarding the imaging sites, clinical tests, as well as the imaging processing and measurement procedures used in the investigations contained within this thesis.

3.3.2.i Imaging sites

Four abdominal imaging sites were used for this research. These included the; lateral abdominal wall (LAW), linea alba (LA), mid-point of the rectus abdominis (RA) muscle, and supra-pubically over the midline of the abdomen (SSP). Transducer orientation followed radiological standard with the indicator right when imaging in the transverse plane (LAW, LA and RA imaging sites), and the indicator cranial when imaging in the sagittal plane (SSP imaging site). As bladder volume influences bladder base motion (Dietz & Wilson 1999) all participants were instructed to follow a standardized bladder filling procedure prior to data collection sessions. Instruction were to, one hour prior to the session, empty their bladder then using a measuring cup drink exactly 250milliliters (ml) of water, and not empty their bladder again until instructed to do so. A similar method has been used by previous investigators (Thompson & O'Sullivan 2003; Sherburn et al. 2005; Thompson et al. 2005; 2006b; 2006c; 2007).

Lateral Abdominal Wall Imaging Site - The transducer was placed transversely on the anterolateral aspect of the abdomen, halfway between the iliac crest and inferior border of the rib cage, to produce an image of the LAW muscles and their associated perimuscular connective tissue (PMCT; Figure 3.2a; Teyhen et al. 2007; Whittaker 2007). The transducer was maintained perpendicular to the body surface and the medial to lateral placement was such that the anteromedial border of TrA was 2cm from the medial edge of the image. The muscle layers were kept in a horizontal orientation on the scanner's screen, as seen in Figure 3.2b (Teyhen et al. 2007; Whittaker 2007).

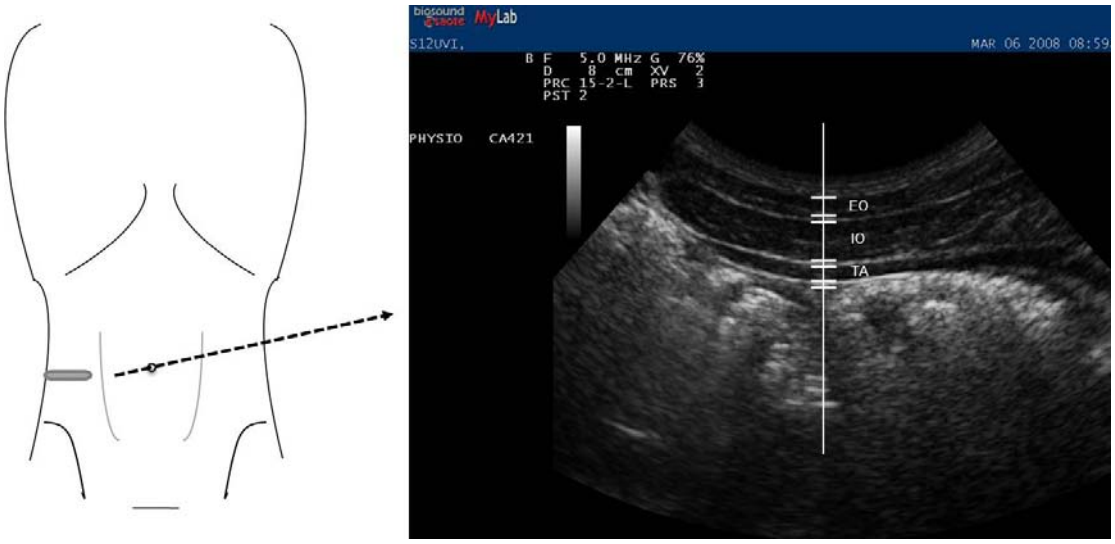


Figure 3.2: A. Lateral abdominal wall (LAW) imaging site. B. Transverse ultrasound image of the right lateral abdominal wall showing a vertical reference line in the middle of the image along which measurements of transversus abdominis (TA), internal oblique (IO), external oblique (EO) muscles, and intervening connective tissue plane thicknesses were made.

Linea Alba Imaging Site - The transducer was placed in a transverse orientation on the midline of the abdomen just below the umbilicus to produce an image of the inter-recti distance (IRD; Figure 3.3a). The transducer was maintained perpendicular to the body surface, and the medial to lateral placement was such that mid-line of the linea alba was in the centre of the image (Figure 3.3b; Teyhen et al. 2007; Whittaker 2007).

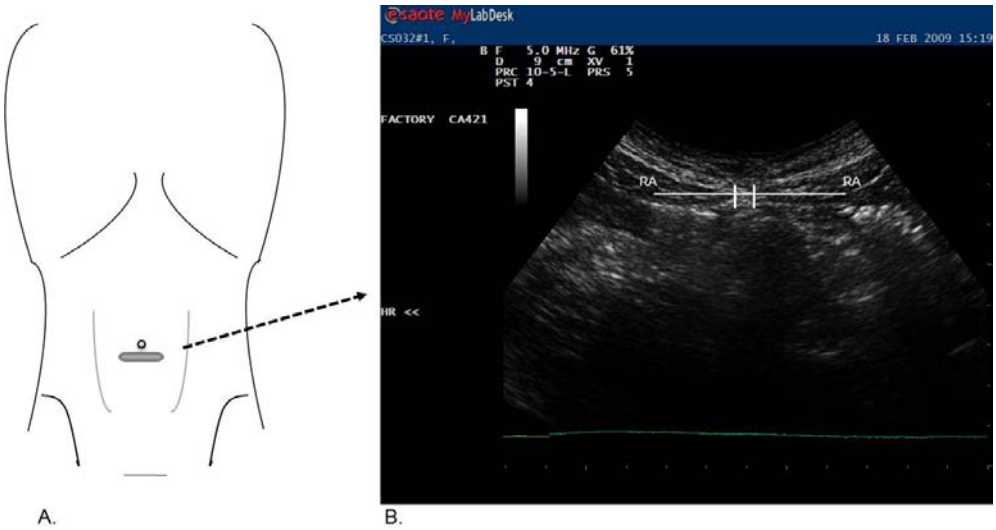


Figure 3.3: A. Linea alba (LA) imaging site. B. Transverse ultrasound image of the linea alba showing a horizontal reference line along which the length of the inter-rectus distance, (IRD), defined as the horizontal distance between the medial aspects of the left and right rectus abdominis (RA) muscles, was made.

Rectus Abdominis Imaging Site - The transducer was placed in a transverse orientation over the midline of the RA muscle at the level of the umbilicus to produce an image of the RA muscle and associated PMCT (Figure 3.4a). The transducer was maintained perpendicular to the body surface, and the medial to lateral placement was such that middle of the RA muscle was in the centre of the image, as seen in Figure 3.4b (Teyhen et al. 2007; Whittaker 2007).

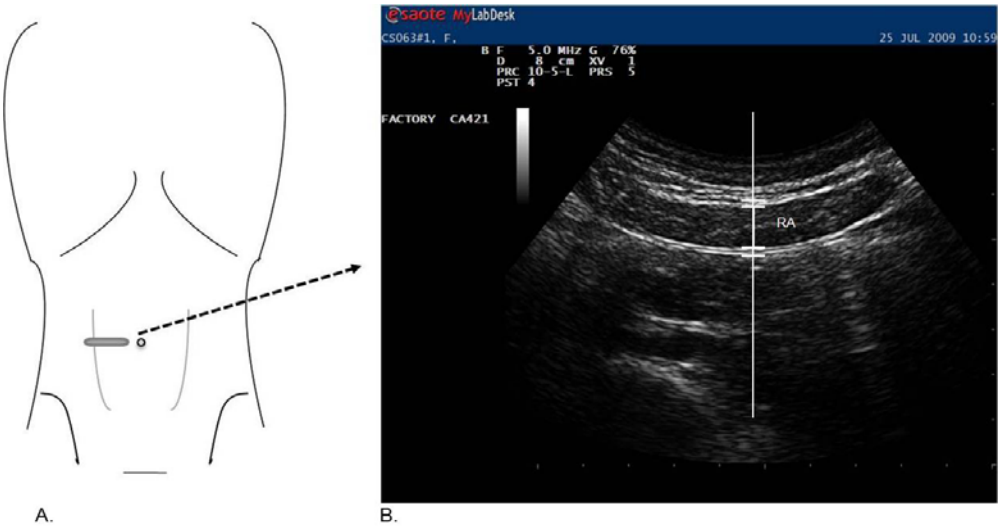


Figure 3.4: A. Rectus abdominis (RA) imaging site. B. Transverse ultrasound image of the right rectus abdominis (RA) showing a vertical reference line along which the thickness of the RA muscle and associated connective tissue planes were made.

Supra-pubic Imaging Site - The transducer was placed in a sagittal orientation over the midline of the abdomen just superior to the pubic symphysis to produce a sagittal image the bladder and bladder base (Figure 3.5a). The angle of the transducer was manipulated until it was approximately 60^0 from the vertical and aimed towards the gluteal or posteroinferior region of the bladder until there was a clear image of the bladder and bladder base as seen in Figure 3.5b (Whittaker 2007; 2007b).

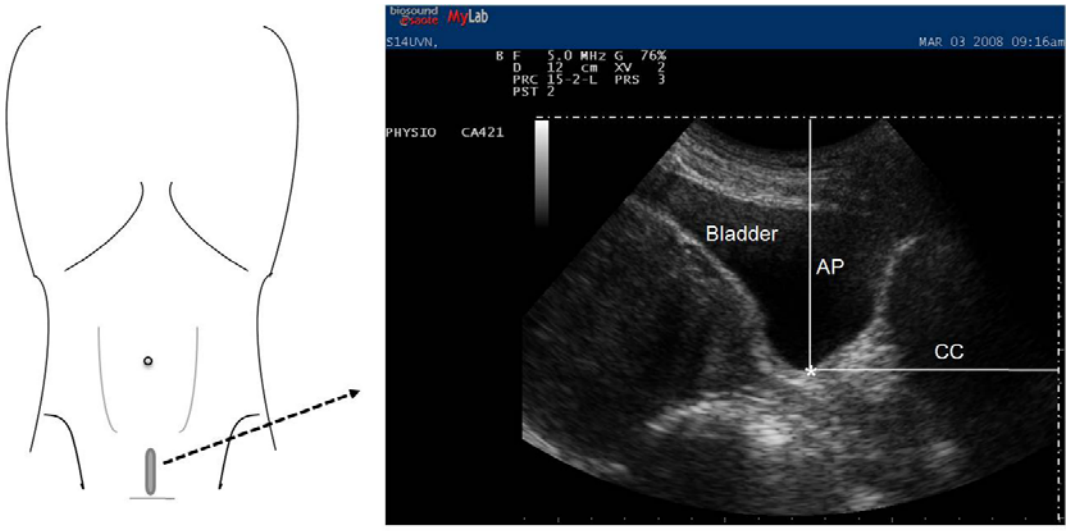


Figure 3.5: A. Sagittal supra-pubic (SSP) imaging site. B. Sagittal ultrasound image of the bladder and bladder base (*) showing the perpendicular anterior / posterior (AP) distance, and the cranial / caudal (CC) distance from the top of the USI image and the side of the USI image respectively to a reference point (* ; the most inferior border of the bladder) on the bladder base.

3.3.2.ii Procedures for clinical tests

Ultrasound images and clips were collected from the side of the abdomen ipsilateral to the symptoms for the LPP cohort, and from the right side of the abdomen in healthy participants. Depending on the study, participants performed some combination of three dynamic clinical tests, or manoeuvres (detailed below); respiration (including both resting tidal respiration and forced expiration), an ipsilateral ASLR, and an Abdominal Drawing in Manoeuvre (ADIM). During the manoeuvres, USI clips were captured at the LAW, LA, RA and SSP imaging sites, with the electrocardiogram (ECG) trace enabled on the ultrasound system. As participants performed the manoeuvres a foot switch was used to deflect the ECG trace to mark the timeline (see Tables 3.1 – 3.3). In an attempt to control for variability in the motor control strategy used to perform the manoeuvres standardized verbal instructions were followed. As the goal was to mimic a clinical setting, these instructions were consistent to what would be used in a clinical environment. During all

manoeuvres, participants lay on a plinth of a standardized height (60cm) and assumed either a standardized supine crook lying position (respiration and ADIM) or fully supine position (ASLR).

Respiratory Trials - The respiratory trails used in study 1 (Chapter 4) followed the protocol outlined in Table 3.1. The USI clip started as the participant breathed out and ECG deflections marked; first tidal inspiration, first tidal expiration, second tidal inspiration, forced expiration, third tidal inspiration, and tidal expiration. Effort of the forced expiration was standardized by the command “breathe out forcing all the air out of your lungs”.

Table 3.1: Respiratory Protocol (Study 1)

VERBAL INSTRUCTION	EVENT	ECG DEFLECTION
The clip will start as you breathe out	Start of trial	1 - Clip on
Breathe in normally	Inspiration	2 - Peak of inspiration
Breath out normally and hold 5,4,3,2,1,	Expiration	3 - Bottom of expiration
Breathe in normally	Inspiration	4 - Peak of inspiration
Breathe out forcing all the air out of your lungs	Forced expiration	5 - Bottom of expiration
Breathe in normally	Inspiration	6 - Peak of inspiration
Breathe out normally	Expiration	7 - Bottom of expiration
Relax	End of trail	8 - Clip off

Active Straight Leg Raise Trials - The ASLR trails in studies 1, 2, 4 and 5 (Chapters 4, 5, 7 and 8) followed the protocol outlined in Table 3.2. The USI clip started as the participant breathed out and ECG deflections marked; first tidal inspiration, first tidal expiration, onset of leg lift (manoeuvre onset), tidal inspiration with leg lift, tidal expiration with leg lift, return of the leg to the bed (manoeuvre release), resting tidal inspiration and expiration. To standardize the leg lift participants lifted their leg until encountering a ruler attached to a tripod set at five cm above the height the plinth.

The ASLR trials used in study 3 (Chapter 6) differed slightly in that after the first tidal expiration, participants performed three ipsilateral leg lifts while sustaining expiration before returning to tidal respiration. Correspondingly, ECG deflections marked; first tidal inspiration, first tidal expiration, onset of the first leg lift, first return of leg to the bed, second leg lift, second return of leg, third leg lift, third return of leg to the bed, resting tidal inspiration and resting tidal expiration.

Table 3.2: Active Straight Leg Raise Protocol (Studies 1, 2, 4 and 5)

VERBAL INSTRUCTION	EVENT	ECG DEFLECTION
The clip will start as you breathe out	Start of trial	1 - Clip on
Breathe in normally	Inspiration	2 - Peak of inspiration
Breath out normally and hold 5,4,3,2,1,	Expiration	3 - Bottom of expiration
Lift your leg and hold 5.4.3.2.1	Leg lift	4 - Onset of leg lift
Breathe in normally	Inspiration	5 - Peak of inspiration
Breathe out normally	Expiration	6 - Bottom of expiration
Lower leg as you hold	Lower leg	7 - First contact of leg on bed
Breathe in normally	Inspiration	8 - Peak of inspiration
Breathe out normally	Expiration	9 - Bottom of expiration
Relax	End of trail	10 - Clip off

Abdominal Drawing in Trials - The ADIM trials used in studies 1, 2, 4 and 5 (Chapters 4, 5, 7 and 8) followed the protocol outlined in Table 3.3. The USI clip was initiated as the participant breathed out and ECG deflections marked; first tidal inspiration, first tidal expiration, onset of the ADIM (manoeuvre onset), tidal inspiration with ADIM, tidal expiration with ADIM, relaxation of the ADIM (manoeuvre release), resting tidal inspiration and expiration. As the ADIM is difficult to standardize (see Section 2.3.1), each participant was given three to six trials, with USI biofeedback, to practice before data collection. Effort was standardized by asking participants to “gently drawing in their lower abdomen”. When participants could consistently perform the manoeuvre over two consecutive repetitions (as observed on USI), data collection resumed. During data collection participants were asked to replicate a closely as possible the effort of the ADIM during all trials. A similar procedure has been used by previous investigators (Henry & Westervelt 2005).

Table 3.3: Abdominal Drawing in Manoeuvre Protocol (Studies 1, 2, 4 and 5)

VERBAL INSTRUCTION	EVENT	ECG DEFLECTION
The clip will start as you breathe out	Start of trial	1 - Clip on
Breathe in normally	Inspiration	2 - Peak of inspiration
Breath out normally and hold 5,4,3,2,1,	Expiration	3 - Bottom of expiration
Gently draw in your lower abdomen and hold 5,4,3,2,1	ADIM	4 – Onset of ADIM
Breathe in normally	Inspiration	5 - Peak of inspiration
Breathe out normally and hold 5,4,3,2,1	Expiration	6 - Bottom of expiration
Relax abdomen	Release ADIM	7 - Command to release
Breathe in normally	Inspiration	8 - Peak of inspiration
Breathe out normally	Expiration	9 - Bottom of expiration
Relax	End of trial	10 - Clip off

The ADIM trials used in study 3 (Chapter 6) differed slightly in that after the first tidal expiration the participants performed three ADIMs while sustaining expiration before returning to tidal respiration. Correspondingly ECG deflections indicated; first tidal inspiration, first tidal expiration, onset of first ADIM, relaxation of first ADIM, onset of second ADIM, relaxation of second ADIM, onset of third ADIM, relaxation of third ADIM, resting tidal inspiration and resting tidal expiration.

3.3.3 Image Processing and Measurement

Different processing and measurement procedures were used for study 1 (Chapter 4), studies 2, 4 and 5 (Chapters 5, 7 and 8), and study 3 (Chapter 6).

3.3.3.i Definition of Ultrasound Parameters

For all studies the accepted convention of defining the boundaries of a muscle as the last hypoechoic pixel before the PMCT plane was employed (Teyhen et al. 2007; Whittaker et al. 2007a). Transversus abdominis (TrA), internal oblique (IO), external oblique (EO) and RA thickness were calculated as the perpendicular distance between the muscle's superficial and deep PMCT planes in the middle of the image (Figures 3.2b, 3.4b respectively). Inter-recti distance was calculated as the horizontal distance between the two most medial aspects of the right and left RA muscle (Figure 3.3b). Measurements of IRD were made in consultation with a video clip of the IRD during a mild RA contraction (isometric trunk flexion in supine) to aid in the precision of delineating muscle boundaries. Intervening PMCT plane thickness was defined as the distance between the outside edges of each connective tissue layer (which corresponded to the last hypoechoic pixel of adjacent muscle layer; Figures 3.2 and 3.4). The definition of bladder and bladder base measurements used in Studies 1, 2, 4 and 5 are described below.

3.3.3.ii Study 1

Ultrasound images were captured, anonymised, stored, and measured off line on a laptop computer using National Institutes of Health (Bethesda, MD) Image J software (V 1.38t; http://rsb.info.nih.gov/nih-image/). In addition to an automatic measurement function (which exports the measurements to a spread sheet keeping the investigator blinded), the Image J software has utilities which enable the operator to overlay a grid and zoom into the region of interest. For this study anterior / posterior (AP) and cranial / caudal (CC) bladder base position was defined as the perpendicular AP distance from the top of the USI image, and the perpendicular CC distance from the side of the USI image, to a reference point (the most inferior border of the bladder) on the bladder base (Figure 3.5) respectively.

3.3.3.iii Studies 2, 4 and 5

Once collected the anonymised USI clips (approximately 20 seconds in length, containing 590 frames) were exported to a personal laptop. Five USI images associate with events of interest (pre-manoeuvre rest, onset of manoeuvre, manoeuvre hold, release of manoeuvre and post-manoeuvre rest; see Figures 3.6 and 3.7 for the definition of these events) were extracted from each USI clip and measured with MATLAB® version 7.1 software (Mathworks, Natick, Massachusetts, USA).

The MATLAB algorithm employed to extract the event frames for measurement first identified (Figure 3.6) and stored the frame numbers corresponding with 10 ECG trace deflections (see Tables 3.2 and 3.3 for descriptions of the ECG deflections). It then calculated and stored the frame numbers corresponding with the five events of interest based upon their relationship to the frame numbers associated with the ECG deflections (Figures 3.7 and 3.8; see Appendix 10b for the MATLAB event detection and frame extraction algorithm).

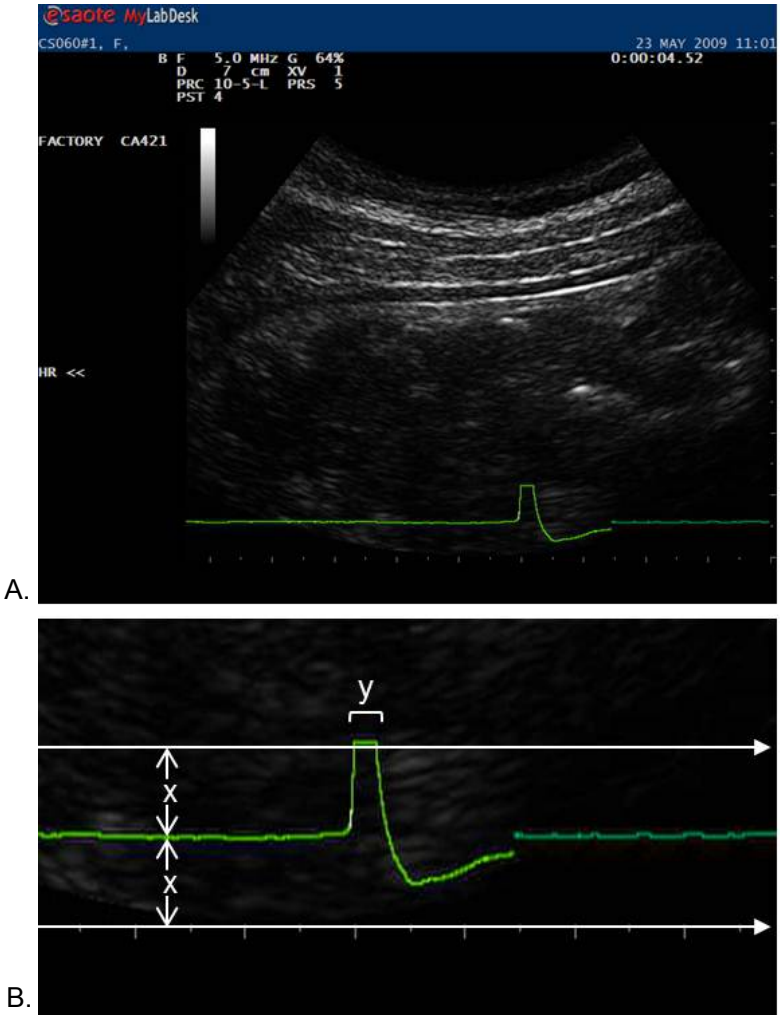


Figure 3.6: Event Detection. A. The ultrasound unit's ECG trace (green trace) was deflected by manually depressing a foot pedal at set points throughout the manoeuvres (see Figures 3.7 and 3.8 for deflection descriptions). B. The MATLAB algorithm set a threshold line (white arrow) defined x pixels above and below the ECG baseline. The algorithm then examined the entire video file for instances when pixels along the threshold line changed from a black/grey colour to green, which indicated an ECG deflection had taken place. The frame number corresponding to the deflections were recorded. As a single deflection may have contained multiple instances of the ECG trace reaching the threshold line the algorithm ignored the subsequent y (i.e. 30) frames before detecting the next ECG deflection.

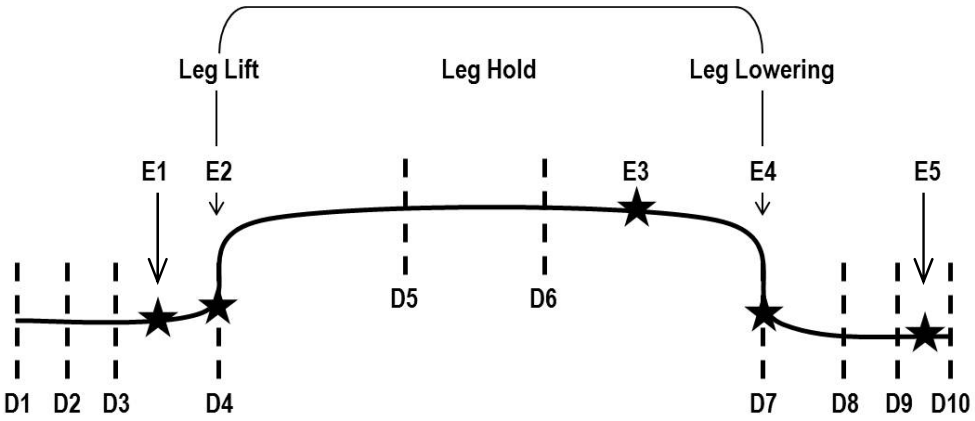


Figure 3.7: Active Straight Leg Raise (ASLR) Timeline. Relationship between the ECG deflections (broken lines labelled D1 – 10, see Table 3.2) and events (★ labelled E1 – 5) corresponding to USI frames that were extracted for measurement. D1 = start of USI clip, D2 = inspiration, D3 = expiration, D4 = leg lift, D5 = inspiration, D6 = expiration, D7 = leg lowering, D8 = inspiration, D9 = expiration, D10 = end of clip. E1 = pre-ASLR rest image (half way between D3 and 4), E2 ASLR leg lift image, E3 = ASLR hold image (half way between D6 and D7), E4 = ASLR release image, E5 = post-ASLR rest image (halfway between D9 and D10).

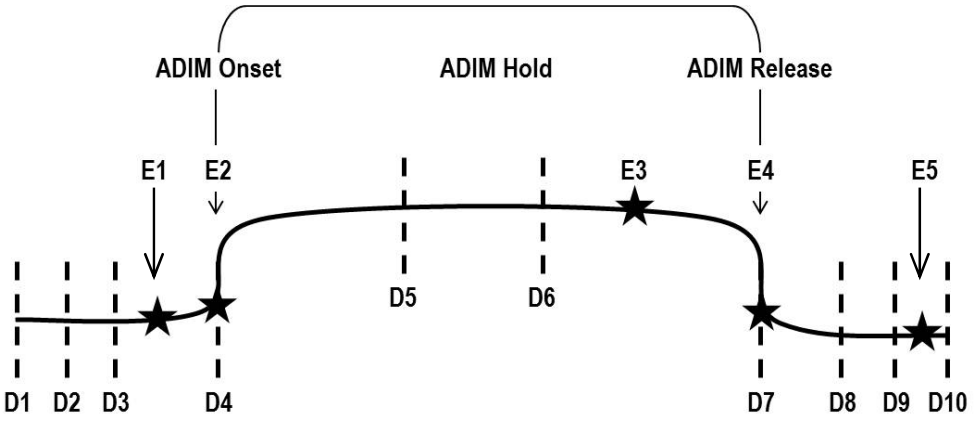


Figure 3.8: Abdominal Drawing in Manoeuvre (ADIM) Timeline. Relationship between the ECG deflections (broken lines labelled D1 – 10, see Table 3.3) and events (★ labelled E1 – 5) corresponding to USI frames that were extracted for measurement. D1 = start of USI clip, D2 = inspiration, D3 = expiration, D4 = ADIM onset, D5 = inspiration, D6 = expiration, D7 = ADIM release, D8 = inspiration, D9 = expiration, D10 = end of clip. E1 = pre-ADIM rest image (halfway between D3 and D4), E2 = ADIM onset image, E3 = ADIM hold image (halfway between D6 and D7), E4 = ADIM release image, E5 = post-ADIM rest image (halfway between D9 and D10).

The measurement algorithms for both the abdominal wall (RA, EO, IO, TrA thickness and IRD) and bladder parameters (global bladder position; GB; global bladder base position; GBB; and relative bladder base position; RBB) automatically loaded the five USI images corresponding to the events of interest from a directory. The algorithm then prompted the operator to calibrate pixel / cm ratio, based upon the horizontal and vertical scale on the USI image, and plot a reference line (vertical in the midline for the LAW and RA images and horizontal for the IRD images) along which measurements could be made. The operator and then marked the inside borders of the boundaries of the muscle (s) (which also corresponded to the outside borders of the PMCT planes; Figures 3.2 and 3.4). The difference in pixels between the borders was multiplied by the pixel/cm scaling factor to convert the measurements to real units (cm; see Appendices 10c-e for MATLAB abdominal wall measurement algorithms).

In contrast, the bladder base measurement algorithm prompted the operator to mark five points of interest on the bladder image; the most inferior border of bladder, the right most border of bladder, the left most edge of bladder base, the right most edge of bladder base and the middle of bladder base (Figure 3.9). From those five points the GB (points 1 and 2), GBB (a line extending between points 3 and 4) and RBB (location of point 5 with respect to the point where the lines demarcating the most inferior and lateral border of the bladder intersect; Figure 3.9) positions were calculated. The bladder measurement algorithm then calculated the difference in cranial/caudal (x axis), ventral/dorsal (y axis) and overall (x and y axes combined) GB, GBB and RBB position (along the x, y and resultant vectors) between the pre-manoeuvre rest and the other four frames (corresponding to the onset of manoeuvre, manoeuvre hold, manoeuvre release and post-manoeuvre rest) in pixels and multiplied this by the pixel/cm scaling factor to convert the measurements to real units (cm; see Appendix 11e for MATLAB bladder measurement algorithm). For all the measurement algorithms values were exported directly into an Excel worksheet which ensured blinding of the operator.

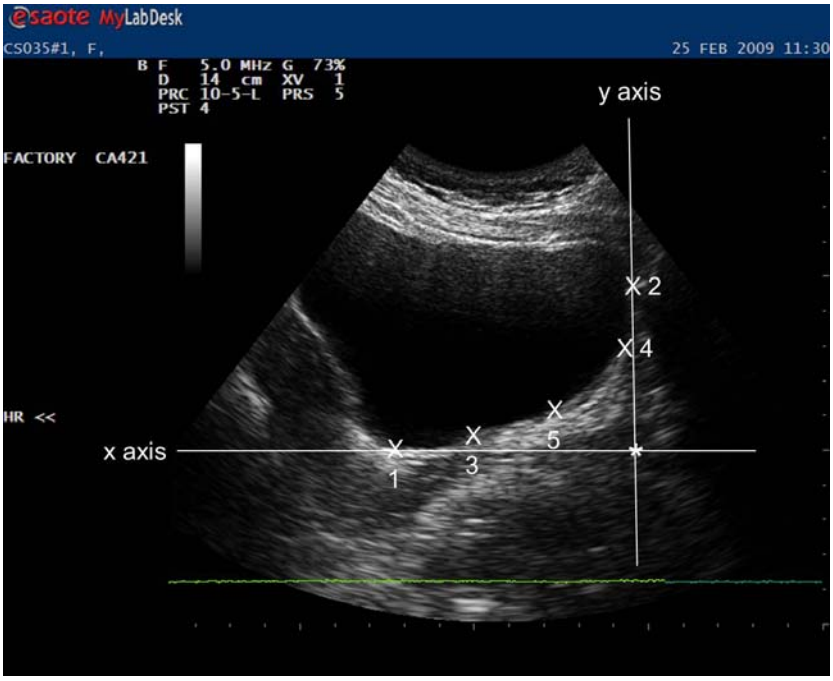


Figure 3.9: Definition and calculation of bladder and bladder base position. The five points used to define the global bladder (GB; 1 and 2), global bladder base (GBB; a line extending between points 3 and 4) and relative bladder base (RBB; location of point 5 with respect to the point * where the lines demarcating the most inferior and lateral border of the bladder intersect) position.

3.3.3.iv Study 3

In this study all USI clips were collected at a rate of 34 frames /second for approximately 25 seconds, anonymised and then exported to a personal laptop. MATLAB® version 7.1 software (Mathworks, Natick, Massachusetts, USA) was used to measure every second frame between the end of the first expiration and last leg lift or ADIM release. The start (end of the first expiration) and end (end of the last leg lift or ADIM release) frame numbers were manually identified using a manufacturer based software system (©MyLab Desk) which allowed the operator to scroll through the individual clips frame by frame. The measurement algorithm, which measured RA, EO, IO and TrA thickness, prompted the operator to enter the start and end frame numbers, automatically loaded the first USI images and then required the operator to calibrate distance (pixel / cm ratio) based upon the vertical scale on the USI image. Once calibrated the measurement algorithm automatically loaded every second frame (between the start and end frame numbers). For each frame the operator was prompted to first plot a vertical reference line (in the midline of the image) along which measurements could be made and then mark the inside borders of the boundaries of the muscle (s) (Figures 3.2 and 3.4). The difference in pixels between the borders was multiplied by the pixel/cm scaling factor to convert the

measurements to real units (cm; see Appendices 9b and 9c for the EO, IO, TrA and RA thickness measurement algorithms).

All the algorithms used for event location and measurement were developed and written by a co-supervisor Dr Martin Warner with the assistance of Professor Victor Humphrey from the Institute for Sound and Vibration Research at the University of Southampton.

3.4 Motion Analysis

This section describes the equipment, calibration process and experimental set-up for the motion analysis system used in study 1 (Chapter4).

3.4.1 Equipment and Calibration Process

Motion of the bony pelvis and USI transducer was monitored by a six camera digital optical motion capture system (Vicon 460, Oxford, UK). This system was capable of providing accurate information about both the angle of rotation of either segment (the pelvic or the transducer) around three axes, or translation through three planes. The 6 cameras were set up to provide a capture volume approximately 2m width x 2m length x 2m height. Prior to each data collection session the direction of the X, Y and Z axes (static calibration) and the relative positions and orientation of the motion analysis cameras (dynamic calibration) were calibrated following the manufacturer's recommended procedure that enabled a mean camera residual below 1mm.

3.4.2 Experimental Set-up

This section contains detailed information regarding the location of the retro-reflective markers, definition of segments and axes, and motion data management and analysis.

3.4.2.i Location of Retro-reflective Markers

Retro-reflective markers (14mm in diameter) were applied bilaterally to the anterior and posterior superior iliac spine's (ASIS and PSIS respectively) and iliac tubercles of each participant. A wand with retro-reflective markers was attached to the ultrasound transducer (Figure 3.10).

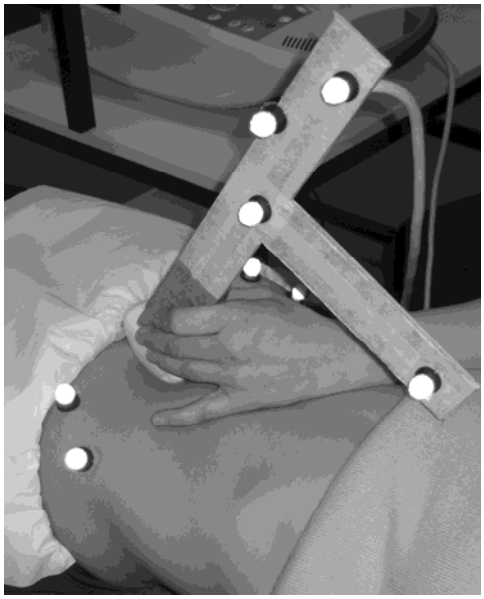


Figure 3.10: Experimental set-up for motion analysis (of transducer) and USI at the sagittal bladder imaging site. Note the retro-reflective markers on the ASIS's, iliac tubercle's and wand attached to the ultrasound transducer.

3.4.2.ii Definition of Segments and Axes

A static standing trial was captured for participant calibration such that virtual PSIS markers could be created when participants removed the retro-reflective PSIS markers when they assumed a supine lying position for data collection. Specifically the PSIS markers were placed into the local coordinate frame of the segment (pelvis) formed by the ASIS and iliac tubercle markers during the standing calibration. The two PSIS markers were then removed as participants assumed a supine lying position. During USI imaging trials virtual PSIS markers were created based upon their location during the static trial within local reference frame formed by ASIS and iliac tubercle markers.

The pelvic segment was formed and local axes defined following the standard used for gait analysis (Kadaba et al. 1990). The line pointing from left to right ASIS markers formed the Y axis, the line pointing forward from PSIS to ASIS formed the X axis, and the line perpendicular to these axes, pointing cranially (following the right hand rule) formed the Z axis. The transducer segment was formed and the local axes defined in a similar fashion. A line pointing from left to right formed the Y axis, a line pointing forward from the most proximal to most distal markers on the main arm of the wand formed the X axis, and a line pointing from the most posterior to anterior marker on the horizontal arm of the wand formed the Z axis (Figure 3.11).

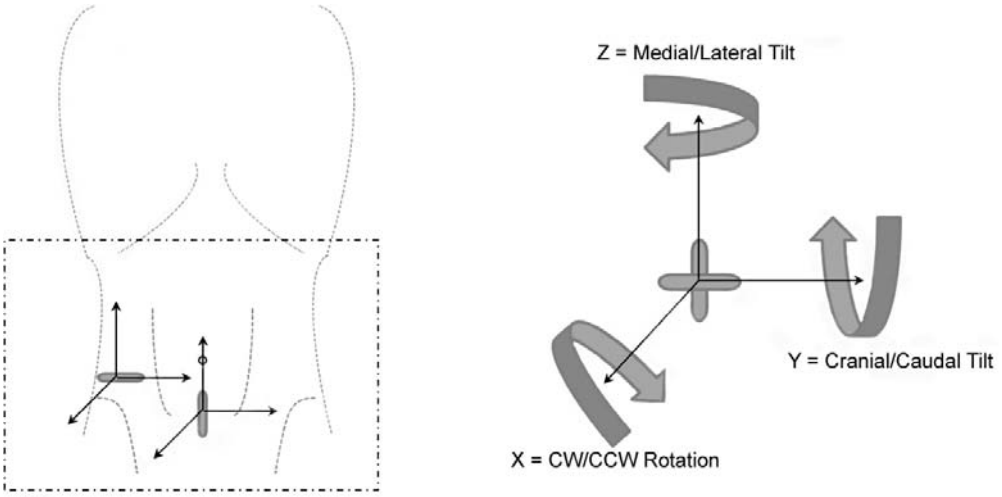


Figure 3.11: Axes and associated motions for induced transducer motion at the lateral abdominal wall and the sagittal suprapubic imaging sites (CW = clockwise, CCW = counter clockwise).

3.4.3 Motion Data Analysis and Measurement

A kinematic model to define the pelvis and USI transducer segments in order to determine the rotation and position of the transducer with respect to the pelvis was developed and written by co-supervisor Dr Martin Warner in Vicon Bodybuilder software (Oxford, UK). The accuracy of the kinematic model was determined to be within one degree for each rotation. This model allowed for transducer rotation to be resolved into X (clockwise / counter clockwise; CW / CCW), Y (cranial / caudal tilt of the proximal end of the transducer) and Z (medial /lateral tilt of the proximal end of the transducer) components (Figure 3.11) as well as the scalar (vertical plane inward and outward motion) distance from the transducer's base to the right ASIS marker for the LAW and RA trials, or the mid-point between the right and left ASIS for the SSP, and LA trials. The relative change in transducer rotation throughout the USI scanning trials was described through Euler angle calculations (with a rotation order of X, Y Z). Specifically, the rotation of transducer throughout the trial was defined in terms of a sequenced composition of the three angles, termed Euler angles (Weisstein 1999), resulting from describing the X followed by the Y and then Z position of the transducer at that point in time to a reference position or frame (in this case the x, y and z position of the transducer at the start of the trial; Figure 3.12).

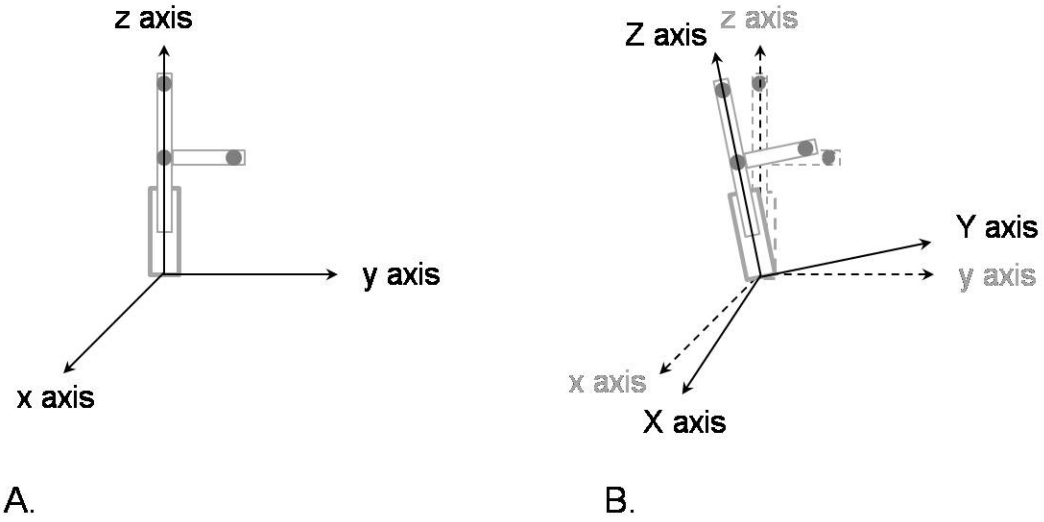


Figure 3.12: Euler angle calculations of transducer rotation for the lateral abdominal wall imaging site. A. The reference position or 'frame' from which the rotation of the USI transducer was defined. In this case the x, y and z position of the transducer at the start of the trial. B. The change in transducer rotation throughout the trials was defined in terms of a sequenced composition of the three angles, termed Euler angles, resulting from comparing the X followed by the Y and then the Z position of the transducer at some point during the trial to a reference position or frame (x, y, and z).

3.5 Standardized Questionnaires.

A series of standardized questionnaires (Appendices 6a–e) were employed to gather information about the perceived low back related disability, perceived pain and fear avoidance beliefs of the LPP cohort. Further, as LPP is linked to other disorders of the lumbopelvic region including urinary incontinence (UI), and respiratory dysfunction (Smith et al. 2006b; 2008b; 2009; Mens et al. 2012) questionnaires which provided information regarding the presence and life impact of urinary incontinence and hypocapnia were administered to both cohorts. The questionnaires employed (see below) were chosen based on prior reporting in the literature and their psychometric properties. Participants completed the questionnaires after filling out the consent and screening forms, during their first data collection session.

3.5.1 Modified Oswestry Disability Questionnaire (ODQ; version 2)

The level of perceived low back related disability of the patient cohort was assessed by administering the ODQ which was originally described by Fairbank et al (1980). The ODQ has been found to have psychometric properties consistent with an outcome measure. This includes high levels of reliability (ICC, 0.90), demonstrated construct validity

(correlations with global patient ratings and other region-specific disability measures >0.80), and responsiveness to treatment (effect size =1.8 in patients receiving physiotherapy interventions for LBP; (Fairbank 2000; Fairbank & Pynsent 2000; Roland & Fairbank 2000).

3.5.2 Numerical Pain Rating Scale (NPRS)

The current and past 24 hour level of perceived pain was assessed by administering an 11-point rating scale. Zero represented 'no pain sensation' and ten 'the most intense pain sensation imaginable'. This method of pain assessment is valid and responsive for use in patients with chronic pain (Jensen et al. 1994; Price et al. 1994; Childs et al. 2005).

3.5.3 Fear Avoidance Beliefs Questionnaire (FABQ)

The fear-avoidance beliefs of the patient cohort were quantified by the FABQ (Waddell et al. 1992). This questionnaire is an 11-item, seven point rating scale with sub-scales related to physical activity and work, that measures pain related fear specific to LBP. The test-retest stability of the FABQ has been reported in the literature for patients with chronic LBP (kappa for individual items = 0.74). The FABQ is believed to be valid because it explains additional amounts of variance in work loss (26%) and disability (23%) after controlling for pain intensity and location (Waddell et al. 1993).

3.5.4 Incontinence Impact Questionnaire (IIQ) & Urogenital Distress Inventory (UDI)

As LPP is linked to other disorders of the lumbopelvic region including UI (Smith et al. 2006b; Smith et al. 2008b; Smith et al. 2008a; Smith et al. 2009) the presence, life impact (activities of daily living, emotional health and social activities) and symptom distress of stress UI of both cohorts were assessed by the IIQ-7 and UDI-6 (Shumaker et al. 1994; Uebersax et al. 1995). The IIQ-7 is commonly used in clinical practice, along with its counterpart, the UDI-6 and the results are usually each reported as a single score. The internal consistency, test–retest reliability, and criterion validity of these tests have been adequately established through comparison to a longer version of each questionnaire, the number of incontinent episodes, a pad test and treatment status (Shumaker et al. 1994; Uebersax et al. 1995).

3.5.5 Nijmegen Questionnaire

The Nijmegen questionnaire (Garssen et al. 1984) was administered to all participants to assess the presence of any clinical symptoms of hypocapnia. This questionnaire contains 16 items asking patients to grade the frequency of various sensations associate with hypocapnia. The questionnaire is reported to be highly reliable (Vansteenkiste et al. 1991)

with sensitivity in relation to a clinical diagnosis of hypocapnia of 91% and a specificity of 95% (van Dixhoorn & Duivenvoorden 1985).

3.6 Summary

This chapter has described the general methodologies used in the experimental chapters of this thesis. The next five chapters will describe these investigations including the rationale, aims, results and their relevance as it relates to the aim of this document. Namely, to develop an argument for the clinical value of conventional USI in routine physiotherapy practice for identifying persons with LPP.

CHAPTER 4 - ULTRASOUND IMAGING IN A CLINICAL ENVIRONMENT: THE IMPACT OF TRANSDUCER MOTION

This chapter describes an investigation aimed at determining if an ultrasound imaging (USI) transducer can be held adequately stationary to gather meaningful measurements during dynamic clinical tests or manoeuvres, typical of a clinical physiotherapy examination of the lumbopelvic region. This investigation was driven by the questions 'how much ultrasound transducer motion is too much', and 'how much transducer motion occurs during clinical tests (a respiratory task, Active Straight Leg Raise test; ASLR, and Abdominal Drawing in Manoeuvre; ADIM) typical of a physiotherapy assessment in the lumbopelvic region?

4.1 Introduction

There is an increasing interest in the clinical use of USI by physiotherapists to evaluate the morphology and behaviour of muscle, and to provide biofeedback about muscle behaviour during restoration of function. These clinical applications commonly involve measurement of the abdominal muscles (Stokes et al. 2007; Teyhen et al. 2007), or position of the bladder base (see Whittaker et al. 2007b for a summary), at rest and during dynamic manoeuvres (i.e. ASLR, ADIM, respiration, balance tests, coughing etc.). The validity of using USI as a method for measuring these structures has been established through comparison to magnetic resonance imaging (MRI; Hides et al. 1995b; Hides et al. 2006b), as have various aspects of intra / inter rater and intra /inter session reliability (Costa et al. 2009b; Koppenhaver et al. 2009a). However, there has been little investigation into how conducive the clinical environment is to generating valid and reliable USI measurements (see Section 2.3.1). As transducer motion distorts structures within an ultrasound image leading to erroneous conclusions (Dupont et al. 2001; Reddy et al. 2001; Klimstra et al. 2007) accurate interpretation of USI studies depends upon maintaining a relatively stationary transducer position throughout. This may be particularly challenging for dynamic USI studies during manoeuvres typical of a lumbopelvic physiotherapy assessment such as the ASLR test (Mens et al. 1999) and the ADIM (Richardson et al. 2004) that likely amplify ultrasound transducer motion due to associated trunk, abdominal wall, and/or limb motion.

Measurement error resulting from transducer motion has been alluded to by several authors. For instance, while measuring supraspinatus and deltoid muscle thickness, Dupont et al (2001) stated that a variation in transducer angle by 30^{o} (from perpendicular to the body surface) resulted in a 15% error. They recommended that steps are taken to ensure that the transducer angle remains consistent throughout an imaging study. Herbert

& Gandevia (1995), while investigating the pennation angle of the brachialis muscle, reported that transducer rotation “by more than about five degrees” tended to decrease the observed pennation angle of the muscle. Reddy et al (2001) reported the magnitude and direction of bladder neck motion (inward/outward and ventral/dorsal translation plane) during a strain, cough and pelvic floor contraction with a sagittal perineal imaging approach. In doing so they determined and compensated for transducer motion relative to the pubic symphysis (bony landmark). They reported that the transducer / pubic symphysis relationship shifted 70% of the time during a strain, 53.5% of the time during coughing and 20% of the time with a pelvic floor contraction. Further, the shift of this relationship resulted in a percentage error in the calculation of the distance and direction of bladder neck motion.

Aware of the potential source of error resulting from transducer motion, previous investigators have chosen to employ elaborate laboratory apparatus and imaging post-processing (Bunce et al. 2002; 2004; Peng et al. 2006; Brown & McGill 2008; Lovegrove Jones et al. 2009; Jhu et al. 2010) in an attempt to maintain or compensate for transducer (or participant) motion. In contrast, others have neglected to indicate how transducer motion was controlled for, or report that transducer position was maintained manually. In keeping with the inconsistency of methodology it is not surprising that the range of reported reliability estimates for sonographic parameters, such as abdominal wall muscle thickness and bladder base position are widespread. For example reported ICC’s of abdominal muscle thickness range from 0.26 – 0.92 (Costa et al. 2009b), while those for bladder base motion range from 0.51 – 0.98 (O'Sullivan et al. 2002; Thompson et al. 2005; 2007). Although there are many factors that could be influencing the spread of these values (experimental set-up, imaging site, operator expertise, statistical analysis etc.), it is interesting to note that 80% of the ICC values for single resting measures were > 0.80 while most values for change in thickness, or during dynamic manoeuvres in which transducer motion was likely, were < 0.70. One plausible interpretation of this is that transducer motion during a dynamic event may interfere with accurate interpretation.

Clearly, changes in transducer position introduce measurement error for a variety of sonographic parameters. What is not known is the amount of transducer motion that can occur before error is introduced, i.e. the threshold motion. Further, if the amount of ultrasound transducer motion that typically occurs during commonly employed clinical physiotherapy manoeuvres falls below this threshold.

4.2 Aims and Hypotheses

The aims of this study were;

4.2.1 To investigate the threshold of ultrasound transducer motion that is acceptable during USI studies before significant error is introduced into measurements of transversus abdominis (TrA) thickness and bladder base position.

4.2.2 To investigate the amount of ultrasound transducer motion that occurs during commonly utilized clinical physiotherapy tests for lumbopelvic pain (respiration an ADIM and an ASLR test), in relation to the bony pelvis, as a means to inform clinicians and more specifically the subsequent investigations in this thesis.

The hypotheses were that;

4.2.3 Small amounts of induced transducer motion would not result in measurements that exceed previously reported indicators of statistical or clinical change and accordingly not significantly interfere with the measurement process.

4.2.4 The small amounts of transducer motion that occur during clinical physiotherapy tests do not exceed the threshold of acceptable transducer motion.

4.3 Methods

This investigation took place in the Biomechanics, Laboratory, Faculty of Health Sciences, University of Southampton, Southampton, UK in collaboration with Dr Martin Warner. Specifically, Dr Warner assisted with the development of the VICON protocol and analysis, as well as wrote the kinematic model used to define the pelvis and USI transducer segments. This section contains the methodology specific to this investigation with the exception of that related to the specifics of the motion analysis which can be found along with general methodological considerations in Chapter 3 (Section 3.4).

4.3.1 Participants

Twelve healthy volunteers (8 female and 4 male) aged 19 - 44 years (yrs) took part in this investigation. Participants averaged 30.6 ± 8.2 yrs, 70.4 ± 10.9 kg and had a mean body mass index (BMI) of 24.3 ± 3.0 kg/m^2 (see Appendix 3a for individual participant details). A further three subjects (1 male and 2 female) volunteered for participation in the study. However after clinical screening all three were excluded, two due to clinical signs of hypocapnia ($ETCO_2$ levels< 35mm Hg in combination with Nijmegen questionnaire score > 24) and the third due to positive findings on both the ASLR test and One Leg Standing tests (see Section 3.2.3). Ethical considerations are discussed in Section 3.1.

4.3.2 Motion Analysis Protocol

A six camera Vicon 460 digital optical motion capture system (Oxford, UK) was used to monitor motion of the bony pelvis and USI transducer throughout data collection. This system was capable of providing accurate information about both the angle of rotation of

either segment (the pelvic or the transducer) around three axes, or translation through three planes (see Section 3.4 for details).

4.3.3 Ultrasound Imaging Protocol

A USI system with a 5.0 MHz curvilinear transducer was used to generate B - mode images with participants in a supine lying position, and mimic collection of real-time clips while participants randomly performed a respiratory task, an ASLR test and an ADIM (see Section 3.3 for details of the USI system and manoeuvres). To determine transducer threshold motion, images of the TrA were gathered from the right anterior lateral abdominal wall (LAW; Figure 3.2), while sagittal images of the bladder and bladder base (Figure 3.5) were gathered from a sagittal mid-line supra-pubic (SSP) imaging site. To determine transducer motion during the clinical manoeuvres a third abdominal imaging site, over the linea alba (LA; immediately inferior to the umbilicus; Figure 3.3), was included (see Section 3.3 for details of the imaging sites).

4.3.4 Procedure for Inducing Transducer Orientation

Prior to manipulating the orientation of the transducer at either the LAW or SPP imaging site, a reference USI image was generated and recorded, then the location through the longitudinal axis of the transducer was marked on the abdominal skin with a black pen to assist in transducer relocation. The position of the transducer relative to the pelvis (at the reference location) was then recorded (by the motion analysis system). This reference image and corresponding transducer orientation (defined as 0^o) served as the reference point from which all induced transducer positions about that axis were compared. This procedure was repeated prior to inducing motion for every axis and the one plane (inward and outward translation) of interest.

As the goal was to mimic transducer motion that may occur during a dynamic study in a clinical environment, the transducer was moved manually approximately 5^o and 10^o in both a positive and negative direction about each axis (X, Y and Z). When inducing inward and outward motion of the transducer (only at the SSP transducer location) the operator first increased the inward force on the transducer (from that of the reference position), an image was recorded then all inward force on the transducer was released and the participant was asked to push their abdominal wall out causing outward transducer motion. Clockwise (CW) and counter clockwise (CCW) motions were induced with the help of a transparency template placed on the skin with both the longitudinal axis of the transducer (0^o), as well as lines corresponding to +5, +10, -5 and -10 degrees marked on it. Cranial / caudal and medial / lateral tilt of the proximal end of the transducer was induced with the help of a goniometer. The actual transducer angles and inward/outward

translation achieved (including out of plane motion) were later confirmed by the motion analysis data and are reported in the results. In total ultrasound images and transducer positions were recorded for 15 different transducer orientations at the LAW location and 19 different transducer orientations at the SPP location, for each participant (5 each about the X, Y and Z axis and 4 associated with inward /outward motion; Table 4.1).

Table 4.1: Summary of Approximate Induced Transducer Positions.

IMAGING SITE	X AXIS ROTATION (CW / CCW)	Y AXIS ROTATION (Cranial / Caudal)	Z AXIS ROTATION (Medial / Lateral)	Z AXIS TRANSLATION (In/Outward)	TOTAL
LAW	-10 -5 0 5 10	-10 -5 0 5 10	-10 -5 0 5 10		15
SPP	-10 -5 0 5 10	-10 -5 0 5 10	-10 -5 0 5 10	Pin 0 Pno Val	19

CW / CCW = clockwise / counter clockwise, LAW = lateral abdominal wall imaging site, SPP = sagittal suprapubic imaging site, Pin = inward pressure, Pno = no inward pressure, Val = voluntary Valsalva manoeuvre.

4.3.5 Procedure for Clinical Manoeuvres

In the second portion of the investigation transducer motion (relative to the pelvis) was recorded as participants performed an ASLR test while a handheld transducer was used to mimic USI data collection at all three abdominal imaging sites. Participants also performed a respiratory task (which included forced expiration) and a ADIM while the handheld transducer was used to mimic USI data collection at the LAW imaging site only. The order of task and imaging site were randomly assigned. Each manoeuvre was repeated three times and the data saved for later analysis. Standardized verbal instructions were employed for all tasks and a foot switch was used to mark specific events (i.e. breath in, breath out, leg lift etc.) in the timeline of motion data for each task (see Section 3.3 for details of the manoeuvres, standardised instructions and events).

4.3.5 Data Analysis

All statistical calculations were performed using the Statistical Package for the Social Sciences version 15.0 software (SPSS; Chicago, USA).

4.3.5.i Transducer threshold motion

Descriptive statistics (mean, standard deviation and range) relating to the amount of transducer motion (relative to the pelvis) that occurred around all three axes, including the inward / outward motion, during changes in transducer orientation were calculated. Ultrasound images were captured, stored, and measured off line on a laptop computer using National Institutes of Health (Bedthesda, MD) ImageJ software (V 1.38t) (http://rsb.info.nih.gov/nih-image/). Transversus abdominis thickness (Figure 3.2b) and bladder base position (Figure 3.5b) were calculated as outlined in Section 3.3. Descriptive statistics for each USI measurement arising from all images taken during manipulation of the transducer around a particular axis (i.e. X) were calculated. The data were tested for normality (Shapiro-Wilk test) and repeated measures analyses of variance (ANOVA) were then performed for each pool of measurements or data sets (i.e. TrA thickness about an X axis) to determine if the values were statistically different from the reference image data (α=0.05). For data sets in which a statistically significant difference resulting from the changes in the transducer orientation was identified the data corresponding from the two outer transducer positions (the so called -10 and +10 degree positions) were removed and the ANOVA recalculated on the smaller data set (i.e. the so called -5 and + 5 degree positions). The motion data corresponding to the images that showed no significant difference ($p>0.05$) in the measurement of the USI parameter were then summarized to provide a range of acceptable transducer motion (relative to the pelvis) for changes in orientation resulting from CW / CCW motion, cranial / caudal tilting, medial / lateral tilting, and inward / outward motion of the transducer.

4.3.5.ii Transducer motion during clinical manoeuvres

Transducer motion data were grouped based upon the imaging site and manoeuvre performed. Descriptive statistics (mean, standard deviation and range) were used to summarize the maximum amount of transducer motion (relative to the pelvis) that occurred in a clockwise (CW) counter clockwise (CCW; X axis rotation), cranial caudal (Y axis rotation) medial lateral (Z axis rotation) and inward / outward (Z axis translation) direction for each imaging site / manoeuvre combination regardless of the point in the task were it occurred. These values were then compared to the error threshold values obtained from the first portion of this investigation.

4.4 Results

Data for this investigation was collected over two periods of time; November 2007 (eight participants) and February 2008 (four participants).

4.4.1 Transducer Threshold Motion

The initial eight subjects provided data for the portion of the investigation aimed at establishing threshold guidelines. In total, 111 transducer orientations and associated USI images of the TrA, and 143 transducer orientations and associated USI images of bladder base, collected from the first eight of the 12 participants, were used for analysis. VICON camera data was unavailable for 18 (7%) induced transducer orientations and the USI images associated with these missing motion analysis data were excluded from analysis.

The descriptive statistics (mean ± standard deviation, range) for actual transducer motion, relative to the pelvis, for the two transducer positions during the various conditions are summarized in Table 4.2 (see Appendix 7a for detailed results). At the LAW imaging site, the actual ranges of induced transducer tilt in the different planes of motion were: -16.3^{o} to 16.2^{o} of CW / CCW; -8.2^{o} to 7.3^{o} of cranial/caudal; and -5.8^{o} to 8.4^{o} of medial/lateral tilt. At the SPP imaging site -23.6^{o} to 24.2^{o} of CW /CCW; -13.4^{o} to 16.8^{o} of cranial/caudal; -25.3^{o} to 12.8^{o} of medial/lateral tilt; and -8.7 to 16.7mm of inward and outward motion of the transducer was induced. An attempt was made to approximate changes in transducer orientation in one direction at a time. However, as it is unlikely that transducer motion will occur about only one axis or in one plane at a time during a dynamic study in a clinical environment out of plane motion was purposely permitted and reported (Table 4.2). Consequently motion about one axis may have occurred during a condition in which motion was being induced about another axis. For example, a greater value of cranial/caudal and medial/lateral transducer motion (at the SPP imaging site) was seen during the condition concerned with inducing CW/CCW transducer rotation.

A summary of the descriptive statistics (mean ± standard deviation, range) for measurements of TrA thickness and bladder base position, before and after changes in transducer orientation are found in Tables 4.3 and 4.4, respectively (see Appendix 7b for detailed results). The reference values (0^{o}) for TrA thickness ranged from 1.6 – 5.0mm with an average of 3.0 ± 0.9mm. Induced values for TrA thickness ranged from 1.4 – 5.4mm with an average of 3.0 ± 0.9mm. The average percent change in TrA when inducing motion about the X, Y and Z axis was 3.3%, 1.5% and 3.1% respectively. The average percent change in AP bladder base position ranged from 0.6% during cranial / caudal tilting to 4.7% during inward and outward motion of the transducer. The average percent change in CC bladder base position ranged from 1.1% during CW / CCW tilt to 3.5% during inward and outward motion of the transducer

Table 4.2: Summary of Actual Induced Ultrasound Transducer Orientation

IMAGING SITE	X AXIS ROTATION (CW / CCW) Degrees Absolute Mean±S.D, (range)	Y AXIS ROTATION (Cranial / Caudal) Degrees Absolute Mean±S.D, (range)	Z AXIS ROTATION (Medial / Lateral) Degrees Absolute Mean±S.D, (range)	Z AXIS TRANSLATION (Inward/Outward) mm Absolute Mean±S.D, (range)
LAW	**X 8.6±4.4 (-16.3 - +16.2)** Y *4.7±3.6 (-11.8 - +13.8)* Z *3.3±2.8 (3.4 - 13.5*	X *5.0±3.3 (-13.0 - +10.3)* **Y 3.3±2.4 (-8.2 - +7.3)** Z *3.2±2.1 (-8.7 - +5.8)*	X *1.5±1.5 (-3.1 - +5.4)* Y *2.6±2.8 (-2.4 - +11.8)* **Z 4.5±2.1 (-5.8 - +8.4)**	
SSP	**X 14.0±8.2 (-23.6 - +24.2)** Y *9.9±13.7 (-9.3 - +16.8)* Z *6.1±4.2 (-13.5 - +12.8)* Zt	X *4.0±4.2 (-16.1 - +2.5)* **Y 8.8±4.7 (-13.4 - +16.6)** Z *2.5±2.5 (-10.7 - +3.1)* Zt	X *6.6±4.2 (-15.4 - +1.7)* Y *3.5±2.4 (-8.0 - +8.50* **Z 7.8±7.7 (-25.3 - +6.3)** Zt	X *2.0±1.3 (-3.4 - +5.0)* Y *2.9±2.4 (-4.4 - +3.1)* Z *1.7±1.2 (-4.4 - +3.1)* **Zt 8.1±4.4 (-8.7 - +16.7)**

Bold font represents the primary axis about which the transducer was manipulated. The smaller font represents associated out of plane motion (CW = clockwise, CCW = counter clockwise, LAW = lateral abdominal wall imaging site, SSP = sagittal suprapubic imaging site).

Table 4.3: Transversus Abdominis Thickness for Induced Transducer Orientation about the X, Y, Z Axes

	TrAX (CW /CCW)	TrAY (Cranial / Caudal)	TrAZ (Medial / Lateral)
Ave. reference value (mm)	3.0±0.9	2.9±1.0	3.0±0.8
Ave induced value (mm)	3.1±1.1	3.0±0.8	3.1±0.9
Ave. change (mm)	0.1±0.4	0.4±0.6	0.04±0.4
Ave % change	3.3	1.5	3.1

TrA = transversus abdominis thickness defined as the perpendicular distance between the muscles superficial and deep fascial boundaries. No significant differences (p=0.05) were found.

Table 4.4: Bladder Base Position Measurements for Induced Transducer Orientation about the X, Y, Z axes, and Zt Plane

	BB APX (CW / CCW)	**BB APY** (Cranial / Caudal)	**BB APZ** (Medial / Lateral)	**BB APZt** (Inward/Outward)
Ave reference value (cm)	8.6±1.8	8.7±1.7	8.6±1.7	8.7±1.9
Ave induced value (cm)	8.4±1.8	8.6±1.8	8.6±1.9	9.1±2*
Ave. change (cm)	0.2±0.5	0.06±0.4	0.07±0.5	0.4±.8
Ave % change	2.6	0.6	0.8	4.7
	BB CCX (CW / CCW)	**BB CCY** (Cranial / Caudal)	**BB CCZ** (Medial / Lateral)	**BB CCZt** (Inward/Outward)
Ave reference value (cm)	11.6±3.9	12.1±4.0	11.3±3.4	11.6±4.1
Ave induced value (cm)	11.4±4.3*	12.5±3.8	11.0±3.8	12.0±3.8
Ave. change (cm)	0.1±1.6	0.4±0.8	0.3±0.8	0.4±1.2
Ave % change	1.1	3.2	2.6	3.5

* Significant difference ($p<0.05$), AP = perpendicular distance from top of image to a reference point on the bladder base, BB = sagittal bladder base imaging site, CC = perpendicular distance from side of image to a reference point on the bladder base, CW = clockwise, CCW = counter clockwise.

Table 4.5: Guidelines for Acceptable Amounts of Transducer Motion for Measurements of TrA Thickness and Bladder Base Position

Measurement	**CW / CCW** motion (degrees)	**Cranial / Caudal** tilt (degrees)	**Medial / Lateral** tilt (degrees)	**Inward / Outward** motion (mm)
TrA	≤ 9°	≤ 5°	≤ 5°	unknown
BB Base AP	≤ 14°	≤ 10°	≤ 8°	< 8mm
BB Base CC	< 10°	≤ 10°	≤ 8°	≤ 8 mm

BB Base AP = perpendicular distance from top of image to a reference point on the bladder base, BB Base CC = perpendicular distance from side of image to a reference point on the bladder base, CW = clockwise, CCW = counter clockwise, TrA = transversus abdominis thickness.

None of the data sets corresponding with TrA thickness measurements during the induced transducer conditions were found to be statistically different ($p>0.05$) to the reference image measurement. In addition to providing ranges of acceptable transducer motion this result suggests that the operator likely maintained some degree of consistency with respect to inward/outward pressure (which was not monitored at this imaging site) during the data collection. Further, only the data sets for the AP bladder base measurement during induced inward / outward transducer motion and the CC bladder base measurement during induced CW / CCW transducer motion were found to be significantly different ($p<0.05$) to the reference image measurement. Consequently it can be concluded that it is unlikely that transducer motion as summarized in Table 4.5 will introduce error into measurements of TrA thickness and bladder base position.

4.4.2 Transducer Motion during Clinical Manoeuvres

In total, 93 LAW (32 ASLR, 32 respiratory and 29 ADIM), 29 LA (ASLR), and 31 SSP (ASLR) motion trials from 11 of the 12 participants, were used for analysis. Data from one subject was not included in the analysis as there was no analogue signal available to determine where the start and end points of the trial were. Of the subjects included in analysis motion analysis data was unavailable for 13 (7%) trails.

Descriptive statistics (mean ± standard deviation, range) for maximum transducer motion (relative to the pelvis) for each imaging site and manoeuvre combination are summarized in Table 4.6 (see Appendix 7c for detailed results). The condition that resulted in the greatest amount of angular transducer motion was the SSP imaging site during the ASLR (2.8±2.2 to 7.1±4.5 degrees), while the least was seen at the LAW imaging site during the ADIM (1.4±0.7 – 2.7±1.5 degrees). The condition that resulted in the greatest amount of inward/outward transducer translation was the LAW imaging site during the ASLR (8.2±2.9 mm), while the least was seen at the SSP imaging site during the ASLR (3.4±2.7 mm). In general, the ASLR was the manoeuvre that produced the greatest amount of transducer motion (2.1±1.4 to 7.1±4.5 degrees of angular motion and 3.5±2.7 to 8.2±2.9mm of inward/outward translation), while the ADIM produced the least (1.4±0.7 to 2.7±1.5 degrees of angular motion and 4.1±2.3mm of inward/outward translation. Further, it is of interest to note that during an ASLR test the maximum transducer motion occurred at the moment that the leg was raised from the supporting surface (Figure 4.1). None of the manoeuvres produced large transducer motions relative to the pelvis (see Tables 4.7 and 4.8), and all findings were within error threshold guidelines (Table 4.5) suggesting that a USI transducer can be held relatively stationary in a clinical setting for the manoeuvres tested in the hands of an experienced operator.

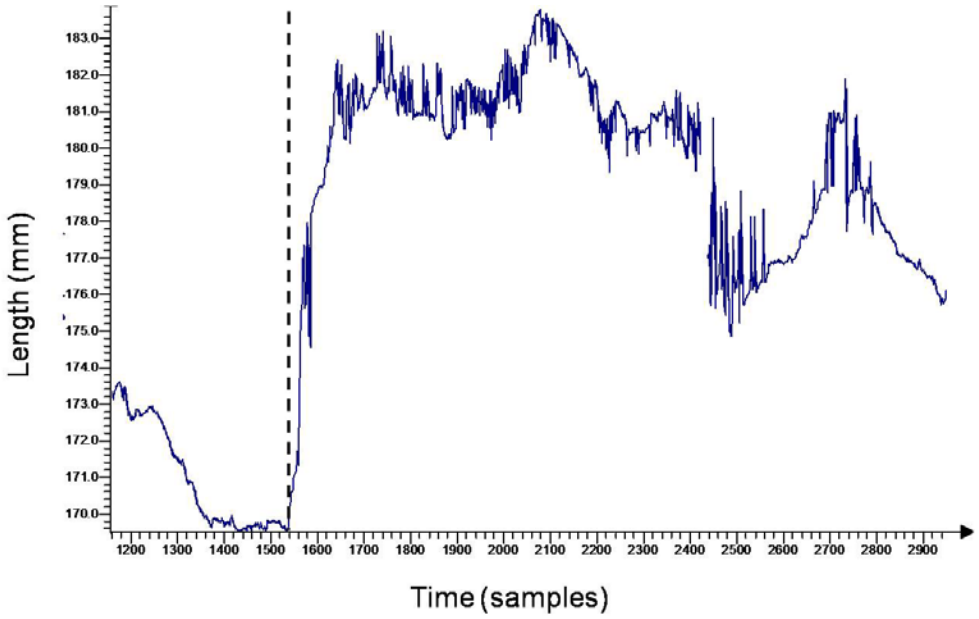


Figure 4.1: Ultrasound transducer motion (outward translation) at the lateral abdominal wall imaging site during an Active Straight Leg Raise test. Note that the majority of the motion occurs at the moment the leg is lifted from the support surface (dashed line).

Table 4.6: Ultrasound Transducer Motion with Respect to the Pelvis During RESP, ADIM & ASLR Manoeuvres

CONDITION		X (AP) AXIS ROTATION (CW / CCW) Degrees Mean±S.D, (range)	Y (LR) AXIS ROTATION (Cranial / Caudal) Degrees Mean±S.D, (range)	Z (CC) AXIS ROTATION (Medial / Lateral) Degrees Mean±S.D, (range)	Z TRANSLATION (Inward / Outward) mm Mean±S.D, (range)
RESP					
	LAW	2.3±0.8, (0.3 – 5.2)	3.3±1.4, (0.8 – 7.2)	2.2±1.1, (0.6 – 4.6)	6.0±2.6, (1.6 - 12.3)
ADIM					
	LAW	1.4±0.8, (0.2 – 3.8)	2.7±1.5, (0.5 – 6.9)	1.4±0.7, (0.5 – 3.4)	4.1±2.3, (0.8 - 11.6)
ASLR					
	LAW	2.1±0.7, (0.7 – 3.3)	2.7±1.1, (1.0 – 6.5)	4.3±1.4, (2.3 – 7.1)	8.2±2.9, (3.0 - 13.8)
	IRD	2.1±1.4, (0.5 – 6.1)	3.3±1.6, (1.0 – 10.3)	4.8±2.4, (2.1 – 11.0)	6.7±2.0, (1.7 - 13 0)
	SSP	5.2±4.0, (0.8 – 19.3)	2.8±2.2, (0.7 – 9.9)	7.1±4.5, (2.2 – 23.2)	3.4±2.7, (0.7 - 14.7)

ADIM = abdominal drawing in manoeuvre, AP = anterior posterior, ASLR = active straight leg raise test, CC = cranial caudal, CW = clockwise, CCW = counter clockwise, LA = linea alba imaging site, LAW = lateral abdominal wall imaging site, LR = left right, ML = medial lateral, RESP = respiratory task, SSP = sagittal supra-pubic imaging site.

Table 4.7: Comparison of Ultrasound Transducer Motion at the LAW Imaging Site to Error Thresholds (Whittaker et al. 2009) during a Respiratory task, the ADIM and the ASLR test

CONDITION	Transducer Motion				Error Thresholds			
	CW / CCW Degree, Mean±S.D	Cranial / Caudal Degree, Mean±S.D	Medial / Lateral Degree, Mean±S.D	Inward / Outward mm, Mean±S.D	CW / CCW Degree	Cranial / Caudal Degree	Medial / Lateral Degree	In / Outward mm
RESP	2.3±0.8	3.3±1.4	2.2±1.1	6.0±2.6				
ADIM	1.4±0.8	2.7±1.5	1.4±0.7	4.1±2.3	< or = 9	< or = 5	< or = 5	unknown
ASLR	2.1±0.7	2.7±1.1	4.1±1.4	8.2±2.9				

ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg raise test, CW = clockwise, CCW = counter clockwise, LAW = lateral abdominal wall imaging site, RESP = respiratory task.

Table 4.8: Comparison of Ultrasound Transducer Motion at the LA, and SSP Imaging Sites to Error Thresholds (Whittaker et al. 2009) during the ASLR Test

CONDITION	Transducer Motion				Error Thresholds			
	CW / CCW Degrees, Mean±S.D,	Cranial / Caudal Degrees, Mean±S.D,	Medial / Lateral Degrees, Mean±S.D,	Inward / Outward mm, Mean±S.D	CW / CCW Degrees	Cranial / Caudal Degrees	Medial / Lateral Degrees	Inward / Outward mm
LA	2.1±1.4	3.3±1.6	4.8±2.4	6.7±2.0	unknown	unknown	unknown	unknown
SSP	5.2±4.0	2.8±2.2	7.1±4.5	3.4±2.7	< 10	< or = 10	< or = 8	< or = 8 mm

AP = anterior posterior, ASLR = active straight leg raise test, CC = cranial caudal, CCW = counter clockwise, CW = clockwise, LA = linea alba imaging site, ML = medial lateral, SSP = sagittal supra-pubic imaging site.

4.5 Discussion

This is the first study that has attempted to establish guidance for acceptable (threshold) amounts of ultrasound transducer motion when measuring TrA thickness and bladder base position. Further, this is the first study to determine if the amount of transducer motion that occurs when undertaking a dynamic USI study of the abdominal wall or bladder base during manoeuvres common to a physiotherapy assessment of the lumbopelvic region falls within these guidelines. The findings (now published in the papers cited below) support the proposed hypotheses (4.2.3 and 4.2.4), that no statistically significant ($p<0.05$) changes in measurements of TrA thickness or bladder base position (from a sagittal transabdominal approach) occur if transducer motion is kept to less than 10 degrees of angular, or 8mm of inward / outward motion (Whittaker et al. 2009), and that it is possible to keep transducer motion within these guidelines during clinical tests, suggesting that meaningful measurements of TrA thickness and bladder base position can be made during these manoeuvres in a clinical setting, if a similar methodology is employed (Whittaker et al. 2010).

4.5.1 Comparison of Threshold Findings to Indicators of Statistical and Clinical Significance.

Although the absolute values of the USI parameters investigated are consistent with previous published values (Rankin et al. 2006) it is useful to compare the threshold amounts of acceptable transducer motion with previously reported indicators of statistical and clinically significant change. Indicators of statistical significance include standard error of measurement (SEM) and minimum detectable change (MDC; Portney & Watkins 1999). However, statistical significance does not necessarily translate to clinical significance, which is defined as the change that must take place in a patient's score to become a score typical of the normal population (Jacobson et al. 1984).

The SEM is a reliability measure of response stability and is calculated by estimating the standard error in a set of repeated scores (Portney & Watkins 1999). The MDC represents the smallest difference or change that would be statistically significant when comparing repeated measures of a particular parameter. There are several studies that provide these statistics for TrA thickness (see Costa et al. 2009b for a summary) and displacement of the bladder base with a pelvic floor muscle (PFM) contraction (Sherburn et al. 2005; Thompson et al. 2005; 2007) but none that have done so for resting bladder base position. Published SEM values for repeated measurements of TrA (resting) thickness in supine vary from 0.1 – 0.45mm (see Costa et al. 2009b for a summary). Kiesel et al (2007) reported a MDC of 0.30mm for thickness measures of TrA thickness (in supine), suggesting that changes less than 0.30mm are not statistically significant. Our findings of

induced changes of TrA thickness between 0.04 – 0.4 mm (Table 4.3) are within these previously reported SEM and MCD values. SEM and MDC values for changes in the position of the bladder base (sagittal supra-pubic USI) during a PFM contraction vary from 0.1 – 0.6mm and 3.6mm respectively (Sherburn et al. 2005; Thompson et al. 2005; 2007). Although the present study was concerned with resting bladder base position measurements at various induced transducer positions, they range between 0.6 – 4mm (Table 4.4) and are in line with the previously reported SEM and MCD values for this parameter during a PFM contraction.

Clinical significance is generally used when interpreting a patient's response to a particular intervention; however it may be useful in the context of this discussion to provide further interpretation of the findings (i.e. is the change in TrA thickness or bladder base position, resulting from manipulation of transducer orientation, of a magnitude that would be considered clinically significant). Jacobson et al (1984) suggest that a clinically significant change in a score is one that moves the score more than two standard deviations from the mean for the patient group. Teyhen et al (2009b) report the difference in the change in TrA thickness between a lumbopelvic pain (LPP; 6.4±2.9%) and normal healthy (23.7±2.9%) cohort during an ASLR test. Based on these findings a clinically significant change would be one that resulted in a 5.8% increase in TrA thickness, which is greater than the percent change in thickness reported in the present study (range 1.5% – 3.9%). In regards to bladder base position Thompson et al (2007) reported that the change in position of the bladder base during a PFM contraction differed between two patient groups (urge incontinence = 2.6±6.1mm; stress urinary incontinence = 5.5±5.1mm) and a normal cohort (5.0±4.9mm). Based on their findings a clinically significant change would be one that resulted in a 9.8mm change in bladder base position, which is greater than the changes reported in the present study (range 0.6 – 4mm). This suggests that the amount of transducer orientation manipulation in the present study did not produce changes in measurements of TrA thickness or bladder base position that were clinically significant.

4.5.2 Clinical Messages

Several clinical messages can be drawn from this investigation. First, sonographic studies and clinical assessments investigating TrA muscle thickness and bladder base position should take transducer orientation into account to improve the reliability of the imaging technique. For general guidance, investigators and clinicians are advised to minimize angular motion of the transducer to less than 10^{o} and inward/outward motion to less than 8mm. It is interesting to note that the condition with the greatest amount of induced error across all participants was for measurements of cranial/caudal bladder base position

when attempting to induce CW/CCW transducer motion (X axis). It is clear that unlike manipulation of the transducer in the other planes, there was significant out of plane transducer motion in the other two directions (cranial/caudal and medial/lateral tilt; Table 4.2), suggesting that there may be a culmination of error when changes in transducer motion occur about several axes. Hence the data indicate an argument that transducer motion around multiple axis or planes should be minimized.

Second, although none of the manoeuvres produced transducer motions greater than the threshold guidelines, it is not surprising that a greater amount of transducer motion was seen during the more dynamic manoeuvres (i.e. ASLR test > forced respiration > ADIM), suggesting that conscious efforts to control transducer motion during these types of manoeuvres may be prudent. In the case of the condition that resulted in the greatest amount of outward transducer motion, the LAW imaging site during an ASLR test, it is interesting to note that the maximum motion occurred at the moment that the leg was raised from the supporting surface. Similarly in the case of the condition that resulted in the greatest amount of angular transducer motion, the SSP imaging site during an ASLR test, the maximum transducer motion occurred again at the moment that the leg was raised from the supporting surface in the form of medial or lateral tilting of the proximal end of the transducer. Consequently a relevant teaching point for instructors, or future investigators employing this manoeuvre, would be to specifically concentrate on controlling for inward / outward translation and medial and lateral tilting of the transducer at the point of the leg lift.

A third clinical message speaks to the utility of trans-abdominal USI of the bladder base. Generally the trans-abdominal approach is commonly dismissed in favour of a trans-perineal one due to the fact that it provides no bony landmark from which to standardize measurements during dynamic events (Thompson et al. 2007; Whittaker et al. 2007b). Arguably the trans-perineal technique is advantageous in some situations as it provides a direct view of the levator ani muscles, facilitating study of their morphology, as well as the pubic symphysis, the bladder neck, and ano-rectal angle (see Figures 2.5, 2.6, 3.5 and 3.6; Dietz et al. 2001; Morkved et al. 2004; Peng et al. 2007a; Lovegrove Jones et al. 2009). However in contrast to the trans-abdominal approach, proficiency requires extensive training, measurements are complex, and transducer location is both intrusive and may at times interfere with functional manoeuvres such as the ASLR test (Whittaker et al. 2007b). The findings of this study suggest that in contrary to some investigators beliefs the trans-abdominal approach may be capable of rendering meaningful measures of bladder base position during dynamic manoeuvres similar to those investigated in this study in that transducer motion can be kept to degree that will not introduce error into the measurement process.

4.5.3 Limitations

Several limitations to this study must be acknowledged. Clearly a more complicated methodology and statistical model are required to provide definitive guidelines for directional threshold values of transducer motion. Specifically, it would be of interest to attempt to initiate transducer motion about only one axis or plane (i.e. inward and outward motion) at a time and determine the influence on specific USI parameters. As the goal of this investigation was to mimic changes in transducer orientation likely to occur during a dynamic imaging study in an attempt to inform researchers, clinicians and future investigations, such an endeavour was beyond its scope. Further, it is important to remember that the depth, size, and consistency of a structure, as well as the surrounding environment influence its appearance within a USI image (Kremkau 2002). For instance, transducer motion relative to the body surface results in greater distortion the further (deeper) a structure is from the USI transducer. Hence care must be taken when generalizing the results of this study to other measurement parameters and under different conditions (i.e. subject position and characteristics, dynamic manoeuvres). Keeping these points in mind, it is critical that the guidance reported here remains in context and absolute values are not quoted as being actual threshold levels for acceptable transducer motion for all USI parameters.

Secondly, it is likely that the abdominal wall muscles and bladder move independent of the bony pelvis during the dynamic manoeuvres. In this investigation we made the assumption that these structures were essentially one for ease of analysis. With that being said the transducer motion seen was within values that have been shown not to produce a statistically significant change in measurements of TrA thickness or bladder base position.

Finally, it is well accepted that persons with pain or dysfunction in the lumbopelvic region employ motor control strategies that differ from healthy subjects (O'Sullivan et al. 2002; Beales et al. 2009b; 2009a). For instance Beales et al (2009a) showed that subjects with unilateral chronic pelvic girdle pain adopt a bracing motor control strategy with their trunk muscles (specifically the external and internal oblique muscles) when performing an ASLR on their affected side. This bracing strategy was associated with higher levels of intra-abdominal pressure (IAP) and greater pelvic floor depression. Accordingly the greater abdominal wall muscle contraction and higher levels of IAP seen in persons with LPP may impart greater USI transduction motion than normal subjects during dynamic manoeuvres. In an attempt to mimic the greater amount of abdominal wall muscle contraction and IAP seen with LPP we included a forced expiration in the respiratory trials investigated here. Although the transducer motion seen during these trials was within the error thresholds

previously reported it would be prudent to include participants with LPP in future investigations.

4.6 Conclusions and Implications

4.6.1 Small amounts of ultrasound transducer motion (between 5^{o} - 10^{o} of angular and 8mm on inward / outward motion) do not introduce error into measurements of TrA thickness or bladder base position.

4.6.2 It is possible to keep transducer motion within the above guidelines during commonly used clinical tests such as the ASLR and ADIM.

4.6.3 The implication of these findings is that an ultrasound imaging transducer can be held relatively stationary in a clinical setting for the manoeuvres tested, in the hands of an experienced operator.

4.6.4 The information gained in this investigation can be used to inform clinical imaging technique, and improve the accuracy and reliability of sonographic data gathered from the abdominal muscles, and BB, during dynamic manoeuvres.

4.7 Summary and Novelty

This chapter has described a novel investigation aimed at determining if a USI transducer can be held adequately stationary to gather meaningful measurements during manoeuvres typical of a clinical physiotherapy examination of the lumbopelvic region. Armed with the findings and their implications, the next chapter will describe an investigation to determine if reliable measurements of the LAW muscles, RA, IRD and bladder base position can be obtained at rest and during and ASLR test and an ADIM in participants with and without LPP.

CHAPTER 5 - RELIABILITY OF ULTRASOUND IMAGING FOR RESTING AND DYNAMIC MEASUREMENTS OF THE ABDOMINAL WALL AND BLADDER BASE

Taking the findings of the investigation described in Chapter 4 into consideration, this chapter describes an investigation aimed at determining if reliable measurements of abdominal muscle thickness, inter-recti distance (IRD) and bladder base can be obtained in a clinical setting, at rest and during dynamic tests (Active Straight Leg Raise test; ASLR and Abdominal Drawing in Manoeuvre; ADIM) commonly employed during a physiotherapy assessment of the lumbopelvic region, in participants with and without lumbopelvic pain (LPP). This investigation lays the foundation for observational studies (presented in Chapter 7 and 8) aimed at comparing the sonographic characteristics of the abdominal wall and bladder, between these two cohorts, at rest and during the aforementioned clinical tests.

5.1 Introduction

The muscles and fascia of the abdominal wall and pelvic floor play a role in controlling the spine (Hodges et al. 2003a; 2005; Barker et al. 2006; 2007b; Sjodahl et al. 2009), and there is evidence of functional deficits of these structures in persons with lumbopelvic pain (see Section 2.1; Hodges & Richardson 1996; 1999; Van Uchelen et al. 2001; Ng et al. 2002b; Hungerford et al. 2003; Cowan et al. 2004; Beales et al. 2009a; Hides et al. 2009; Teyhen et al. 2009b; see Section 2.1 for more information). Ultrasound imaging (USI) provides a non-invasive method to quantify muscle size (which may reflect structure and function), fascial length, and changes in bladder position (which may reflect the interaction between pelvic floor muscle; PFM, activity and intra-abdominal pressure; IAP). Consequently it is being increasingly used as both a measurement and biofeedback tool by physiotherapists (see Section 2.3.3; Potter et al. 2011).

The validity of USI with respect to measuring abdominal wall muscle morphology has been partially established (healthy subjects under resting conditions) through comparison to magnetic resonance imaging (MRI) for thickness measurements of the transversus abdominis (TrA) and internal oblique (IO) muscles (Hides et al. 2006b). Further, the relationship between changes in muscle size and muscle activity have been investigated in small numbers of healthy subjects during isometric contractions for the external oblique (EO), IO and TrA muscles (see Section 2.3.1; Hodges et al. 2003b; Ferreira et al. 2004; McMeeken et al. 2004; John & Beith 2007a; Brown & McGill 2010). In contrast, there are no studies that have compared measurements of bladder base position obtained with USI and MRI. However, there are several MRI studies describing changes in the position of

the bladder base during voluntary contraction and straining (Christensen et al. 1995; Fielding et al. 1998; Bo et al. 2001). Although not directly compared to values gathered with USI, they are consistent with the ranges reported in similar experimental designs employing trans-abdominal USI (Bo et al. 2003; Sherburn et al. 2005).

As the abdominal muscles are the most common trunk muscles to be examined with USI, there are a considerable number of studies looking at the reproducibility of their measurement (see Section 2.3.2 and Table 2.1 for a summary). In a systematic review, Costa et al (2009b) identified 315 studies which included thickness measurements of one or more of the four abdominal wall muscles, but considered only 21 eligible for analysis. They reported that these investigations were generally of low quality in that they were primarily carried out on small asymptomatic samples. The reviewed studies reported moderate to excellent reliability (Interclass correlation coefficient; ICC, 0.62 - 0.92) for repeated single measures of thickness, and poor to good reliability (ICC, 0.26 - 0.85) for measures of thickness change. 80% of the ICC values for single measures were > 0.80 while most values for change in thickness were < 0.70. Recently two additional reliability studies have been published (Costa et al. 2009a; Koppenhaver et al. 2009a). In the first, Koppenhaver et al (2009a) calculated intra and interrater reliability in participants with low back pain (LBP), reporting values for single within, and between day measures of thickness and thickness change of the TrA muscle. Interclass correlation coefficient values for same day intra and interrater reliability ranged from 0.96 – 0.99 and 0.88 – 0.94 respectively, and 0.87 – 0.98 and 0.80 – 0.92 respectively for between day comparisons. In the second, Costa et al (2009a) investigated intrarater reliability in participants with LBP reporting values for reproducibility of measurement of thickness, thickness change and thickness changes from single images before and after treatment of the EO, IO and TrA muscles. Interclass correlation coefficient values for intrarater reliability ranged from 0.96 – 0.97 for thickness measurements, 0.65 – 0.76 for thickness change and 0.33 – 0.58 for changes from single images before and after treatment.

In contrast to the large number of studies investigating the reliability of abdominal muscle measurements there is only one study in the literature that has investigated the reliability of measuring the inter-recti distance (IRD) with USI (Liaw et al. 2006). In that investigation, Liaw et al (2006), reported intrarater and interrater ICC values ranging from 0.78 – 0.89 and 0.85 – 0.95 respectively, for resting measures at four imaging sites along the length of the linea alba in a young healthy cohort. Further, they reported standard error of measurement (SEM) values associated with the intrarater condition ranging from 0.07 – 0.10cm.

The reliability of measuring global bladder base (GBB) motion has been investigated during voluntary pelvic floor muscle (PFM) contraction (Sherburn et al. 2005), straining, abdominal curl-up, and the ASLR test (O'Sullivan et al. 2002; Sherburn et al. 2005; Thompson et al. 2005; 2006a). Good intrarater and interrater reliability for measurement of GBB motion during a PFM (ICC, 0.81-0.88; Sherburn et al. 2005), as well as good to excellent intrarater reliability during the ASLR test (ICC, 0.98: O'Sullivan et al. 2002) have been reported. In contrast, Thompson et al (2005; 2006a) report only moderate reliability for the measurement of GBB motion (sagittal view) during an abdominal curl-up (ICC, 0.53) and straining (ICC, 0.51) likely due to difficulty in maintaining a consistent transducer position when the abdominal wall is displaced outward with the contraction of the abdominal muscles or increase in IAP. To date there are no studies looking at measures of GB position, or the reliability of measuring GBB displacement between days.

As indicated in previous chapters, the clinical environment poses challenges to USI data collection (potential for greater ultrasound transducer motion, standardization of tasks, variability of movement patterns etc.). As such, the generalizability of the findings of the above reliability studies to the clinical setting is uncertain. As the primary goal of this thesis is to develop an argument for the role of USI during the clinical assessment of persons with LPP, it is critical that data collection occurs in a clinical setting.

5.2 Aim and Hypothesis

The aim of this study was to;

5.2.1 Evaluate the intrarater reliability of USI in obtaining thickness measurements of the abdominal wall muscles (rectus abdominis; RA, EO, IO, TrA), IRD as well as bladder and bladder base (sagittal) position, at rest and during an ASLR test and ADIM, within a single session (within day), and between two sessions (between day), in healthy and LPP cohorts in a clinical setting.

The hypothesis was that;

5.2.2 USI measurements of these parameters would be adequately reliable (ICC>0.75) for research and clinical use.

5.3 Methods

This section contains the methodology specific to this investigation which took place at a private physiotherapy practice in Surrey, British Columbia, Canada. General methodological considerations can be found in Chapter 3.

5.3.1 Participants

A convenience sample of 18 women (9 controls and 9 with LPP) participated in this investigation. The control participants averaged 40.7 ± 8.4 years of age (yrs) and had a mean body mass index (BMI) of 22.6 ± 2.2 kg/m^2, while the LPP cohort averaged 47.7 ± 7.5 yrs and had a mean BMI of 23.5 ± 2.5 kg/m^2 (see Appendix 3b for individual participant details). A further two persons with LPP (one male and one female) volunteered for participation in the study however, after screening both were excluded due to clinical signs of hypocapnia ($ETCO_2$ levels< 35mmHg in combination with Nijmegen questionnaire score > 24; see Section 3.2.3). Inclusion and exclusion criteria for both groups are described in detail in Section 3.2.1 and ethical considerations are discussed in Section 3.1.

5.3.2 Examiner

All imaging procedures were performed by one operator, the principle investigator (JW) who is an experienced physiotherapist (qualified 16 years) and has ten years of USI experience. In a previously published peer reviewed publication (Whittaker 2008) this investigator has demonstrated intrarater reliability of within day measurements of TrA and IO thickness (ICC, 0.98).

5.3.3 Ultrasound Imaging Protocol

A USI system with a 5.0 MHz transducer was used to collect anonymised B - mode USI clips of the lateral abdominal wall muscles (EO, IO and TrA; Figure 3.2), the IRD (Figure 3.3), the RA muscle (Figure 3.4), and the bladder (sagittal; Figure 3.5) while participants performed an ASLR test from a supine lying position, and an ADIM in a crooked lying position (see Section 3.3 for details of the USI system, imaging sites, and manoeuvres). Ultrasound clips were collected on two separate days (mean ± standard deviation; range, 3.4 ± 1.8; 1 – 7 days apart) with the exception of the IRD (ADIM and ASLR) and bladder (ASLR). Three USI clips were acquired at each imaging site for both dynamic manoeuvres (during which probe location was maintained) on day one, and two of both manoeuvres on day two. A standard bladder filling protocol was employed on both days (Thompson et al. 2005; 2006a; see Section 3.3.2 for bladder filling protocol). Resting and contracted frames from each clip were extracted and measured (see Section 3.3.3 for details on clip processing and management). Average values were calculated and used for analysis. To help avoid an order or fatigue effect, the order in which the muscles and manoeuvres were imaged was performed in random fashion.

Information from a previous study (presented in Chapter 4; Whittaker et al. 2009; Whittaker et al. 2010) regarding the influence of transducer motion on measurements of

TrA thickness and bladder base position, as well as the pattern of transducer motion that occurs during and ASLR test and ADIM, were taken into consideration during the data collection. Namely, the operator made every attempt to keep the angular and inward / outward motion of the transducer to a minimum, and paid specific attention to countering transducer motion at the point of initiation of the leg lift during the ASLR test (see Section 4.5.2).

5.3.4 Image Processing and Measurement

Images were measured offline using custom written measurement codes in MATLAB® version 7.1 software (Mathworks, Natick, Massachusetts, USA). The measurement codes had two unique features relevant to this investigation. Firstly, they prompted the operator to plot a reference line which ensured that measurements could be made at the same location in both day 1 and day 2 resting, and contracted images. Secondly, the codes concealed measurements from the operator by directly exporting them into an Excel worksheet. This ensured blinding of the examiner throughout the measurement process (see Section 3.3.3 for more information on the measurement codes). Measurements of IRD were made in consultation with a video clip of the IRD during a mild RA contraction (isometric trunk flexion in supine) to aid in the precision of delineating muscle boundaries.

5.3.5 Data Analysis

Statistical analysis was performed using the SPSS version 15.0 software (Chicago, IL). T-tests and chi square tests were used to compare cohorts for participant characteristics. Resting and contracted RA, EO, IO and TrA muscle thickness and IRD (width), for both the ASLR and ADIM across two days were included for analysis. This resulted in 4 different measurement conditions (supine ASLR rest, supine ASLR contracted, crook ly ADIM rest and crook ly ADIM contracted) for each parameter. Global change in position (ventral / dorsal, cranial / caudal and the resulting trajectory) of the bladder (GB) and bladder base (GBB), as well as the change in position of the bladder base relative to the bladder (RBB) during an ASLR and an ADIM within one day and during an ADIM between days were included for analysis (see Section 3.3 for definition of the bladder parameters)

Within day analyses were based on day one measurements. Interclass correlation coefficients' with 95% confidence intervals (CI) were calculated to assess intrarater reliability both within (model 3,3) and between (model 3,1) days (Shrout & Fleiss 1979). To assess measurement precision, SEM was calculated as SD x $\sqrt{}$(1-ICC), (Portney & Watkins 1999). The minimal detectable change (MDC), which represents the minimal change in thickness that must occur to be 95% confident that a true change has occurred, was calculated as 1.96xSEMx $\sqrt{}$2 (Terwee et al. 2007). Biases was estimated by

calculating the mean difference between days, while the limits of agreement (LOA) were calculated as the mean difference between days ± 2 x SD (Bland & Altman 1986).

5.4 Results

Demographic and baseline characteristics of both cohorts are provided in Table 5.1. The two groups were evenly matched in age, BMI, parity, end tidal carbon dioxide levels, breaths per minute, and scores of incontinence impact. The LPP cohort scored higher on the Nijmegen (clinical symptoms of hypocapnia) and Urinary Distress Index questionnaires. In total 1178 ultrasound images were measured and used in the analysis. 6.5% of the images were unavailable for analysis due to; poor image quality making delineation of the boundaries impractical, insufficient filling of the bladder, or corruption of the video clip file.

Table 5.1: Demographic and Baseline Characteristics of Participants

Characteristic	Controls (n = 9)	Lumbopelvic Pain (n = 9)
Age (yrs)	44.7±8.4 (31-53)	48.3±7.7 (39-59)
BMI (kg/m^2)	22.6±2.15 (20-26)	23.3±2.6 (20-26)
Parity	0.8±0.8 (0-2)	1.1±1 (0-3)
Gender Female/male (%)	100%/0%	100%/0%
Oswestry Disability Score (%)	n/a	20.2±14.4 (2-50)
Pain Intensity (NPRS 0 – 10)	n/a	2.7±1.6 (1-6)
Pain Duration (years)	n/a	11.3±6.0 (1.5-20)
FABQPA (0 - 24)	n/a	10.8±8.0 (0-24)
FABQW (0 - 42)	n/a	9.9±12.4 (0-38)
End Tidal CO_2 (mmHG)	37.4±2.2 (35-40)	38.0±2.8 (35-42)
Breaths / minute	11.1±1.7 (9-14)	12.3±2.3 (7-14)
Nijmegen (0 - 64)	7.9±5.8 (0-18)	16.0±4.3 (9-13)*
IIQ-7 (%)	2.1±6.3 (0-19)	2.6±5.4 (0-14)
UDI-6 (%)	3.1±5.7 (0-17)	19.4±14.8 (0-44)*

Values are in mean ± standard deviation (range). *Statistically significant ($p < 0.05$). BMI = Body mass index, FABQBP = Fear Avoidance Beliefs Questionnaire (Physical Activity sub scale), FABQW = Fear Avoidance Beliefs Questionnaire (Work sub-scale), IIQ = Incontinence Impact Questionnaire, NPRS = Numerical Pain Rating Scale, UDI = Urogenital Distress Index.

Within day abdominal wall muscle thickness and IRD (rest, contracted and change; mean ± SD), intrarater $ICC_{3,3}$ (95% CI), SEM and MDC values are summarized in Table 5.2 (ASLR) and 5.3 (ADIM) while between day values are found in Tables 5.4 (ASLR) and 5.5 (ADIM; see Appendices 8a and 8b for raw data). Within day changes in GB, GBB and RBB (mean ± SD), intrarater $ICC_{3,3}$ (95% CI), SEM, MDC, bias and LOA, for

both manoeuvres, are summarized in Table 5.6, while between day changes in the bladder parameters during an ADIM are summarized in Table 5.7 (see Appendix 8c for raw data).

Depending on the abdominal wall parameter and manoeuvre intrarater reliability (ICC) ranged from 0.84 – 0.99 for within day comparisons and 0.80 – 0.99 for between day comparisons (with the exception of 0.73 for resting thickness measurements of TrA in the case cohort) suggesting good to excellent reliability (Table 5.2). With respect to the bladder parameters within day and between day comparisons (ICC) for change in GBB and RBB position ranged between 0.85 – 0.99 and 0.89-0.99 respectively, again suggesting good to excellent reliability. In contrast, ICC values of change in GB position ranged between 0.71 – 0.99 for within day, and 0.31 – 0.82 for between day leaving some doubt as to the reproducibility of measuring this parameter. In general there was a tendency for the within day estimates to be higher than the between day values, and for the control estimates to be slightly higher than LPP case estimates. Further, with respect to the abdominal wall parameters the ICC values for the ASLR were slightly higher than those for the ADIM. This was in contrast to the bladder measures were the ADIM estimates were slightly higher than those for the ASLR.

Within and between day SEM values of abdominal muscle thickness ranged from 0.1 – 0.4mm, values for IRD width ranged from 0.2 – 1.5mm. Standard error of measurement values for the bladder parameters ranged between 0.1 – 1.8mm. Within and between day MDC values for abdominal muscle thickness were small and ranged from 0.1 – 1.7 mm, values for IRD width ranged from 0.5 – 4.4mm, while values for the bladder parameters ranged between 0.7 – 5.0mm. Between day bias estimates and LOA for abdominal wall muscle thickness ranged from 0.1 ± 0.1mm to 0.6 ± 1.7 mm, values for IRD width (rest only) ranged between 1.5 ± 3.0 to 5.6 ± 8.4 while between day measures of the bladder parameters ranged from 0.3 ± 0.4mm to 1.8 ± 1.9mm. Bland-Altman plots were used to look for any systematic bias, outliers and relationships between the difference in values between days and their magnitude (see Figure 5.1 for examples). Although several of the variables demonstrated slight biases (i.e. the mean of the between day measurements did not equal zero), which are indicative of a systematic error (i.e. day one measurements were consistently larger than day two), none of these was greater than the MDC suggesting that the bias did not represent a true difference. For example, the bias for the change in thickness of the TrA during the ADIM was 0.17mm while the MDC ranged between 0.2 – 0.7mm (see Figure 5.1a).

Table 5.2: Abdominal Wall Within Day Intrarater Reliability (Mean of 3 Measures); ASLR†

Muscle	Condition	Cohort	Mean±SD(mm*)	$ICC_{3,3}$(95% CI)	SEM(mm*)	MDC(mm*)
EO	Supine rest	All	3.4 ± 1.0	0.97 (.93-.99)	0.2	0.5
		Controls	3.6 ± 1.2	0.99 (.97-.99)	0.1	0.3
		Cases	3.3 ± 0.9	0.95 (.84-.99)	0.2	0.6
	ASLR hold	All	3.4 ± 1.0	0.98 (.96-.99)	0.1	0.4
		Controls	3.5 ± 1.1	0.99 (.98-.99)	0.1	0.3
		Cases	3.4 ± 0.9	0.95 (.85-.99)	0.2	0.5
	Change	All	-0.1 ± 0.3	0.93 (.85-.97)	0.1	0.2
		Controls	-0.2 ± 0.1	0.92 (.74-.98)	0.0	0.1
		Cases	-0.1 ± 0.3	0.93 (.79-.98)	0.1	0.2
IO	Supine rest	All	5.1 ± 1.2	0.97 (.94-.99)	0.2	0.5
		Controls	5.4 ± 1.2	0.97 (.89-.99)	0.2	0.6
		Cases	4.8 ± 1.1	0.97 (.92-.99)	0.2	0.5
	ASLR hold	All	6.0 ± 1.0	0.97 (.93-.99)	0.2	0.7
		Controls	6.0 ± 1.0	0.98 (.95-.99)	0.2	0.5
		Cases	6.0 ± 1.0	0.94 (.82-.99)	0.3	0.8
	Change	All	0.7 ± 0.6	0.88 (.73-.96)	0.2	0.6
		Controls	0.6 ± 0.5	0.89 (.57-.98)	0.2	0.5
		Cases	0.8 ± 0.6	0.90 (.67-.97)	0.2	0.6
TrA	Supine rest	All	2.6 ± 0.8	0.95 (.90-.98)	0.2	0.5
		Controls	2.5 ± 0.6	0.94 (.82-.99)	0.1	0.4
		Cases	2.7 ± 1.0	0.96 (.88-.99)	0.2	0.5
	ASLR hold	All	2.8 ± 0.7	0.93(.84-.97)	0.2	0.5
		Controls	2.8 ± 0.5	0.96 (.82-.99)	0.1	0.4
		Cases	2.8 ± 0.8	0.98 (.95-.99)	0.1	0.3
	Change	All	0.3 ± 0.3	0.96 (.92-.99)	0.1	0.2
		Controls	0.3 ± 0.3	0.96 (.86-.99)	0.1	0.2
		Cases	0.3 ± 0.3	0.97 (.91-.99)	0.1	0.2
RA	Supine rest	All	8.0 ± 1.4	0.99 (.97-.99)	0.2	0.5
		Controls	8.7 ± 0.9	0.97 (.87-.99)	0.2	0.4
		Cases	7.4 ± 1.5	0.99 (.95-.99)	0.2	0.5
	ASLR hold	All	8.2 ± 1.5	0.99 (.96-.99)	0.2	0.5
		Controls	8.7 ± 1.4	0.99 (.95-.99)	0.1	0.4
		Cases	7.6 ± 1.5	0.98 (.94-.99)	0.2	0.6
	Change	All	0.2 ± 0.6	0.92 (.81-.97)	0.2	0.5
		Controls	0.0 ± 0.7	0.91 (.65-.98)	0.2	0.6
		Cases	0.3 ± 0.5	0.93 (.77-.99)	0.1	0.4
IRD	Supine rest	All	12.1 ± 8.6	0.99 (.98-.99)	0.9	2.4
		Controls	9.3 ± 5.9	0.99 (.99-.99)	0.2	0.5
		Cases	14.2 ± 9.7	0.99 (.96-.99)	1.1	3.1
	ASLR hold	All	10.5 ± 7.2	0.99 (.97-.99)	0.9	2.4
		Controls	9.2 ± 5.8	0.99 (.99-.99)	0.3	0.7
		Cases	11.5 ± 8.1	0.98 (.94-.99)	1.1	3.0
	Change	All	-1.3 ± 2.6	0.96 (.91-.99)	0.5	1.4
		Controls	-0.7 ± 1.1	0.97 (.88-.99)	0.2	0.5
		Cases	-2.1 ± 3.4	0.96 (.86-.99)	0.7	1.9

†Day one values, *Values in millimetres except % change, ASLR = active straight leg raise test EO = external oblique, IO = internal oblique, IRD = inter-recti distance, LPP = lumbopelvic pain, RA = rectus abdominis, TrA = transversus abdominis.

Table 5.3: Abdominal Wall Within Day Intrarater Reliability (Mean of 3 Measures); ADIM†

Muscle	Condition	Cohort	Mean±SD(mm*)	$ICC_{3,3}$(95% CI)	SEM(mm*)	MDC(mm*)
EO	Crook ly rest	All	3.3 ± 1.0	0.97 (.92-.99)	0.2	0.5
		Controls	3.6 ± 1.1	0.97 (.88-.99)	0.2	0.5
		Cases	3.1 ± 0.8	0.95 (.83-.99)	0.2	0.5
	ADIM Hold	All	3.3 ± 1.0	0.93 (.83-.98)	0.3	0.7
		Controls	3.5 ± 1.2	0.94 (.75-.99)	0.3	0.8
		Cases	3.1 ± 0.8	0.92 (.74-.98)	0.2	0.6
	Change	All	-0.1 ± 0.2	0.93 (.83-.98)	0.1	0.2
		Controls	-0.1 ± 0.3	0.96 (.82-.99)	0.1	0.2
		Cases	-0.04 ± 0.2	0.84 (.47-.97)	0.1	0.2
IO	Crook ly rest	All	4.8 ± 1.1	0.96 (.91-.99)	0.2	0.6
		Controls	5.2 ± 1.0	0.94 (.75-.99)	0.2	0.6
		Cases	4.4 ± 1.1	0.97 (.95-.99)	0.1	0.4
	ADIM Hold	All	5.0 ± 1.0	0.97 (.92-.99)	0.2	0.6
		Controls	5.0 ± 1.0	0.99 (.94-.99)	0.1	0.3
		Cases	4.0 ± 1.0	0.94 (.81-.99)	0.3	0.7
	Change	All	0.2 ± 0.4	0.97 (.94-.99)	0.1	0.2
		Controls	0.3 ± 0.4	0.95 (.85-.99)	0.1	0.3
		Cases	0.0 ± 0.4	0.99 (.95-.99)	0.1	0.2
TrA	Crook ly rest	All	2.5 ± 0.3	0.89 (.70-.96)	0.1	0.3
		Controls	2.4 ± 0.4	0.88 (.48-.97)	0.1	0.3
		Cases	2.5 ± 0.3	0.89 (.51-.98)	0.1	0.3
	ADIM Hold	All	3.8 ± 0.6	0.90 (.72-.96)	0.2	0.5
		Controls	3.9 ± 0.4	0.93 (.67-.98)	0.1	0.3
		Cases	3.7 ± 0.7	0.90 (.54-.97)	0.2	0.6
	Change	All	1.3 ± 0.5	0.94 (.85-.98)	0.1	0.4
		Controls	1.4 ± 0.2	0.94 (.73-.99)	0.1	0.2
		Cases	1.2 ± 0.7	0.95 (.83-.99)	0.2	0.4
RA	Crook ly rest	All	8.2 ± 1.5	0.98 (.95-.99)	0.2	0.6
		Controls	9.1 ± 1.2	0.98 (.91-.99)	0.2	0.4
		Cases	7.3 ± 1.2	0.98 (.95-.99)	0.2	0.5
	ADIM Hold	All	7.5 ± 1.6	0.99 (.96-.99)	0.2	0.6
		Controls	7.9 ± 1.7	0.99 (.94-.99)	0.2	0.6
		Cases	7.1 ± 1.5	0.98 (.94-.99)	0.2	0.5
	Change	All	-0.5 ± 0.8	0.98 (.95-.99)	0.1	0.3
		Controls	-0.7 ± 1.0	0.98 (.93-.99)	0.1	0.4
		Cases	-0.3 ± 0.3	0.94 (.80-.99)	0.1	0.2
IRD	Crook ly rest	All	10.9 ± 7.7	0.99 (.99-.99)	0.4	1.2
		Controls	9.6 ± 6.5	0.99 (.98-.99)	0.5	1.4
		Cases	12.8 ± 8.6	0.99 (.99-.99)	0.4	1.1
	ADIM Hold	All	10.1 ± 7.9	0.99 (.99-.99)	0.4	1.2
		Controls	10.1 ± 6.4	0.99 (.96-.99)	0.6	1.7
		Cases	10.1 ± 9.0	0.99 (99-.99)	0.3	0.8
	Change	All	-2.0 ± 5.3	0.99 (.99-.99)	0.4	1.0
		Controls	-1.2 ± 1.7	0.99 (.98-.99)	0.1	0.3
		Cases	-2.7 ± 6.8	0.99 (.98-.99)	0.5	1.3

†Day one values, *Values in millimetres except % change, ADIM = abdominal drawing in manoeuvre, EO = external oblique, IO = internal oblique, IRD = inter-recti distance, LPP = lumbopelvic pain, RA = rectus abdominis, TrA = transversus abdominis.

Table 5.4: Abdominal Wall Between Day Intrarater Reliability; ASLR

Muscle	Condition	Cohort	Mean±SD(mm*)†	$ICC_{3,1}$(95% CI)	SEM(mm*)	MDC(mm*)	Bias±LOA(mm)*
EO	Supine rest	All	3.4 ± 0.1	0.97 (.91-.98)	0.2	0.5	0.1 ± 0.6
		Controls	3.6 ± 0.1	0.97 (.88-.99)	0.2	0.5	0.1 ± 0.6
		Cases	3.3 ± 0.1	0.97 (.85-.99)	0.2	0.5	0.1 ± 0.6
	ASLR hold	All	3.4 ± 1.0	0.96 (.90-.99)	0.2	0.5	0.2 ± 0.8
		Controls	3.5 ± 1.1	0.98 (.80-.99)	0.2	0.4	0.1 ± 0.6
		Cases	3.4 ± 0.9	0.94 (.74-.99)	0.2	0.6	0.2 ± 0.9
	Change	All	-0.1 ± 0.3	0.93 (.84-.97)	0.1	0.2	0.2 ± 0.5
		Controls	-0.1 ± 0.1	0.91 (.77-.98)	0.0	0.1	0.4 ± 0.5
		Cases	-0.0 ± 0.3	0.91 (.77- 98)	0.1	0.3	0.1 ± 0.2
IO	Supine rest	All	5.2 ± 1.2	0.93 (.82-.97)	0.3	0.9	0.4 ± 1.0
		Controls	5.4 ± 1.2	0.90 (.55-.98)	0.4	1.0	0.6 ± 1.0
		Cases	4.9 ± 1.1	0.96 (.84-.99)	0.2	0.6	0.2 ± 0.9
	ASLR hold	All	6.0 ± 1.0	0.95 (.87-.98)	0.3	0.9	0.4 ± 1.0
		Controls	6.0 ± 2.0	0.98 (.90-.99)	0.2	0.7	0.2 ± 0.9
		Cases	6.0 ± 1.0	0.91 (.58-.98)	0.4	1.0	0.6 ± 1.0
	Change	All	0.7 ± 0.6	0.92 (.84-.97)	0.2	0.5	0.3 ± 0.6
		Controls	0.6 ± 0.6	0.93 (.78-.99)	0.2	0.5	0.4 ± 0.8
		Cases	0.8 ± 0.6	0.92 (.80-.98)	0.2	0.5	0.3 ± 0.5
TrA	Supine rest	All	2.5 ± 0.8	0.96 (.90-.99)	0.1	0.4	0.3 ± 0.4
		Controls	2.5 ± 0.6	0.93 (.69-.98)	0.2	0.3	0.3 ± 0.5
		Cases	2.6 ± 0.9	0.98 (.89-.99)	0.1	0.3	0.2 ± 0.4
	ASLR hold	All	2.8 ± 0.7	0.89 (.70-.96)	0.2	0.6	0.3 ± 0.6
		Controls	2.8 ± 0.6	0.88 (.46-.97)	0.2	0.4	0.3 ± 0.4
		Cases	2.8 ± 0.8	0.89 (.54-.98)	0.3	0.5	0.4 ± 0.6
	Change	All	0.3 ± 0.3	0.96 (.92-.98)	0.1	0.2	0.1 ± 0.2
		Controls	0.3 ± 0.3	0.96 (.90-.99)	0.1	0.1	0.1 ± 0.3
		Cases	0.3 ± 0.3	0.96 (.90-.99)	0.1	0.1	0.1 ± 0.2
RA	Supine rest	All	8.0 ± 1.4	0.90 (.73-.96)	0.4	1.2	0.6 ± 1.2
		Controls	8.7 ± 0.9	0.89 (.50-.98)	0.3	0.9	0.4 ± 1.1
		Cases	7.4 ± 1.4	0.86 (.38-.97)	0.5	1.5	0.8 ± 1.3

	ASLR hold	All	8.0 ± 1.4	0.82 (.45-.94)	0.6	1.7	0.7 ± 1.6
		Controls	8.5 ± 1.1	0.80 (.73-.95)	0.5	1.4	0.9 ± 1.8
		Cases	7.6 ± 1.5	0.91 (.62-.98)	0.4	1.2	0.6 ± 1.5
	Change	All	0.1 ± 0.5	0.96 (.92-.99)	0.1	0.3	0.2 ± 0.3
		Controls	0.0 ± 0.6	0.95 (.80-.99)	0.1	0.4	0.2 ± 0.4
		Cases	0.3 ± 0.5	0.96 (.89-.99)	0.1	0.3	0.2 ± 0.3
IRD	Supine rest	All	12.1 ± 8.6	0.98 (.97-.99)	1.3	3.5	3.8 ± 7.8
		Controls	9.3 ± 5.9	0.99 (.98-.99)	0.5	1.4	1.5 ± 3.0
		Cases	14.2 ± 9.7	0.98 (.95-.99)	1.5	4.4	5.6 ± 8.4

*Values in millimetres except % change, †Pooled from all day 1 and day 2 data, ASLR = active straight leg raise test, EO = external oblique, IO = internal oblique, IRD = inter-recti distance, LPP – lumbopelvic pain, RA = rectus abdominis, TrA = transversus abdominis

Table 5.5: Abdominal Wall Between Day Intrarater Reliability; ADIM

Muscle	Condition	Cohort	Mean±SD(mm*)†	$ICC_{3,1}$(95% CI)	SEM(mm*)	MDC(mm*)	Bias±LOA (mm)*
EO	Crook ly rest	All	3.3 ± 0.9	0.94 (.88-.98)	0.2	0.6	0.3 ± 0.9
		Controls	3.6 ± 0.9	0.95 (.85-.99)	0.2	0.6	0.2± 0.9
		Cases	3.1 ± 0.7	0.93 (.81-.98)	0.2	0.5	0.3 ± 1.0
	ADIM Hold	All	3.2 ± 0.9	0.94 (.88-.98)	0.2	0.6	0.1 ± 1.2
		Controls	3.4 ± 1.1	0.96 (.87-.99)	0.2	0.6	0.2 ± 1.3
		Cases	3.1 ± 0.7	0.92 (.77-.98)	0.2	0.6	0.1± 1.0
	Change	All	-0.1 ± 0.3	0.93 (.86-.98)	0.1	0.2	0.2 ± 0.3
		Controls	-0.2 ± 0.4	0.96 (.88-.99)	0.1	0.2	0.2 ± 0.4
		Cases	-0.1 ± 0.2	0.75 (.34-.94)	0.1	0.2	0.2 ± 0.2
IO	Crook ly rest	All	4.8 ± 1.1	0.96 (.91-.99)	0.2	0.7	0.3 ± 1.0
		Controls	5.2 ± 1.1	0.95 (.84-.99)	0.3	0.7	0.3 ± 1.0
		Cases	4.4 ± 1.0	0.96 (.90-.99)	0.2	0.5	0.3 ± 1.0
	ADIM Hold	All	4.9 ± 1.2	0.97 (.93-.99)	0.2	0.6	0.5 ± 1.0
		Controls	5.5 ± 1.1	0.97 (.89-.99)	0.2	0.6	0.6 ± 1.0
		Cases	4.4 ± 1.1	0.97 (.91-.99)	0.2	0.5	0.4 ± 1.0
	Change	All	0.1 ± 0.4	0.92 (.84-.97)	0.1	0.3	0.3 ± 0.5
		Controls	0.2 ± 0.4	0.92 (.80-.98)	0.1	0.3	0.2 ± 0.4
		Cases	0.0 ± 0.4	0.91 (.77-.98)	0.1	0.3	0.3 ± 0.5
TrA	Crook ly rest	All	2.5 ± 0.4	0.82 (.60-.93)	0.2	0.5	0.3 ± 1.0
		Controls	2.4 ± 0.4	0.91 (.69-.99)	0.1	0.3	0.3 ± 1.0
		Cases	2.5 ± 0.3	0.73 (.55-.94)	0.3	0.3	0.3 ± 1.0
	ADIM Hold	All	3.8 ± 0.6	0.84 (.68-.94)	0.3	0.7	0.5 ± 1.2
		Controls	3.8 ± 0.5	0.93 (.79-.98)	0.2	0.3	0.4 ± 0.6
		Cases	3.8 ± 0.7	0.81 (.47-.95)	0.3	0.5	0.7 ± 1.6
	Change	All	1.3 ± 0.5	0.97 (.93-.99)	0.1	0.2	0.2 ± 0.2
		Controls	1.4 ± 0.3	0.91 (.69-.99)	0.1	0.2	0.2 ± 0.3
		Cases	1.3 ± 0.6	0.98 (.94-.99)	0.1	0.2	0.2 ± 0.2
RA	Crook ly rest	All	8.2 ± 1.5	0.99 (.97-.99)	0.2	0.5	0.4 ± 1.0
		Controls	9.0 ± 1.1	0.98 (.91-.99)	0.2	0.5	0.6 ± 1.0
		Cases	7.4 ± 1.3	0.99 (.96-.99)	0.2	0.5	0.2 ± 0.9

ADIM Hold	All	7.6 ± 1.5	0.98 (.97-.99)	0.2	0.5	0.4 ± 1.0
	Controls	8.1 ± 1.6	0.99 (.96-.99)	0.2	0.5	0.3 ± 1.0
	Cases	7.2 ± 1.4	0.98 (.93-.99)	0.2	0.6	0.4 ± 1.1
Change	All	-0.4 ± 0.7	0.97 (.94-.99)	0.1	0.3	0.2 ± 0.3
	Controls	-0.6 ± 0.9	0.99 (.94-.99)	0.1	0.3	0.2 ± 0.4
	Cases	-0.3 ± 0.3	0.93 (.81-.98)	0.1	0.2	0.2 ± 0.3

*Values in millimetres except % change, †Pooled from all day 1 and day 2 data, ADIM = abdominal drawing in manoeuvre, EO = external oblique, IO = internal oblique, IRD = inter-recti distance, LPP = lumbopelvic pain, RA = rectus abdominis, TrA = transversus abdominis.

Table 5.6: Bladder Parameters' Within Day Intrarater Reliability; ASLR and ADIM†

Parameter	Condition	Cohort	Direction	Mean±SD(mm*)	$ICC_{3,3}$(95% CI)	SEM(mm*)	MDC(mm*)
Bladder (global)	ASLR Change	All	X axis	6.9 ± 4.5	0.93 (.82-.98)	1.2	3.0
			Y axis	4.4 ± 3.3	0.93 (.83-.98)	0.9	2.4
			Trajectory	1.8 ± 1.1	0.83 (.56-.94)	0.4	1.2
		Controls	X axis	4.8 ± 2.4	0.92 (.68-.99)	0.7	1.8
			Y axis	3.3 ± 1.4	0.88 (.50-.98)	0.5	1.4
			Trajectory	1.6 ± 0.9	0.87 (.46-.98)	0.3	0.9
		Cases	X axis	8.9 ± 5.2	0.88 (.55-.98)	1.8	5.0
			Y axis	5.4 ± 4.2	0.92 (.69-.99)	1.2	3.3
			Trajectory	2.0 ± 1.2	0.82 (.34-.97)	0.4	1.0
	ADIM Change	All	X axis	3.8 ± 3.1	0.91 (.75-.97)	0.1	2.6
			Y axis	2.1 ± 1.1	0.86 (.65-.95)	0.4	1.2
			Trajectory	1.6 ± 0.7	0.80 (.50-.93)	0.3	0.9
		Controls	X axis	3.9 ± 3.6	0.96 (.81-.99)	0.1	2.1
			Y axis	2.1 + 1.4	0.89 (.49-.98)	0.5	1.3
			Trajectory	1.5 ± 0.7	0.84 (.33-.98)	0.3	0.8
		Cases	X axis	3.4 ± 2.4	0.71 (.28-.94)	1.3	3.6
			Y axis	2.1 + 0.9	0.83 (.41-.96)	0.4	1.0
			Trajectory	1.7 ± 0.7	0.73 (.08-.94)	0.3	1.0
Bladder base (global)	ASLR Change	All	X axis	-2.5 ± 2.2	0.92 (.79-.97)	0.6	1.7
			Y axis	-4.8 ± 4.6	0.99 (97-.99)	0.5	1.5
			Trajectory	-3.1 ± 3.9	0.99 (.97-.99)	0.4	1.2
		Controls	X axis	-1.5 ± 1.8	0.91 (.60-.98)	0.5	1.5
			Y axis	-2.3 ± 1.7	0.95 (.79-.99)	0.4	1.0
			Trajectory	-1.6 ± 2.4	0.97 (.88-.99)	0.4	1.1
		Cases	X axis	-3.5 ± 2.1	0.89 (.49-.97)	0.7	1.9
			Y axis	-7.3 ± 5.2	0.98 (.93-.99)	0.7	1.9
			Trajectory	-4.5 ± 4.5	0.99 (.95-.99)	0.5	1.4
	ADIM Change	All	X axis	-2.1 ± 2.1	0.97 (.93-.99)	0.4	1.1
			Y axis	-2.6 ± 3.2	0.98 (.96-.99)	0.4	1.2
			Trajectory	-0.1 ± 2.0	0.94 (.86-.98)	0.5	1.3

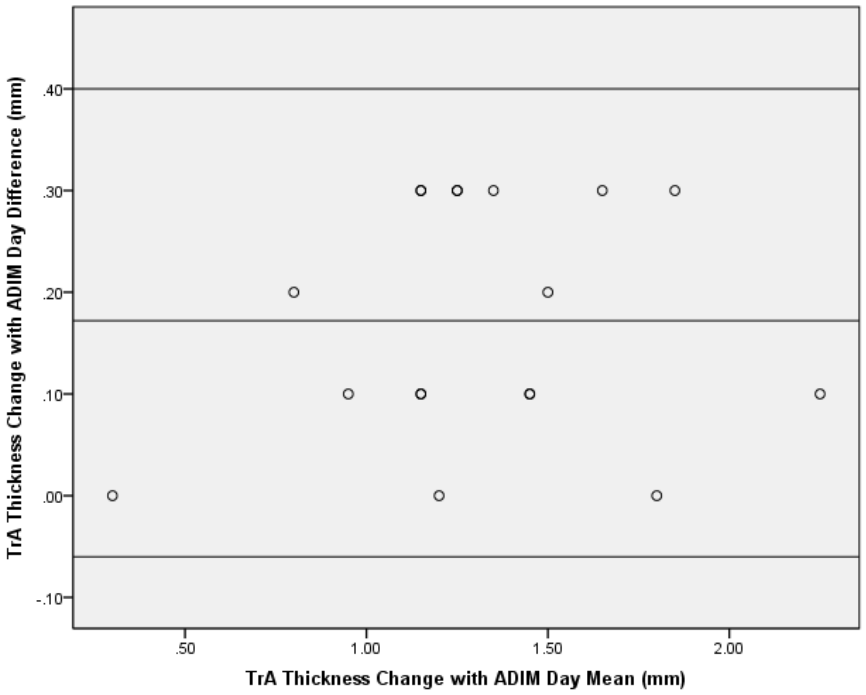
		Controls	X axis	-1.3 ± 1.3	0.90 (.67-.97)	0.4	1.2
			Y axis	-1.6 ± 2.9	0.98 (.90-.99)	0.4	1.2
			Trajectory	-0.4 ± 2.0	0.95 (.77-.99)	0.5	1.3
		Cases	X axis	-2.8 ± 2.4	0.98 (.93-.99)	0.4	1.0
			Y axis	-3.5 ± 3.3	0.98 (.96-.99)	0.4	1.2
			Trajectory	0.3 ± 1.9	0.95 (.82-.99)	0.3	0.7
Bladder base (relative to bladder)	ASLR Change	All	X axis	0.5 ± 2.7	0.93 (.84-.97)	0.7	2.0
			Y axis	-1.8 ± 2.3	0.86 (.65-.96)	0.9	2.4
			Trajectory	-3.5 + 3.4	0.97 (.92-.99)	0.6	1.8
		Controls	X axis	0.2 ± 2.6	0.97 (.91-.99)	0.4	1.2
			Y axis	-1.1 ±1.6	0.87 (.44 - .98)	0.6	1.6
			Trajectory	-2.0 ± 1.9	0.92 (.64-.99)	0.6	1.5
		Cases	X axis	0.7 ± 2.7	0.90 (.68-.98)	0.9	2.4
			Y axis	-2.6 ± 2.7	0.85 (.44-.97)	1.0	2.9
			Trajectory	-5.0 ± 3.9	0.97 (.88-.99)	0.7	1.9
	ADIM Change	All	X axis	0.7 ± 2.7	0.94 (.84-.98)	0.5	1.4
			Y axis	-2.4 ± 2.3	0.98 (.95-.99)	0.3	0.9
			Trajectory	-2.2 ± 2.4	0.97(.93-.99)	0.4	1.2
		Controls	X axis	1.2 ± 1.3	0.93 (.68-.99)	0.3	1.0
			Y axis	-2.0 ± 1.6	0.95 (.78-.99)	0.4	1.0
			Trajectory	-2.4 ± 2.5	0.93 (.70-.99)	0.7	1.8
		Cases	X axis	0.2 ± 2.4	0.94 (.78-.99)	0.6	1.7
			Y axis	-1.9 ± 2.7	0.99 (.96-.99)	0.3	0.8
			Trajectory	-2.0 ± 2.3	0.98 (.92-.99)	0.4	1.0

†Day one values, *Values in millimetres except % change, ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg raise test.

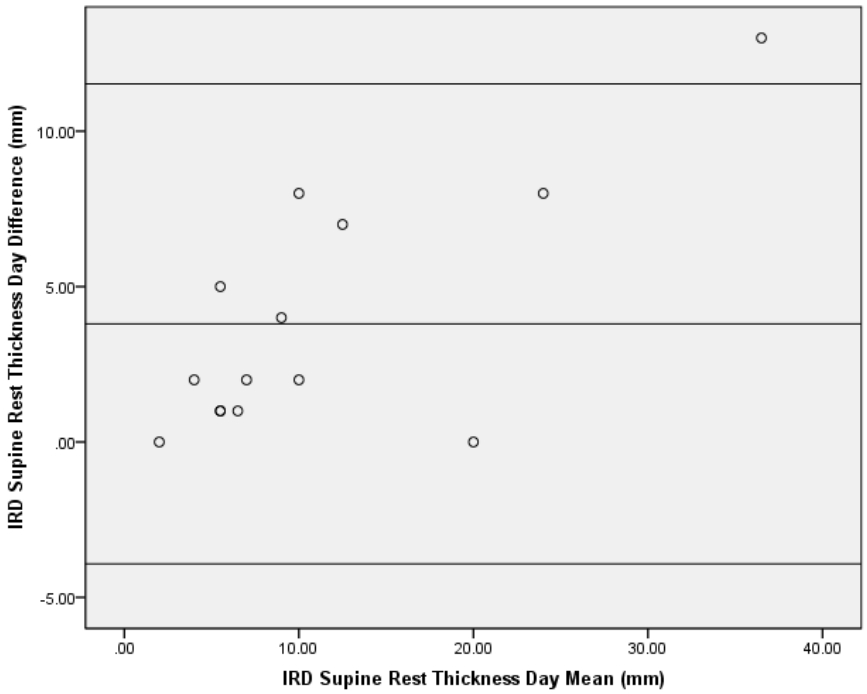
Table 5.7: Bladder Parameters' Between Day Intrarater Reliability; ADIM

Parameter	Condition	Cohort	Direction	Mean±SD(mm*)†	$ICC_{3,1}$(95% CI)	SEM(mm*)	MDC(mm*)	Bias±LOA(mm)*
Bladder (global)	ADIM Change	All	X axis	3.6 ± 2.8	0.62 (.10-.88)	1.7	4.6	1.5 ± 2.0
			Y axis	2.0 ± 1.2	0.79 (.51-.93)	0.5	1.5	0.9 ± 1.2
			Trajectory	1.6 ± 0.7	0.82 (.58-.94)	0.3	0.8	0.7 ± 1.0
		Controls	X axis	3.5 ± 3.1	0.82 (.39-.97)	1.3	3.7	1.3 ± 2.1
			Y axis	2.1 ± 1.4	0.81 (.37-.97)	0.6	1.6	0.9 ± 1.1
			Trajectory	1.5 ± 0.6	0.82 (.41-.97)	0.3	0.7	0.9 ± 1.2
		Cases	X axis	3.5 ± 2.4	0.31 (-1.6-.92)	1.8	5.0	1.8 ± 1.9
			Y axis	1.9 ± 1.0	0.75 (.19-.96)	0.5	1.3	1.0 ± 1.4
			Trajectory	1.7 ± 0.7	0.78 (.29-.97)	0.3	0.9	0.5 ± 0.8
Bladder base (global)	ADIM Change	All	X axis	-2.2 ± 2.0	0.97 (.94-.99)	0.3	0.9	0.6 ± 1.0
			Y axis	-2.5 ± 3.1	0.99 (.97-.99)	0.3	1.0	0.8 ± 1.0
			Trajectory	-0.2 ± 2.1	0.97 (.93-.99)	0.4	1.0	0.5 ± 0.9
		Controls	X axis	-1.2 ± 1.1	0.89 (.71-.97)	0.4	1.0	1.0 ± 1.2
			Y axis	-1.6 ± 2.7	0.98 (.95-.99)	0.3	0.9	0.7 ± 1.2
			Trajectory	-0.5 ± 2.3	0.96 (.87-.99)	0.5	1.3	0.7 ± 1.0
		Cases	X axis	-3.1 ± 2.2	0.98 (.94-.99)	0.3	0.9	0.6 ± 1.0
			Y axis	-3.5 ± 3.3	0.99 (.96-.99)	0.4	1.1	0.9 ± 0.6
			Trajectory	0.2 ± 1.8	0.98 (.93-.99)	0.3	0.7	0.3 ± 0.4
Bladder base (relative to bladder)	ADIM Change	All	X axis	0.7 ± 1.9	0.96 (.90-.99)	0.4	1.1	0.5 ± 0.8
			Y axis	-2.4 ± 2.1	0.96 (.91-.99)	0.4	1.2	0.6 ± 0.9
			Trajectory	-2.3 ± 2.4	0.98 (.95-.99)	0.4	1.0	0.4 ± 0.7
		Controls	X axis	1.2 ± 1.3	0.95 (.83-.99)	0.3	0.8	0.4 ± 0.7
			Y axis	-2.7 ±1.5	0.95 (.93-.99)	0.3	1.0	0.7 ± 1.0
			Trajectory	-2.3 ± 2.5	0.95 (.83-.99)	0.6	1.6	0.3 ± 0.5
		Cases	X axis	0.2 ± 2.3	0.96 (.86-.99)	0.5	1.3	0.6 ± 0.9
			Y axis	-2.1 ± 2.5	0.98 (.92-.99)	0.4	1.1	0.5 ± 0.7
			Trajectory	-2.2 ± 2.3	0.99 (.95-.99)	0.3	0.8	0.5 ± 0.5

*Values in millimetres except % change, †Pooled from all day 1 and day 2 data, ADIM = Abdominal Drawing in Manoeuvre.


TrA Thickness Change with ADIM Day Difference (mm)
.40
.30
.20
.10
.00
-.10
.50
1.00
1.50
2.00
TrA Thickness Change with ADIM Day Mean (mm)

A.


IRD Supine Rest Thickness Day Difference (mm)
10.00
5.00
.00
-5.00
.00
10.00
20.00
30.00
40.00
IRD Supine Rest Thickness Day Mean (mm)

B.

C.

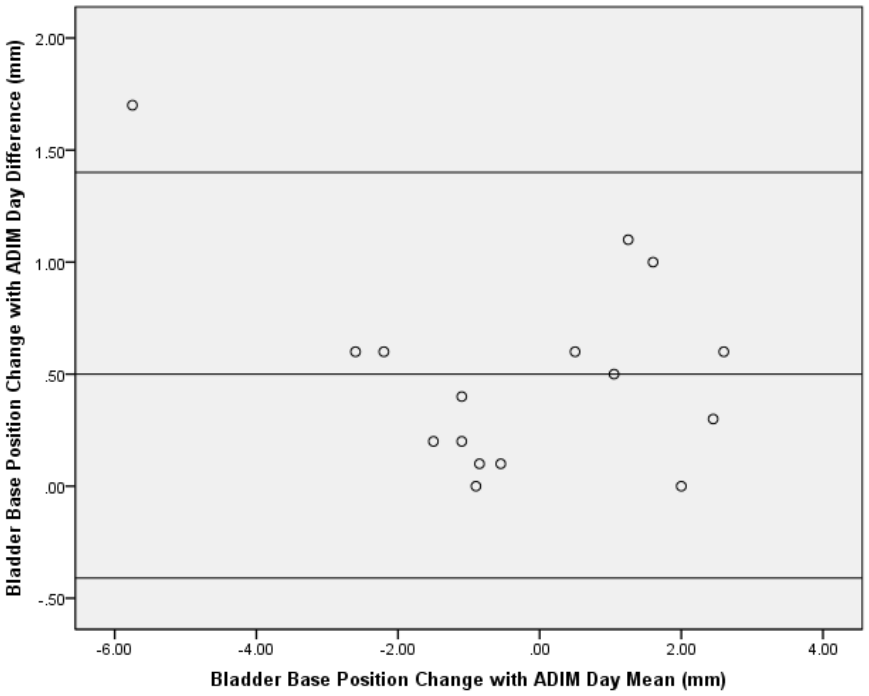


Figure 5.1: Bland and Altman distribution plots showing the mean measurement (day one + day two / 2) against differences between measurements (day one - day two) for between day intrarater reliability of A. transversus abdominis (TrA) thickness change during an ADIM, B. inter-recti distance (IRD) at supine rest, and C. bladder base (global) position change (trajectory) during an ADIM. The middle horizontal line represents the mean value of the difference between the score on day one – day 2, while the other two represent the limits of agreement (mean day difference ± 2 standard deviation).

5.5 Discussion

This study investigated several aspects of intrarater reliability of the USI technique for obtaining USI measurements of abdominal muscle thickness (RA, EO, IO, TrA), IRD and bladder base (sagittal) position; at rest and during an ASLR test and ADIM; within a single session (within day) and between two sessions (between day); in healthy and LPP cohorts in a clinical setting. Intrarater comparisons of all measures showed excellent reliability with only the ICC values of the between day TrA crook lying thickness comparisons for control subjects, and the values associated with measurements of the change in GB position below 0.75. In general the reliability estimates, SEM and MDC are consistent with previous studies that investigated both case (Teyhen et al. 2005a; Thompson et al. 2005; Norasteh et al. 2007; Costa et al. 2009a; Koppenhaver et al. 2009a) and control subjects (Bunce et al. 2002; McMeeken et al. 2004; Sherburn et al. 2005; Ainscough-Potts et al. 2006; Liaw et al. 2006; Hides et al. 2007b; see Table 2.1 for a summary) and support our

hypothesis (5.2.2) that these USI measurements (with the exception of change in GB position) are adequately reliable for research and clinical use in patients with LPP.

With respect to the abdominal wall parameters, there was a tendency for the ICC values to be slightly higher for the controls than the cases. This phenomenon that is likely explained by the fact that it is harder to delineate the boundaries of muscles in symptomatic persons due to associated changes in muscle composition (Andary et al. 1998; Elliott et al. 2006) and the most likely the reason for the slightly lower ICC value (0.73) for the between day crook lying resting thickness measurements for the TrA in the case cohort. Of further interest is the finding that the ICC values for the change in thickness during the ASLR test were slightly higher than those for the ADIM. This is likely due to the fact it is difficult to standardize the ADIM (see Section 2.3.3) and is consistent with findings of a previous investigation (Koppenhaver et al. 2009a).

Unlike the lateral abdominal wall muscles there are few studies that have investigated the reliability of measures of RA thickness (Misuri et al. 1997; Norasteh et al. 2007) and IRD (Liaw et al. 2006). Although the repeatability of resting measures of RA and IRD have been established in young healthy men and women and non-specific LBP respectively, little has investigated during dynamic clinical manoeuvres or between days. In comparison to these previous studies, our findings are unique as the ICC values are slightly higher (i.e. more repeatable) and include; both within and between day, as well as resting, contracted, and percent change reliability estimates (ICC), with 95% CI, SEM, MDC as well as bias and LOA values, for both case and control cohorts. Possible explanations for the better reliability for the resting measurements include; the level of expertise of the examiner, the use of an average of multiple measurements for each parameter during analysis which is known to improve reliability (Koppenhaver et al. 2009c), the employment of software functions that assist in the precision of measurement (i.e. grid and zoom functions), as well as the convention of viewing a clip of the linea alba during a RA contraction whilst measuring IRD from still images. Further, in accordance with the findings of the study presented in Chapter 4, every attempt was taken by the operator to minimize the angular and inward / outward motion of the transducer.

With respect to the bladder and bladder base parameters, this is the first investigation to include both within and between day reliability estimates, further, to measure both changes in global and relative position of the bladder base, and global position of the bladder. The ICC values for the change in the GBB and RBB were excellent while the values for the change in the GB ranged from poor to excellent (0.31 – 0.96). In general, there was little difference in reliability estimates between cohorts, within or between days, or between tasks. The low reliability estimates of the GB measures were likely related to

how the bladder was defined by the operator in MATLAB® and possible inconsistency in bladder volume between days. Specifically, to define the position of the bladder in MATLAB®, the operator was prompted to mark the most posterior and inferior boundaries of the bladder. Although every effort was made to ensure standardized bladder volume (and corresponding shape) between days, a certain amount of inconsistency was identified. The inconsistency in bladder shape would result in different points on the bladder being identified as the most posterior and inferior, and led to the lower estimates. In future studies, it would be prudent to further standardize the bladder filling procedure. Due to the low reliability estimates associated with measuring changes in the GB position, it would be prudent to forgo this parameter in describing differences in control and case cohorts (Chapter 7 and 8) in favour of the change in GBB and RBB parameters.

5.5.1 Limitations

There are several limitations to this study. Firstly, abdominal wall muscle thickness and IRD have been found to vary depending on the location of measurement (Liaw et al. 2006; Rankin et al. 2006), while bladder motion and shape vary with volume (Dietz & Wilson 1999) and posture (Dietz & Clarke 2001). Although the current investigation used standardized participant positioning and transducer placement specific transducer placement was not marked between image acquisitions and likely varied to some small degree. Further, as indicated above a standardized bladder filling procedure was employed however several participants reported inconsistency in following the instructions (i.e. the amount or timing of the bladder filling). Secondly, pain was only assessed at the first data collection session. As resting muscle tone is known to vary in the presence and absence of pain it is possible that the thickness of the abdominal wall muscles in the case cohort may have varied between days due to participants being in more or less discomfort. Thirdly, all of the participants in this study were female. As such, the generalizability of the findings to male participants may be questioned. With that being said, the values in this study are consistent with those of previous investigations in which male participants were included. Finally, some of the ICC estimates were associated with wide 95% CIs, with the upper and lower-bound values representing very different degrees of reliability. Although every attempt was made to standardize all aspects of data collection with and between days, it is important to acknowledge that the responses being measured (muscle thickness, fascia width and bladder base motion) are inherently unstable as are the contraction strategies employed. However, as the goal of this investigation was to determine the reliability of these measurements in a clinical setting, it was expected that some sources of error would not be controlled for. It is likely that the inherent instability of the parameters being measured, the clinical tests employed, and the clinical environment, led to this variability.

5.6 Conclusions and Implications

5.6.1 Within and between day, resting and contracted, USI measurements of abdominal muscle thickness, IRD, and changes in GBB and RBB motion, during an ASLR test and ADIM, in healthy and LPP cohorts, within a clinical setting are highly reliable, when taken by the lead investigator.

5.6.2 Within and between day, resting and contracted, reliability estimates for GB position during an ASLR test and ADIM, in healthy and LPP cohorts were found to be poor.

5.6.3 This investigation presents novel information regarding the reliability of USI measurements of RA thickness, IRD, global and relative bladder and bladder base position, as well as provides further support for the reliability of USI for the measurement of lateral abdominal muscles.

5.6.4 The findings of this investigation imply a certain confidence in the study design, protocols and methodology employed in generating these measurements, and a foundation upon which to compare these USI parameters (with the exception of GB position), in healthy and LPP cohorts, in the upcoming Chapters (7 and 8).

5.7 Summary and Novelty

This chapter has described an investigation that determined that reliable measurements of the LAW muscles, RA, IRD and BB position can be obtained at rest and during dynamic tests (ASLR and ADIM) commonly employed during a physiotherapy assessment of the lumbopelvic region, in participants with and without LPP. In doing so it has contributed to the literature by providing novel information about the reliability of RA, IRD, RBB and GBB measurements, as well as the lack of reliability of GB motion measurement using the described methodology. Having established that reliable measurements can be collected with the established clinical protocol, Chapters 7 and 8 will present observational studies aimed at comparing the sonographic characteristics of the abdominal wall (muscles and perimuscular connective tissue) of participants with and without LPP, at rest (Chapter 7), and during an ASLR and ADIM (Chapter 8). However, prior to that, the next chapter presents an investigation aimed at better understanding the relationship between changes in muscle thickness (measured by USI), and electrical activity (measured by electromyography), during and ASLR and ADIM, to assist in the interpretation of the dynamic data from the observational study presented in Chapter.

CHAPTER 6 - COMPARISON OF ELECTROMYOGRAPHIC AND SONOGRAPHIC MEASURES OF ABDOMINAL WALL MUSCLES DURING CLINICAL MANOEUVRES IN INDIVIDUALS WITH AND WITHOUT LUMBOPELVIC PAIN

This chapter presents a prospective descriptive study involving the simultaneous recording of fine wire electromyography (EMG) and ultrasound imaging (USI) data from the abdominal muscles (rectus abdominis; RA, external oblique; EO, internal oblique; IO, transversus abdominis; TrA), of participants with and without lumbopelvic pain (LPP), during two clinically relevant manoeuvres (Active Straight Leg Raise test; ASLR test and Abdominal Drawing in Manoeuvre; ADIM). This investigation was conducted in collaboration with Dr Linda McLean from the School of Rehabilitation Therapy, Faculty of Health Sciences, Queen's University, Kingston, Canada. It was undertaken to develop a greater understanding of the relationship between changes in abdominal muscle activity, and changes in muscle thickness, that occur during the ASLR test and ADIM. The findings will assist in the interpretation of the results presented in Chapter 8.

6.1. Introduction

The muscles of the abdominal wall play a role in controlling motion of the spine (see Section 2.1; Hodges et al. 2003a; 2005; Barker et al. 2006; 2007b) and there is evidence of functional deficits involving these muscles in persons with LPP (see Section 2.1; Hodges & Richardson 1996; 1999; Ng et al. 2002b; Hungerford et al. 2003; Cowan et al. 2004; Beales et al. 2009a; Hides et al. 2009; Teyhen et al. 2009b). As USI provides a non-invasive valid method to quantify changes in abdominal muscle size (see Section 2.3.1.1; Whittaker et al. 2007a) there is a current trend in physiotherapy to use USI to determine the extent of muscle contraction during the assessment of LPP, and as a source of real-time biofeedback about muscle function during manoeuvres commonly employed in core stability training (Ferreira et al. 2004; Teyhen et al. 2005b; Henry & Teyhen 2007; Hides et al. 2007c; Reeve & Dilley 2009; Potter et al. 2011). Some authors have even gone as far as stating that changes in muscles thickness measured with USI are indirect measures of muscle activity (Ferreira et al. 2004; McMeeken et al. 2004; Reeve & Dilley 2009) and activation (Raney et al. 2007; Koppenhaver et al. 2009b; Saliba et al. 2010; Rasouli et al. 2011). However, as the literature investigating the relationship between changes in abdominal muscle activity (measured with EMG), and changes in muscle thickness (measured with USI) during a contraction is inconclusive, this interpretation may be premature (see Section 2.3.1.2).

There have been five studies that have investigated the relationship between EMG activation amplitude and thickness of the abdominal muscles measured using USI. These investigations have considered the EO, IO and TrA muscles in predominantly small numbers of young healthy participants utilizing ramped, or targeted isometric contractions, leaving a gap of information regarding this relationship in persons with LPP, during clinically relevant manoeuvres, and for others muscles in the lumbopelvic region (see Section 2.3.1). There are large discrepancies in the findings with reported correlations for the EO, IO, and TrA muscles ranging from r = 0.22 – 0.23, r = 0.14 – 0.84, and r = 0.40 - 0.90 respectively (Hodges et al. 2003b; McMeeken et al. 2004; John & Beith 2007a; Brown & McGill 2009; Ferreira et al. 2011).

The range in results may be explained by the varied methodologies utilized by the different investigative teams (see Table 2.1 for a summary). For instance, two of the investigations employed surface EMG to describe the EMG-thickness relationship for EO and IO, which, given the close proximity of muscles in the lower abdominal region, was likely problematic. Electromyographic data recorded from the IO using surface electrodes is likely contaminated by crosstalk, which means that EMG activity recorded from the muscle of interest may have originated from other nearby muscles (i.e. TrA), which would have serious consequences on the study outcomes. Further, although all investigators normalised their EMG data to a maximum voluntary contraction (MVC), three different study tasks were employed: targeted isometric contractions, isometric trunk rotation and ramped abdominal drawing in. As it is likely that the relationship between changes in muscle thickness and EMG activity are task specific, it is not surprising that the authors reported different results.

A further consideration is the variable amount of consideration by the previous investigators of other factors that influence muscle thickness such as; initial muscle length, initial state of muscle contraction, the extensibility (Ito et al. 1998), and structure (parallel versus pennate muscle fibre orientation) of a musculotendinous unit (Herbert & Gandevia 1995; Brown & McGill 2010), contraction type (isometric, concentric, eccentric), the presence of external forces that an expanding muscle must compete against (i.e. increases in intra-abdominal pressure; IAP, or contraction of adjacent muscles; Cresswell & Thorstensson 1989; Delaney et al. 2010), out-of-plane changes (Boyett et al. 1991), and imaging technique (see Section 2.3.1.2; Klimstra et al. 2007; Whittaker et al. 2009). For instance, two of the investigating teams collected data while participants were in a supine position, while the other two did so in some degree of an upright position. The differences in test position could have a significant effect on study outcomes, as the length and thickness of the abdominal muscles differ between the supine and the upright positions due to the shift of the abdominal contents and effect of gravity. As the change in thickness

of a muscle reflects the combined influence of many factors in addition to changes in muscle activity it is important that their impact be considered when interpreting the correlation between USI and EMG measures.

In summary, the literature reporting on the relationship between changes in abdominal muscle activity (EMG) and thickness change (USI) during a muscle contraction is not conclusive. Furthermore, there is a lack of information regarding this relationship with regards to the RA muscle, in patients as compared to healthy control subjects, and during clinically relevant tasks such as the ASLR test and ADIM. The results of this study will address this gap.

6.2. Aims and Hypotheses

The aims of this pilot study were to;

6.2.1. Investigate the correlation between the magnitude and timeline of EMG amplitude, and the thickness of the RA, EO, IO and TrA muscles over the course of an ADIM and an ASLR test.

6.2.2. To compare the magnitude and timeline of EMG amplitude and thickness of the abdominal muscles during these two tasks between healthy and LPP cohorts.

The hypotheses were that;

6.2.3. A relationship would emerge between changes in EMG activity and abdominal muscle thickness during these dynamic manoeuvres.

6.2.4. The nature of the relationship between EMG activity and abdominal muscle thickness would differ between healthy and LPP cohorts.

6.3. Methods

This was a prospective descriptive study involving simultaneous recordings of fine wire EMG, and USI data from the abdominal muscles (RA, EO, IO, TrA) of persons with and without LPP, during two clinically relevant manoeuvres (the ASLR test and ADIM). This investigation took place in collaboration with Dr Linda McLean. Specifically, Dr McLean assisted with the development of the EMG protocol, was responsible for all fine-wire insertions and supervised the EMG data collection. Further, Dr McLean and a post-doctoral fellow (Dr Joanne Hodder) carried out the EMG data reduction, cross-correlation and regression calculations. This section contains the methodology specific to this investigation, general methodological considerations can be found in Chapter 3.

6.3.1. Participants

A convenience sample of 14 participants (7 controls and 7 with LPP) participated in this investigation. Control participants averaged 32.0 ± 10.6 years of age (yrs) and had a mean body mass index (BMI) of 24.8 ± 1.8 kg/m^2, while the LPP cohort averaged 29.7 ± 12.0 yrs and had a mean BMI of 21.3 ± 9.8 kg/m^2 (see Appendix 3b for individual participant details). Inclusion and exclusion criteria for both groups are described in detail in Section 3.2.1 and ethical considerations are discussed in Section 3.1.

6.3.2. Data Acquisition

Sonographic and EMG data were gathered simultaneously from the RA, EO, IO and TrA muscles (ipsilateral to the side of symptoms in the LPP cohort, and from the right side of in the control cohort) while participants performed three repetitions of an ADIM and ASLR test (lifting the leg ipsilateral to data acquisition) from a supine crook lying and supine position respectively. Participants performed both tasks with the breath held at the end of expiration with an open glottis. EMGWorks^{TM} acquisition software (Delsys Inc., Boston, Massachusetts) was used to collect EMG data using fine-wire EMG electrodes (Motion Lab Systems 000-318-30; 30mm, 27 gauge needle with a pair of 0.051mm insulated hooked wires) inserted into the RA, EO, IO and TrA muscle fibres interfaced with custom modified D.E. 2.1 pre-amplifiers configured for find wire recordings (bandpass 20 Hertz;Hz to 1 kiloHertz; kHz) and attached to EMG amplifiers (DelsysTM AMT-8; CMRR - 80dB@60Hz, input impedance >1Gohm). A sampling rate of 2kHz was used for all channels. Prior to EMG electrode insertion the skin over the insertion sites was cleaned using 90% compound rubbing alcohol and allowed to completely dry. The TrA electrode was inserted roughly 2 cm medial and superior to the ASIS, the IO electrode roughly 1cm above this and the EO electrode roughly 1cm lateral. The RA electrode was inserted in the middle of the muscle width approximately 2cm below the level of the umbilicus. Finally, a common reference electrode was located on the skin overlying the ipsilateral ASIS after the skin was cleaned and abraded using a gauze pad soaked in 90% rubbing alcohol and allowed to dry (Figure 6.1). The insertion of the EMG electrodes was performed by Dr Linda McLean under ultrasound guidance (Hodges et al. 2003b), and the position validated using audio and visual inspection of the EMG interference pattern of each abdominal muscle. Several repetitions of moderate level contractions were performed after each wire was inserted in order to ensure that the wire electrodes were firmly embedded into the appropriate muscle, and that participants could contract the muscle with no discomfort.

A USI system with a 5.0 MHz transducer was used to collect B - mode USI clips from a lateral abdominal wall (LAW), and RA imaging site (Figure 6.1; see Section 3.3 for details

of the USI system, imaging sites, and manoeuvres). A simple circuit switch was sampled by a separate channel on the EMG data acquisition system to indicate the time when the USI clip acquisition began so as to synchronize the USI and EMG data.

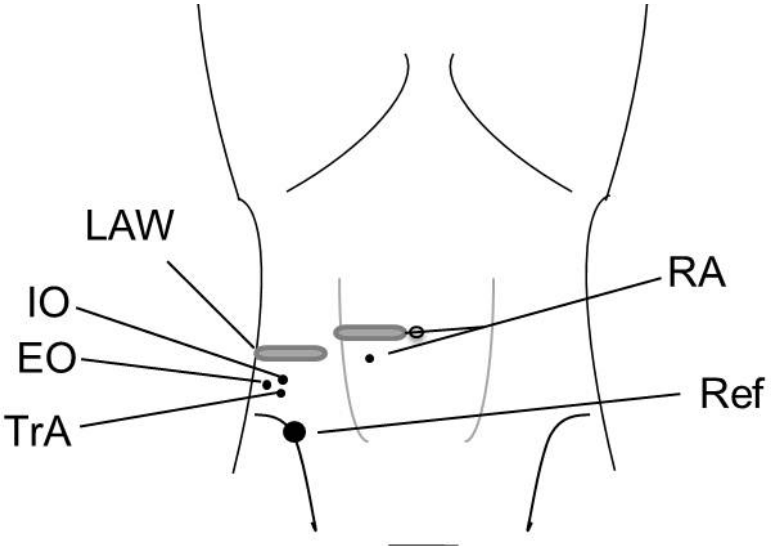


Figure 6.1: Experimental set-up showing the location of the ultrasound imaging sites (grey shaded areas; lateral abdominal wall; LAW, and rectus abdominis; RA), fine-wire electromyography insertion sites (black circles; RA, external oblique; EO, internal oblique; IO, transversus abdominis; TrA), and reference electrode (Ref).

6.3.3. Data Reduction

MATLAB® version 7.1 software (Mathworks, Natick, Massachusetts, USA) was used to extract ultrasound frames corresponding to 59 milliseconds (ms) time intervals (17Hz) over the course of each manoeuvre, and measure the thickness of the RA, EO, IO and TrA muscles (see Section 3.3 for details of the imaging sites, extraction and measurement codes). After the offsets had been removed the EMG data were full-wave rectified and then smoothed using a third-order dual-pass Butterworth filter with a low pass cut-off at 3Hz. Since the sampling rate of the EMG data was much higher than that of the USI data, smoothed EMG amplitudes were extracted at each point (59ms) corresponding to a measured frame of USI data. In this way, for each participant, two time-series (muscle thickness and EMG amplitude) were created for each muscle - task combination (i.e. TrA during the ADIM) from the simultaneously sampled data. Finally, the smoothed EMG data were normalised to the maximum EMG amplitude value attained across the three repetitions of each task, and the muscle thickness data were normalised to the resting muscle thickness for each participant and task.

6.3.4. Data Analysis

Statistical analysis was performed using SPSS version 15.0 software (Chicago, IL) and MATLAB® version 7.12 software (Mathworks, Natick, Massachusetts, USA). T-tests and chi square tests were used to compare cohorts for participant characteristics. To examine the relationship between the USI and EMG data, cross-correlation functions were computed for the muscle thickness and EMG amplitude time series determined for each participant, and each muscle-task combination (Winter 2005). The correlation coefficient (r) determined at the peak of the cross-correlation function indicated how well muscle thickness and EMG data tracked one another, while the time lag (τ) indicated the time delay between the EMG activation and the thickness time series that resulted in the highest correlation. The peak cross-correlation coefficients and the time lags were tested for normality (Shapiro-Wilk test) and analyses of variance (ANOVA) were used to test for significant differences between the cohorts (α=0.05). Finally, regression analyses were performed on the normalised data to describe the relationship between percent change in EMG activation (y axis, dependent variable), and percent change in thickness (x axis, independent variable), for each muscle, task, and cohort (α=0.05).

6.4. Results

Demographic and baseline characteristics of both cohorts are provided in Table 6.1. The two groups were evenly matched in terms of age, BMI, parity, gender and the Nijmegen Questionnaire (clinical symptoms of hypocapnia).

Table 6.1: Demographic and Baseline Characteristics of Participants

Characteristic	Controls (n = 7)	Lumbopelvic Pain (n = 7)
Age (yrs)	32.0±10.6 (23-50)	29.7±12.0 (22-49)
BMI (kg/m^2)	24.8±1.8 (22-27)	21.3±9.8 (20-31)
Parity	0.6±1.1 (0-3)	0.4±1.1 (0-3)
Gender Female/male (%)	86%/14%	86%/14%
Oswestry Disability Score (%)	n/a	12.3±6.7 (4-22)
Pain Intensity (NPRS 0 – 10)	n/a	3.1±1.3 (1-5)
Pain Duration (years)	n/a	3.8±3.3 (0.5-10)
FABQPA (0 - 24)	n/a	11.4±7.8 (0-22)
FABQW (0 - 42)	n/a	12.3±7.3 (0-21)
Nijmegen (0 - 64)	5.6±4.1 (0-12)	4.7±5.4 (0-12)

Values are in mean ± standard deviation (range). BMI = Body Mass Index, FABQBP = Fear Avoidance Beliefs Questionnaire (Physical Activity sub scale), FABQW = Fear Avoidance Beliefs Questionnaire (Work sub-scale), NPRS = Numerical Pain Rating Scale.

In total 112 USI and EMG data sets were recorded simultaneously (4 muscles x 2 tasks x 14 participants). Fifteen (13%) data sets were not included in the analysis as the trigger which synchronized the USI clip and EMG data was not sufficiently depressed to mark the EMG trace. The peak cross-correlation coefficients and associated time lags for each muscle-task combination are summarized in Table 6.2 (ASLR) and 6.3 (ADIM) respectively. Overall, the group mean peak cross-correlation coefficient values were low (mean ± standard deviation; range: r = 0.28 ± 0.09; 0.13-0.56 for the ASLR and, r = 0.35 ± 0.11; 0.15 – 0.62 for the ADIM), and there was a great deal of variability in the associated time lags (mean ± standard deviation; range: τ = 0.69s ± 2.56 seconds (s); -3.47 – 5.82s for the ASLR and, τ = 0.53s ± 3.75s; -5.76 – 10.58s for the ADIM), suggesting a weak relationship between the magnitude and timeline of EMG amplitude, and muscle thickness. ANOVAs revealed no significant differences in peak cross-correlation coefficient values or time lags between cohorts (see Appendix 9a for individual peak cross-correlation coefficient and time lag values).

The most striking feature of the data was the variability across subjects, regardless of cohort. An appreciation for this diversity can be gained by considering the data from individual participants. A range of examples are presented in Figure 6.2 (ASLR) and 6.3 (ADIM). These examples demonstrate instances where the muscle of interest increased in thickness and no increase in EMG signal was detected, where the EMG signal increased and no corresponding changes in muscle thickness were seen, and where the direction of change in thickness of a muscle and the change in EMG signal were opposite to each other. For instance, during the ASLR, participant S01 (control) demonstrated a change in thickness of the TrA without a corresponding change in EMG activity (r = 0.35, τ = -1.00s). Conversely, participant S17 (case) demonstrated an increase in EMG activity of the TrA without a corresponding change in muscle thickness (r = 0.27, τ = 0.24s), while participant S08 (case) demonstrated an increase in EMG activity of the TrA associated with a corresponding decrease in muscle thickness (r = 0.33, τ = 5.82s). Similar differences in findings existed for the other abdominal muscles, and during the ADIM.

Table 6.2: ASLR; Mean Peak Cross-Correlation Coefficients(r), and Associated Time Lags(τ; seconds), between Change in Muscle Thickness and EMG Amplitude

	RA			EO			IO			TrA		
	Control	Case	p	Control	Case	p	Control	Case	p	Control	Case	p
r	0.22±0.07	0.29±0.13	0.304	0.25±0.07	0.27±0.04	0.584	0.24±0.07	0.34±0.11	0.072	0.36±0.11	0.31±0.07	0.315
τ (s)	0.62±2.7	1.13±1.4	0.675	0.46±3.6	-0.13±1.2	0.690	1.62±3.9	0.28±1.5	0.420	1.25±4.1	0.45±1.8	0.649

ASLR = active straight leg raise test, EO = external oblique, IO = internal oblique, RA = rectus abdominis, s = seconds, TrA = transversus abdominis

Table 6.3: ADIM; Mean Peak Cross-Correlation Coefficients(r), and Associated Time Lags(τ; seconds), between Change in Muscle Thickness and EMG Amplitude

	RA			EO			IO			TrA		
	Control	Case	p	Control	Case	p	Control	Case	p	Control	Case	p
r	0.30±0.13	0.32±0.16	0.772	0.30±0.12	0.27±0.07	0.631	0.39±0.16	0.35±0.07	0.589	0.35±0.12	0.40±0.13	0.573
τ (s)	0.87±6.8	1.15±3.4	0.932	-0.44±2.6	0.83±4.0	0.587	-0.44±2.6	0.83±4.0	0.587	-0.44±2.6	0.83±4.0	0.587

ADIM = abdominal drawing in manoeuvre, EO = external oblique, IO = internal oblique, RA = rectus abdominis, s = seconds, TrA = transversus abdominis

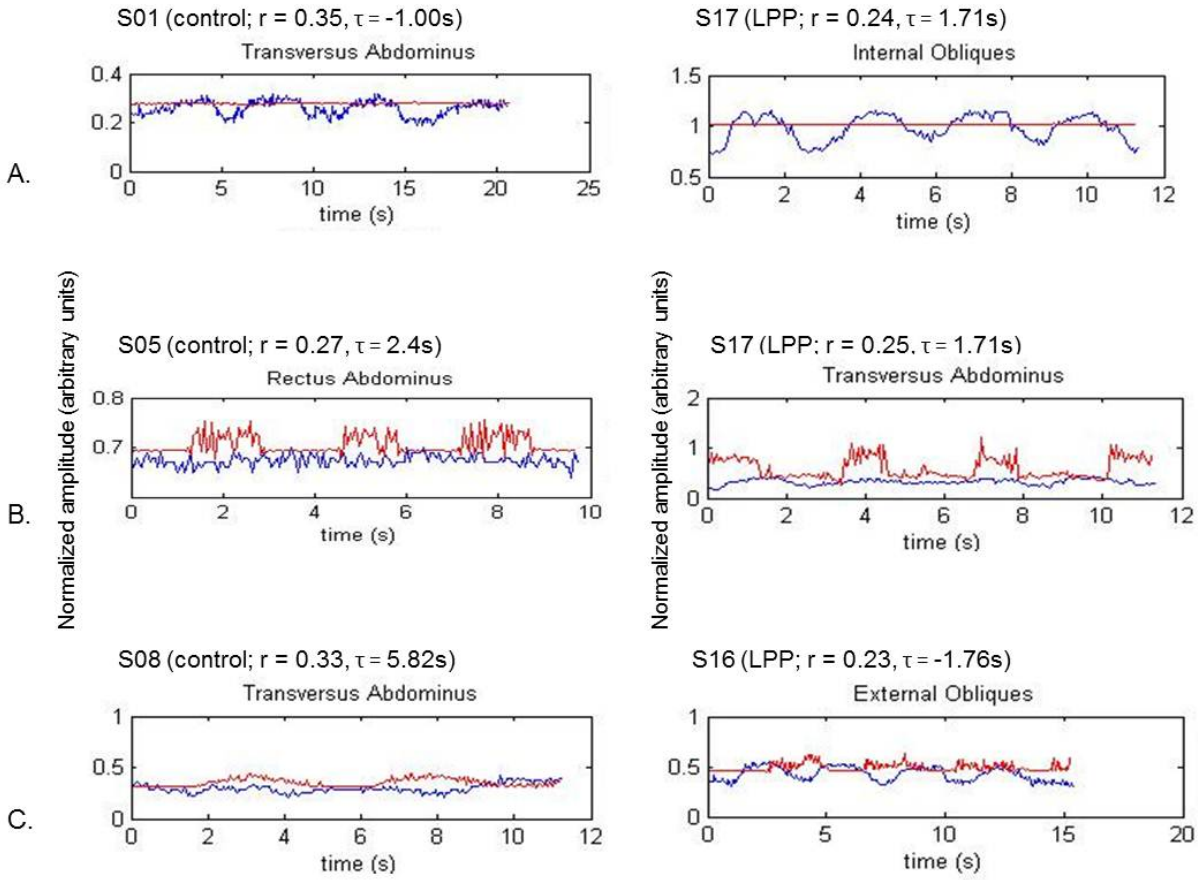


Figure 6.2: Examples of the variability in the pattern of muscle thickness (blue trace) and electromyographic amplitude (red trace) during an ASLR test. These demonstrate situations where A. muscle thickness increased with no increase in EMG signal, B. the EMG signal increased and no change in muscle thickness was seen, and C. the change in muscle thickness and EMG signal were out of phase. r = cross-correlation coefficient, τ = time lag in seconds (s).

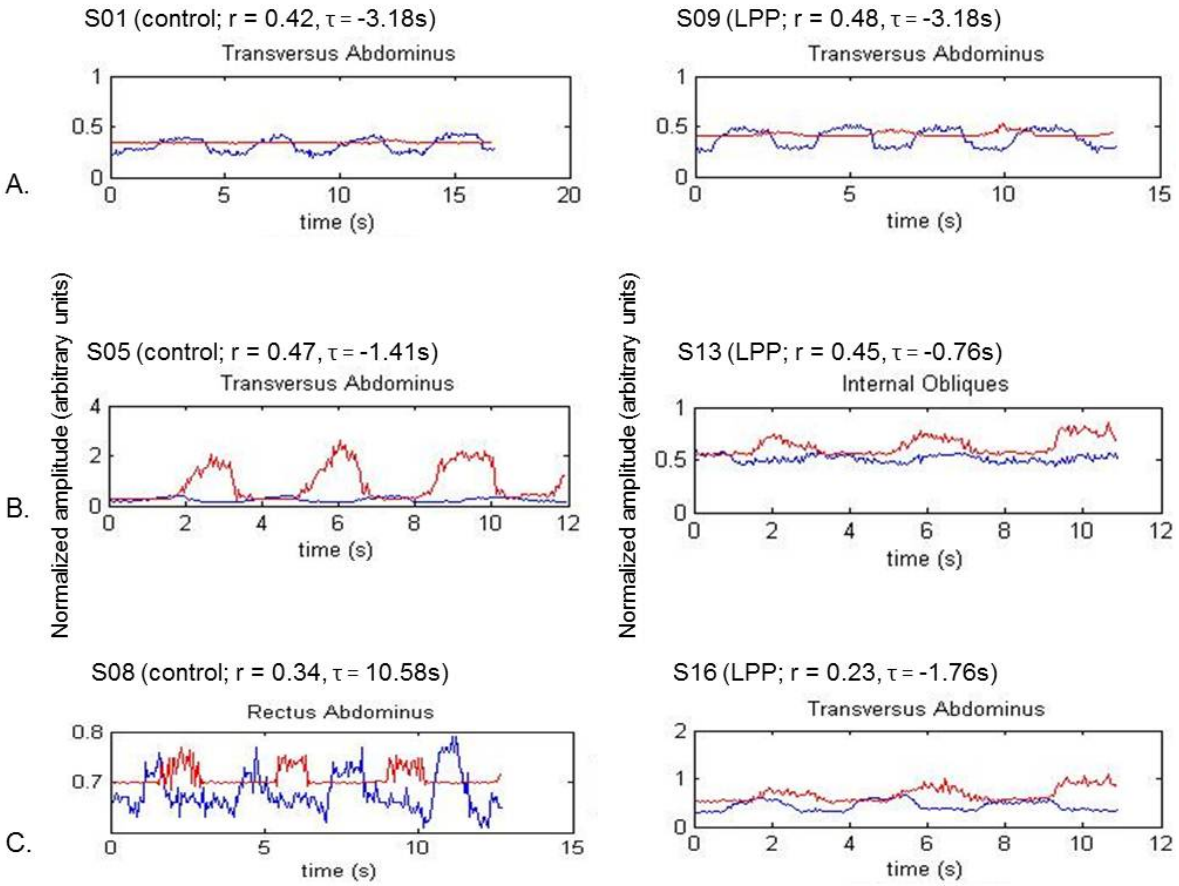


Figure 6.3: Examples of the variability in the pattern of muscle thickness (blue trace) and electromyographic amplitude (red trace) change during an ADIM. These demonstrate instances where A. muscle thickness increased with no increase in EMG signal, B. the EMG signal increased and no corresponding changes in muscle thickness were seen, and C. the change in muscle thickness and EMG signal were out of phase. r = cross-correlation coefficient, τ = time lag in seconds (s).

Due to the degree of variability in the USI and EMG data, it was decided that analysis based on pooled data would be ineffectual and potentially misleading. This observation is supported by the results of the regression analyses which are summarized by individual participant in Tables 6.4 (ASLR) and 6.5 (ADIM). The regression values clearly show no relationship between changes in EMG activity and muscle thickness for the EO and RA for either task. For the TrA and IO muscles there are a number of regressions that are statistically significant however the coefficient of determination (r^2) values, which are an indicator of the variance of EMG activity that can be explained by muscle thickness, are very low (r^2 = 0.00 – 0.13 during the ASLR, and r^2 = 0.00 – 0.18 during the ADIM). Further, the slope, or regression constant, values indicate a positive relationship for some muscle-task combinations, a negative relationship for others, and in many cases these values are zero, indicating no relationship.

Table 6.4: Linear Regression Analyses Results for Change in Muscle Thickness and Muscle Activity; ASLR

		RA				EO				IO				TrA			
Participant		Intercept	Slope	r^2	p	Intercept	Slope	r^2	p	Intercept	Slope	r^2	p	Intercept	Slope	r^2	p
Control	1	79.22	0.02	0.00	0.33	4.82	-0.05	0.00	0.20	50.36	0.36	0.01	0.04*	68.01	-0.15	0.07	0.00*
	2	46.86	-0.15	0.01	0.06	59.66	0.03	0.00	0.80	73.31	0.11	0.00	0.36	28.71	-0.56	0.07	0.00*
	3	49.41	-0.70	0.07	0.00*	49.14	0.15	0.01	0.11	77.70	-0.23	0.02	0.02*	66.98	0.10	0.03	0.00*
	5	37.00	-1.16	0.01	0.28	71.70	0.12	0.02	0.06	34.75	1.08	0.08	0.00*	41.80	-0.25	0.01	0.21
	7	85.46	0.09	0.01	0.15	60.86	0.08	0.00	0.51	57.72	-0.04	0.00	0.52	31.84	0.25	0.07	0.00*
	8					89.91	-0.07	0.01	0.26	81.64	0.07	0.00	0.61	62.47	-0.03	0.00	0.58
	11	88.84	-0.22	0.01	0.35												
LPP	9	17.31	0.00	0.00	0.99	82.21	0.06	0.03	0.03*	14.44	0.36	0.01	0.23	6.28	0.37	0.05	0.00*
	13	7.76	0.47	0.04	0.01*	80.28	-0.06	0.00	0.56	38.12	-1.18	0.13	0.00*	46.85	0.13	0.00	0.61
	14	84.74	0.27	0.01	0.17	46.10	0.04	0.00	0.46	28.60	0.16	0.02	0.06	34.58	0.16	0.01	0.13
	15	82.46	-0.09	0.00	0.56	72.70	0.01	0.00	0.86	78.14	-0.24	0.03	0.03*	46.31	0.14	0.02	0.06
	16	19.76	-0.16	0.00	0.30	33.13	-0.10	0.01	0.10	27.03	-0.21	0.01	0.06	9.29	0.09	0.03	0.00*
	17	38.66	-1.02	0.05	0.00*	44.80	0.20	0.03	0.01*	74.98	-0.05	0.01	0.14	30.24	0.00	0.00	0.98
	18	54.79	-0.02	0.00	0.87	26.02	-0.08	0.00	0.31	70.83	0.55	0.03	0.01*	38.20	-0.12	0.09	0.00*

* Denotes statistical significant (P<0.05), ASLR = active straight leg raise test, EO = external oblique, IO = internal oblique, LPP = lumbopelvic pain, p = p-value, RA, r^2 = coefficient of determination, TrA = transversus abdominis

Table 6.5: Linear Regression Analyses Results for Change in Muscle Thickness and Muscle Activity; ADIM

		RA				EO				IO				TrA			
Participant		Intercept	Slope	r^2	p	Intercept	Slope	r^2	p	Intercept	Slope	r^2	p	Intercept	Slope	r^2	p
Control	1					37.84	0.36	0.10	0.00*	29.61	0.26	0.02	0.03*	38.66	-0.02	0.00	0.34
	2	88.10	-0.02	0.00	0.60												
	3	3.32	0.61	0.08	0.00*												
	5	33.98	-0.71	0.04	0.00*	66.24	0.18	0.07	0.00*	36.20	-0.45	0.15	0.00*	32.07	-0.31	0.18	0.00*
	7																
	8	9.46	-0.12	0.00	0.70	49.76	-0.08	0.00	0.70	25.14	0.75	0.03	0.02*	28.40	0.17	0.05	0.00*
	11	84.21	0.02	0.00	0.80	80.44	0.03	0.00	0.51	20.86	1.16	0.06	0.00*	33.12	-0.10	0.03	0.01*
LPP	9	78.96	0.32	0.03	0.01*	66.75	-0.03	0.00	0.39	34.34	-0.80	0.04	0.00*	33.26	-0.20	0.16	0.00*
	13	37.58	-0.09	0.00	0.71	77.64	-0.10	0.02	0.04*	38.28	0.32	0.01	0.34	40.06	-0.14	0.04	0.01*
	14	57.69	1.11	0.10	0.00*	40.47	0.59	0.05	0.00*	30.77	-0.05	0.00	0.41	36.13	-0.29	0.07	0.00*
	15	67.31	-0.35	0.03	0.02*	58.13	-0.10	0.00	0.53	61.94	0.16	0.00	0.61	56.00	-0.13	0.03	0.02*
	16	49.84	-0.52	0.07	0.00*	66.18	-0.26	0.04	0.01*	73.99	-0.13	0.00	0.38	54.32	-0.04	0.03	0.01*
	17	56.46	-0.20	0.01	0.16	30.39	0.06	0.00	0.61	68.61	0.10	0.00	0.49	48.33	-0.03	0.03	0.02*
	18	34.55	1.11	0.08	0.00*	34.24	0.06	0.00	0.82	45.97	0.03	0.00	0.91	15.27	0.01	0.00	0.60

* Denotes statistical significant (P<0.05), ADIM = abdominal drawing in manoeuvre, EO = external oblique, IO = internal oblique, LPP = lumbopelvic pain, p = p-value, RA = rectus abdominis, r^2= coefficient of determination, TrA = transversus abdominis

6.5. Discussion

This study achieved its aim to investigate the relationship between changes in muscle thickness (measured with USI), and muscle electrical activity (measured with EMG), of the RA, EO, IO and TrA muscles, over the course of an ASLR test and ADIM, in a control and LPP cohort. Although some aspects of this relationship have been examined by other investigators (Hodges et al. 2003b; McMeeken et al. 2004; John & Beith 2007a; Brown & McGill 2009; Ferreira et al. 2011) this study is novel in that it is the first to consider this relationship in all four abdominal muscles, during both a voluntary (ADIM) and involuntary (ASLR) abdominal task, and in more diverse (with respect to gender and age) control and LPP cohorts. Further, it is the first to employ cross-correlation functions which are commonly used in signal processing to produce a measure of the similarity (timing and shape) of two signals, or waves (USI and EMG), as a function of a time-lag applied to one. The results, which are in contrast to the proposed hypotheses (6.2.3 and 6.2.4), imply that there is no clear relationship between the magnitude and timeline of muscle activity, and corresponding measures of muscle thickness, for any of the abdominal muscles during either task, nor is there a difference in this relationship between control and LPP cohorts. Consequently, the results indicate that during the ASLR test and ADIM, changes in abdominal muscle thickness cannot be interpreted solely as changes in muscle activity.

Perhaps the most salient finding of this study was the degree of variability of the EMG-thickness relationship across participants regardless of cohort. This is reflected by the wide range of time lag values from the cross-correlation analysis, and the slope values from the regression analysis which indicate a positive relationship between EMG and thickness for some muscle-task combinations, a negative relationship for others, and in many cases no relationship. This variability can be best appreciated by considering the data from individual participants as there are examples where one of the signals (EMG amplitude or muscle thickness) increased while the other did not change, or where the changes in signals were completely out of phase with each other (i.e. an increase in EMG activity corresponded to a decrease in muscle thickness; see Figures 6.3 and 6.3 for specific examples). Due to the degree of variability in the USI and EMG data, it was decided that analyses based on pooled data would be potentially misleading as it would conceal the diversity of the results, which in and of itself was an important finding. A possible explanation for the variability in the EMG-thickness relationship are that the participants, regardless of whether they are in pain or not, use unique muscle strategies to perform these two manoeuvres. This is supported by theories proposed for postural control and alterations in motor control in response to pain (Hall et al. 2010; Hodges 2011), which suggest that individuals do not use stereotypical motor control strategies for postural control, or movement tasks (regardless of whether they are in pain or not), and

that they employ individually unique strategies based upon patho-anatomical, biomechanical, physical, cognitive, genetic, neurophysiological and psychosocial factors (O'Sullivan & Beales 2007c). An alternate explanation is that the participants in this investigation were representatives of several sub-groups that may become evident by studying larger numbers of participants (Dankaerts & O'Sullivan 2011).

The results of the current investigation add to the uncertainty in the literature with regards to the relationship between changes in abdominal muscle activity and abdominal muscle thickness. Specifically they support the findings of previous investigations that have concluded that changes in the thickness of the EO and IO muscles cannot be used to detect changes in muscle activity (John & Beith 2007b; Brown & McGill 2010), but differ with those that have concluded that changes in the thickness of the IO and TrA muscles can be used to indicate changes in muscle activity (Hodges et al. 2003b; McMeeken et al. 2004; Ferreira et al. 2011). As there are many factors, in addition to muscle activity, that influence muscle thickness (see Section 2.3.1.2), there are several explanations for these discrepancies ranging from the magnitude of muscle contraction elicited by the task employed, the participant's position, the method of EMG used, the location of the imaging site, to whether previous investigators controlled for respiration. For instance, it is possible that an increase or decrease in muscle thickness without any associated EMG activity could be due to the use of fine-wire electrodes which only sample a small population of muscle fibres. Additionally, it is possible that the location of the USI imaging site used to collect the thickness measurements were at a point along the length of the muscle that did not change in thickness. Further, a close review of the data collection, reduction, and analyses sections of these previous investigations reveal considerable variability in the methods employed, and are likely another explanation for the difference in findings. Cross-correlations were chosen for the current investigation as they are the most robust method of measuring the relationship between two signals in that they do no assume linearity (Peeples 2000), and can be used to consider the correlation between the magnitude and pattern of signals over the entire task, as opposed to the magnitude of the signals at targeted levels of contraction.

When the results of this investigation are considered in conjunction with the existing literature, several observations emerge. Firstly, that the relationship between changes in abdominal muscle activity and muscle thickness is complex. This complexity is a result of the fact that a change in muscle thickness is a reflection of the impact of a combination of many variables, only one of which is muscle activity (Whittaker & Stokes 2011). For instance, the resting state (activity and length) of a muscle, the extensibility (Ito et al. 1998) and structure (parallel versus pennate muscle fibre orientation) of a musculotendinous unit (Herbert & Gandevia 1995; Brown & McGill 2010), the type of

contraction occurring (isometric, concentric, eccentric), the presence of external forces that a muscle must compete against (i.e. increases in IAP or contraction of adjacent muscles; Cresswell & Thorstensson 1989; Delaney et al. 2010), out-of-plane changes (Boyett et al. 1991), and imaging technique (Klimstra et al. 2007; Whittaker et al. 2009) will all impact the change in muscle thickness seen on USI during a contraction (see Section 2.3.1.2 for a more detailed explanation). This is clearly illustrated by several of the participants who demonstrated an increase in TrA EMG activity during the ASLR test that was associated with either no change, or a decrease in TrA thickness (see Figure 6.2b, c; S08 and S17). An observation that may be explained by the presence of some other factor (s) that is preventing the TrA from shortening (and correspondingly thickening), or causing it to lengthen, such an increase in intra-abdominal pressure (IAP) or contraction of the adjacent IO muscle. Secondly, due to the complexity of the relationship between muscle activity and muscle thickness, it is unlikely that muscle thickness can serve as a surrogate or indirect measure of muscle activity unless the variables that influence muscle thickness can be controlled for. In fact, it is likely that investigations (either in the past, or the future) that employ methodology that control for the influence of these additional variables, have (Hodges et al. 2003b), or will find, high correlations between muscle thickness and muscle activity. Alternatively, investigations that did (Brown & McGill 2010), or do not, control for these variables, perhaps in an attempt to mimic more clinically relevant situations, have, or will discover, lower correlations. Accordingly, the nature of the relationship between changes in abdominal muscle activity (measured with EMG) and muscle thickness (measured with USI) may remain inconclusive unless future researchers take these facts into consideration.

Although this investigation has found a weak relationship between the magnitude and timeline of abdominal muscle EMG amplitude, and muscle thickness that occur during an ASLR and ADIM, it is possible that USI may still have a clinical role to play in detecting altered abdominal muscle function (i.e. motor control) in persons with LPP, and as a source of biofeedback about abdominal muscle function during treatment programs. For instance, it is possible that parameters of abdominal muscle morphology that were not monitored during this study may be shown to have a better relationship with muscle activity then muscle thickness. For example, novel methods for measuring the change in length of the TrA through monitoring the lateral slide of the anterior musculotendinous junction (Hides et al., 2010, Jhu et al., 2010), and width of the RA (Coldron et al., 2008) have been proposed in the literature. Secondly, it is possible that the value of USI for assessing and providing biofeedback about abdominal muscle function will come from comparing differences in a cluster, or set, of ultrasound parameters between persons with and without LPP, as opposed to individual discrete measurements (i.e. muscle thickness).

This set of parameters may include not only resting muscle size (i.e. which may indicate atrophy and hypertrophy), and the pattern of architectural change in muscle thickness, length or width during an assessment manoeuvre (i.e. which represent the combined influence of several indicators of altered motor control such as IAP, increased resistance to expansion by adjacent muscles, contraction type, and changes in muscle activity), but changes in structures that are influenced by the function of the abdominal muscles both directly, and through their influence on IAP, such as the IRD and bladder base position. Clearly however, neither of these possibilities can be determined without further research.

6.5.1. Limitations

There are several possible limitations to this study. Firstly, the sample size was relatively small (14 participants). With that being said three of the previous studies of this nature have used smaller samples (n = 3, 5, and 9) of predominantly healthy male subjects (Hodges et al. 2003b; McMeeken et al. 2004; Brown & McGill 2009). Although limited in numbers it could be argued that the inclusion of participants with and without LPP, of both sexes, and encompassing a larger age range (22 – 50 years) may provide more telling estimates of the relationship between EMG amplitude and muscle thickness changes. Secondly, fine-wire EMG electrodes were used to sample muscle electrical activity. A drawback of fine-wire EMG is that the population of motor units represented in the EMG recording is small (Merletti & Parker 2004). However given the close proximity of muscles in the lower abdominal region and the depth of the TrA it is likely that the EMG data recorded from these muscles using a surface electrode would be contaminated by crosstalk from other nearby muscles (McGill et al. 1996; Marshall & Murphy 2003). Lastly, we chose to normalise the EMG amplitude to the maximum value attained across each task as opposed to a maximal voluntary contraction (MVC) which would be impractical to acquire in subjects with LPP (van Dieen et al. 2003b). In doing so it is impossible to determine if the effort level at which participants were performing the two tasks was high enough to produce architectural changes of the abdominal muscles. Specifically, Hodges et al (2003b) have shown that the majority of thickness change of the TrA and IO muscles occurs between 12-23% of MVC. Accordingly, it is entirely plausible that in the instances in which there was an increase in EMG activity with no corresponding change in muscle thickness, it was because the task did not require the muscle to contract greater than 12%. Consequently it is important that the findings of this investigation are interpreted within the context of which they were investigated.

6.6. Conclusions and Implications

6.6.1. Changes in abdominal muscle thickness during an ASLR test, or ADIM cannot be used as an indirect measure of changes in the level of muscle activity.

6.6.2. There is a great deal of variety in the relationship between changes in muscle thickness and EMG amplitude across individuals, tasks and cohorts.

6.6.3. When the results of this investigation are considered in conjunction with the existing literature, they point to the complexity of the relationship between muscle activity and muscle thickness, and suggest that the interpretation of a change in muscle thickness observed during a sonographic study must take into consideration all factors that influence the shape of a muscle.

6.6.4. Although USI measurements of abdominal muscle thickness are not a clear indicator of changes in the level of abdominal muscle activity during the ASLR test and ADIM, it is possible that USI may still have a role in detecting altered muscle function in persons with LPP for measurement and biofeedback purposes, however further research is required to determine this.

6.7. Summary and Novelty

This chapter describes an investigation aimed at better understanding the relationship between changes in abdominal muscle activity, and changes in muscle thickness, that occur during the ASLR test and ADIM in both control and case (LPP) cohorts. It contributes to the literature by providing novel information about this relationship in all four abdominal muscles, during two clinically relevant tasks, and in more diverse cohorts of participants, than has been previously investigated. Although abdominal muscle thickness was not found to be an indirect measure of changes in the level of muscle activity during these two tasks, it is possible that USI may still have a role in detecting, and providing biofeedback about altered muscle function in persons with LPP through its ability to provide novel information about the morphology of the abdominal muscles, their associated connective tissue, and position of the bladder base. Accordingly, the next two chapters will describe observational studies aimed at identifying differences in the resting (Chapter 7) and dynamic (Chapter 8) sonographic characteristics of the abdominal wall, IRD, and bladder base position between persons with and without LPP.

CHAPTER 7 – RESTING SONOGRAPHIC CHARACTERISTICS OF THE ABDOMINAL WALL IN INDIVIDUALS WITH LUMBOPELVIC PAIN: MUSCLES AND CONNECTIVE TISSUE

The next two chapters present observational studies aimed at comparing the sonographic characteristics of the abdominal wall and bladder base at rest and during two manoeuvres, typical of a physiotherapy assessment, in participants with and without lumbopelvic pain (LPP). This chapter considers the resting characteristics (thickness and width) of the abdominal wall (muscles and associated connective tissue) while the next compares changes in abdominal muscle thickness, inter-recti distance (IRD), and bladder base position during two dynamic clinical manoeuvres (Active Straight Leg Raise test; ASLR, and Abdominal Drawing in Manoeuvre; ADIM).

7.1 Introduction

The muscles of the abdominal wall are morphologically unique (Brown et al., 2011) and include in the midline the rectus abdominis (RA), and laterally, three layers consisting of the external oblique (EO), internal oblique (IO) and transversus abdominis (TrA). These muscles play a role in controlling the spine through their ability to function in a coordinated manner to pressurize the abdominal cavity and transfer loads around the trunk, through their associated connective tissue (see Section 2.1; Richardson et al. 2002; Reeves et al. 2006b; Brown et al. 2011).

Functional deficits of the abdominal muscles resulting from altered motor control have been identified in persons with LPP (Hodges & Moseley 2003; Hungerford et al. 2003). These range from delayed onset (Hodges & Richardson 1998) and diminished responses (smaller percent increase in thickness during a dynamic task) of the TrA (Teyhen et al. 2009a; 2009b), to excessive responses (greater increase in electromyography amplitude, or greater percent increase in thickness during a dynamic task) of the RA, EO and IO muscles (see Section 2.1; Radebold et al. 2000; van Dieen et al. 2003b; Beales et al. 2009a). Further, it has been hypothesized that abnormal movement patterns resulting from altered motor control may contribute to physiological changes in the perimuscular connective tissue (PMCT) in the lumbopelvic region in persons with LPP (see Section 2.3.1; Langevin & Sherman 2007; Langevin et al. 2009). Although no studies could be identified that have investigated this hypothesis with respect to the PMCT of the abdominal wall, there is one ultrasound-based comparison of the structure of the lumbar PMCT. In that investigation Langevin et al (2009), demonstrated thicker, and more disorganized lumbar PMCT, at the L2,3 vertebral level in participants with longstanding low back pain in comparison to a healthy cohort.

Various methods can be used to assess the abdominal muscles in persons with LPP ranging from electromyography (EMG; Beith et al. 2001; Hodges et al. 2003b; McMeeken et al. 2004; John & Beith 2007b; Brown & McGill 2010; Ferreira et al. 2011), magnetic resonance imaging (MRI; Hides et al. 2006b; Hides et al. 2007a; Hides et al. 2010) and ultrasound imaging (USI; see Section 2.2; Hides et al. 2007b; Whittaker 2008; Teyhen et al. 2009a; Pulkovski et al. 2011). Ultrasound imaging is non-invasive and can be used to assess the morphology or architectural characteristics of muscle (Whittaker et al. 2007a; Whittaker & Stokes 2011) and PMCT (see Section 2.1.3; Langevin et al. 2009). However, the majority of the sonographic studies investigating the abdominal wall in LPP cohorts consider only the TrA and IO muscles (Critchley & Coutts 2002; Stuge et al. 2006b; Hides et al. 2009; Teyhen et al. 2009a; 2009b; Jansen et al. 2010). It could be reasoned that by not considering the EO, RA and the associated PMCT, important information about the differences in structure and function of the abdominal wall in persons with LPP may be missed. To further understand what information USI can provide regarding morphological differences of the abdominal wall between participants with and without LPP, it seems prudent that all aspects of the abdominal wall (inclusive of muscle and connective tissue) are considered.

7.2 Aim and Hypothesis

The aim of this investigation was to;

7.2.1 Compare the resting thickness of the four abdominal muscles and intervening PMCT planes, as well as IRD, between persons with and without LPP using USI.

The hypothesis was that;

7.2.2 Persons with LPP would exhibit differences in abdominal muscle and PMCT thickness, as well as IRD in comparison to a healthy cohort.

7.3 Methods

This section contains the methodology specific to this investigation which took place at a private physiotherapy practice in Surrey, British Columbia, Canada. General methodological considerations can be found in Chapter 3.

7.3.1 Participants

A convenience sample of 50 participants (25 controls and 25 with LPP) participated in this investigation. The control participants averaged 36.3 ± 9.4 years of age (yrs), and had a mean body mass index (BMI) of 23.5 ± 2.5 kg/m^2, while the LPP cohort averaged 46.5 ± 8.3 yrs, and had a mean BMI of 24.8 ± 3.9 kg/m^2 (see Appendix 3b for individual participant details). A further two persons with LPP (one male and one female)

volunteered for participation in the study. However, after screening both were excluded due to clinical signs of hypocapnia ($ETCO_2$ levels< 35mmHg in combination with Nijmegen questionnaire score > 24; see Section 3.2.3). Inclusion and exclusion criteria for both groups are described in detail in Section 3.2.1 and ethical considerations are discussed in Section 3.1.

7.3.2 Ultrasound Imaging Protocol

A USI system with a 5.0MHz curvilinear transducer was used to generate resting B – mode USI images of the RA, EO, IO and TrA muscles and their associated PMCT planes (Figure 3.2 and 3.4), as well as the IRD (Figure 3.3) with participants in a crook lying position (see Section 3.3 for details of the USI system, and imaging sites). Three images from each site (during which the transducer location was maintained) were captured at the same point in the respiratory cycle (end of expiration). Thickness measurements of RA, EO, IO, TrA and PMCT planes (Figure 3.2 and 3.4) as well as the IRD (Figure 3.3) were calculated, and the mean of three measures of each used for analysis. To help avoid an order or fatigue effect, the order in which the muscles and manoeuvres were imaged was performed in random fashion.

7.3.3 Image Processing and Management

Images were measured offline using MATLAB® version 7.1 software (Mathworks, Natick, Massachusetts, USA). The measurement code employed automatically loaded the ultrasound images from a directory and then prompted the operator to use an on-screen cursor to: calibrate distance, plot a reference line along which measurements could be made, mark the inside borders of the boundaries of the muscle (s) (which also corresponded to the outside borders of the PMCT planes; see Figures 3.2-3.4) being measured, then concealed the measurements from the operator by directly exporting them into an Excel worksheet. This ensured blinding of the examiner throughout the measurement process (see Section 3.3.3 for information on the measurement code and parameter definitions)

7.3.4 Data Analysis

T-tests and chi square tests were used to compare cohorts for participant characteristics. Data were tested for normality (Shapiro-Wilk test) and univariate correlation analysis based on Pearson's r (r; parametric data) and Spearman's rho (r_s; non-parametric data) were used to examine the relationship between the ultrasound parameters and: age, BMI, gender, and parity in all participants, as was well pain, pain duration, and Oswestry disability score in the LPP cohort. Analyses of co-variance (ANCOVA; parametric data)

and Kruskal-Wallis (non-parametric data) tests were used to compare muscle thickness, PMCT thickness, and IRD, between cohorts. Statistical analyses were performed using SPSS Version 19.0 (Somers NY, USA). Significance levels were determined based on α=0.05.

7.4 Results

Participant characteristics of the LPP and control cohorts are shown in Table 7.1. Cohorts did not differ in gender (p=0.73), BMI (p=0.20), or parity (p=0.09) however, the LPP cohort was statistically older (p=0.02), and scored higher on the Nijmegen and Urogenital Distress Inventory (UDI) questionnaires. Pain duration, pain intensity (Numerical Pain Rating Scale; NPRS) and perceived low back related disability (Oswestry disability score) for the LPP cohort were 5.7±5.7yrs, 3.9±1.6 and 19.9±12% respectively.

Table 7.1: Demographic and Baseline Characteristics of Participants

Characteristic	Controls (n=25)	LPP (n=25)
Age (yrs)	36.3±9.4 (19-52)	46.6±8.3 (29-57)*
BMI (kg/m^2)	23.5±2.5 (18–29)	24.0±3.5 (17-31)
Parity	0.4±0.6 (0-2)	0.8±1.0 (0-3)
Gender Female/male (%)	76%/24%	80%/20%
Oswestry Disability Score (%)	n/a	19.9±11.5 (2-50)
Pain Intensity (NPRS 0 – 10)	n/a	3.9±1.6 (1-7)
Pain Duration (years)	n/a	5.7±5.7 (0.8-20)
FABQPA (0 - 24)	n/a	10.2±6.3 (0-24)
FABQW (0 - 42)	n/a	12.6±12.5 (0-38)
End Tidal CO_2 (mmHG)	37.9±2.2 (35-43)	37.8±2.5 (35-43)
Breaths / minute	13.1±3.6 (8-24)	12.2±2.9 (5-17)
Nijmegen (0 - 64)	4.2±6.3 (0-21)	13.9±6.5 (2-27)*
IIQ-7 (%)	0.8±3.8 (0-19)	1.7±3.9 (0-14)
UDI-6 (%)	1.6±3.8 (0-17)	12.2±11.6 (0-44)*

Values are in mean ± standard deviation (range). *Statistically significant (p< 0.05). BMI = Body Mass Index, FABQBP = Fear Avoidance Beliefs Questionnaire (Physical Activity sub scale), FABQW = Fear Avoidance Beliefs Questionnaire (Work sub-scale), IIQ = Incontinence Impact Questionnaire, LPP = lumbopelvic pain, NPRS = Numerical Pain Rating Scale, UDI = Urogenital Distress Index.

In total 450 ultrasound images were measured in the analysis. The means ± standard deviations for all muscle and PMCT plane thickness, as well as IRD, for both cohorts are

summarized in Table 7.2. Muscle and PMCT thickness did not correlate with age (r=-0.12, 0.30 respectively) or parity (r=-0.30, -0.03 respectively).Total muscle thickness correlated with BMI (r=0.43, p<0.001), and gender (r=0.52, p<0.001), while PMCT thickness correlated with BMI (r=0.60, p<0.001). Inter-recti distance did not correlate with BMI (r_s=0.19), gender (r_s=-0.03), parity (r_s=0.21) nor age (r_s=0.35; see Appendix 10a for all correlation values). Accordingly, ANCOVA using BMI and gender as covariates for muscle thickness, and BMI as a covariate for PMCT thickness, were performed to compare cohorts. Further, a Kruskal-Wallis test was used to compare IRD between the cohorts. The LPP cohort had less total abdominal muscle thickness (ANCOVA adjusted for BMI and gender p=0.03), thicker PMCT (ANCOVA adjusted for BMI p=0.007) and a wider IRD (p=0.005). Analysis of individual muscle thickness revealed no difference in EO, IO and TrA thickness but a thinner RA muscle (ANCOVA adjusted for BMI and gender p<0.001) in the LPP cohort, as seen in Table 7.2, and illustrated in Figure 7.1.

Table 7.2: Ultrasound Parameter Measurements (mean ± standard deviation)

Parameter	Control (mm)	LPP (mm)	p value
RA	9.1±1.2 (7.3-11.7)*	7.8±1.5 (4.5-10.6)	0.000*
EO	3.3±0.9 (2.1-6.3)	3.3±0.9 (1.8-5.5)	0.750
IO	5.5±1.7 (2.5-9.9)	5.2±1.6 (3.2-9.7)	0.287
TrA	2.5±0.5 (1.5-4.0)	2.6±0.6 (1.9-4.7)	0.403
Total Muscle Thickness	20.3±3.4 (16.0-30.6)*	18.9±3.4 (13.7-27.0)	0.034*
Anterior PMCT	2.0±0.4 (1.1-2.7)	2.6±0.8 (1.5-5.2)*	0.018*
Lateral PMCT	2.3±0.4 (1.6-3.2)	2.9±0.8 (2.1-4.7)*	0.002*
Total PMCT Thickness	4.3±0.2(2.8-5.3)	5.5±0.2 (3.7-9.2)*	0.007*
IRD Width	7.4±3.2 (2.0-19.9)	13.0±8.8 (2.6-26.3)*	0.005*

Values are in mean ± standard deviation (range). *Statistically significant (p<.05). EO = external oblique, IO = internal oblique, IRD = inter-recti distance, PMCT = perimuscular connective tissue RA = rectus abdominis, TrA = transversus abdominis.

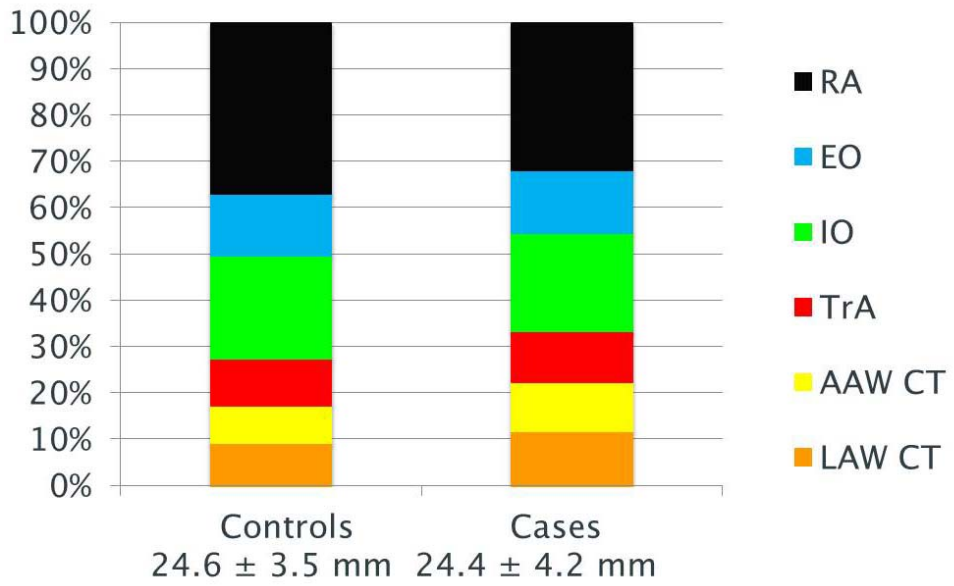


Figure 7.1: Relative percentage (%) contribution of muscle and perimuscular connective tissue (CT) to total abdominal wall thickness. The bar graphs allow side by side comparison of the contribution of all four muscles as well as the anterior abdominal wall PMCT planes (AAW CT) and lateral abdominal wall PMCT planes (LAW CT). Note the difference in profiles between the two cohorts (controls and cases with lumbopelvic pain). EO = external oblique, IO = internal oblique, IRD = inter-recti distance, RA = rectus abdominis, TrA = transversus abdominis.

Symptom characteristics are summarized in Table 7.1. Duration of pain correlated moderately with IRD (r_s = 0.51, p<0.001), and weakly with PMCT (r=0.36, p=0.01), and muscle (r=-0.28, p<0.05) thickness, while the NPRS score correlated moderately with total PMCT (r=0.54, p<0.001). Finally, the Oswestry score correlated moderately with PMCT (r=0.58, p<0.001) thickness, and IRD (r_s=0.43, p=0.02).

7.5 Discussion

This is the first study to consider the resting thickness of all four abdominal wall muscles in conjunction with their intervening PMCT planes and the IRD in persons with LPP. It is also the first to report differences in the thickness of the RA muscle, PMCT, and IRD in this population. These findings are consistent with the proposed hypothesis (7.2.2) that differences between the two cohorts would emerge.

The most definitive investigation looking at the resting size of the abdominal muscles was a study aimed at establishing normative reference ranges published by Rankin et al (2006). They reported resting values in a large cohort of 123 persons ranging from ages 20 – 72 yrs. As part of the analysis, they included the relative contribution of each muscle

to total abdominal muscle thickness. Specifically, they reported that the RA, EO, IO and TrA represented 35.0%, 22.8%, 28.4%, and 13.8% of the total muscle thickness respectively, irrespective of age and gender. When compared to the data from the control cohort in the present study, the order of thickness is the same and similar contributions from the IO (28%) and TrA (12%) are seen. In contrast the RA (45%) contribution is larger and the EO (16%) smaller. These differences may be related to the sample of the aforementioned investigation, or the fact that the imaging site used by Rankin et al (2006) for the RA muscles was more cephlad than the present investigation.

Previous ultrasound-based studies that have compared abdominal muscle thickness between control and case cohorts focus primarily on the TrA and IO muscles (Critchley & Coutts 2002; Stuge et al. 2006b; Hides et al. 2009; Teyhen et al. 2009a; 2009b; Jansen et al. 2010). Most of these investigations found no difference in thickness of these muscles with LBP (Critchley & Coutts 2002; Hides et al. 2009; Teyhen et al. 2009a; 2009b), or pregnancy related pelvic girdle pain (Stuge et al. 2006b) cohorts. With respect to the EO, both Critchley & Coutts (2002) and Jansen et al (2010) reported no difference in thickness between controls and case cohorts of low back pain (LBP), and long standing groin pain, respectively. There is one study which investigated the thickness of the RA muscle and IRD in controls and a case cohort of post-partum women, in which the RA was found to be significantly thinner and the IRD wider in the post-partum group (Coldron et al. 2008). It is important to point out that in all the aforementioned investigations, the prevailing methodology for determining muscle thickness with USI was used. These measurements are made between the inside edges of the muscle borders (see Figure 3.2), which excludes the PMCT. The findings of this current study echo the literature with regards to the EO, IO and TrA muscles. As the two cohorts in this study did not differ in parity, and parity was not identified as a covariate, comparison of our findings of RA thickness and IRD to a post-partum cohort is not practical.

Although PMCT has been hypothesized to play a role in the pathogenesis of chronic LBP (Langevin & Sherman 2007) only one other investigation that has quantitatively evaluated these tissues was identified in the literature. In that study, USI was used to measure PMCT thickness and echogenicity at the L2,3 vertebral level in a group of 47 control, and 60 participants with chronic LBP (Langevin et al. 2009). The authors reported the thickness of this tissue to be 25% greater in the LBP cohort (Langevin et al. 2009). The current finding of 22% greater thickness of the abdominal wall PMCT in the LLP cohort is consistent with these results. The authors speculated that these changes were secondary to chronic inflammation and associated fibrosis of these tissues which is consistent with increased exposure to load (Ettema et al., 2004, Perry et al., 2005).

When the findings of the current investigation (thinner RA, thicker PMCT and increased IRD in the LPP cohort) are considered simultaneously a similar explanation emerges; namely, adaptive PMCT and linea alba remodelling due to muscle atrophy and/or ineffective muscle strategies resulting from altered motor control in the LPP cohort. Specifically, altered motor control strategies may result in a smaller contribution of the RA and/or, increased contribution from other abdominal muscles, to trunk control leading to RA atrophy, and increased PMCT loading. It is however, important to remember that this rationale is just speculation, as USI only describes the morphology of a tissue and does not provide information about the mechanisms behind these changes. With that being said, the positive correlation between duration of pain, and width of IRD, supports an adaptive loading response. Further, there is partial support in the literature for this theory in the form of numerous investigators who have identified patterns of greater oblique abdominal muscle activity in subjects with LBP and LPP pain (van Dieen et al. 2003b; Beales et al. 2009a; Dankaerts et al. 2009; Hodges et al. 2009). Unfortunately investigations comparing the difference in size, or activity, of the RA muscle in control, and LBP or LPP cohorts, are lacking.

In summary, the findings of the present investigation indicate the importance of considering the pattern of contribution of all the muscles and connective tissues to the abdominal wall as opposed to focusing on individual components. The value of this shift is demonstrated by the ease in differentiating the control and LPP cohorts by the two distinctly different patterns of architectural make-up depicted in Figure 7.1. Further, that by using USI to first identify a series of parameters that differed between the cohorts, and then consider their interaction and pattern of contribution to the abdominal wall as a whole, it is possible to speculate on the presence and specific characteristics (i.e. insufficient contribution of the RA resulting in increased load on the PMCT and linea alba) of altered muscle function in the LPP cohort.

7.5.1 Limitations

The primary limitation of this investigation was the decision to collect measurements of abdominal wall muscle and PMCT thickness from only one side of the abdominal wall. This decision was made based on the findings of several investigations in which the thickness of the abdominal muscles was independent of hand dominance (Rankin et al. 2006), side measured or side of symptoms (Springer et al. 2006) unless the cohort had occupational, recreational or biomechanical propensities to asymmetrical loading such as elite cricketers (Hides et al. 2008) or unilateral lower limb amputees (Springer & Gill 2007). A further limitation is the fact that the LPP cohort was significantly older that the control cohort. Although the impact of aging on PMCT thickness is unknown, abdominal

muscle thickness has been shown to be independent of age or gender (Rankin et al. 2006). Additionally, none of the sonographic parameters measured were shown to correlate with age. With that being said the results of this investigation must be considered with this limitation in mind.

7.6 Conclusions and Implications

7.6.1 The findings of this investigation present novel information about the RA muscle, the abdominal wall PMCT planes, and IRD in persons with LPP. Specifically, that the participants with LPP studied in this research had significantly thicker PMCT, thinner RA muscles, and greater IRD.

7.6.2 These results suggest that changes of RA and PMCT thickness may be more evident than changes of the EO, IO and TrA muscles in persons with LPP, and highlight the need to expand our attention beyond the IO and TrA muscles, to consider the contribution of all four abdominal muscles and PMCT to the architectural make-up of the abdominal wall when investigating LPP.

7.6.3 A further implication is that the role of the RA and PMCT in the development and persistence of LPP warrants investigation, as does the functional implications of these changes on how the abdominal wall contributes to spinal control during dynamic tasks.

7.6.4 Finally, the findings of this investigation show that USI can provide information about the morphology of the abdominal muscles and their associated connective tissue, that when considered together, may provide a basis upon which altered patterns of muscle function can be identified.

7.7 Summary and Novelty

This chapter has presented the first of two observational studies aimed at comparing the sonographic characteristics of participants with and without LPP. It has identified novel information regarding the distribution of morphological changes in the abdominal wall associated with LPP and shown that by considering these changes in conjunction with each other, it is possible to speculate on the presence of altered muscle function in the LPP cohort. The next chapter will compare and contrast differences in the change in thickness of the abdominal wall muscles, the IRD and bladder base position, measured with USI, during an ADIM and ASLR test, in these same two cohorts.

CHAPTER 8 - SONOGRAPHIC CHARACTERISTICS OF THE ABDOMINAL WALL AND BLADDER IN INDIVIDUALS WITH LUMBOPELVIC PAIN DURING DYNAMIC CLINICAL TESTS

This chapter describes a second observational study aimed at comparing the sonographic characteristics of participants with and without lumbopelvic pain (LPP). It builds upon the results of the previous chapter by comparing changes in abdominal muscle thickness, inter-recti-distance (IRD) and bladder base position, in participants with and without LPP, during dynamic clinical tests (Active Straight Leg Raise test; ASLR and Abdominal Drawing in Manoeuvre; ADIM) typical of a physiotherapy assessment of the lumbopelvic region.

8.1 Introduction

There is considerable evidence that persons with persisting or re-occurring LPP demonstrate altered motor control strategies, involving their trunk muscles (both superficial and deep), during postural demands and movement (see Section 2.1). Further, that these changes in motor control are individually unique due to patho-anatomical, biomechanical, physical, cognitive, genetic, neurophysiological and psychosocial factors (O'Sullivan & Beales 2007c). Consequently many physiotherapy interventions for LPP aim to modify these alterations in muscle function through an intervention rooted in motor learning (a process of improving the smoothness and accuracy of movement by ensuring proper function of the muscle and nervous system through error correction, augmented feedback and part-practice) that considers the unique presentation of each individual patient (Stuge et al. 2004; O'Sullivan & Beales 2007a; Tsao & Hodges 2008; Dankaerts & O'Sullivan 2011). Fundamental to this approach is the ability of a physiotherapist to detect the specific patterns of altered motor control of the trunk muscles in these patients during the assessment process so that they can tailor the intervention accordingly (Hodges & Tucker 2011). This is primarily achieved through clinical reasoning (an inferential process used by practitioners to collect and evaluate data and to make judgments about the diagnosis and management of patient problems; Lee & Ryan-Wenger 1997) where by the therapist integrates findings from history taking, observation, palpation and clinical movement tests such as the ASLR and ADIM. There are potential limitations to this approach based on the reproducibility of the clinical tests, and the potential variability in interpretation resulting from clinician expertise. A further drawback is that this approach does not allow for direct assessment of the deeply located trunk muscles. Unfortunately few objective tools exist to augment the clinical reasoning process and enable physiotherapists to more accurately detect and identify the distinctive motor control

changes of persons with LPP in a clinical setting. As proposed throughout this thesis, ultrasound imaging (USI) is a potential tool as it is safe, non-invasive, clinically accessible, and permits physiotherapists to monitor changes in muscle thickness (superficial and deep), connective tissue width as well as bladder base position during a typical physiotherapy assessment (Stokes et al. 1997; Whittaker et al. 2007a; 2007b). Although several preliminary investigations have been undertaken to investigate the sonographic characteristics if the abdominal wall and bladder base in this population during dynamic tasks (O'Sullivan et al. 2002; Hides et al. 2009; Teyhen et al. 2009a; 2009b; Vasseljen & Fladmark 2010; Pulkovski et al. 2011) there are shortcomings resulting from the lack of homogeneity of the case cohorts, inadequate reliability for USI measurements in a clinical setting, the use of laboratory based manoeuvres, and a lack of consideration of the abdominal wall as a functional unit (i.e. inclusion of the rectus abdominis; RA, muscle) nor the interaction of intra-abdominal pressure (IAP) and the pelvic floor muscles (PFM) on the bladder base (see Section 2.5 for implications). Further, to date investigations have only considered a change in muscle thickness, or bladder base position, between two points in a manoeuvre (pre-manoeuvre and manoeuvre hold) versus reporting the change in these parameters over the entire task. Keeping in mind that a USI video clip of a manoeuvre such as the ASLR test or ADIM may contain up to 720 individual frames (assuming a frequency of 20-40 frames / second for 18 seconds) it is likely that by considering only two frames during such an event, valuable information regarding intermediary changes may be overlooked (Peng et al. 2006). Consequently, the ability of USI to detect differences in the change in thickness of the abdominal muscles and bladder base position during clinical tests common to a typical physiotherapy assessment between persons with and without LPP has yet to be established.

8.2 Aim and Hypothesis

The aim of this investigation was to;

8.2.1 Compare changes in the thickness of the four abdominal muscles, the IRD, and bladder base position, from rest, to four points during an ASLR and an ADIM, between persons with and without LPP using USI.

The hypothesis was that;

8.2.2 Persons with LPP would exhibit differences in the magnitude and pattern of change of abdominal muscle thickness, IRD and bladder base position, during an ASLR and an ADIM in comparison to a healthy cohort.

8.3 Methods

This section contains the methodology specific to this investigation which took place at a private physiotherapy practice in Surrey, British Columbia, Canada. General methodological considerations can be found in Chapter 3.

8.3.1 Participants

The same convenience sample of 50 participants (25 controls and 25 with LPP) described in Section 7.3.1 participated in this investigation (see Appendix 3a for individual participant details).

8.3.2 Ultrasound Imaging Protocol

A USI system with a 5.0MHz curvilinear transducer was used to generate B – mode USI video clips of the RA, external oblique (EO), internal oblique (IO) and transversus abdominis (TrA) muscles (Figure 3.2 and 3.4), the IRD (Figure 3.3) and the bladder base (Figure 3.5) while participants performed an ASLR test from supine, and an ADIM from a crook lying position. Three video clips from each imaging site (during which the transducer location was maintained) were captured. Thickness measurements of RA, EO, IO and TrA (Figure 3.2 and 3.4), IRD (Figure 3.3), and bladder base position (Figure 3.8), were calculated at pre-manoeuvre rest, onset of manoeuvre, manoeuvre hold, release of manoeuvre and post-manoeuvre rest, and the average used for analysis (see Section 3.3 for details of the USI system, imaging sites and manoeuvres). To help avoid an order or fatigue effect, the order in which the muscles and manoeuvres were imaged was performed in random fashion.

8.3.3 Imaging Processing and Management

After the USI clips were exported to a personal laptop, five USI images associate with the five events of interest (pre-manoeuvre rest, onset of manoeuvre, manoeuvre hold, release of manoeuvre and post-manoeuvre rest; see Figures 3.6 and 3.7) were extracted from each USI clip and measured with MATLAB® version 7.1 software (Mathworks, Natick, Massachusetts, USA; see Section 3.3.3 for details of the extraction and measurement codes). The measurement codes that were employed automatically loaded the five ultrasound images from a directory and then prompted the operator to; calibrate distance, plot a reference line along which measurements could be made, mark the boundaries of the muscle, IRD or bladder (see Figures 3.2, 3.3, 3.4 and 3.8), then concealed the measurements from the operator by directly exporting them into an Excel worksheet. This ensured blinding of the examiner throughout the measurement process (see Section 3.3.3 for more information on the measurement code and definition of the parameters).

8.3.4 Data Analysis

T-tests and chi square tests were used to compare cohorts for subject characteristics. Percent (%) thickness (RA, EO, IO and TrA), and width (IRD) change, were calculated by using the following equation:

$$thickness\ or\ width_{contracted} - thickness\ or\ width_{rest} / thickness\ or\ width_{rest} \times 100\%$$

Data were tested for normality (Shapiro-Wilk test), and univariate correlation analysis based on Pearson's r (r; parametric data) were used to examine the relationship between the ultrasound parameters and: age, body mass index (BMI), gender, and parity in all participants, as was well pain, pain duration, and Oswestry disability score in the LPP cohort. Analyses of co-variance (ANCOVA) were used to compare % change in muscle thickness, while analyses of variance (ANOVA) were used to compare % change in IRD, as well as global and relative bladder base (GBB and RBB respectively) position, between cohorts. Statistical analyses were performed using SPSS Version 19.0 (Somers NY, USA). Significance levels were determined based on α=0.05.

8.4 Results

Participant characteristics of the two cohorts are shown in Table 7.1 and summarized in Section 7.3.1. In total 5,289 ultrasound images were measured and used in the analysis. 11.8% of the images were unavailable for analysis due to; poor image quality making delineation of the boundaries impractical, insufficient filling of the bladder, or corruption of the video clip file. The means ± standard deviations for changes in muscle thickness and IRD with respect to rest at; onset of manoeuvre, manoeuvre hold, release of manoeuvre and post-manoeuvre rest during the ASLR and ADIM are summarized in Table 8.1, while changes in GBB and RBB position during the two manoeuvres are summarized in Table 8.2.

Table 8.1: Change in Muscle Thickness and IRD (relative to rest) during the ASLR and ADIM

Parameter	Condition	ASLR (mm)		ASLR (% change)		ADIM (mm)		ADIM (% change)	
		Control	LPP	Control	LPP	Control	LPP	Control	LPP
RA	Manoeuvre Onset	-0.4 ± 4.0	-0.4 ± 3.0	-0.5 ± 5.1	-0.3 ± 4.8	-1.0 ± 5.0	-0.2 ± 0.4	-1.4 ± 6.2	-2.4 ± 4.6
	Manoeuvre Hold	-1.0 ± 5.0	0.6 ± 7.0	-1.5 ± 5.9	1.3 ± 9.8	-3.0 ± 5.0	-0.3 ± 0.4	-2.8 ± 5.8	-3.4 ± 4.7
	Manoeuvre Release	-3.0 ± 4.0	-0.7 ± 5.0	-3.5 ± 4.6	-0.5 ± 5.7	0.2 ± 4.0	-0.02 ± 0.3	0.4 ± 4.6	-0.2 ± 3.3
	Post Manoeuvre	-3.0 ± 3.0	-1.0 ± 2.0	-3.3 ± 3.2	-1.8 ± 3.1	-0.1 ± 0.4	-0.01 ± 0.3	-0.1 ± 4.6	0.3 ± 3.5
EO	Manoeuvre Onset	-0.4 ± 2.0	-0.9 ± 3.0	-0.9 ± 6.0	-2.9 ± 9.5	-0.2 ± 2.0	0.00 ± 0.2	-0.3 ± 7.0	0.6 ± 4.8
	Manoeuvre Hold	-1.0 ± 3.0	-0.9 ± 3.0	-4.8 ± 9.1	-2.1 ± 10.0	-1.0 ± 3.0	-0.03 ± 0.2	-4.0 ± 8.6	-0.6 ± 6.7
	Manoeuvre Release	0.1 ± 4.0	0.1 ± 4.0	-0.7 ± 11.4	0.03 ± 13.5	-2.0 ± 2.0	-0.01 ± 0.2	-4.5 ± 6.8*	-0.0 ± 6.2
	Post Manoeuvre	-0.1 ± 2.0	-0.7 ± 2.0	-0.6 ± 6.3	-2.7 ± 5.7	-3.0 ± 2.0	-0.02 ± 0.2	-0.4 ± 5.9	-0.2 ± 5.3
IO	Manoeuvre Onset	1.0 ± 4.0	4.0 ± 8.0	2.2 ± 5.8	7.0 ± 12.5	-0.6 ± 2.0	-0.01 ± 0.3	-0.5 ± 3.8	0.2 ± 5.3
	Manoeuvre Hold	4.0 ± 9.0	5.0 ± 8.0	5.9 ± 12.4	10.5 ± 14.8	0.6 ± 4.0	-0.02 ± 0.4	1.5 ± 7.2	-0.1 ± 7.9
	Manoeuvre Release	5.0 ± .08	4.0 ± 6.0	8.6 ± 12.0	8.3 ± 12.6	1.0 ± 4.0	0.05 ± 0.4	2.4± 7.1	1.1 ± 7.1
	Post Manoeuvre	1.0 ± 3.0	0.6 ± 3.0	0.7 ± 6.0	1.0 ± 5.9	-0.3 ± 3.0	0.05 ± 0.3	-0.3 ± 4.8	1.2 ± 4.9
TrA	Manoeuvre Onset	4.0 ± 3.0	1.0 ± 3.0	16.2 ± 12.9	3.0 ± 10.4*	3.0 ± 4.0	0.2 ± 0.3	13.6 ± 17.5	9.5 ± 14.0
	Manoeuvre Hold	3.0 ± 5.0	1.0 ± 4.0	17.2 ± 21.3	4.9 ± 14.5*	17.0 ± 9.0	1.3 ± 0.7	69.6 ± 35.7	50.2 ± 28.4
	Manoeuvre Release	3.0 ± 4.0	1.0 ± 4.0	15.4 ± 18.1	2.9 ± 16.5*	14.0 ± 9.0	1.2 ± 0.8	55.7 ± 31.1	46.5 ± 30.7
	Post Manoeuvre	1.0 ± 4.0	-1.0 ± 3.0	7.4 ± 15.9	-4.3 ± 10.5*	2.0 ± 3.0	0.1 ± 0.3	6.7 ± 11.6	5.3 ± 11.7
IRD	Manoeuvre Onset	0.1 ± 11.0	-5.0 ± 16.0	0.3 ± 10.2	-2.6 ± 11.0	-9.0 ± 12.0	-0.5 ± 1.0	-9.8 ± 8.1	-5.3 ± 7.7
	Manoeuvre Hold	-8.0 ± 13.0	-13.0 ± 21.0	-5.5 ± 11.8	-7.2 ± 17.4	-8.0 ± 14.0	-0.9 ± 1.4	-6.4 ± 9.5	-8.9 ± 11.5
	Manoeuvre Release	-7.0 ± 18.0	-8.0 ± 25.0	-3.8 ± 10.4	-1.2 ± 23.4	-10.0 ± 13.0	-1.0 ± 1.6	-11.4 ± 8.9	-9.3 ± 10.8
	Post Manoeuvre	-7.0 ± 18.0	-4.0 ± 15.0	-4.1 ± 8.6	-1.6 ± 10.9	-9.0 ± 12.0	-0.1 ± 0.8	-10.1 ± 11.2	-1.6 ± 6.7*

***** Statistically significant ($p<0.05$). ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg raise test, EO = external oblique, IO = internal oblique, IRD = inter-recti distance, LPP = lumbopelvic pain, RA = rectus abdominis, TrA = transversus abdominis

Table 8.2: Change in Global and Relative Bladder Base Position During the ASLR and ADIM

Parameter	Condition	ASLR (mm)		ADIM (mm)	
		Control	LPP	Control	LPP
GBB X axis	Onset of Manoeuvre	-3.0 ± 15.0	8.0 ± 19.0*	4.0 ± 16.0	8.0 ± 19.0
	Manoeuvre Hold	-18.0 ± 24.0	-24.0 ± 29.0	-17.0 ± 20.0	-17.0 ± 19.0
	Manoeuvre Release	47.0 ± 29.0	78.0 ± 54.0*	40.0 ± 36.0	39.0 ± 20.0
	Post Manoeuvre	4.0 ± 14.0	7.0 ± 17.0	-2.0 ± 10.0	-0.3 ± 13.0
GBB Y axis	Onset of Manoeuvre	-20.0 ± 18.0	-29.0 ± 30.0	-20.0 ± 14.0	-16.0 ± 22.0
	Manoeuvre Hold	-25.0 ± 32.0	-46.0 ± 53.0	-15.0 ± 38.0	-18.0 ± 23.0
	Manoeuvre Release	36.0 ± 26.0	59.0 ± 46.0*	27.0 ± 13.0	28.0 ± 16.0
	Post Manoeuvre	2.0± 10.0	4.0 ± 13.0	-2.0 ± 11.0	0.6 ± 12.0
GBB Trajectory	Onset of Manoeuvre	-30.0 ± 27.0	-53.0±41.0*	-16.0 ± 22.0	-16.0 ± 22.0
	Manoeuvre Hold	-15.0 ± 31.0	-33.0 ± 47.0	9.0 ± 20.0	7.0 ± 13.0
	Manoeuvre Release	28.0 ± 15.0	32.0 ± 17.0	22.0 ± 11.0	29.0 ± 16.0
	Post Manoeuvre	2.0 ± 12.0	6.0 ± 13.0	-4.0 ± 10.0	-3.0 ± 14.0
RBB X axis	Onset of Manoeuvre	-11.0 ± 24.0	-31.0±37.0*	-3.0 ± 11.0	-3.0 ± 19.0
	Manoeuvre Hold	2.0 ± 23.0	10.0 ± 27.0	10.0± 17.0	14.0 ± 19.0
	Manoeuvre Release	2.0 ± 10.0	-7.0 ± 18.0*	3.0 ± 6.0	-2.0 ± 15.0
	Post Manoeuvre	5.0 ± 15.0	9.0 ± 20.0	-5.0 ± 11.0	-1.0 ± 13.0
RBB Y axis	Onset of Manoeuvre	-4.0 ± 15.0	-7.0 ± 14.0	0.3 ± 10.0	0.8 ± 13.0
	Manoeuvre Hold	-18.0 ± 18.0	-23.0 ± 29.0	-24.0 ± 18.0	-19.0 ± 22.0
	Manoeuvre Release	3.0 ± 16.0	-7.0 ± 29.0	3.0 ± 7.0	-2.0 ± 10.0
	Post Manoeuvre	4.0 ± 14.0	7.0 ± 17.0	-2.0 ± 10.0	-0.3 ± 13.0
RBB Trajectory	Onset of Manoeuvre	36.0 ± 20.0	43.0 ± 27.0	33.0 ± 20.0	32.0 ± 17.0
	Manoeuvre Hold	-24.0 ± 25.0	-44.0±42.0*	-21.0 ± 26.0	-17.0 ± 24.0
	Manoeuvre Release	3.0 ± 19.0	-6.0 ± 28.0	7.0 ± 10.0	7.0 ± 13.0
	Post Manoeuvre	2.0 ± 10.0	4.0 ± 13.0	-2.0 ± 12.0	0.6 ± 12.0

***** Statistically significant ($p<0.05$). ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg raise test, GBB = global bladder base position, LPP = lumbopelvic pain, RBB = relative bladder base position, X = x axis (+ = caudal, - = cranial), Y = y axis (+ = anterior, - = posterior).

The general pattern of muscle thickness change during the ASLR and ADIM can be seen in Figures 8.1 and 8.2 respectively, while the change in position of the GBB during an ASLR and ADIM are displayed in Figures 8.3 and 8.4.

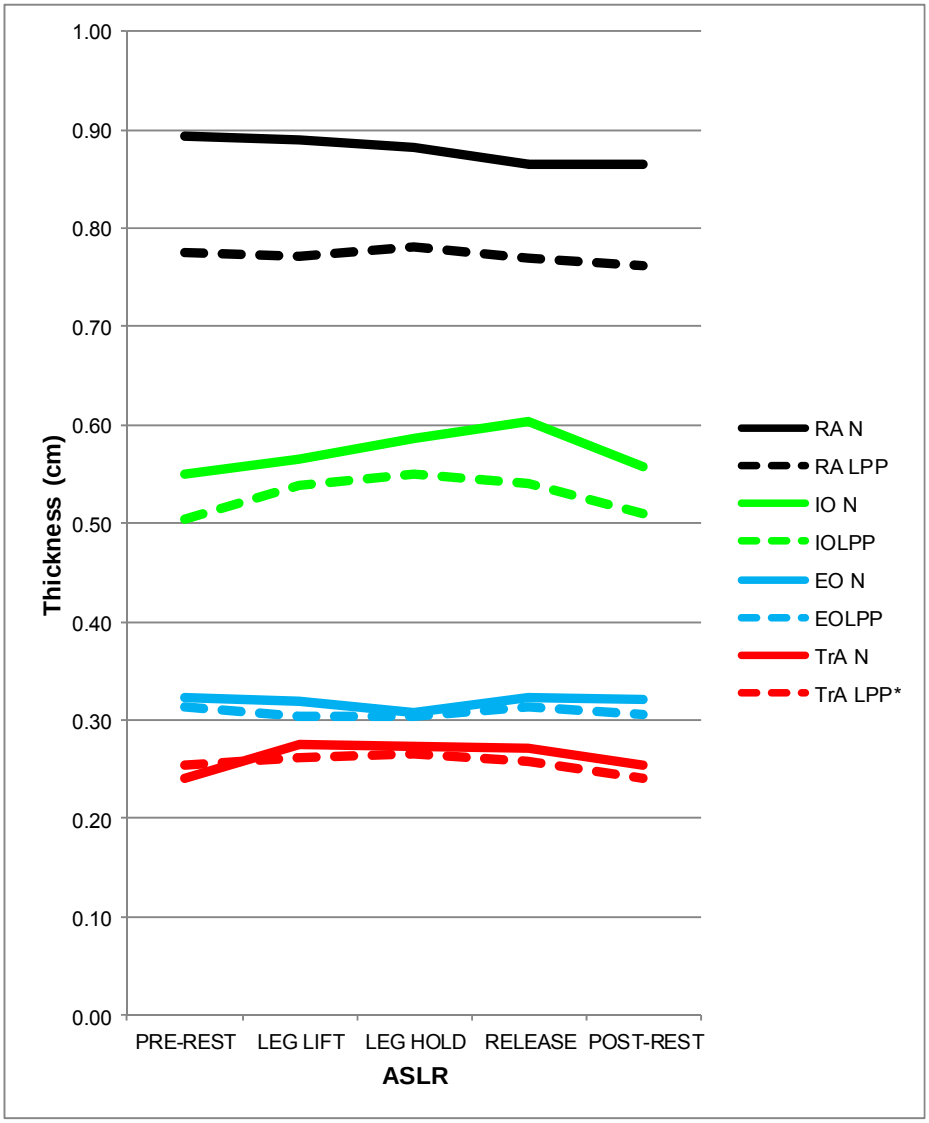


Figure 8.1: Abdominal muscle thickness during an ASLR test. EO = external oblique, IO = internal oblique, LPP = lumbopelvic pain, N = control, RA = rectus abdominis, TrA = transversus abdominis.

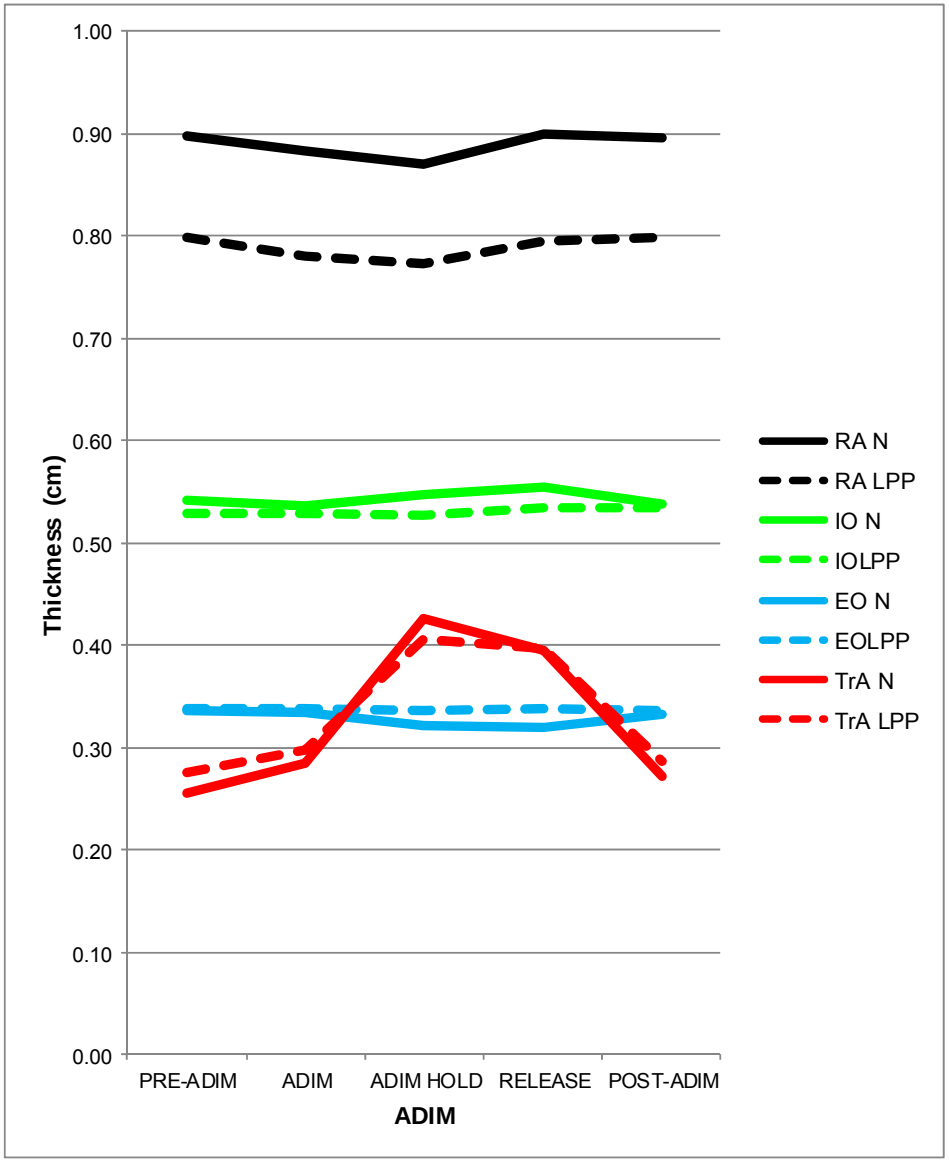


Figure 8.2: Abdominal muscle thickness during an ADIM. EO = external oblique, IO = internal oblique, LPP = lumbopelvic pain, N = control, RA = rectus abdominis, TrA = transversus abdominis.

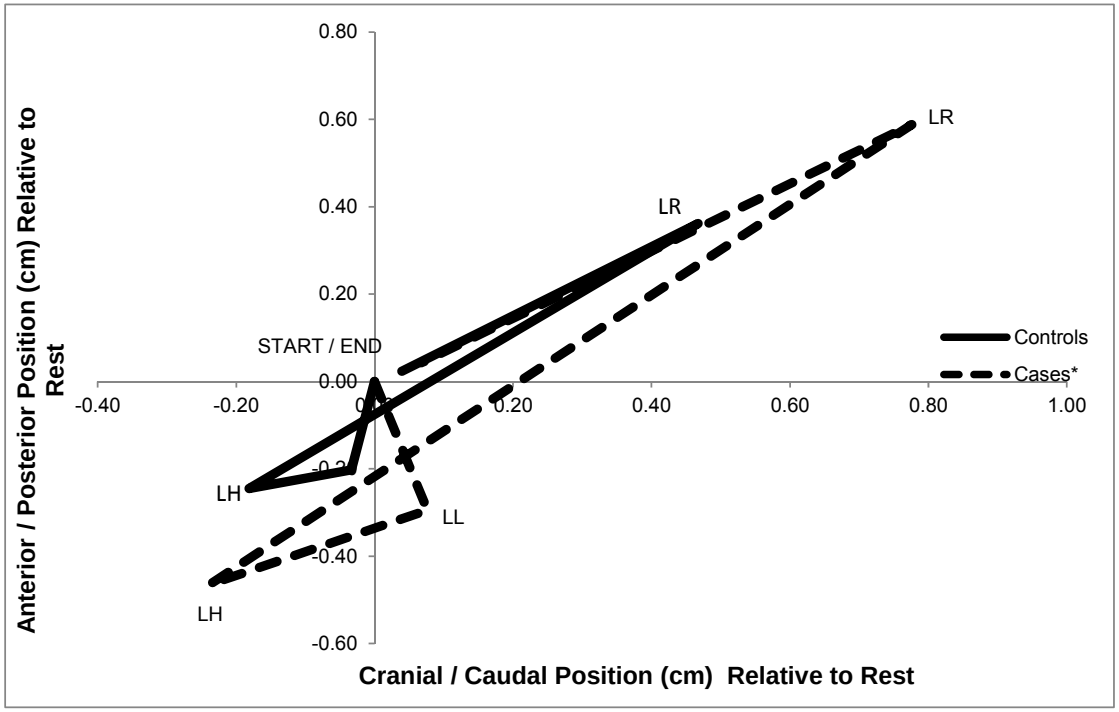


Figure 8.3: Global bladder base position during an Active Straight Leg Raise test. LL = Leg Lift, LH = Leg Hold, LR = Leg Release

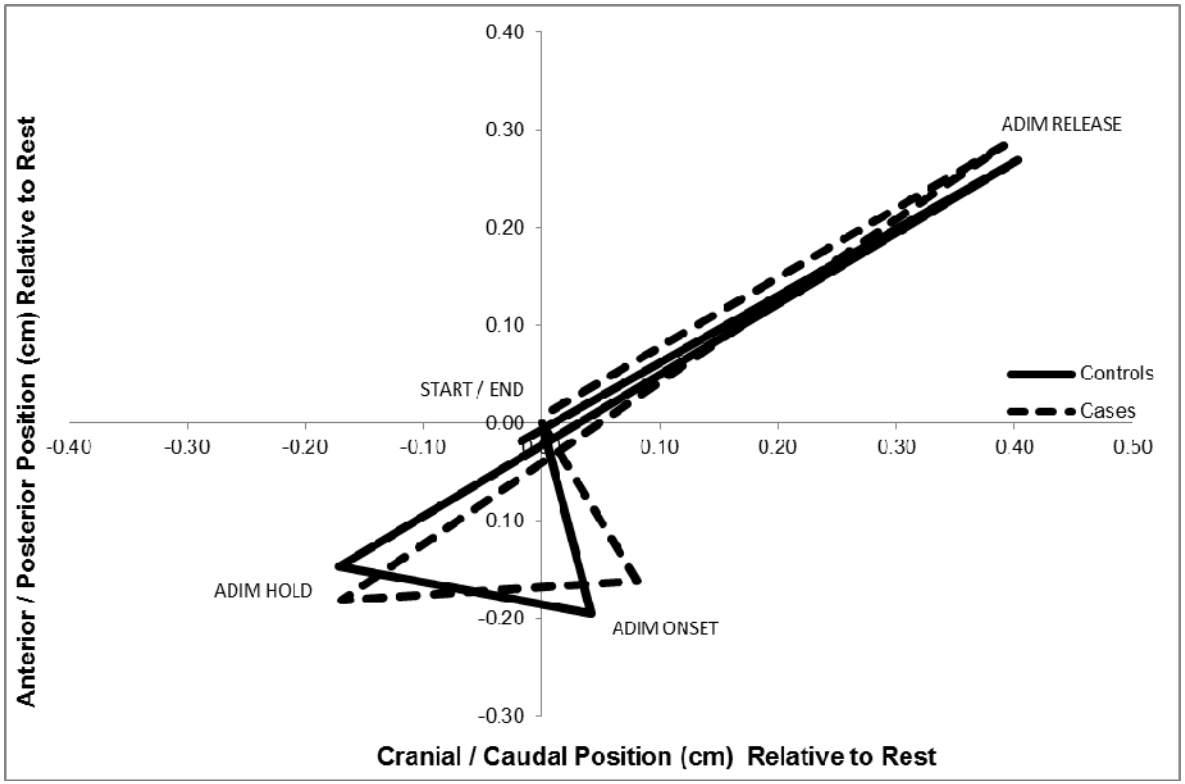


Figure 8.4: Global bladder base position during an Abdominal Drawing in Manoeuvre (ADIM)

Percent change in muscle thickness did not correlate with parity but did with age (RA; r=0.53, p=0.001), gender (IO; r=0.43, p=0.001) and BMI (IO; r=0.40, p=0.01). In contrast, % change in IRD and bladder base position (mm) did not correlate with BMI, gender, age or parity (see Appendices 11a and 11b for all correlation values). Accordingly, ANCOVA using BMI, gender and age as a covariate for % muscle thickness change, and ANOVA for % IRD change, and GBB and RBB, were performed to compare cohorts.

There were no significant differences between the two cohorts during the ADIM other than the LPP cohort demonstrated a smaller decrease in EO thickness (relative to rest) at the release of the manoeuvre (ANCOVA adjusted for age, gender and BMI; p=0.04), and a smaller decrease in IRD width (relative to rest) post manoeuvre (ANOVA; p=0.01; see Appendix 11c for results of all ADIM significance testing). In both groups the RA and EO muscles decreased in thickness during an ADIM, and although not statistically significant there was a trend for the decrease in RA thickness to be greater in the case cohort, and the decrease in EO thickness to be greater in the control cohort. A further observation was that the IRD decreased in both cohorts during the manoeuvre and although again, not statistically significant, there was a trend for the decrease to be greater in the control (10%) versus the case (5%) cohort.

With respect to the ASLR, the LPP cohort demonstrated significantly smaller increases in TrA thickness (relative to rest) throughout (ANCOVA adjusted for age, gender and BMI; p=0.00 – 0.0. 5; see Appendix 11d for results of all ASLR significance testing). Further, the LPP cohort exhibited greater change in trajectory (GBB, ANOVA; p=0.02), and inferior (GBB and RBB, ANOVA; p=0.03) bladder base position (relative to rest), during the leg lift, and greater change in inferior (GBB and RBB, ANOVA; p=0.02 and 0.03 respectively), and anterior (GBB, ANOVA; 0.04) bladder base position (relative to rest), with the return of the leg to the plinth. Of further interest was the observation that in the LPP cohort the % change in TrA thickness, during the ASLR, was found to have a fair correlation with pain intensity (r = -0.42 - -0.44, p = 0.002 – 0.001), Oswestry disability score (r = - 0.44, p = 0.001), and pain duration (r = - 0.38, p = 0.01).

8.5 Discussion

This is the first study to concurrently consider the pattern of change of abdominal muscle thickness, IRD, and bladder base position in participants with and without LPP, during the ADIM and ASLR test. Although there was little variation identified between cohorts during the ADIM, commensurate with our hypothesis, differences emerged during the ASLR test. Specifically, the LPP cohort demonstrated smaller increases in TrA thickness (relative to rest) throughout the ASLR, as well as a greater change in inferior bladder base position at leg lift, and with the return of the leg to the plinth.

In addition to comparing the changes in these parameters between cohorts, the results describe a pattern of change for the USI parameters at four points over the course of the two manoeuvres, as opposed to previous investigations that have only measured these parameters at rest and at some point during contraction (Teyhen et al. 2009a; 2009b; Pulkovski et al. 2011). Of interest, is that in all cases, there were fluctuations in the magnitude of the USI parameters from the point of onset of the two manoeuvres until they were released (i.e. ASLR leg lift to ASLR leg release, or ADIM onset to ADIM release), suggesting that the magnitude of the USI parameter (thickness, IRD or bladder base position) is not consistent as the manoeuvre is held. This finding may explain why there is disagreement in the literature regarding the change in magnitude of these USI parameters during these two manoeuvres, as the conventional methodology of considering only the magnitude of these USI parameters in two USI frames is unlikely to reflect what is happening over the course of the manoeuvre.

8.5.1 Abdominal Drawing in Manoeuvre

As outlined in Section 2.3.3, the ADIM is the most commonly investigated clinical muscle test of the abdominal wall, as clinical trials that have focused on re-educating this drawing in action have been successful in decreasing LPP. Its origin is based on the principles of traditional muscle testing, as the ADIM is considered a muscle test for the TrA muscle.

There are no studies to date that have reported on changes of the RA, EO or IRD during the ADIM. In contrast, there are several that have compared the change in thickness of the TrA and IO muscles between various case cohorts and healthy participants (see Section 2.3.3). None of the investigations reported differences in the change in thickness of the IO between cohorts during the manoeuvre. With respect to the TrA, three have identified a smaller increase in thickness in a case (low back pain; LBP and LPP) cohort (Critchley & Coutts 2002; Kiesel et al. 2007; Teyhen et al. 2009a), while two found no difference in persisting pelvic girdle pain (PGP; Stuge et al. 2006b), or chronic LBP cohorts (Pulkovski et al. 2011). The findings of the current investigation are consistent with the literature as it pertains to the IO, and contribute to the lack of consensus with respect to the TrA, as no difference in cohorts was identified. The rationale for this disparity may be due to the fact that as the ADIM is a voluntary motor skill, its performance hinges upon a variety of factors (i.e. how the skill is taught, the participant's ability to learn the skill, and any previous exposure to the skill), and consequently it is an extremely difficult test to standardize (see Section 2.3.3). A further consideration, as highlighted in Figure 8.2, is that TrA thickness varies significantly from the point of onset of the manoeuvre until it is released. Consequently the point at which the contracted

image was captured by the individual investigators may have influenced the change in thickness reported.

This investigation presents novel findings with respect to the EO, RA, and IRD during an ADIM. Although not statistically significant, there was a trend for a greater decrease in RA thickness in the case cohort, and a greater decrease in EO thickness and IRD in the control cohort. The greater decrease in RA thickness in the LPP cohort is possibly explained by an increase in compliance of the RA resulting from altered length tension properties, or decreased muscle size (see results for RA in Section 7.4) and / or tone. Consequently, the lateral pull imparted to the RA by the TrA during the ADIM resulted in an increase in RA length, and corresponding decrease in thickness. The greater decrease in EO thickness in the control cohort is possibly explained by changes in the activity of the EO and / or IO during the manoeuvre. However, as the relationship between the change in muscle thickness and changes muscle activity are unclear (see Chapter 6) this hypothesis would need to be investigated with electromyography (EMG). Finally, the decrease in IRD observed supports the hypothesis that has arisen out of anatomical studies of the linea alba (Axer et al. 2001a; 2001b) and TrA, as well as one case study, that suggest the perimuscular connective tissue (PMCT) of the TrA is continuous from one side to the other, and that the TrA is a digastric muscle capable of decreasing the width of the linea alba in post-natal rehabilitation (Sheppard 1996). This hypothesis is further supported by the fact that the decrease in IRD was greater with the ADIM than with the ASLR (see Table 8.1). However, the impact of the ADIM on the width of the linea alba in a post-natal population would need to be confirmed with an interventional study.

With respect to the bladder base, Bø et al (2003) reported a 4.3mm ± 0.1 – 4.4mm cranial-ventral displacement of the bladder base in a young healthy female cohort during the ADIM. In contrast, the current investigation found a 16mm caudal-dorsal displacement with the onset of the ADIM in the control cohort, followed by the bladder base moving cranial as the manoeuvre was held, and then travelling caudal-ventral, before returning to the resting position when the manoeuvre was released (Figure 8.4). This pattern of bladder base motion was mirrored by the LPP cohort. Once again the discrepancy in findings to the aforementioned investigation may be related to the point during the ADIM at which the contracted image was captured, or due to methodological difference in how bladder base motion was quantified.

In summary, although the ADIM is a commonly used clinical test during the assessment of LPP, its ability to differentiate persons with and without LPP should be questioned based on the findings of the present, and other investigations (Pulkovski et al. 2011). Specifically, on the growing evidence that person's with and without LPP exhibit similar

patterns of abdominal muscle thickness, IRD and bladder base position change throughout the manoeuvre.

8.5.2 Active Straight Leg Raise Test

The ASLR test is commonly employed in clinical practice (Lee 2004) for the purpose of assessing the ability of the lumbopelvic region to effectively transfer load (see Section 3.2.3 for details). With respect to the abdominal wall there are no studies that have reported on changes of the RA, EO, or IRD during the ASLR. In contrast, Teyhen et al (2009b) compared the change in TrA and IO thickness between healthy, and LPP cohorts, and reported a 23.7% and 11.2% increase in TrA and IO thickness respectively in the control group, and significantly smaller (6.4% and 5.7% respectively) increases in thickness in the LPP group. The findings of the current study are similar with respect to TrA (controls; 17.2%, LPP; 4.9%), but differ with respect to the IO, identifying a greater increase in thickness in the LPP cohort at leg hold (controls; 5.9%, LPP; 10.5%). It is possible that the reason for this disparity is that IO thickness varies significantly from the point of onset of the manoeuvre until it is released. Consequently differences may be related to the point during the ASLR at which the contracted image was captured. The findings of the current study build upon those of the earlier literature by considering the change in thickness of the IO and TrA at five points during the ASLR test (rest, onset of the leg lift, leg hold, leg release and post rest; see Figure 3.6). It is interesting to note that greatest change in TrA and IO thickness, for both cohorts, was found at the point of leg lift, suggesting that future investigations that only have the facility to generate measurements at only two points during this manoeuvre should do so at rest and at the point of leg lift.

This investigation presents novel findings with respect to the EO, RA, and IRD during an ASLR. Although there was no statistical difference between cohorts, the EO and RA demonstrated a trend to decrease in thickness, while the IRD demonstrated a trend to decrease in width during the ASLR in both groups. As highlighted by the findings of Chapter 6 the interpretation of these findings must take into account all factors that may be influencing or impacting these structures. One plausible explanation for the decrease in EO and RA thickness may be an increase in muscle length resulting from movement of the origin and insertion of these muscles away from each other with either anterior pelvic rotation or, thoracic extension, during the task. Finally, the decrease in IRD observed further supports the hypothesis that the linea alba is an extension of the PMCT of the lateral abdominal wall muscles (Axer et al. 2001a; 2001b), and correspondingly its width is influenced by a contraction of these muscles.

As with the abdominal parameters, this is the first investigation to report the change in position of the bladder base (relative to a resting position) at five points during the ASLR (Figure 8.3). Previous investigations that have reported on the change in bladder base position at two points (rest and leg hold) during the ASLR, have demonstrated increased bladder base descent associated with an increase in IAP in a case (PGP) cohort (see Section 2.4.4 for a summary; O'Sullivan et al. 2002; Beales et al. 2009a; 2009b; 2010). The current study echoes these investigations by demonstrating a greater change in inferior bladder base position at leg lift, and with the return of the leg to the plinth.

When it comes to interpreting the significance of the difference in findings between cohorts with respect to the TrA and bladder base during this task, the value of an encompassing approach that considers the findings in conjunction with each other becomes apparent. For instance, taken as separate observations it would be easy to jump to the conclusion that the smaller increase in TrA thickness in the LPP cohort meant that they used less muscle activity, in comparison to the control cohort. Further, that the greater descent of the bladder base was due to weakness of the PFM. However, when the smaller increase in TrA thickness is considered in conjunction with the greater descent of the bladder base, another plausible explanation emerges; namely that the participants in the LPP cohort were employing an altered motor control strategy that produced an increase in IAP which prevented the TrA from shortening (and correspondingly thickening), and displaced the bladder caudal. Again it is important to remember that this rationale is just speculation, as the current study did not monitor IAP. With that being said this motor control strategy has been previously documented in the literature in a similar cohort with PGP (O'Sullivan et al. 2002; Beales et al. 2009a; 2009b; 2010). Specifically, investigators (using EMG to record oblique abdominal muscle activity, and a nasogastric catheter with two small lumens situated in the esophagus and abdomen to record IAP and intra-thoracic pressure) have identified that participants with PGP demonstrate a splinting type activation of their diaphragm, and abdominal wall muscles, which results in an increase in IAP and subsequently descent of the bladder. Further, this rationale is supported by the correlation between the smaller increases in TrA thickness during the ASLR with duration of pain, which suggests a progressive pattern.

In summary, the LPP cohort in this investigation demonstrated differences in the change in thickness of the TrA muscle and bladder base position during an ASLR test in comparison to healthy controls. These findings demonstrate how USI can provide a series of observations about the change in thickness of the abdominal muscles, and position of the bladder base during the ASLR, that when considered together, suggest that an altered motor control strategy is being used by the LPP cohort to perform the task. Further, this information can be used to speculate on the nature of the altered strategy.

8.5.3 Limitations

The limitations of this investigation echo those of the previous chapter (see Section 7.5.1) with one additional consideration. Specifically, in an attempt to develop a better understanding of the pattern of architectural change of abdominal muscle thickness, IRD and bladder base position during these two manoeuvres a decision was made to gather measurements at five, as opposed to the prevailing convention of two, points in time. As reported above, this led to the discovery that there are fluctuations in the magnitude of these parameters over the course of these two manoeuvres. On analysis of the ASLR test results it appears that the greatest change in these parameters occurs at the point of leg lift. However, bearing in mind that a USI video clip of a manoeuvre such as the ASLR test may contain up to 720 individual frames (assuming a frequency of 20-40 frames / second for 18 seconds) it is impossible to know if the point of leg lift is truly the most optimal time during the manoeuvre to detect the biggest difference between the two cohorts. Future investigations employing more sophisticated methods of describing the pattern of architectural change of these parameters over the course of the entire manoeuvre will be required to confirm or negate this finding.

8.6 Conclusions and Implications

8.6.1 The findings of this investigation present novel information about the pattern of abdominal muscle thickness, IRD and bladder base position at five points over the course of the ASLR test and ADIM, in both control and LPP cohorts.

8.6.2 The results identify fluctuations in the magnitude of abdominal muscle thickness, IRD, and bladder base position from the point of onset of the two manoeuvres until they are released (i.e. ASLR leg lift to ASLR leg release, or ADIM onset to ADIM release), suggesting that the value of these parameters is not consistent throughout the duration of these manoeuvres. This has implications for interpreting the literature, as well as future study design. Specifically, unless the timeline for gathering measurements is standardized, comparison between investigations is impractical.

8.6.3 There was little difference between abdominal muscle thickness, IRD and bladder base position, between cohorts, during the ADIM. This finding questions the value of the ADIM for distinguishing persons with LPP.

8.6.4 The LPP cohort demonstrated smaller increases in TrA thickness (relative to rest) throughout the ASLR, as well as greater changes in inferior bladder base position. The greatest change in these measurements, for both cohorts, was found at the point of leg lift, suggesting that this may be the optimal point to capture during the ASLR for distinguishing between persons with and without LPP.

8.6.5 These findings demonstrate how USI can provide a series of observations about the change in thickness of the abdominal muscle, IRD and bladder base position, that when considered together, may serve as an indicator upon which altered patterns of muscle function can be identified.

8.7 Summary and Novelty

This chapter has presented an observational study aimed at comparing the sonographic characteristics of participants with and without LPP during two dynamic clinical tests (ADIM and ASLR) typical of the physiotherapy assessment of the lumbopelvic region. It has identified novel information about the pattern of abdominal muscle thickness, IRD and bladder base position over the course of the ASLR test and ADIM, in healthy and LPP cohorts which will impact the interpretation of the literature and future study design. Further, in conjunction with the investigation from the previous chapter, it has demonstrated how USI can be used to identify a series of observations about the morphology of the abdominal wall, and change in bladder base position, that taken together may not only identify altered muscle function, but provide insight into intricacies of the motor control strategy that persons with LPP are employing. What remains unknown is whether or not consideration of this sonographic information, in addition to findings revealed from a patient's history, self-report measures, and a typical clinical examination is of any added value. The next chapter introduces secondary analyses of the data generated by the observational studies presented in Chapters 7 and 8 which is being piloted in an attempt to answer this question.

CHAPTER 9 – THE ROLE OF SONOGRAPHIC INFORMATION FOR DISCRIMINATING LUMBOPELVIC PAIN

This chapter introduces on-going work involving secondary analyses of the data from the previous two investigations (Chapters 7 and 8). It is aimed at identifying which variables (non-sonographic and sonographic), measured in the previous two investigations, are best for discriminating lumbopelvic pain (LPP), as well as the added value of considering sonographic information. These analyses were conducted in collaboration with Dr Peter Worsley from the Faculty of Health Sciences, University of Southampton, UK. This chapter introduces the work, discusses preliminary results, and points to limitations and areas for future study.

9.1 Introduction

As detailed in earlier chapters of this thesis ultrasound imaging (USI) can provide accurate information about the morphology of various connective tissues (i.e. muscle, perimuscular connective tissue; PMCT, and fascial planes like the linea alba), and the position of structures such as the bladder base (Stokes et al. 1997; Whittaker et al. 2007a; 2007b). Accordingly, there have been an increasing number of investigations aimed at comparing these types of sonographic variables between various cohorts in an attempt to better understand how the groups differ. Of relevance to the research contained in this thesis are the investigations aimed at comparing the sonographic parameters of the abdominal muscles and bladder base at rest, and during various manoeuvres, between cohorts with and without LPP (see Sections 2.3.3 and 2.4.4; Teyhen et al. 2007; Whittaker et al. 2007b). To date, there have been discrepancies in the findings of these investigations with some reporting differences between case and control cohorts (Critchley & Coutts 2002; Kiesel et al. 2007; Teyhen et al. 2009a), while others do not (see Sections 7.5 and 8.5; Stuge et al. 2006b; Pulkovski et al. 2011). The investigations presented in Chapters 7 and 8 were undertaken to not only contribute to the literature, but to clarify some of the discrepancy that exists. They are more extensive than what has been previously published in that they include resting, and change values from various points over the course of two dynamic tasks, for a larger number of sonographic variables (muscle, PMCT, and bladder base).

These two investigations have identified a series of sonographic features about the lumbopelvic region which differed between a healthy and LPP cohort. These included;

- Total resting abdominal wall muscle thickness (specifically resting rectus abdominis; RA, thickness).
- Total resting abdominal wall PMCT.

- Resting Inter-recti distance (IRD).
- Percent (%) change in transversus abdominis (TrA) muscle thickness (relative to rest) at five points during an Active Straight Leg Raise test (ASLR).
- Change in bladder base position at the point of leg lift and on leg lowering during the ASLR test.

In addition to providing more comprehensive information about differences in the sonographic features of the abdominal wall and bladder base position in persons with LPP, these investigations highlight the value of considering these differences in relation to each other, as opposed to viewing them as separate unrelated findings. Further, they have demonstrated how a series of observations about the morphology of the abdominal wall, and position of the bladder base, considered together, may assist in identifying altered patterns of muscle function in a LPP cohort (see Sections 7.5 and 8.5).

What remains unknown is whether or not consideration of sonographic information is of any added value to findings revealed by a patient's history, clinical examination techniques and self-report measures. That is, does the addition of sonographic information make it easier to discriminate participants LPP? With that question in mind novel secondary analyses of the data gathered in Chapters 7 and 8 is piloted in this chapter. These analyses involve using a multivariate classification technique (linear discriminant analysis; LDA) to determine which linear combinations of features (representing a variety of types of data) best discriminate between two or more classes of data (i.e. in this case those with and without LPP). Further, to compare the discriminatory power of different combinations of variables (i.e. non-sonographic and sonographic).

Linear discriminant analysis is a method of projecting high dimensional data (i.e. multiple variables, from numerous participants) onto a lower dimensional space (2-dimensional data known as z-scores) in a way that best separates the data between two or more known groups (Balakrishnama & Ganapathirju 2000; Kamvar 2002). Further, LDA provides a measure (coefficient of LDA or linear discriminant) of the maximal separation between groups based upon a function which maximizes the ratio of between-class variance to the within-class variance in any particular data (see Appendix 12a for more detailed description of LDA). Linear discriminant analysis was first described in 1936 (Fisher 1936) and has been applied in a wide variety of circumstances such as defining differences in gait characteristics between healthy and osteoarthritic cohorts (Astephen & Deluzio 2005), identifying variables which offer the highest discrimination between healthy and knee arthroplasty cohorts (Worsley 2011), and determining which sonographic parameters, are best at distinguishing malignant breast tumors (Alvarenga et al. 2010).

9.2 Aims & Hypotheses

The aims of the secondary analyses are to;

9.2.1 Rank all self-reported, participant, clinical, and sonographic features collected in two previous observational studies (Chapters 7 and 8) based upon their ability to discriminate participants with LPP. Further, using this rank order, determine the best performance set of features (sub-set of self-report, participant, clinical and sonographic) for discriminating participants with LPP.

9.2.2 Determine if the classification of participants with and without LPP is strengthened by the addition of sonographic variables.

9.2.3 Compare the ability of the best performance set generated by LDA to a best performance set derived from the variables identified to be statistically significant in Chapters 7 and 8 for discriminating between participants with and without LPP.

9.2.4 Determine the feasibility and appropriateness of LDA for these aims as well as any limitations, and areas for future work.

The hypotheses were that;

9.2.5 The sonographic features identified in Chapters 7 and 8, comparing participants with and without LPP, would be found to have a high discriminate power and be included in the best performance set.

9.2.6 The addition of sonographic features to self-report measures, participant characteristics and clinical examination outcomes, improves the ability to discriminate participants with LPP.

9.2.7 The best performance sets derived from the LDA, and from the variables identified to be statistically significant in Chapters 7 and 8 would have similar discriminative power.

9.3 Methods

This is an on-going retrospective pilot study involving secondary analyses of the data presented in Chapters 7 and 8. The creation of the databases and subsequent analyses was performed in collaboration with Dr Peter Worsley. This section contains the methodology specific to this analytical investigation. General methodological considerations related to how the data were collected can be found in Chapter 3, as well as Sections 7.3 and 8.3.

9.3.1 Database Features

In this retrospective pilot study, two databases were used. The first originated from the 230 previously identified features from each of 50 participants who had taken part in the

observational studies presented in Chapters 7 and 8 (see Section 7.3.1 and Appendix 3a). These 230 features included six participant characteristics (i.e. age and BMI etc.), eight self-report measure scores (i.e. Numerical Pain Rating Scale; NPRS, Oswestry disability score etc.), outcomes of four clinical tests (i.e. the pattern of compression that normalised the ASLR test) and 212 sonographic variables. Of the 212 sonographic parameters 52 were excluded as they represented duplicate information (i.e. absolute muscle thickness values were excluded in lieu of normalised muscle thickness values), while a further 86 were excluded due to missing data sets. The remaining 116 parameters (per participant) were used along with the participant characteristics, self-report scores and clinical observations to create the database that will be referred to as the 'large database' (a list of these parameters and their description can be found in Appendix 12b). The second, 'small database', was a slimmed down version of the 'large database' containing only 38 parameters. These 38 parameters included the same six participant characteristics, eight self-report measure scores, and four clinical observations as the 'large database', and only 20 sonographic parameters which had been identified in Chapters 7 and 8 to be statistically different in participants with LPP (a list of these parameters can be found in Appendix 12c).

9.3.2 Data Analysis

Statistical analysis was performed using and MATLAB® version R2010b software (Mathworks, Natick, Massachusetts, USA). The analysis of the 'large database' involved several steps. First each of the 116 data points for each participant were normalised by their standard deviation. A preliminary LDA was then performed to calculate the measure of maximal separation [linear discriminant; $J(w)$], or discriminatory power], of each individual feature in the database (0 = no discriminatory power). This discriminatory power was derived by calculating the Rayleigh Quotient [$J(w)$] which is a ratio of the between and within class covariance (Figure 9.1).

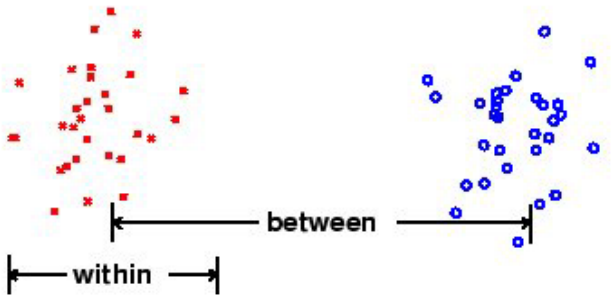


Figure 9.1: Example of within and between class covariance

Based on this initial analysis, the features were organized into rank order. A stepwise procedure was then applied to the rank order of discriminant features to select the most

discriminant combination of features or ‘best performance set’. Essentially this process involved a second Fisher LDA aimed at determining the cumulative discriminatory power [$J(w)$] of the variables by adding one at a time until all 116 were included, and then assessing the $J(w)$ for each step of the process to determine the optimal sub-set of features to classify the data [namely the combination of features that produced the highest $J(w)$]. The stepwise process was then applied to the 38 features contained in the ‘small database’ to determine the best performance set from this database and their cumulative discriminatory power. Finally, the potential of the large’, and ‘small databases’, as well as the non-sonographic and sonographic features from these databases to classify participants with and without LPP was assessed by finding a discriminatory point in the z-scores produced by the LDA to estimate classification accuracy (percentage of correct classification).

9.4 Results

This section contains the results from a preliminary exploratory analysis. The $J(w)$ values of the 116 parameters from the ‘large database’ (inclusive of the ‘small database’ parameters) varied from 5.41E-08 to 0.42 [see Appendix 12b for the rank order and $J(w)$ values for all 116 parameters] The highest value was achieved by the ‘pattern of compression that normalised the ASLR test’ [$J(w)$ = 0.42]. The top self-report discriminate (ranked 2nd out of 116) was the NPRS score for pain intensity [$J(w)$ = 0.12], and the top participant characteristic determinate (ranked 10th) was ‘age’ [$J(w)$ = 0.01]. With respect to the sonographic features, the top discriminate (ranked 7th) was ‘percent contribution of PMCT to abdominal wall (defined at the total muscle + total PMCT) thickness’ [$J(w)$ = 0.02] followed by 'percent contribution of muscle to abdominal wall thickness’ [$J(w)$ = 0.02], ranked 8th, and the ’percent change in TrA thickness at the point of leg lift during the ASLR test’ [$J(w)$ = 0.01] ranked 12th.

The best performance set of features from the ‘large database’ are shown in Table 9.1. This sub-set consisted of 24 determinates including seven self-report measure scores, one participant characteristic, two clinical observations and 14 sonographic parameters. The discriminate power of this subset was $J(w)$ = 1.20, and it provided clear separation of groups with no misclassification (99.9% accurate). A graphical representation of this separation is seen with a frequency plot of the z-scores produced by the LDA (Figure 9.2).

Table 9.1: Best Performance Set of Features from the Large Database.

Rank	Feature	$J(w)$	Cumulative $J(w)$	Feature Category
1	ASLR Compression Pattern	0.4195	0.4195	Clinical
2	Numerical Pain Rating Scale Score	0.1202	0.6299	Self-report
3	Oswestry Disability Score	0.0621	0.6433	Self-report
4	Fear Avoidance Belief Questionnaire (Physical Activity Sub-set) Score	0.0544	0.6580	Self-report
5	Nijmegen (Hypocapnia) Questionnaire Score	0.0235	0.6853	Self-report
6	Fear Avoidance Belief Questionnaire (Work Sub-set) Score	0.0212	0.7386	Self-report
7	% contribution of PMCT to abdominal wall thickness	0.0183	0.7465	Sonographic
8	% contribution of muscle to abdominal wall thickness	0.0183	0.7465	Sonographic
9	Urogenital Distress Index	0.0160	0.8955	Self-report
10	Age in years	0.0139	0.9028	Participant
11	Length of Pain in years	0.0137	0.9140	Self-report
12	% change in TrA thickness at ASLR leg lift	0.0131	0.9207	Sonographic
13	% contribution of inferior RA PMCT to total PMCT thickness	0.0120	0.9604	Sonographic
14	% contribution of TrA to total abdominal muscle thickness	0.0085	0.9632	Sonographic
15	% change in TrA thickness at ASLR post manoeuvre	0.0078	0.9669	Sonographic
16	Inter-recti distance width (cm)	0.0074	1.0015	Sonographic
17	% contribution of superior RA PMCT to total PMCT thickness	0.0066	1.0043	Sonographic
18	% change in TrA thickness at ASLR manoeuvre release	0.0054	1.0050	Sonographic
19	Change in GBB cranial/caudal position at ASLR manoeuvre release (cm)	0.0053	1.0059	Sonographic
20	Predominate breathing pattern	0.0050	1.0421	Clinical
21	% change in EO thickness at ADIM manoeuvre release	0.0049	1.0721	Sonographic
22	Change in GBB trajectory position at ASLR manoeuvre release (cm)	0.0048	1.0954	Sonographic
23	% change in TrA thickness at ASLR leg hold	0.0047	1.1074	Sonographic
24	% contribution of RA to total abdominal muscle thickness	0.0043	1.2001	Sonographic

ASLR – active straight leg raise test, cm – centimetres, EO – external oblique, GBB – Global bladder base position, $J(w)$ = linear discriminant, PMCT – perimuscular connective tissue, RA – rectus abdominis, TrA – transversus abdominis.

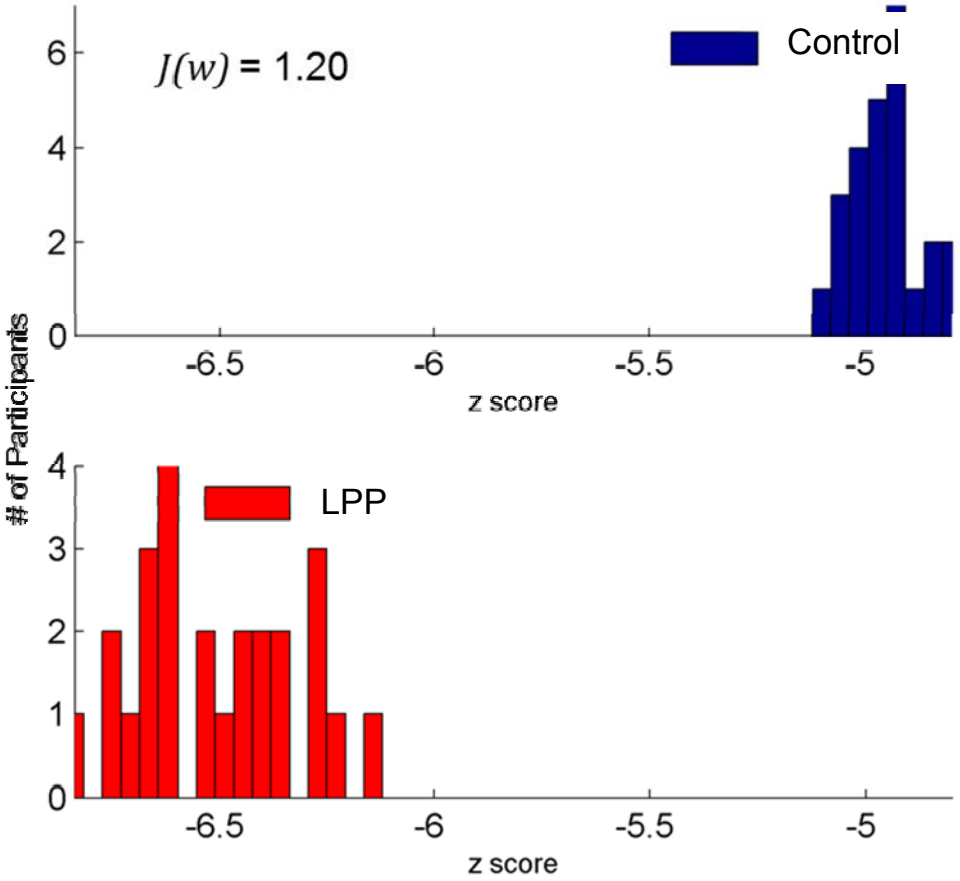


Figure 9.2: A Frequency plot of the Z-scores produced by the LDA of the 'large database' representing participants in the control (blue) and LPP (red) cohorts. Note the clear separation of the z scores (between class covariance). $J(w)$ = linear discriminant, LPP = lumbopelvic pain.

The best performance set of the parameters from the 'small database' are summarized in Table 9.2 [see Appendix 12c for the rank order and $J(w)$ values for all 38 parameters]. This sub-set consisted of 21 determinates including the same seven self-report measure scores, one participant characteristics, and two clinical observations as the sub-set from the 'large database', and 11 sonographic parameters. The discriminate power of this subset was slightly lower [$J(w)$ = 1.13] than the subset from the 'large database', however it too resulted in a clear separation of the groups with no misclassification (99.9% accurate) as can be seen with a frequency plot of the z-scores representing the participants in both cohorts (Figure 9.3). Further, all determinates from the best performance set of the 'small database', which was generated based on the findings of the observational studies presented in Chapters 7 and 8, were found in the best performance set of the 'large database'.

Table 9.2: Best Performance Set of Features from the Small Database.

Rank	Feature	$J(w)$	Cumulative $J(w)$	Feature Category
1	ASLR Compression Pattern	0.4195	0.4195	Clinical
2	Numerical Pain Rating Scale Score	0.1202	0.6299	Self-report
3	Oswestry Disability Score	0.0621	0.6433	Self-report
4	Fear Avoidance Belief Questionnaire (Physical Activity Sub-set) Score	0.0544	0.6580	Self-report
5	Nijmegen (Hypocapnia) Questionnaire Score	0.0235	0.6853	Self-report
6	Fear Avoidance Belief Questionnaire (Work Sub-set) Score	0.0212	0.7386	Self-report
7	% contribution of PMCT to abdominal wall thickness	0.0183	0.7465	Sonographic
8	% contribution of muscle to abdominal wall thickness	0.0183	0.7465	Sonographic
9	Urogenital Distress Index	0.0160	0.8955	Self-report
10	Age in years	0.0139	0.9028	Participant
11	Length of Pain in years	0.0137	0.9140	Self-report
12	% change in TrA thickness at ASLR leg lift	0.0131	0.9207	Sonographic
13	% change in TrA thickness at ASLR post manoeuvre	0.0078	0.9220	Sonographic
14	Inter-recti distance width (cm)	0.0074	0.9596	Sonographic
15	% change in TrA thickness at ASLR manoeuvre release	0.0054	0.9599	Sonographic
16	Change in GBB cranial/caudal position at ASLR manoeuvre release (cm)	0.0053	0.9612	Sonographic
17	Predominate breathing pattern	0.0050	0.9949	Clinical
18	% change in EO thickness at ADIM manoeuvre release	0.0049	1.0107	Sonographic
19	Change in GBB trajectory position at ASLR manoeuvre release (cm)	0.0048	1.0337	Sonographic
20	% change in TrA thickness at ASLR leg hold	0.0047	1.0379	Sonographic
21	% contribution of RA to total abdominal muscle thickness	0.0043	1.1279	Sonographic

ASLR – active straight leg raise test, cm – centimetres, EO – external oblique, GBB – Global bladder base position, $J(w)$ = linear discriminant, PMCT – perimuscular connective tissue, RA – rectus abdominis, TrA – transversus abdominis.

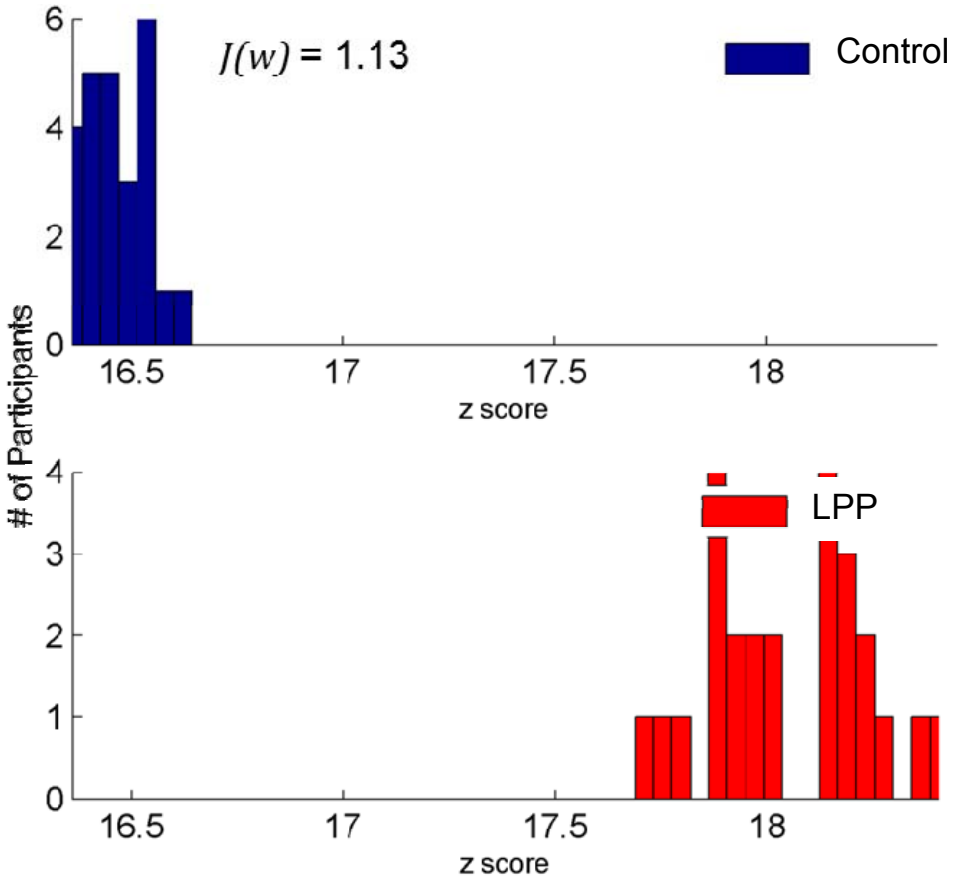


Figure 9.3: A Frequency plot of the Z-scores produced by the LDA of the 'small database' representing participants in the control (blue) and LPP (red) cohorts. Note the clear separation of the z scores (between class covariance). *J(w)* = linear discriminant, LPP = lumbopelvic pain.

The discriminatory power the non-sonographic and sonographic features from the two databases are summarized in Table 9.3 and graphically displayed in Figure 9.4. In both the 'large' and 'small databases' the coefficient of determination increased [*J(w)* going from 0.91 to 1.20, and 1.12 for the 'large' and 'small' databases respectively] when the sonographic determinates were considered in conjunction with the non-sonographic determinates, which suggests that the addition of the sonographic features improves the ability to distinguish between cohorts. Of further interest is that the 14 sonographic features from the 'large database' and the 11 sonographic features from the 'small database' successfully classify the groups 94% [*J(w)* = 0.08], and 84% [*J(w)* = 0.07] of the time respectively (see Figure 9.4).

Table 9.3: List of Sonographic and Non-Sonographic Features of the 'Large' and 'Small' Databases.

*Non-Sonographic Features $J(w)$ = 0.91		Sonographic Features (Large Database) $J(w)$ = 0.08		Sonographic Features (Small Database) $J(w)$ = 0.07	
Feature	$J(w)$	**Feature**	$J(w)$	**Feature**	$J(w)$
ASLR Compression pattern	0.420	% contribution of PMCT thickness	0.018	% contribution of PMCT thickness	0.018
NPRS	0.120	% contribution of muscle thickness	0.018	% contribution of muscle thickness	0.018
Oswestry Disability Score	0.062	% Δ in TrA thickness, ASLR leg lift	0.013	% Δ in TrA thickness, ASLR leg lift	0.013
FABQPA Score	0.054	% contribution of inferior RA PMCT thickness	0.012	% Δ in TrA thickness, ASLR post manoeuvre	0.008
Nijmegen Questionnaire Score	0.024	% contribution of TrA thickness	0.009	Inter-recti distance	0.007
FABQW Score	0.021	% Δ in TrA thickness, ASLR post manoeuvre	0.008	% Δ in TrA thickness, ASLR release	0.005
Urogenital Distress Index	0.160	Inter-recti distance	0.007	Δ GBB cranial/caudal position, ASLR release	0.005
Age in years	0.014	% contribution of superior RA PMCT thickness	0.007	% Δ in EO thickness, ADIM release	0.005
Length of Pain in years	0.014	% Δ in TrA thickness, ASLR release	0.005	Δ in GBB trajectory position, ASLR release	0.005
Predominate breathing pattern	0.005	Δ GBB cranial/caudal position, ASLR release	0.005	% Δ in TrA thickness, ASLR leg hold	0.005
		% Δ in EO thickness, ADIM release	0.005	% contribution of RA thickness	0.004
		Δ in GBB trajectory position, ASLR release	0.005		
		% Δ in TrA thickness, ASLR leg hold	0.005		
		% contribution of RA thickness	0.004		

* Included in both databases.
ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg raise test, EO = external oblique, FABQPA = Fear Avoidance Beliefs Questionnaire Physical Activity subscale, FABQW = Fear Avoidance Beliefs Questionnaire Work subscale, GBB – global bladder base position, $J(w)$ = linear discriminant, NPRS = Numerical Pain rating Score, PMCT = perimuscular connective tissue, RA = rectus abdominis, TrA = transversus abdominis, Δ = change, % = percent.

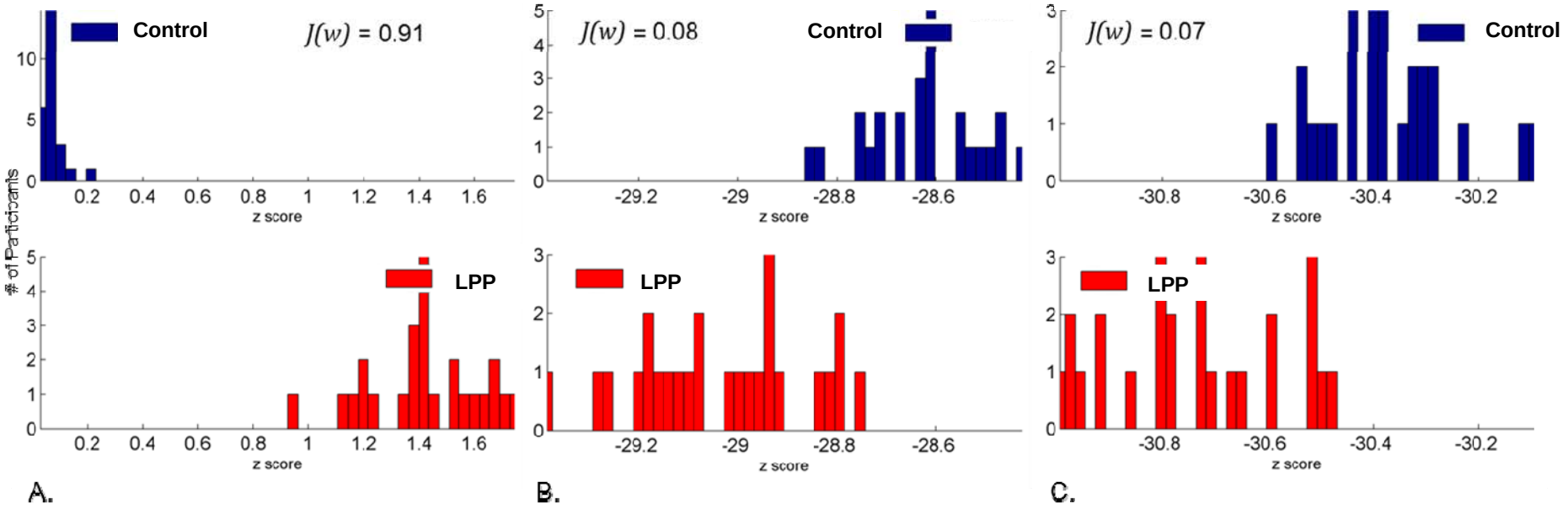


Figure 9.4: A Frequency plot of the Z-scores produced by the LDA of A. non-sonographic determinants [both databases, $J(w)$ = 0.91, 99.9 % classification], B. 'large database' sonographic determinants [$J(w)$ = 0.08, 94% classification] and, C. 'small database' sonographic determinants [$J(w)$ = 0.07, 84% classification representing participants in the control (blue) and LPP (red) cohort. Note the spread of the between and within class covariance. $J(w)$ = linear discriminant, LPP = lumbopelvic pain.

It is important to reiterate that these results represent preliminary exploratory analyses and need to be interpreted with caution. Linear discriminate analysis only performs an optimal separation of the data and further techniques are required to incorporate known errors in the variables, uncertainty in the classification process, and to test the performance (namely the accuracy, sensitivity and specificity) of the individual and best performance set features in differentiating the two cohorts.

9.5 Discussion

Although LDA has been used to investigate the discriminatory potential of sonographic features between various cohorts, this is the first investigation to use this type of analyses with the sonographic features of the lumbopelvic region in participants with LPP. While the primary aim of these secondary analyses was to determine if consideration of sonographic information is of any added value in discriminating between participants with and without LPP, LDA provided a method to identify the best individual, and best combination, of sonographic and non-sonographic features for discriminating participants with LPP. Further, these analyses provided a means by which to compare the discriminatory power of the subset of sonographic features identified in Chapters 7 and 8 to those generated by the LDA alone.

9.5.1 Discriminatory Power of Individual Parameters and Best Performance Set

The non-sonographic features that demonstrated the highest discriminatory power were the ‘pattern of compression that normalised the ASLR test’ and the scores on the NPRS, Oswestry, Fear Avoidance Beliefs Questionnaire (FABQ), and Nijmegen Questionnaires (see Table 9.1). Additional non-sonographic features that were found in the best performance set for both databases included; score on the Urogenital Distress Index (UDI), age, length of pain and ‘predominant supine breathing pattern’. It is important that of these the NPRS, Oswestry, FABQ and length of pain are considered in light of the fact that the participants in the healthy cohort all had a score of zero. Hence, it is not surprising that these features had high discriminatory power due to the low within class covariance of the healthy participants. Further, it is important to point out that as the LPP cohort was statistically older than the control cohort (see Section 7.4) it is possible that $J(w)$ value for age may be biased. However, this can only be determined by repeating this analysis with a database from two cohorts that are similar in age. Of interest is the finding that the score on the UDI, as well as two parameters related to respiration (Nijmegen questionnaire and the ‘predominant supine breathing pattern’) were included in the best performance subset. This echoes the findings of the analysis performed in Chapter 7, which found that the LPP cohort scored statistically higher on both these questionnaires. Further, it supports the literature which has found an epidemiological link between LPP and an increased

potential for developing disorders of continence and respiration (Smith et al. 2006b), especially in light of the fact that all the LPP participants were screened for respiratory conditions.

The sonographic features that demonstrated the highest discriminatory power were '% contribution of PMCT to abdominal wall thickness (defined at the total muscle + total PMCT)' and '% contribution of muscle to abdominal wall thickness'. These findings support the hypothesis (9.2.6) that sonographic features identified in previous observational studies comparing participants with and without LPP would be found to have a high discriminate power. Additional sonographic features that were found in the best performance set, that were also identified as differentiating the two cohorts in the observational studies (see Chapters 7 and 8), included; '% change in TrA thickness at all four points during the ASLR test', the '% contribution of the RA PMCT to total PMCT thickness', 'IRD', 'change in bladder base position during the ASLR test', '% contribution of the RA to total abdominal muscle thickness' and '% change in external oblique (EO) thickness at ADIM manoeuvre release'. Of further interest was the inclusion of the '% contribution of TrA thickness to total abdominal muscle thickness' in the best performance set, as it had not been identified as being statistically different in the observational studies. These findings echo the conclusions made at the end of Chapters 7 and 8 about the importance of considering the thickness of the PMCT, RA as well as IRD (which have been virtually ignored in the literature to date), in addition to the change in TrA thickness and bladder base position during the ASLR when differentiating persons with LPP. Further, the importance of considering these variables in relation to each other specifically as it applies to the % contribution of the PMCT and muscles to abdominal wall (defined at the total muscle + total PMCT) thickness (i.e. Figure 7.1).

9.5.2 Comparison of Large and Small Database Best Performance Sets

The discriminatory power of the best performance sets from both the 'large and 'small databases' were high [$J(w)$ = 1.20, and $J(w)$ = 1.13 respectively]. Further, as both produced a clear separation of the two cohorts with no misclassification (99.9% accurate), the findings support the hypothesis (9.2.8) that the best performance sets from the two databases (one based entirely on LDA alone, and the other based upon the findings of the observational studies presented in Chapters 7 and 8) would have similar discriminative power. The best performance set of features from both the 'large' and 'small databases' consisted of the same seven self-report measure scores, one participant characteristics, two clinical observations and 11 sonographic parameters. The 'large database' best performance set contained three additional sonographic parameters ('% contribution of the inferior and superior RA PMCT to total PMCT', and the '% contribution of TrA to total

abdominal muscle thickness'). The fact that all the features from the 'small database' best performance set were contained in the best performance set from the 'large database' provides additional confidence in the set of sonographic parameters identified in the two previous observational studies for differentiating persons with LPP, as well as further impetus for future investigations aimed at confirming these results and exploring the mechanisms behind them.

9.5.3 Comparison of Best Performance Sets with and without Sonographic Determinates

As stated above, the primary aim of this secondary analysis was to determine if consideration of sonographic information is of any added value in discriminating between participants with and without LPP. To achieve this, a comparison has been made between the discriminatory power of the non-sonographic determinates alone, and the non-sonographic in combination with the sonographic determinates, for the best performance sets from both databases. In both cases the discriminatory power increased when the non-sonographic and sonographic determinates were combined. Specifically, the linear discriminant value increased from $J(w)$ = 0.91 to 1.20 for the 'large database' and from $J(w)$ = 0.91 to 1.12 for the 'small database'. These findings support the proposed hypothesis (9.2.7) and suggest that consideration of sonographic information may assist in the discrimination of LPP. It is important to acknowledge that in both databases the majority of the classification was driven by the non-sonographic data. This was likely due to the sensitivity of the measures, and the type of data they produced (i.e. small within class variance). However, as several of the non-sonographic features are subjective and self-report in nature, it may be argued that the value of the sonographic features is not only in their added discriminatory power, but in the increased objectivity that they provide. Accordingly, these findings support an argument for the clinical value of USI in routine physiotherapy practice for identifying persons with LPP.

9.5.4 Implications

Keeping in mind that the results of this investigation are based upon preliminary exploratory analyses, and need to be interpreted with caution, there are some interesting themes that have arisen which are important to acknowledge. First, as indicated above, the findings are consistent with those presented in the previous two chapters in that the LDA has identified basically the same group of sonographic features that might be useful in discriminating between persons with and without LPP. Secondly, that the greatest discriminatory power comes from considering a set (as opposed to individual) of discriminants, consisting of both sonographic and non-sonographic features (i.e. participant characteristics, scores on self-report measures, outcomes of clinical tests). This is a finding that echoes the process of pattern recognition used by many clinical

experts during the clinical reasoning process (Jensen et al. 2007), and provides further rationalization for the value of considering individual findings in light of each other, as opposed to in isolation. Further, this observation promotes the value of considering sonographic features alongside non-sonographic features. Consistent with this theme is the observation that the sonographic features that exhibit the highest discriminatory power were those that consider the relative contribution of a specific parameter (i.e. % contribution of PMCT or muscle thickness) as opposed to its absolute magnitude. These themes have implications for the construct of future investigations as well as for clinical practice.

A further implication of this work is related to the identification of a best performance set of 20 sonographic parameters for discriminating participants with LPP. Although the value of this set of parameters needs to undergo further investigation, it may have implications for both clinicians and researchers. Specifically, this may allow clinicians to better manage their time by assisting them in determining which sonographic features to focus on when assessing individuals with LPP. Further, knowing which sonographic parameters best discriminate LPP will assist in future study design, specifically as it relates to determining which sonographic parameters to monitor.

9.5.5 Limitations and Areas for Future Work

As stated above, the results of this analysis need to be interpreted with caution. The present pilot study used LDA to find the variables which offer the highest discrimination between the LPP and healthy cohorts used in this research in an attempt to determine the feasibility of applying this statistical model in this population, and to inform an argument about the added value of considering sonographic features. There are several key limitations that must be acknowledged. The first is related to the relatively small number of participants, and the fact that the sample was one of convenience. A more robust classifier for discriminating LPP would emerge by using a larger random sample of participants. Further, it is important to keep in mind that the goal of LDA is to provide a measure of maximal separation in the data between the two cohorts. Additional techniques are required to incorporate known errors in the variables, uncertainty in the classification process, and to test the performance (namely the accuracy, sensitivity and specificity) of the individual, and best performance set features in differentiating the two cohorts. Finally, the results must be viewed in light of the fact that both databases consisted of parameters which represent mixed types of data. Although the differences in the data type has been offset by normalising the data to its standard deviation the results of the LDA can only be used for classification, not for regression. Further, comparing the $J(w)$ values between determinates should be viewed with some caution.

Although this analysis has its limitations it has generated useful and relevant observations suggesting that LDA may be a useful tool for building a full classifier for persons with LPP, as well as determining the added value of sonographic features. However, based upon this preliminary analysis, it would be important that any future work toward this end consider using a larger sample of randomly allocated participants, more stringent feature selection and classification evaluation.

9.6 Conclusion

9.6.1 The sonographic features identified in previous observational studies (see Chapter 7 and 8) comparing participants with and without LPP were found to have a high discriminate power for identifying participants with LPP. The top two features were; the '% contribution of PMCT to abdominal wall thickness (defined as the total muscle + total PMCT)' and '% contribution of muscle to abdominal wall thickness'.

9.6.2 The discriminatory power of the best performance sets from the two databases (one based entirely on LDA alone and the other based upon the findings of the observational studies) had similar discriminative power. This finding provides additional confidence in the set of sonographic parameters identified in two previous observational studies (see Chapters 7 and 8) for differentiating a LPP cohort.

9.6.3 There appears to be added value in considering sonographic features in combination with non-sonographic features (i.e. participant characteristics, self-report scores and outcomes of clinical tests) when discriminating between groups with and without LPP. This finding supports an argument for the clinical value of USI in routine physiotherapy practice for assessing persons with LPP.

9.6.4 Linear discriminant analysis (LDA) may be a useful tool for identifying which features best discriminate LPP, as well as determining the added value of considering sonographic features. However, future research is required.

9.7 Summary and Novelty

This chapter has presented preliminary exploratory secondary analyses of the data collected in Chapters 7 and 8 aimed at identifying the variables which offer the highest discrimination between the LPP and control cohorts in an attempt to further an argument for the added value of considering sonographic features to differentiate LPP. In doing so, it has provided a method to identify the best individual, and best combination of, sonographic and non-sonographic features for discriminating participants with LPP, as well as a means by which to compare the discriminatory power of the subset of sonographic features identified in Chapters 7 and 8 to those generated by a multivariate classification technique (LDA) alone. The results provide added confidence in the set of

sonographic parameters identified in the two previous observational studies for differentiating a LPP cohort, and support an argument for the clinical value of USI in routine physiotherapy practice for assessing LPP. The remaining chapters of this thesis will contain a general discussion of the research in this document (Chapter 10), as well as conclusions, recommendations, and a summary of the areas for future study (Chapter 11)

CHAPTER 10 - GENERAL DISCUSSION

This chapter contains a general discussion of the findings of the research presented in this thesis. In doing so, it seeks to integrate the information presented in the preceding chapters as it applies to the central aim of the research, as well as describe the contributions that have been made to the evidence base and the implications of the findings for clinical practice. Key limitations of the work will also be acknowledged. The chapter will end with a discussion of the potential applications for ultrasound imaging (USI) based on this research.

10.1 Introduction

The aim of the research contained within this thesis was to develop an argument for the clinical value of ultrasound imaging (USI) in routine physiotherapy practice as it applies to detecting altered structure and function of the abdominal muscles, and changes in bladder base position in persons with lumbopelvic pain (LPP). This chapter will start with a discussion of the findings from two investigations concerned with the validity and reliability of USI technique in a clinical setting. This will include the first published guidelines regarding transducer motion during sonographic studies of the lumbopelvic region, and novel information about the reliability of sonographic measurements of the rectus abdominis (RA), inter-recti distance (IRD), and bladder base. This will be followed by a discussion about another aspect of validity, the relationship between changes in muscle thickness (measured with USI) and muscle activity (measured with electromyography; EMG), as it applies to all four abdominal muscles during the Active Straight Leg Raise test (ASLR) and Abdominal Drawing in Manoeuvre (ADIM). The chapter will continue by examining the findings from two observational studies that compared sonographic characteristics of the abdominal wall and bladder base of participants with and without LPP, including a secondary analysis that has been piloted to investigate the added value of sonographic features in distinguishing the LPP cohort. These two observational studies are more extensive than what is found in the existing literature in that they include resting, and percent change values from various points over the course of two dynamic tasks (i.e. ASLR and ADIM), for a larger number of sonographic variables (muscle and perimuscular connective tissue; PMCT thickness, inter-recti distance; IRD, and bladder base). Accordingly, they present novel findings about several structures that have virtually gone unrecognised in the literature such as greater thickness of abdominal PMCT in the LPP cohort which may be suggestive of an abnormal loading history. The chapter will conclude with the main limitations of this research followed by a summary of the implications for clinical practice.

10.2 Ultrasound Imaging in a Clinical Setting

The clinical environment poses challenges unique to objective data collection that are more easily controlled for in a laboratory setting. This is particularly relevant with studies employing USI during dynamic manoeuvres typical of a lumbopelvic physiotherapy assessment, as transducer motion relative to the trunk may distort the ultrasound image and lead to inaccurate measurements and erroneous conclusions (Dupont et al. 2001; Reddy et al. 2001; Klimstra et al. 2007). Hence, the first step towards establishing the clinical value of USI was determining if a USI transducer could be held adequately stationary, to gather measurements free from error caused by transducer motion, during manoeuvres typical of a clinical examination of the lumbopelvic region. Further, it was necessary to see if a clinic based experimental system was capable of generating reliable sonographic measurements of the abdominal wall and bladder base.

10.2.1 Can an Ultrasound Transducer be Held Adequately Still to Gather Accurate Measurements during a Clinical Examination?

Most investigators employing USI concede that maintaining a relatively stationary transducer position during an imaging study is essential to minimize measurement error (Reddy et al. 2001; Hodges 2005; Peng et al. 2006). However, no previous investigations have proposed guidelines for acceptable (error threshold) amounts of transducer motion for parameters that are of interest in the field of rehabilitative ultrasound imaging (RUSI; i.e. abdominal muscle thickness and bladder base position). Further, no investigations have quantified the amount of transducer motion that occurs when undertaking a dynamic USI study of the abdominal wall or bladder base during manoeuvres common to a physiotherapy assessment of the lumbopelvic region. Consequently, the first experimental investigation of the thesis (Chapter 4) was undertaken with the aims of establishing guidance in regards to how much USI transducer motion is too much, and to determine if the amount of transducer motion that occurs during commonly employed clinical manoeuvres falls within these values. The findings revealed that small amounts of ultrasound transducer motion (between 5^{o} - 10^{o} of angular and 8mm on inward / outward motion) do not introduce error into measurements of transversus abdominis (TrA) thickness or bladder base position. Further, the findings demonstrated that it is possible to keep ultrasound transducer motion within the above guidelines during clinical tests commonly used in the assessment of the lumbopelvic region (ASLR and ADIM). Considered together, these findings support the argument that a USI transducer can be held adequately stationary during a clinical examination involving dynamic manoeuvres, to gather measurements of abdominal muscle thickness and bladder base position.

In addition to the primary aims of this research, several observations were made during the analyses of the data from this investigation that can be used to inform imaging technique, so as to minimize measurement error associated with transducer motion. These can be summarized as; minimizing transducer motion around multiple axes or planes, accounting for characteristic patterns of transducer motion, and making a deliberate effort to keep transducer motion within the established error thresholds.

10.2.1.i Minimizing transducer motion around multiple axes or planes

As noted in Section 4.4.1 a greater amount of bladder base measurement error occurred when the ultrasound transducer was moved around more than one axis of rotation. This observation suggests that there may be a culmination of error when transducer motion occurs about several axes. Consequently, effort should be made to minimize transducer motion around multiple axes or planes during sonographic studies.

10.2.1.ii Accounting for characteristic patterns of transducer motion

During the analysis of transducer motion during an ASLR test, ADIM and forced expiration, several observations regarding transducer motion were made (see Section 4.4.2). Firstly, the more dynamic of the manoeuvres, the ASLR test, produced the greatest amount of transducer motion. Secondly, the majority of transducer motion seen during the ASLR test occurred at the moment of leg lift. Finally, at the sagittal suprapubic imaging site, the majority of the transducer motion that occurred with the leg lift was in the form of medial or lateral tilting of the proximal end of the transducer. Consequently it may be relevant for future investigators employing USI during an ASLR test to specifically concentrate on controlling for transducer motion at the point of the leg lift, and in the case of the sagittal suprapubic imaging site, be cognizant of medial and lateral tilting of the transducer.

10.2.1.iii Observing established error threshold guidelines

Although a more complicated methodology and statistical models are required to provide definitive guidelines for directional threshold values of transducer motion, the results of this investigation suggest that transducer motion less than 10^{o} of angular and 8mm of inward / outward motion, may not distort an ultrasound image and introduce measurement error. Consequently, whenever possible, investigators and clinicians examining these parameters should attempt to keep transducer motion within these guidelines.

10.2.2 Reliability of a Clinic Based Experimental System

Having determined that a USI transducer can be held adequately stationary to gather measurements free from transducer motion error, the next step in developing an argument for the clinical value of USI was to investigate the reproducibility of sonographic

measurements of abdominal muscle thickness, IRD, and bladder base position within a clinical environment. As outlined in Chapters 2 (Sections 2.3.2 and 2.4.3) and 5 (Section 5.1), several investigators have reported on the reproducibility of USI measurements of abdominal muscle thickness (Norasteh et al. 2007; Costa et al. 2009b; Koppenhaver et al. 2009a), IRD (Liaw et al. 2006), and global bladder base (GBB) motion (O'Sullivan et al. 2002; Thompson et al. 2006a), at rest and during dynamic tasks. However, as many of these investigations have taken place in laboratory settings, and involved the use of apparatus and testing procedures that are not easy to replicate in a clinical setting, it is difficult to synthesize their findings in an attempt to inform clinical practice. Further, for several of these parameters (specifically IRD, RA and GBB) information is lacking either due to the fact that the studies were conducted on an asymptomatic cohort, considered only resting or within day estimates, did not include confidence intervals (95% CI), or did not calculate minimum detectable change (MDC), or measures of agreement such as the standard error of measurement (SEM). Accordingly, the second experimental investigation of the thesis (Chapter 5) was undertaken to evaluate the within and between day intrarater reliability of sonographic measurements of abdominal muscle thickness, IRD, as well as change in bladder (global), and bladder base position (both relative and global), at rest and during an ASLR test and ADIM. Consistent with the theme of the pending argument, this investigation was carried out on both healthy and LPP cohorts within a clinical setting. The resulting within and between day reliability estimates, for measurements of abdominal muscle thickness, IRD, and changes in GBB and relative bladder base (RBB) motion, were found to be highly reliable (Interclass correlation coefficient; ICC values ranged from 0.84 – 0.99 for within day, and 0.80 – 0.99 for between day comparisons). Additionally, the associated SEM and 95% CI were generally small. In contrast, the reliability estimates for global bladder position (GB) were poor (ICC values ranged between 0.71 – 0.99 for within day, and 0.31 – 0.82 for between day comparisons) leaving some doubt as to value of this measurement.

This investigation contributed novel information regarding the reliability of USI measurements of RA thickness and IRD by reporting within and between day, resting, contracted, and change reliability estimates (ICC), with 95% CI, SEM, MDC, as well as bias and limits of agreement (LOA) values for both LPP and healthy cohorts. Further, it was the first to provide ICC, 95% CI, SEM, MDC, and LOA values for measures of change in GB, as well as GBB and relative bladder base (RBB) position, during the ASLR and ADIM in these two cohorts. In addition to these novel findings, this investigation provided added support for the reliability of sonographic measurements of the lateral abdominal muscles (external oblique; EO, internal oblique; IO, and TrA), and GBB (during the ASLR), as the reliability estimates, SEM, and MDC values for these measurements were

consistent with previous investigations of case and control cohorts (see Table 2.1; Thompson et al. 2006a; Costa et al. 2009a; Koppenhaver et al. 2009a; Jhu et al. 2010). Finally, in regards to the context of this thesis, the findings support the argument that a clinic based experimental system is capable of generating sonographic measurements of the abdominal wall muscles, IRD, and bladder base that are adequately reliable for research and clinical use in participants with LPP

10.2.3 Confidence in a Clinic Based Experimental System

Considered together, the findings of the first two investigations support the argument that meaningful and reliable USI measurement of the abdominal muscles, IRD and bladder base, can be made in a clinical environment when employing a clinic based experimental system (participant set-up, operator, ultrasound imaging unit, clinical manoeuvres, measurement software, and rater) similar to the one investigated. Further, that this experimental system can be employed to confidently gather observations about the abdominal wall and bladder base in both healthy and LPP cohorts.

10.3 Validity: Relationship between Changes in Muscle Thickness and Electrical Activity

As USI provides a non-invasive method to quantify changes in abdominal muscle thickness (Hides et al. 2006b; Teyhen et al. 2007) there is a current trend in physiotherapy to use USI to determine the extent of abdominal muscle contraction during the assessment of persons with LPP (Gill et al. 2007; Koppenhaver et al. 2011), and as a source of real-time biofeedback about muscle function during manoeuvres commonly employed in core stability training (Henry & Teyhen 2007; Whittaker et al. 2007a; Potter et al. 2011). Some authors have even gone as far as stating that changes in muscles thickness measured with USI are indicators of muscle activity (Ferreira et al. 2004; McMeeken et al. 2004; Reeve & Dilley 2009) and activation (Raney et al. 2007; Koppenhaver et al. 2009b; Saliba et al. 2010; Rasouli et al. 2011). However, the literature investigating the relationship between changes in abdominal muscle thickness (measured with USI) and muscle activity (measured with EMG) is inconclusive (see Section 2.3.2.2). Specifically, there is a wide range of reported correlations between the two modalities (EO, r = 0.22 – 0.23; IO, r = 0.14 – 0.84; and TrA, r = 0.40 - 0.90) in the five studies that have previously investigated this relationship (Hodges et al. 2003b; McMeeken et al. 2004; John & Beith 2007a; Brown & McGill 2009; Ferreira et al. 2011). Further, no studies have investigated this relationship for the RA muscle or in persons with LPP during clinically relevant tasks. Consequently, the next step in developing an argument regarding the clinical value of USI, particularly as it applies to detecting altered structure and function of the abdominal muscles in persons with LPP, was to gain better understanding

of what a change in abdominal muscle thickness means. Accordingly, the third experimental investigation of this thesis (Chapter 6) aimed to investigate the correlation between the magnitude and pattern of EMG activity, and the thickness of the RA, EO, IO, and TrA muscles, over the course of an ADIM and ASLR test, in both healthy and LPP cohorts.

The results of this investigation suggest that changes in abdominal muscle thickness during an ASLR test or ADIM cannot be used as an indirect measure of changes in the level of muscle activity, as no clear relationship between changes in the magnitude, or timing of muscle activity and corresponding measures of muscle thickness were observed for any of the abdominal muscles during either task. Specifically, peak cross-correlation coefficients between the two signals ranged between r = 0.28 ± 0.09 to 0.13-0.56 for the ASLR and, r = 0.35 ± 0.11 to 0.15 – 0.62 for the ADIM, and the associated time lags ranged from 0.69s ± 2.56s to -3.47 – 5.82s for the ASLR and, 0.53s ± 3.75s to -5.76 – 10.58s for the ADIM. Further, the findings of this investigation revealed a great deal of variety in the relationship between changes in muscle thickness and EMG amplitude across individuals, tasks and cohorts.

This investigation contributed novel information about the relationship between EMG amplitude and muscle thickness in all four abdominal muscles (including the RA which had not been previously investigated), during two clinically relevant tasks, and in more diverse cohorts of participants, than has been previously investigated. Specifically, although two of the previous investigations had used larger sample sizes (John & Beith 2007a; Ferreira et al. 2011; n = 24, and n = 20 respectively), they consisted of predominately healthy young males (with the exception of Ferreira et al. who included 10 LBP participants, gender withheld). Consequently, it could be argued that, although the current investigation employed only 14 participants (7 healthy and 7 with LPP), the inclusion of participants with and without LPP, of both sexes, and encompassing a larger age range (22 – 50 years) than previous investigations, may provide more telling estimates of the relationship between EMG amplitude and muscle thickness changes.

The findings of this investigation point to the complexity of the relationship between changes in muscle thickness and muscle activity, and suggest that the interpretation of a change in muscle thickness observed during a sonographic study must take into consideration all factors that influence the shape of a muscle (Whittaker and Stokes, 2011). Accordingly, it is likely that the most important contribution that this investigation makes towards the goal of this thesis (and to the field of RUSI) is to highlight the need for a shift in thinking regarding the basis for using USI to assess muscle function, whether it is during the assessment of persons with LPP or when providing real-time biofeedback.

Specifically, there needs to be a shift away from thinking of USI solely as a source of information about muscle activity. Instead, it needs to be realized that changes in muscle morphology (thickness, length etc.) during a task represent the combined influence of several indicators of motor control including IAP, increased resistance to expansion by adjacent muscles (Delaney et al. 2010), contraction type, and changes in muscle electrical activity. Further, a change in muscle shape observed on USI is influenced by the resting state of the muscle, the extensibility (Ito et al. 1998) and structure (parallel versus pennate muscle fibre orientation) of a musculotendinous unit (Herbert & Gandevia 1995; Brown & McGill 2010), out-of-plane changes (Boyett et al. 1991), and imaging technique (Klimstra et al. 2007; Whittaker et al. 2009). Consequently, the role of USI in assessing altered muscle function in persons with LPP may be through its ability to provide previously unavailable information about the morphological characteristics of the abdominal muscles and their effect on other structures, such as associated connective tissue (i.e. PMCT and IRD), and position of the bladder base (which is influenced by changes in abdominal muscle activity through their effect on intra-abdominal pressure; IAP; see Section 2.1.1).

10.4 Differences in the Sonographic Characteristics of the Abdominal Wall and Bladder Base between Persons with and without Lumbopelvic Pain

Having made the shift regarding the role of USI in the assessment of muscle function, the final steps (in this thesis) for developing an argument regarding the clinical value of USI for identifying persons with LPP were taken. This involved two observational studies comparing and contrasting the sonographic characteristics of the abdominal wall and bladder base, at rest (Chapter 7) and during the ASLR test and ADIM (Chapter 8) between cohorts with and without LPP. Although other studies have investigated the sonographic characteristics of the abdominal wall and bladder base in LPP cohorts (see Section 2.3.3 and 2.4.4) there are gaps in the literature resulting from the lack of homogeneity of the case cohorts, the use of laboratory based manoeuvres (Ferreira et al. 2004; Hides et al. 2009), and a lack of consideration of the abdominal wall as a functional unit (i.e. the majority of studies have only considered the IO and TrA muscles; Critchley & Coutts 2002; Stuge et al. 2006b; Hides et al. 2009; Teyhen et al. 2009a; 2009b; Jansen et al. 2010). Further, the interaction of the abdominal wall muscles, IAP, and the pelvic floor muscles on the bladder base have received little attention.

The primary analyses of these two investigations identified a series of sonographic characteristics which differed between participants with and without LPP. Specifically, the LPP cohort was found to have less total abdominal muscle thickness ($p = 0.03$), thicker PMCT ($p = 0.007$), and a wider IRD ($p = 0.005$). Analysis of individual muscle thickness revealed no difference in EO, IO and TrA thickness but a thinner RA muscle ($p<0.001$) in

the LPP cohort. Further, there was a positive correlation between duration of pain and width of IRD (r_s = 0.51, p<0.001), which may be suggestive of an adaptive response of the linea alba. There were no significant differences found between the two cohorts during the ADIM. However, the LPP cohort demonstrated significantly smaller increases in TrA thickness (relative to rest), and greater changes in inferior bladder base position, throughout the ASLR. Of further interest, was the observation that in the LPP cohort the percent change in TrA thickness during the ASLR, was found to have a fair correlation with pain intensity (r = -0.42 - -0.44, p = 0.002 – 0.001), Oswestry disability score (r = -0.44, p = 0.001), and pain duration (r = - 0.38, p = 0.01). Specifically, participants that had more pain, poorer levels of self-reported function and had been in pain longer demonstrated smaller increases in TrA thickness during the ASLR, suggesting that this variable may be a possible marker of LPP severity.

These investigations were more extensive than what had been previously published in that they considered a larger number of sonographic parameters (i.e. RA, EO, IO TrA and PMCT thickness, IRD and relative and global bladder base position), and accordingly contributed novel information about morphological differences of the RA, EO, PMCT, IRD and changes in bladder base in a LPP cohort, while adding to the knowledge base regarding the IO, and TrA. Further, the results built upon the existing literature by considering the change in the investigated sonographic parameters at five points during the ASLR test and ADIM as opposed to just two. Accordingly, they identified fluctuations in the magnitude of abdominal muscle thickness, IRD, and bladder base position from the point of onset of the two manoeuvres until they were released (i.e. ASLR leg lift to ASLR leg release, or ADIM onset to ADIM release), suggesting that the value of these parameters is not consistent throughout the duration of these manoeuvres. This finding has implications for interpreting the literature, as well as future study design as unless the timeline for gathering measurements is standardized, comparison between investigations is impractical. Finally, these investigations are the first to identify information regarding the distribution of morphological changes in the abdominal wall associated with LPP. Specifically, it is the first to identify differences in the resting thickness of the PCMT and RA in a LPP cohort, and the first to suggest that these changes may be more evident than changes of the EO, IO and TrA muscles. Accordingly, the findings highlight the need to expand research and clinical approaches aimed at identifying the mechanisms behind, and rehabilitation of, LPP beyond the IO and TrA muscles, and to consider the abdominal wall as a functional unit.

Besides providing more comprehensive information about differences in the sonographic characteristics of the abdominal wall and bladder base position in persons with LPP, these investigations highlight the value of considering these differences in relation to each other,

as opposed to separate unrelated findings. Further, they demonstrate how a series of sonographic observations, considered simultaneously, and with the understanding that changes in these parameters (such as muscle thickness and bladder base position) during a dynamic manoeuvre reflect information about the interaction of a variety of factors, may assist in identifying altered patterns of muscle function and direct treatment. For example, when a thinner RA muscle, thicker PMCT and wider IRD, are considered in conjunction with each other, and alongside a smaller increase in TrA thickness and greater bladder descent during an ASLR test, evidence upon which to identify altered motor control in the LPP cohort emerges. Namely, a predominating pattern of muscle function that involves a smaller contribution of the RA muscle while relying on significant increases in IAP which prevents the TrA from shortening (and correspondingly thickening), displaces the bladder caudal, and imparts greater load on the PMCT, and linea alba. Understanding the intricacies of the altered pattern of muscle function provided a foundation upon which treatment can be formulated. For instance, the design of a motor control approach to treatment aimed at increasing the contribution of the RA, while decreasing the amount of IAP generated (perhaps by eliminating any breath holding), during a series of progressively challenging exercises aimed at loading the lumbopelvic region (i.e. exercises in non-weight bearing, followed by seated then standing positions, and finally during functional movements patterns).

In addition to the primary aims of this research, several important observations were made during the analyses of the data from this investigation that can be used to better interpret the existing literature base, as well as inform clinical practice and future imaging studies. These can be summarized as; differentiating between perimuscular and muscular connective tissue, the importance of considering sonographic characteristics over an entire manoeuvre, the role of the ASLR test in the assessment of persons with LPP, and the limitations of the ADIM.

10.4.1 Differentiating between Perimuscular and Muscular Tissue

The majority of sonographic investigations of the abdominal muscles have employed the convention of measuring muscle thickness from the inside edges of the muscle borders (see Figures 3.2 and 3.4), which excludes the PMCT. However, there are a few investigations in which the PMCT was included in the measurement of muscle thickness (Teyhen et al. 2005b; Springer et al. 2006; 2008), or the convention used to define the thickness of the abdominal muscles was not reported explicitly (Endleman & Critchley 2008). As the findings of the research presented in Chapter 7, as well as that by Langevin et al (2009), suggest that PMCT thickness may differ between control and case cohorts, any previous literature that either did not report the convention used to define muscle

thickness, or incorporated layers of PMCT into the measurement should be interpreted with caution. Further, it is prudent that future investigators exclude the PMCT when measuring muscle.

10.4.2 Importance of Monitoring Sonographic Parameters over an Entire Manoeuvre

The investigation presented in Chapter 8 identified fluctuations in the magnitude of abdominal muscle thickness, IRD, and bladder base position from the point of onset of the ASLR test and ADIM until they were released (see Figures 8.1 – 8.4). These findings suggest that the value of these variables is not consistent throughout the duration of these manoeuvres and have implications for interpreting the literature, as well as future study design. Specifically, the prevailing methodology for calculating a change in muscle thickness or bladder base position has been to subtract the 'resting' measurement from a measurement generated from a 'contracted' imaged (Teyhen et al. 2009a; 2009b; Pulkovski et al. 2011). As the point in the manoeuvre at which the 'contracted' image has been captured has not been standardized across investigations, it is highly likely that the 'change' value reported has been influenced by the point at which the 'contracted' image was captured by individual investigators. This observation makes comparison of existing literature impractical. Further, it provides one explanation for the disagreement found between investigators.

The identification of these fluctuations in magnitude also has implications for clinical practice and future study design. Specifically, they imply a need for standardizing the timeline for gathering measurements of muscle thickness, IRD or bladder base position such that comparisons within and between individuals can be made. In situations where clinicians or researchers have the facility to generate measurements at only two points during ASLR test the results of this investigation suggest that they do so at rest and at the point of leg lift, as this was the point at which the greatest change was found. However, bearing in mind that a USI video clip of a manoeuvre such as the ASLR test or ADIM may contain several hundred individual frames, it is critical that more sophisticated methods of measuring the pattern of architectural change of these parameters over the course of the entire manoeuvre are devised such that a true representation of the changes that occur can be discovered.

10.4.3 The Role of the Active Straight Leg Raise Test in the Assessment of Lumbopelvic Pain

The ASLR test (Mens et al. 1999) is a common clinical test (Mens et al. 2001; O'Sullivan et al. 2002; de Groot et al. 2008; Beales et al. 2009b; 2009a; 2009c; 2010) used to assess the ability of the lumbopelvic region to effectively transfer load (Mens et al. 1999;

Hungerford et al. 2004). The test has been shown to have a significant association with increased pelvic joint motion (Mens et al. 1999), demonstrates good sensitivity and specificity for detecting LPP, and good test re-test reliability (see Section 3.2.3.3; Mens et al. 2001). There is an increasing number of studies, including that presented in Chapter 8, which have identified differences in abdominal muscle thickness change (Teyhen et al. 2009b) and bladder base position (O'Sullivan et al. 2002) during the ASLR between healthy and LPP cohorts. Specifically, these studies have found smaller increases in TrA thickness, as well as greater changes in inferior bladder base position, throughout the ASLR in the LPP cohort. These investigations provide growing evidence that participants with and without LPP exhibit different patterns of abdominal muscle thickness and bladder base position change throughout the manoeuvre. Consequently, the ASLR appears to be a useful test for differentiating persons with and without LPP.

10.4.4 The Limitations of the Abdominal Drawing in Manoeuvre in the Assessment of Lumbopelvic Pain

There is a trend in physiotherapy to use the ADIM as a test of TrA muscle function. Further, based on the findings of past investigations that have shown that participants with LPP cannot draw their abdominal wall in as far as those without pain (Critchley & Coutts 2002; Kiesel et al. 2007; Teyhen et al. 2009a) it has become somewhat common clinical practice to use the ADIM as a test to differentiate between persons with and without LPP. However, as the ADIM is a voluntary motor skill its performance hinges upon a variety of factors related to how the skill is taught, the participant's ability to learn the skill, and any previous exposure, consequently it is an extremely difficult test to standardize (see Section 2.3.3 for a detailed explanation). More recent investigations, (Pulkovski et al., 2011), including that presented in Chapter 8, have attempted to more rigorously standardize the test by allowing each participant three to six repetitions of the task, with USI biofeedback, until the performance standardizes before collecting data. These investigations provide growing evidence that participant's with and without LPP exhibit similar patterns of abdominal muscle thickness, IRD and bladder base position change throughout the manoeuvre. Consequently, the ability of the ADIM to differentiate persons with and without LPP should be questioned.

10.5 Added Value of Sonographic Characteristics for Discriminating Lumbopelvic Pain

The findings of the investigations in Chapters 7 and 8 show that through its ability to provide information about the morphological characteristics of the abdominal muscles and their effect on associated connective tissue, and position of the bladder base, USI can provide a basis upon which altered patterns of muscle function can be identified in

persons with LPP. Further, these findings provide a basis for an argument supporting the clinical value of USI in routine physiotherapy practice as it applies to detecting altered structure and function of the abdominal muscles, and changes in bladder base position in persons with LPP. What remains unclear is whether or not consideration of these USI parameters, in addition to findings revealed from a patient's history, a typical clinical examination and self-report measures is of any added value. Accordingly, novel secondary analyses of the data gathered in Chapters 7 and 8 using a multivariate classification technique (linear discriminant analysis; LDA) were piloted in Chapter 9 to investigate the potentiality of sonographic features for discriminating LPP. This analysis technique not only provides a means to determine if consideration of sonographic information is of any added value in discriminating participants with LPP, it provides a possible method to identify the best individual, and best combination (best performance set) of sonographic and non-sonographic features for discriminating groups of participants with LPP. Further, LDA provides a means by which to compare the discriminatory power of the subset of sonographic features identified in the previous two observational studies to the best performance set generated by the LDA alone.

The preliminary results suggest that consideration of sonographic features alongside participant characteristics, self-report scores and outcomes of clinical tests is of added value for discriminating cohorts with LPP. Further, the findings provide added confidence in the sonographic features identified in previous observational studies (Chapters 7 and 8), and echo the importance of considering the PMCT, RA thickness, and change in TrA thickness and bladder base position during the ASLR, as these parameters were found to have a high discriminate power. It is important to re-iterate that the results represent preliminary exploratory analyses, and need to be interpreted with caution. Furthermore, the feasibility of LDA for determining which features best discriminate LPP is still undetermined. However, with that being said, the findings appear to support an argument for the clinical value of USI in routine physiotherapy practice for identifying persons with LPP.

10.6 Limitations of the Research

Although specific limitations to each investigation were discussed in the relevant experimental chapters, there are some overriding limitations to the studies contained within this thesis that need to be acknowledged.

10.6.1 Generalizability of Results

As previously stated, every experimental system is unique and has its own measurement properties (Portney & Watkins 1999). Accordingly, care must be taken when generalizing

the results of the investigations contained within this document to other sonographic parameters, participant type, testing position / manoeuvre, and examiner.

For instance, although the findings of the first investigation suggest that there is no significant error resulting from transducer motion, introduced into USI measurements of the abdominal wall or bladder base during specific manoeuvres, it is critical to acknowledge that these investigations were undertaken on healthy participants. It is well accepted that persons with pain or dysfunction in the lumbopelvic region employ motor control strategies that differ from healthy subjects (O'Sullivan et al. 2002; Beales et al. 2009b; 2009a). Specifically participants with LPP have been shown to utilize motor control strategies that involve splinting type contractions of the oblique abdominal muscles and higher levels of IAP (Beales et al. 2009a). These strategies may impart greater USI transduction motion than seen in normal subjects during dynamic manoeuvres. Although an attempt was made to mimic the greater amount of abdominal wall muscle contraction and IAP seen with LPP by including a forced expiration in the respiratory trials (see Section 4.5.3) it would be prudent to repeat these investigations within a LPP cohort as opposed to generalize the findings.

It is also important to consider that the examiner who undertook the investigations aimed at establishing the validity and reliability of USI measurements in a clinical setting was an experienced physiotherapist (qualified 16 years) that had 10 years of USI experience. Accordingly, the findings may not be representative of novice physiotherapists, or new USI operators. Hence it would be sensible to compare the amounts of transducer motion that occur during imaging studies of these dynamic manoeuvres between novice and experienced operators.

One final example of care that must be taken when generalizing the results pertains to the characteristics of the participants in the reliability investigation presented in Chapter 5, and the observational studies presented in Chapters 7 and 8, as a large proportion of the participants were female. As such, the generalizability of the findings to a male cohort may be questioned. With that being said, the values in these studies are consistent with those of previous investigations in which male participants were included (Costa et al. 2009a; Koppenhaver et al. 2009a; Teyhen et al. 2009a; Teyhen et al. 2009b; Jhu et al. 2010).

10.6.2 Size and Homogeneity of Control and LPP Cohorts

The sample size (n = 50; 25 healthy, 25 LPP) of the two observational studies presented in Chapters 7 and 8 were larger than in previous studies (O'Sullivan et al. 2002; Teyhen et al. 2009a; 2009b; n = 30 [15 control, 15 LPP], and n = 26 [13 control, 13 LPP] respectively). However, the sample size used in the reliability study (n = 18; 9 healthy, 9

LPP) presented in Chapter 5 was smaller than some of the more recent literature (Costa et al. 2009a; Koppenhaver et al. 2009a; Jhu et al. 2010; n = 24 [12 control, 12 LPP], n = 30 LBP, n = 18 control respectively). Although limited in numbers, it could be argued that the inclusion of participants with and without LPP, of both sexes, and encompassing an older age range (31 – 59 years) may provide more telling estimates of reliability due to the fact that older symptomatic populations may be harder to measure due to associated changes in muscle composition (Andary et al. 1998; Elliott et al. 2006).

It is also important to re-iterate that the LPP cohort in the observational studies presented in Chapters 7 and 8 was older than the control cohort. Although abdominal muscle thickness has been shown to be independent of age or gender (Rankin et al. 2006), and none of the sonographic parameters measured were shown to correlate with age, the impact of aging on PMCT thickness is unknown. Accordingly, the results of these investigations must be considered with this limitation in mind. Further, future investigations, with larger and better matched cohorts, are needed to confirm the findings.

10.6.3 Collection of Sonographic Data

In developing the protocol for data collection a decision to collect measurements of abdominal wall muscle and PMCT thickness from only one side of the abdominal wall and at only 5 points during the ASLR and ADIM manoeuvres was made. This decision was based on the findings of several investigations in which the thickness of the abdominal muscles was found to be independent of hand dominance (Rankin et al. 2006), side measured, or side of symptoms (Springer et al. 2006) unless the cohort had occupational, recreational or biomechanical propensities to asymmetrical loading such as elite cricketers (Hides et al. 2008) or unilateral lower limb amputees (Springer & Gill 2007). Further, the decision to collect unilateral data and data at only five points during the two manoeuvres was made to ensure that the amount of data to be analysed was manageable. Specifically, the research contained within this thesis represents thousands of individual USI measurements. Although increasing the amount of data by considering bilateral values, or a greater number of measures during the ASLR and ADIM would have likely provided additional information, the added time required for analysis would have been impractical.

10.6.4 The Value of Sonographic Features in Discriminating Individuals with Lumbopelvic Pain

As stated in Section 9.5.5, the results of secondary analyses piloted in Chapter 9 need to be interpreted with caution. Specifically, it must be pointed out that the goals of those analyses were to find the variables which offer the highest discrimination between the LPP

and healthy cohorts used in this research as a means to determine the feasibility of applying this statistical model in this type of population, and to inform an argument about the added value of considering sonographic features. The results by no means provide a basis upon which a definitive argument regarding the discriminatory power of the identified sonographic features for identifying individuals with LPP. For this to be achieved, a more robust classifier would need to be developed using a larger sample of randomly allocated participants, more stringent feature selection and classification evaluation, and the use of additional techniques to test the performance (namely the accuracy, sensitivity and specificity) of the individual, and best performance set features in differentiating the two cohorts.

10.7 Implications for the Clinical Management of Lumbopelvic Pain

The inspiration for this work came directly from reflections made during clinical practice. Namely, from the observation that the author's ability to manage patients with LPP seemingly improved by incorporating USI into the assessment process. Specifically, it appeared that the information provided by sonographic studies of the abdominal muscles and bladder base assisted in defining a patient's impairment more precisely, which resulted in more effective and efficient physiotherapy interventions, and greater appropriateness of referral for additional imaging or medical management. It was speculated that USI was providing information about the structure and function of the abdominal wall and bladder base, that had not been previously available, and that this information was being incorporated into and improving, the clinical reasoning process. Two specific examples (in the form of case histories) of how sonographic information can guide the management of patients with LPP can be found in Appendix 13. The first is a 32 year old young mother with a 16 month history of right low back, buttock and lateral hip pain that began with an increase in physical activity after the birth of her second child. The second is a 22 year old male complaining of pain and tightness in the right lower back, buttock and tailbone that he attributed to a fall he had experienced snowboarding three months previous. Both case demonstrates how USI provides critical information about the abdominal muscles, linea alba and bladder base that direct physiotherapy treatment and in the first case, surgical referral.

Before considering the added value of USI to the clinical reasoning process, or case management, it was crucial to determine what sonographic parameters were the most important to pay attention to when assessing this population of individuals. Consequently, the need to identify the most useful sonographic parameters for assessing individuals with LPP became the primary impetus for this work, specifically as it relates to a physiotherapist interacting with a patient in a clinical environment. However, prior to being

able to explore this question it was crucial to determine if meaningful and reliable USI measurements could be generated in a clinical environment, as well as to gain a better understanding of the relationship between changes in muscle thickness and electrical muscle activity. The investigations presented in this research were undertaken with these clinical needs in mind and accordingly, the findings have direct implications for clinical practice. Further they address issues regarding the utility and evaluative value of USI in clinical environments raised by three clinical commentaries published after the 1st international symposium on RUSI held in 2006 (Teyhen et al. 2007; Whittaker et al. 2007a; 2007b), and provide a basis upon which further clinical protocols and clinical research, using USI can be undertaken (see Section 10.8).

10.7.1 Implications for Imaging Technique in a Clinical Setting

The results of the investigations in Chapters 4, 5 and 7 have several direct clinical implications regarding imaging technique. Firstly, they imply that clinicians using USI to measure abdominal muscle thickness or bladder base position, can generate more accurate measurements by attempting to keep transducer motion to less than 10^{o} of angular and 8mm of inward / outward motion, as well as minimising transducer motion around multiple axes or planes. Likewise, they highlight the need to pay specific attention to controlling for transducer motion at the point of the leg lift during an ASLR test, and to exclude PMCT from measures of muscle thickness. Finally, the findings presented in Chapter 5, imply that if clinicians employ a similar methodology they can generate meaningful and reliable USI measurements of the abdominal muscles, IRD and bladder base in a clinical environment.

10.7.2 Implications for Interpreting Changes in Muscle Thickness during Dynamic Sonographic Studies

The findings of the investigation presented in Chapter 6 have implications regarding the interpretation of sonographic studies of the abdominal wall muscles during dynamic events such as the ASLR test and ADIM. Specifically, they imply that clinicians employing USI to study muscle function during a dynamic event need to shift their thinking away from seeing USI as solely a source of information about muscle activity, and instead realizing that changes in muscle morphology seen during dynamic sonographic studies represent the combined influence of several indicators of motor control (see Section 10.3). Consequently, interpretation of a change in muscle size must take into consideration the impact of all these factors (see example in Section 10.7.3 below), suggesting that USI is not a standalone assessment tool, rather a source of valuable and previously unavailable information about the impact of movement strategies on muscle, and its associated structures, that can be incorporated into the clinical reasoning process.

10.7.3 Implications for the Assessment of Individuals with Lumbopelvic Pain

The findings from the investigations presented in Chapters 7 and 8 imply that clinicians using USI to assess the function of the abdominal muscles in persons with LPP need to expand their attention beyond the IO and TrA muscles, and consider the thickness of all four abdominal muscles (specifically the RA), and how they contribute to the architectural makeup of the abdominal wall. Further, that the thickness and contribution of the PMCT to the abdominal wall, magnitude of the IRD, as well as the pattern of architectural change of TrA thickness and change in position of the bladder base throughout the ASLR test also need to be considered. Finally, the findings provide an example of how a more comprehensive and accurate interpretation of the motor control strategy being utilised by a patient can be obtained by considering these parameters in relation to each other, as opposed to separate unrelated findings. For example, taken as separate observations, it would be easy to jump to the conclusion that a small increase in TrA thickness and a large descent of the bladder base seen during an ASLR test was due to inactivity of the TrA and pelvic floor muscles. However, when the smaller increase in TrA thickness is considered in conjunction with the greater descent of the bladder base, another plausible explanation emerges; namely that the individual is employing an altered motor control strategy that produced an increase in IAP which prevented the TrA from shortening (and correspondingly thickening), and displaced the bladder caudal. Although not yet supported by evidence, it could be hypothesized that by taking this more encompassing approach to interpreting the results of a sonographic study a therapist may be able to more precisely defined a patient's impairment and accordingly, be more efficient in developing an effective and tailored treatment plan.

10.7.4 Implications for the use of Ultrasound Imaging for Biofeedback

Although the aims of the thesis were not directly related to the use of USI as a source of biofeedback during the restoration of motor control (Henry & Teyhen 2007), the findings of the investigation presented in Chapter 6 have implications for this application of USI. Specifically, therapists using USI to provide biofeedback to a patient during either an ASLR test or ADIM need to consider that any changes in abdominal muscle thickness observed may not be solely due to a change in muscle activity, as changes in muscle thickness can be influenced by a variety of factors, including changes in IAP and the activity of adjacent muscle layers in addition to changes in muscle activity (see Section 10.3). Accordingly, if the goal of providing the biofeedback is to provide the patient with an indicator of muscle activity, abdominal muscle thickness may not be the best parameter to monitor. With that being said, it is possible that parameters of abdominal muscle morphology, not monitored during this study, which are more commonly used to provide biofeedback such as the lateral slide of the anterior musculotendinous junction of the TrA

(Hides et al. 2010; Jhu et al. 2010) during the ADIM, may have greater utility. Further, it is possible that these other parameters may be shown to have a better relationship with muscle activity than muscle thickness. However, further research would be needed to determine this.

10.8 Potential Applications of Ultrasound Imaging of the Abdominal Wall and Bladder Base

There are three main potential applications of the research contained within this thesis. They are related to: identifying individuals at risk of developing LPP; enhancing clinical practice through increasing the effectiveness of physiotherapy case management of LPP; and improving the homogeneity of LPP cohorts during research design.

10.8.1 Identifying Individuals at Risk of Developing Lumbopelvic Pain

Ultrasound imaging has a potential role to play in identifying at risk populations through its ability to identify differences in the resting characteristics of the abdominal wall (i.e. muscle and PMCT thickness, IRD) and changes in these and the position of the bladder base during common physiotherapy tests (ADIM and ASLR). Specifically, it is possible that a series of sonographic features that differ between a sub-group of an at risk population that go on to develop LPP, and those that do not, may be predictive of the development of LPP. By identifying these features, and then using them as a screening mechanism to identify these individuals, it is possible that implementation of a tailored intervention will pre-empt future disability and circumvent associated costs. Examples of populations in which the results of this research would have an obvious application are post-partum women (Coldron et al. 2008) and sporting groups (Hides et al. 2010; Jansen et al. 2010) as changes in abdominal function have been identified in both. However, further research is required to provide evidence of these potential applications (see Section 11.4.3 and 11.4.5).

10.8.2 Enhancing Clinical Practice

Through its ability to provide novel and previously unavailable information about the loading history and function of the abdominal wall and balder base USI has a potential to augment the clinical reasoning process. In doing so it would serve to streamline case management and enhance clinical practice as it relates to LPP and associated disorders. Specifically, as suggested in Section 10.7, and as illustrated in the two case examples in Appendix 13, information provided by sonographic studies of the abdominal muscles and bladder base can assist in defining a patient's impairment more precisely. This would result in more effective and efficient physiotherapy interventions, and greater

appropriateness of referral for additional imaging or medical management. This enhancement of clinical practice would not only have a direct impact on the patient's quality of life but also the efficacy of the therapist and the growing trend of economic impact associated with the management of these disorders (Maniadakis & Gray 2000; Deyo et al. 2009). For this potential to be realized it is critical that it be tested in large clinical trials (see Section 11.4.5). For example, a trial could be conducted in which LPP patients are randomly allocated into one of two physiotherapy treatment arms. In one arm (control) decisions about individual tailored treatment and onward referral would be made using a clinical decision making model based on current best practice, while in the other treatment arm (intervention), a similar model would be used with the addition of information gained from sonographic studies. Primary outcomes would be measures of functional status, length of intervention (from intake to discharge) and economic impact. Once research has provided the evidence that USI can improve the effectiveness (patient outcome, time and cost) of treatment this will justify spending resources on purchasing USI equipment and training therapists which would enable routine practice to change.

Although the research presented in this thesis provides a basic underpinning for such trials, several intervening steps are needed before it can be undertaken. Specifically, clinical training and mentoring programmes aimed at equipping clinicians with the skills for carrying out and accurately interpreting sonographic studies, as well as incorporating their findings into the clinical reasoning process to design individualized treatment plans, need to be designed, and then tested in a quality improvement study.

10.8.3 Research Design

In addition to the two clinical applications described above, it is likely that USI has a role to play in the research arena as a tool by which the homogeneity of cohorts can be improved. Specifically, implementation of a series of sonographic criteria for inclusion within, or exclusion from, a specific cohort is a likely mechanism to ensure the uniformity of participants and improve the strength of any findings. However, the identification of the specific sonographic criteria that were important to define a particular cohort would require pilot work (see Section 11.4.3.ii).

10.9 Summary

After laying a foundation of relevant literature, the series of investigations contained within this document have investigated: the validity and reliability of USI technique in a clinical setting as it applies to sonographic measurements of the abdominal wall and bladder base during the assessment of persons with LPP; the relationship between changes in muscle thickness and electrical activity during manoeuvres commonly used by physiotherapists to

assess the lumbopelvic region; and compared the sonographic characteristics of the abdominal wall and bladder base between persons with and without LPP. They have provided recommendations about imaging protocols in terms of transducer motion and optimal points at which images can be taken during clinical manoeuvres. They have also provided evidence; that meaningful and reliable measurements of the abdominal wall and bladder base position can be made at rest and during dynamic tasks in persons with and without LPP in a clinical setting; that the relationship between changes in muscle thickness and electrical activity during an ASLR and ADIM is complex and interpretation of a change in muscle thickness must take into consideration all factors that influence the shape of a muscle; that persons with LPP may have less total abdominal muscle thickness (specifically due to a thinner RA), thicker PMCT, wider IRD and demonstrate significantly smaller increases in TrA thickness, and greater changes in inferior bladder base position throughout an ASLR. Further, they have provided preliminary evidence that consideration of sonographic features are useful and provide added value when discriminating persons with LPP. Taken together, the findings of this research suggest that USI can contribute useful information about the structure and function of the abdominal wall and changes in position of the bladder base to a typical physiotherapy assessment of the lumbopelvic region. Accordingly, an argument that USI has a clinical role to play in the assessment of LPP can be made.

This chapter has presented a general discussion of the findings of the research presented in this thesis, with the aim of integrating the information presented in the preceding chapters as it applies to the central aim of the research, and in a way that highlights how these findings contribute to the evidence base (specifically the field of RUSI), and impact clinical practice. Key limitations have also been acknowledged. The final chapter presents the main conclusions and recommendations of this research, and a summary of the main priorities for future work.

CHAPTER 11 – CONCLUSIONS, RECOMMENDATIONS AND FUTURE STUDIES

11.1 Introduction

The aim of this research was to develop an argument for the clinical value of ultrasound imaging (USI) in routine physiotherapy practice, as it applies to detecting altered function of the abdominal muscles and changes in position of the bladder base in persons with lumbopelvic pain (LPP). After careful consideration of the literature and the potential barriers that may be encountered along the way, five investigations have been conducted. These studies have investigated the validity and reliability of USI technique in a clinical setting, the relationship between changes in muscle thickness and electrical activity, and differences in the sonographic characteristics of the abdominal wall and bladder base between healthy persons and those with LPP. The main conclusions and recommendations of the work, as well as key areas for future study in this field are presented below.

11.2 Conclusions

This research has demonstrated that conventional grey-scale USI can contribute useful and novel information to a typical physiotherapy assessment of LPP, hence an argument can be made that USI has a clinical role to play in the assessment of LPP.

11.2.1 Ultrasound Imaging in a Clinical Setting: Validity (Chapter 4) and Reliability (Chapter 5)

11.2.1.i Small amounts of ultrasound transducer motion (between 5^{o} - 10^{o} of angular and 8mm on inward / outward motion) do not introduce error into measurements of transversus abdominis (TrA) muscle thickness or bladder base position. Further, it is possible to keep ultrasound transducer motion within the above guidelines during commonly used clinical tests, such as the Active Straight Leg Raise test (ASLR) and Abdominal Drawing in Manoeuvre (ADIM). Hence, an ultrasound imaging transducer can be held relatively stationary in a clinical setting for the manoeuvres tested.

11.2.1.ii Within and between day, resting and contracted, USI measurements of abdominal muscle thickness, inter-recti distance (IRD), and changes in global and relative bladder base motion (GBB and RBB respectively), during an ASLR test and ADIM, in healthy and LPP cohorts, within a clinical setting are highly reliable, while reliability estimates for global bladder (GB) position are poor. Hence, meaningful

measurements of these USI parameters (excluding GB position) can be attained in a clinical setting, during these manoeuvres, in both healthy and LPP cohorts.

11.2.2 The Relationship between Changes in Muscle Thickness and Electrical Muscle Activity (Chapter 6)

11.2.2.i Changes in sonographic measurements of abdominal muscle thickness cannot be used as an indirect measure of changes in the level of muscle activity during an ASLR test, or ADIM. Further, there is a great deal of variety in the relationship between changes in muscle thickness and electromyography (EMG) amplitude across individuals, tasks and cohorts.

11.2.2.ii The relationship between changes in muscle thickness and electrical activity is complex. Accordingly, the interpretation of a change in muscle thickness observed during a sonographic study must take into consideration all factors that influence the shape of the muscle including; changes in muscle activity, initial muscle length, initial state of contraction, the extensibility and structure of a musculotendinous unit, contraction type, the presence of external forces that an expanding muscle must compete against, out-of-plane changes, and imaging technique.

11.2.2.iii These findings indicate that a shift is needed regarding the basis for using USI to assess muscle function from thinking of it solely as a source of information about muscle activity, and realizing that measurements of muscle morphology reflect valuable and novel information about a variety of additional factors (see 11.2.2.2) and how they interact. Consequently, the role of USI for assessing muscle function, whether it is during the assessment of persons with LPP, or when providing real-time biofeedback, may be through its ability to provide previously unavailable information about the morphological characteristics of the abdominal muscles and their effect on other structures, such as associated connective tissue (i.e. perimuscular connective tissue; PMCT and inter-recti distance; IRD), and position of the bladder base.

11.2.3 Differences in the Sonographic Features of the Abdominal Wall and Bladder Base between Individuals with and without Lumbopelvic Pain (Chapters 7 and 8)

11.2.3.i The LPP cohort studied in this research had significantly thicker PMCT, thinner rectus abdominis (RA) muscles, and wider IRD than the healthy controls. These findings are novel in that to date these three structures have virtually gone unrecognised in the literature. Further, they suggest that changes in these structures may be more evident than changes of the external oblique (EO), internal oblique (IO) and TrA muscles in persons with LPP, and highlight the need to consider the

contribution of all four abdominal muscles and PMCT to the abdominal wall when investigating LPP.

11.2.3.ii Physiotherapists and research teams need to expand their focus beyond the TrA and IO muscles, to consider the abdominal wall as a functional unit. Specifically, consider the status and contribution of the RA muscle, and the mechanisms that can lead to thickening of the PMCT.

11.2.3.iii Abdominal muscle thickness, IRD, and bladder base position are not consistent during the effort phase of the ASLR and ADIM (i.e. ASLR leg lift to ASLR leg release, or ADIM onset to ADIM release). This implies a need for standardizing the timeline for gathering these measurements during these clinical tests such that comparisons within and between individuals can be made.

11.2.3.iv There was little difference between cohorts in the pattern of abdominal muscle thickness, IRD and bladder base position during the ADIM. These findings question the value of the ADIM for differentiating persons with LPP.

11.2.3.v The LPP cohort demonstrated smaller increases in TrA thickness (relative to rest) throughout the ASLR, as well as a greater change in inferior bladder base position at leg lift, and with the return of the leg to the plinth. These findings suggest that the ASLR may have value in differentiating persons with LPP.

11.2.3.vi Ultrasound imaging can provide a series of independent observations about the abdominal wall and bladder base, that when considered together, can provide insight into the type of motor control strategy that an individual with LPP is employing.

11.2.4 The Role of Sonographic Features in Discriminating Persons with Lumbopelvic Pain (Chapter 9)

11.2.4.i Linear discriminant analysis (LDA) has shown that a set of 11 sonographic features have a high cumulative discriminate power for identifying participants with LPP. In rank order these included; ‘% contribution of PMCT to abdominal wall thickness (defined as total muscle + total PMCT)’ ‘% contribution of muscle to abdominal wall thickness’. ‘% change in TrA thickness at all four points during the ASLR test’, IRD, ‘change in bladder base position during the ASLR test’, and ‘% change in EO thickness at ADIM manoeuvre release’ and ‘% contribution of the RA to total abdominal muscle thickness’

11.2.4.ii There appears to be added value in considering sonographic features alongside participant characteristics, self-report scores and clinical test outcomes when

discriminating between groups with and without LPP. This finding supports an argument for the clinical value of USI in routine physiotherapy practice for assessing persons with LPP.

11.2.4.iii Linear discriminant analysis may be a useful tool for identifying which features best discriminate individuals with LPP, as well as determining the added value of considering sonographic features. However, future research is required.

11.3 Recommendations

This section summarises the main recommendations resulting for the findings of the studies presented throughout the thesis.

11.3.1 Ultrasound Imaging in the Lumbopelvic Region: Imaging Technique

11.3.1.i In an attempt to minimise measurement error, future researchers and clinicians undertaking sonographic studies to measure the abdominal muscles, or bladder base, should attempt to keep transducer motion to less than 10^{o} of angular and 8mm of inward / outward motion, as well as minimize transducer motion around multiple axes or planes. Further, if the ASLR test is employed, specific attention needs to be paid to controlling for transducer motion at the point of the leg lift, and in the case of the sagittal suprapubic imaging site, medial and lateral tilting of the transducer.

11.3.2 Ultrasound Imaging in the Lumbopelvic Region: Study Design and Clinical Practice

11.3.2.i To ensure accurate interpretation of muscle size PMCT planes should not be included in measures of muscle morphology (thickness, width, cross-sectional area etc.).

11.3.2.ii To facilitate synthesis of the evidence base, future investigators need to consider that there are fluctuations in the magnitude of abdominal muscle thickness, IRD, and bladder base position from the point of onset of the ASLR and ADIM until they are released (i.e. ASLR leg lift to ASLR leg release, or ADIM onset to ADIM release). Consequently the timeline for gathering measurements during these tasks must be standardized and reported. Further, in situations where the facility to only generate sonographic measurements at two points during ASLR test exist, it would be prudent to do so at rest, and at the point of leg lift, as this was the point at which the greatest change was found.

11.3.2.iii The ASLR test may be better at discriminating between individuals with LPP than the ADIM.

11.3.3 Interpreting a Change in Muscle Thickness during a Dynamic Sonographic Study

11.3.3.i Future researchers and clinicians employing USI to study muscle function need to shift their thinking away from seeing USI as solely a source of information about muscle activity, and instead realizing that changes in muscle morphology (thickness, length etc.) represent the combined influence of several indicators of motor control including; intra-abdominal pressure (IAP), increased resistance to expansion by adjacent muscles, contraction type, and changes in electrical muscle activity. Further, the changes in muscle shape observed on USI are influenced by the resting state of a muscle, the extensibility and structure (parallel versus pennate muscle fibre orientation) of a musculotendinous unit, out-of-plane changes, and the imaging technique used.

11.3.3.ii Physiotherapists using USI to provide patient's with real-time biofeedback about the performance of their abdominal muscles, should consider using a parameter other than muscle thickness (i.e. lateral slide of the anterior musculotendinous junction of TrA) if the goal of providing the feedback is to give the patient an indicator of muscle activity.

11.3.4 Sonographic Assessment of Individuals with Lumbopelvic Pain

11.3.4.i Future researchers and clinicians using USI to assess the function of the abdominal muscles in persons with LPP need to expand their attention beyond the IO and TrA muscles, and consider the thickness of all four abdominal muscles (specifically the RA), and how they contribute to the architectural makeup of the abdominal wall. Additionally, the thickness and contribution of the PMCT to the abdominal wall, magnitude of the IRD, as well as the pattern of architectural change of TrA thickness and change in position of the bladder base throughout the ASLR test also need to be considered. Further, any differences found, need to be considered in relation to each other, as opposed to separate unrelated findings.

11.3.4.ii Future researchers and clinicians should consider sonographic information about the lumbopelvic region alongside findings from participant characteristics, self-report scores and clinical test outcomes when discriminating between groups with and without LPP.

11.4 Summary of the Main Areas for Future Investigation

This section highlights the main priorities for further work in this area of research.

11.4.1 Ultrasound Imaging in a Clinical Setting: Validity and Reliability

11.4.1.i More definitive guidelines for directional threshold values of transducer motion (i.e. the amount of transducer motion that can occur before measurement error is introduced), including inward transducer pressure, for different muscles and structures are needed.

11.4.1.ii The amount of ultrasound imaging transducer motion that occurs during commonly utilized physiotherapy tests for assessing the lumbopelvic region (i.e. ADIM and ASLR test) needs to be investigated in a LPP cohort. Further, the importance of sonographic training for developing imaging technique needs to be explored by comparing transducer motion between novice and experienced operators.

11.4.1.iii The within and between day reproducibility of USI measurements of RA muscle thickness, IRD, and bladder base position, at rest and during manoeuvres typical of a physiotherapy assessment of the lumbopelvic region (i.e. ADIM and ASLR), in healthy and LPP male cohorts need to be better established.

11.4.2 Understanding what a Change in Abdominal Muscle Shape Represents during a Dynamic Sonographic Study

11.4.2.i The correlation between the magnitude and timeline of EMG amplitude, and parameters of abdominal muscle morphology other than thickness (i.e. lateral motion of the anterior musculotendinous junction of the TrA, or change in RA width), during a dynamic sonographic study, need to be investigated in healthy and LPP cohorts to aid in understanding how a change in muscle activity relates to changes in morphology.

11.4.2.ii The correlation between the change in magnitude of IAP and parameters of abdominal muscle morphology (thickness, length or width), during a dynamic sonographic study, need to be investigated in healthy and LPP cohorts to aid in understanding the influence of changes in IAP on abdominal muscle morphology.

11.4.3 Ultrasound Imaging to Identify Dysfunction of the Lumbopelvic Region

11.4.3.i More sophisticated technical methods of measuring the pattern of architectural change of the sonographic parameters of the lumbopelvic region over the course of an entire clinical test (i.e. ASLR and ADIM) need to be developed so that a true representation of the changes that occur can be discovered.

11.4.3.ii Exploration and comparison of the sonographic characteristics of the lumbopelvic region in other cohorts, both healthy (i.e. sporting and non-sporting,

nulliparous and parous), and clinical cases (i.e. subgroups of non-specific low back pain, lumbar stenosis, post-partum pelvic pain, lower extremity dysfunctions, respiratory disorders and incontinence related dysfunction etc.) are needed.

11.4.3.iii The feasibility of using linear discriminate analysis, or other classification methods, for identifying the value of various sonographic (and non-sonographic) features in discriminating LPP or other disorders of the lumbopelvic region (i.e. post-partum pelvic pain and incontinence related disorders) needs to be investigated.

11.4.3.iv The value of sonographic characteristics, other than those considered in this thesis (i.e. cross sectional area of the multifidus, position of the urethrovesical junction), for discriminating disorders in the lumbopelvic region needs to be investigated.

11.4.4 Understanding the Mechanisms and Implications of Altered Movement Control in a LPP population

11.4.4.i Research aimed at better understanding the role of the RA muscle, PMCT, and IRD in postural and dynamic control of the spine is needed to better understand the role these structures may play in the development and persistence of LPP. Further, this research is needed so that the functional implications of any changes identified in these structures in a LPP cohort can be better understood.

11.4.5 The Impact of using USI to Enhance Clinical Practice

11.4.5.i The impact of athletic training, rehabilitation, specific injuries (i.e. groin strain), and disease processes (i.e. lumbar stenosis, hip osteoarthritis) on the sonographic characteristics of the lumbopelvic region, and how these relate to injury prevention as well as clinical outcomes need to be studied.

11.4.5.ii The value of sonographic characteristics of the lumbopelvic region for directing rehabilitation aimed at restoring motor control in a LPP population, and the impact that this has on clinical outcomes such as number of treatments to discharge and re-occurrence, need to be investigated to aid in determining the economic benefit of employing USI in the management of persons with LPP.

11.4.5.iii The ability of lumbopelvic sonographic characteristics to discriminate individuals at risk of injury (i.e. pre-season screening for risk low back strain or groin pull), or lumbopelvic dysfunction (i.e. identifying women post-partum at risk of developing pelvic pain or incontinence) is needed to aid in determining the role that USI may play in screening at risk populations.

APPENDICIES

Appendices are bound here. They are also found in electronic form in which the size of the font can be manipulated on the attached CD.

APPENDIX 1a: Ethics Approval for Study 1 (Chapter 4)

29 August 2007

Jackie Whittaker
School of Health Professions and Rehabilitation Sciences
University of Southampton

Dear Jackie

Submission No: PO7/08-01

Title: Sonographic characteristics of the abdominal and pelvic floor muscles

I am pleased to confirm **full approval** for your study has now been given. The approval has been granted by the School of Health Professions and Rehabilitation Sciences Ethics Committee.

Before you proceed with this study, please ensure that you amend the several spelling mistakes in the Information Sheet. Do not distribute any recruitment materials (i.e. e-mails, posters) until you have received written permission from the people you have approached for their permission to do so.

You are required to complete a University Research Governance Form (enclosed) in order to receive insurance clearance before you begin data collection. You need to submit the following documentation in a plastic wallet to Dr Martina Dorward in the Research Support Office (RSO, University of Southampton, Highfield Campus, Bldg. 37, Southampton SO17 1BJ):

- Completed Research Governance form (**signed by both student and supervisor**)
- Copy of your research protocol (final and approved version)
- Copy of participant information sheet
- Copy of SoHPRS Risk Assessment form (**signed by yourself and supervisor)**
- Copy of your information sheet and consent form
- Copy of this SoHPRS Ethical approval letter

Your project will be registered at the RSO, and then automatically transferred to the Finance Department for insurance cover. **You can not commence data collection until you have received a letter stating that you have received insurance clearance.**

Please note that you have ethics approval only for the project described in your submission. If you want to change any aspect of your project (e.g., recruitment or data collection) you must discuss this with your supervisor and you may need to request permission from the Ethics Committee.

Yours sincerely

Dr Emma Stack
Chair, SHPRS Ethics Committee
Enc.

APPENDIX 1b: Ethics Approval for Studies 2, 4 and 5 (Chapters 5, 7 and 8)

Jackie Whittaker
School of Health Professions and Rehabilitation Sciences

19 May 2008

Dear Jackie

Ethics Submission No: SHPRS-ETHICS 08-015
Title: Sonographic Characteristics associated with Lumbopelvic Pain

I am pleased to confirm **full approval** for your study has now been given. The approval has been granted by the School of Health Professions and Rehabilitation Sciences Ethics Committee.

You are required to complete a University Insurance and Research Governance Research Governance Application Form (IRGA) in order to receive insurance clearance before you begin data collection. The blank form can be found via the SUSSED portal under Research Governance Office http://www.resource1.soton.ac.uk/legalservices/rgo/regprojs/whatdocs.html .

You need to submit the following documentation in a plastic wallet to Dr Martina Prude in the Research Governance Office (RGO, University of Southampton, Highfield Campus, Bldg. 37, Southampton SO17 1BJ):

- Completed IRGA Research Governance form
- Copy of your research protocol/School Ethics Form (final and approved version)
- Copy of participant information sheet
- Copy of SoHPRS Risk Assessment form, **signed** (original should be with Zena Galbraith)
- Copy of your information sheet and consent form
- Copy of this SoHPRS Ethical approval letter

Continued overleaf

Your project will be registered at the RGO, and then automatically transferred to the Finance Department for insurance cover. **You can not begin recruiting until you have received a letter stating that you have received insurance clearance.**

Please note that you have ethics approval only for the project described in your submission. If you want to change any aspect of your project (e.g. recruitment or data collection) you must request permission from the Ethics Committee and RGO (students should discuss changes with their supervisor before submitting the request to the Ethics Committee).

Yours sincerely

Maggie Donovan-Hall
Chair, SHPRS Ethics Committee

Direct tel: +44 (0)23 8059 8880
Direct fax: +44 (0)23 8059 4792
email: mh699@soton.ac.uk

Secretary SoHPRS Ethics Committee: Zena Galbraith
Direct tel: +44 (0)23 8059 4791
email: Z.Galbraith@soton.ac.uk

APPENDIX 1c: Ethics Approval for Studies 4 and 5 (Chapters 7 and 8)

From: Whittaker J.L. <J.L.Whittaker@soton.ac.uk>
Sent: June-22-09 12:36 PM
To: jwphysio@telus.net
Subject: FW: Amendment to ethics approval ref #08-015

From: McFadyen H.R.
Sent: 14 November 2008 09:24
To: Whittaker J.L.
Cc: Stokes M.J.; Rgoinfo
Subject: RE: Amendment to ethics approval ref #08-015

Jackie,

Thank you for advising of this change.

I would confirm that we have noted the amendment and insurance remains in place for this project.

Ruth

Ruth McFadyen
Insurance Services Manager
023 8059 2417

-----Original Message-----
From: Whittaker J.L.
Sent: 13 November 2008 17:13
To: McFadyen H.R.
Cc: Stokes M.J.
Subject: FW: Amendment to ethics approval ref #08-015

Hi Ruth, my name is Jackie Whittaker. I am a PhD student in the School of Health Sciences (Health Professions). I have asked for an amendment regarding the inclusion criteria for age to my study (ethics approval ref # 08-015). The school ethics board has approved that I change my inclusion criteria for age from 18 - 50 to 18 - 60 yrs (see below) however they wanted me to check with you to ensure that I am still covered as far as insurance goes with the ammendemnts in place.

I would appreciate your thoughts,

Much Thanks,

Jackie

From: Donovan-Hall M.K.
Sent: 13 November 2008 16:48
To: Whittaker J.L.
Subject: RE: Amendment to ethics approval ref #08-015

Hi Jackie

Ruth MacFadyen's email address is HRM@soton.ac.uk and her telephone number is 023 8059 2417.

All best wishes
Maggie

Dr Maggie Donovan-Hall CPsychol
School of Health Sciences - Building 45
University of Southampton
Highfield
Southampton
Hants
SO17 1BJ

Tel: 44 (0)23 80 598880
Fax:44 (0)2380 595301

-----Original Message-----
From: Whittaker J.L.
Sent: 13 November 2008 15:47
To: Donovan-Hall M.K.
Subject: RE: Amendment to ethics approval ref #08-015

Hi Maggie, good news. I will contact Ruth. Do you have an email address or phone number for her?

Much Thanks,

Jackie

_____

From: Donovan-Hall M.K.
Sent: 13 November 2008 12:43
To: Galbraith Z.; Whittaker J.L.
Subject: RE: Amendment to ethics approval ref #08-015

Dear Jackie

Thanks for your email and I am sorry for the delay in getting back to you. I am happy for you to increase the upper age limit to 60 year, but please can you contact Ruth McFadyen in the insurance office to ensure that you are covered.

Many thanks
Maggie

Dr Maggie Donovan-Hall CPsychol
School of Health Sciences - Building 45
University of Southampton
Highfield
Southampton
Hants
SO17 1BJ

Tel: 44 (0)23 80 598880
Fax:44 (0)2380 595301

-----Original Message-----
From: Galbraith Z.
Sent: 28 October 2008 12:59
To: Donovan-Hall M.K.
Subject: FW: Amendment to ethics approval ref #08-015

Amendment request received for project 08-015

Many thanks
Zena

_____
Zena Galbraith
Research Secretary
Research and Enterprise Services Office
School of Health Sciences
University of Southampton
Highfield Campus, Bldg. 67
Southampton
SO17 1BJ
United Kingdom

Phone: +44-(0)23-8059 8233 internal 28233
Fax: +44-(0)23-8059 8308 internal 28308
E-Mail: zg@soton.ac.uk

-----Original Message-----
From: Whittaker J.L.
Sent: 28 October 2008 01:04
To: Galbraith Z.
Cc: Stokes M.J.
Subject: RE: Admendment to ethics approval ref #08-015

Hi Zena, I hope that you are well.

I would like to amend the age criteria for my current study; Ethics approval reference #08-015 Long Title; "Real-time sonographic characteristics of the abdominal wall and bladder in individuals with sacroiliac dysfunction with or without urinary incontinence."

The protocol that was approved was to include subjects age 18-50. Maria and I have discussed this and would like to open it up t subjets age 18-6. The primary reason for this change is to ; 1. increase the number of potential subjets that are eligiable to volunteer and 2. to increase the population that the findings of the study may be extraplolated to.

Maria had indicated that you could pass this amendment request onto the ethics committee. This would be greatly appreciated. I am not sure if they require more information if so please advise.

Much Thanks,

Jackie Whittaker PhD/Mhil Candidate

APPENDIX 1d: Ethics Approval for Study 3 (Chapter 6)

QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD

Queen's University

April 13, 2010

This Ethics Application was subject to:

☐ Full Board Review
Meeting Date:
☒ Expedited Review

Dr. Linda McLean
School of Rehabilitation Therapy
Louise D. Acton Building
Queen's University

Dear Dr. McLean,

Study Title: **Electromyography and Sonography Assessment of Abdominal Muscle Function in Individuals**
Co-Investigators: **Ms. Jackie Whittaker**

I am writing to acknowledge receipt of your recent ethics submission. We have examined the protocol and consent form for your project (as stated above) and consider it to be ethically acceptable. This approval is valid for one year from the date of the Chair's signature below. This approval will be reported to the Research Ethics Board. Please attend carefully to the following list of ethics requirements you must fulfill over the course of your study:

- **Reporting of Amendments:** If there are any changes to your study (e.g. consent, protocol, study procedures, etc.), you must submit an amendment to the Research Ethics Board for approval. (see http://www.queensu.ca/vpr/reb.htm).

- **Reporting of Serious Adverse Events:** Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other serious adverse events must be reported within 15 days after becoming aware of the information.

- **Reporting of Complaints:** Any complaints made by participants or persons acting on behalf of participants must be reported to the Research Ethics Board within 7 days of becoming aware of the complaint. Note: All documents supplied to participants must have the contact information for the Research Ethics Board.

- **Annual Renewal:** Prior to the expiration of your approval (which is one year from the date of the Chair's signature below), you will be reminded to submit your renewal form along with any new changes or amendments you wish to make to your study. If there have been no major changes to your protocol, your approval may be renewed for another year.

Yours sincerely,

Chair, Research Ethics Board

April 13, 2010
Date

ORIGINAL TO INVESTIGATOR - COPY TO DEPARTMENT HEAD- COPY TO HOSPITAL(S) /P&T (If appropriate) - FILE COPY

Study Code: REH-467-10

- **Investigators please note that if your trial is registered by the sponsor, you must take responsibility to ensure that the registration information is accurate and complete**

QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD

The membership of this Research Ethics Board complies with the membership requirements for Research Ethics Boards as defined by the Tri-Council Policy Statement; Part C Division 5 of the Food and Drug Regulations, OHRP, and U.S DHHS Code of Federal Regulations Title 45, Part 46 and carries out its functions in a manner consistent with Good Clinical Practices.

Federalwide Assurance Number : #FWA00004184
#IRB00001173

Current 2010 membership of the Queen's University Health Sciences & Affiliated Teaching Hospitals Research Ethics Board

Dr. A.F. Clark	**Emeritus Professor, Department of Biochemistry, Faculty of Health Sciences, Queen's University (Chair)**
Dr. H. Abdollah	**Professor, Department of Medicine, Queen's University**
Rev. T. Deline	**Community Member**
Dr. M. Evans	**Community Member**
Dr. S. Irving	**Psychologist, Providence Care, St. Mary's of the Lake Hospital Site**
Dr. L. Keeping-Burke	**Assistant Professor, School of Nursing, Queen's University**
Dr. J. Low	**Emeritus Professor, Department of Obstetrics and Gynaecology, Queen's University and Kingston General Hospital**
Dr. W. Racz	**Emeritus Professor, Department of Pharmacology & Toxicology, Queen's**
Dr. B. Simchison	**Assistant Professor, Department of Anesthesiology, Queen's University**
Dr. A.N. Singh	**WHO Professor in Psychosomatic Medicine and Psychopharmacology Professor of Psychiatry and Pharmacology Chair and Head, Division of Psychopharmacology, Queen's University Director & Chief of Psychiatry, Academic Unit, Quinte Health Care, Belleville General Hospital**
Dr. E. Tsai	**Associate Professor, Department of Paediatrics and Office of Bioethics, Queen's University**
Rev. J. Warren	**Community Member**
Ms. K. Weisbaum	**LL.B. and Adjunct Instructor, Department of Family Medicine (Bioethics)**
Dr. S. Wood	**Director, Office of Research Services (Ex-Officio)**

UNIVERSITY OF Southampton
School of Health Sciences

Research and Enterprise Services Office
Form PR1/Feb 2010/V1.5

Peer Review Form

IMPORTANT

- Timeframe for this process: *minimum 3* weeks *(AND allow extra time in case amendments are recommended by the peer reviewer)*
- Please make sure that you use the most up to date version of this information by checking with the Research and Enterprise Services Office (RESO) before you start.
- If you have any queries please contact the Head of Research & Enterprise Services (Susan Rogers, ssr@soton.ac.uk or 023 8059 7942).

Part 1: To be completed by the applicant

Guidance Notes:
Please complete the Investigator Details and Enclosures sections overleaf and submit the whole form and the relevant enclosures **via email** to the Research and Enterprise Services Office (sohsreso@soton.ac.uk). The subject of your e-mail should be "Peer Review" and documents should be labelled appropriately, e.g. protocol **"J Bloggs, Protocol, v1.0, 17Jul08".**

The RESO will contact a peer reviewer and notify you when the reviewer has completed their task. Please ensure you leave sufficient time to incorporate any changes the peer reviewer recommends or requires.

The peer reviewers is asked to complete the review within three weeks from receiving your documentation, however, you should allow extra time in case amendments are recommended by the peer reviewer.

Please make sure you arrange for a final check of the proposal and supporting documents with your project supervisor(s)/project lead before submission.

If the outcome of the initial peer review requires you to submit amendments for further review you should submit your amended protocol together **with an amendment sheet, for the latter please follow the exemplary format below** (copy relevant row/section from reviewer's form and indicate page number/s on revised protocol):

2.	Research Question/Hypothesis: Is there a clear hypothesis/ question/purpose which leads on from the background and literature?	No	Literature review emphasises spousal care givers, but this is not specified in study inclusion criteria. **Eg. Amendments (i.e. your changes/reply to reviewer):** **For the purposes of the study 'care-givers' are defined as the person who provides the main source of support for the person with MS. The term 'spousal' has been omitted to avoid confusion.** **pp. 2, 5, 6**

Investigator Details		Enclosures	
Name:	Jackie L. Whittaker		**Please tick**
Address:	14763 Thrift Ave. White Rock, BC, Canada, V4B 2J4	Full Proposal	☒
Tel No:	(604) 542 0945	Other documentation (e.g.):	
Email:	j.l.whittaker@soton.ac.uk	• Information sheet(s)	☒
Student (Y/N)	Y	• Invitation letter(s)	☐
Level (e.g. PhD):	PhD candidate	• Consent forms	☒
Other investigators / collaborators:	Dr. Linda McLean		
Supervisors:	Professor Maria Stokes Professor Victor Humphrey	Please confirm that your supervisor/s have reviewed your Peer Review application	☒
Title of proposal	**EMG and Sonography Assessment of Abdominal Muscle Function in Individuals with and without Lumbopelvic Pain.**		

Part 2: to be completed by the Reviewer

Please would you provide a Peer Review of the enclosed research proposal on behalf of the School. This is required before the project can be submitted to Ethics.

Please complete your assessment **electronically** on the enclosed form and qualify your views where necessary. You are not asked to assess the ethical issues in this review. However, if you feel specific issues are likely to be queried by an internal or external ethics committee please note them in the general comments section with possible solutions.

Please return your assessment by : date on email request
Please provide your views on the project proposal, commenting specifically on the areas identified in the left hand column.

Research Quality			
Questions:		**Yes / No**	**Specific Comments**
1.	**Background & Literature:** Is the current state of knowledge outlined, well structured, coherent and well referenced?	Yes	This is a comprehensive outline of the literature with a clear justification for the research question.
2.	**Research Question/Hypothesis:** Is there a clear hypothesis/ question/purpose which leads on from the background and literature?	No	With the applicants experience and the background knowledge I am certain a clearer hypothesis could be proposed. It is important to provide a clear outline of the relationships that will be explored.
3.	**Objectives:** Are the objectives: a) stated clearly?	N/A	No objectives are specifically stated but their inclusion could clarify the hypothesis.
	b) appropriate?	N/A	
	c) achievable?	N/A	

Questions:		Yes / No	Specific Comments
4.	**Sample:** a) Is the sample population described?	Yes	
	b) Is the recruitment process feasible?	Yes	
	c) Will the sample size provide meaningful data once analysed?	Yes	The sample is not based on a calculation but as it is an observational study I am sure meaningful data will emerge.
5.	**Design:** a) is the design stated?	Yes	
	b) Is there a rationale for the approach?	Yes	
6.	**Methodology:** a) Are the methods chosen appropriate?	Yes	
	b) Is the protocol of procedures clear?	Yes	
7.	**Research tools:** Are the research tools (such as equipment, questionnaires and interviews) well structured, informed, and suitable for analysis?	Yes	
8.	**Analysis:** a) Is there an effective analytical plan?	Yes	The analysis section appears to be very comprehensive.
	b) Quantitative methods – are statistical tests appropriate?	Yes	
	c) Qualitative methods – are methods of analysis appropriate?		

Research Planning & Practice			
Questions:		**Yes / No**	**Specific Comments**
9.	**Project management:** a) Is there evidence of a well-structured and achievable plan?	Yes	It appears to be well planned with supervision.
	b) Is the timetable realistic?	No	The time table needs updating
	c) Is the project manageable given the resources identified?		
10.	**The investigating team:** Does the research team (including supervisors & collaborators) have the appropriate experience/skills to undertake the study?	Yes	
11.	Is there evidence of appropriate statistical support, where appropriate?	Yes	

Please use the boxes below to summarise your general comments, any specific changes you require and then select your overall assessment below and complete the signature box.

General comments
This is a clear and comprehensive study. As this work is being carried out in Canada, an advanced peer review has been carried out and no obvious ethical problems have been identified. .
Specific Changes Required **(Please use numbers for points from previous pages)**
There are no specific changes required, but please consider addressing the hypothesis and specify objectives. Thank you

Peer Reviewer: Do you wish to remain anonymous?
No

UNIVERSITY OF Southampton
School of Health Sciences

Peer Review: Overall Assessment	
	Accept (will be returned **electronically** to the student/researcher)
X	**Minor revisions** - will be returned **electronically** to the applicant: **IF** a student: revisions to be checked by main supervisor **OR** if a researcher: revisions to be checked by PI **OR** if a PI: revisions to be checked by Head of Research Group **OR** if a Head of Research Group: revisions to be checked by Director of Research. The 'authorised person' (Supervisor/PI/Head of Research Group/Director of Research) completes the final sign-off* below to notify RESO that revisions are satisfactory.
	Revisions required (will be returned **electronically** to the supervisor for discussion / researcher and PI for discussion with revisions to go back to peer reviewer via the RESO). When the Peer Reviewer can confirm the revisions are satisfactory the Peer Reviewer completes the final sign-off* below to notify RESO.
	Reject (will be returned **electronically** to the supervisor/PI/Head of the Research Group/Director of Research for discussion)

Name of Applicant	Whittaker
Title of Proposal	EMG & Sonography assessment of abdominal muscles function in individuals with and without lumbopelvic pain.
Name of Reviewer	Professor Ashburn
Reviewer's Signature	
Date review completed	07.05.10

* Final sign off when no amendments necessary	
Name of authorised person	
Signature of authorised person	
Date of final sign off	

Thank you for taking the time to complete this project review.
Please return the completed form via email to Sohsreso@soton.ac.uk

Please also post the signed last sheet to Research & Enterprise Services Office, School of Health Sciences, Building 67, University of Southampton, Highfield, Southampton, SO17 1BJ

University of Southampton

School of Health Professions and Rehabilitation Sciences

Consent Form (Version 1): Sonographic Characteristics of the Abdominal & Pelvic Floor Muscles

I _____ **(full name in block capitals)** have read the information sheet (dated Version 1) and consent to participate in this study. I understand that I may withdraw my consent and discontinue participation at any time without penalty or loss of benefits to myself. I understand that the data collected as part of this study will be treated confidentially, and that published results of this project will maintain my confidentiality. In signing this consent letter, I am not waving my legal claims, rights, or remedies. A copy of this letter has been offered to me.

I have reviewed and understand the Information for Research Participants Information Sheet and have asked any questions I may have to the researcher taking my consent:

(please initial box) **YES** ☐ **NO** ☐

I give consent to participate in the above study:

(please initial box) **YES** ☐ **NO** ☐

I am participating in another other study:

(please initial box) **YES** ☐ **NO** ☐

If 'yes' please describe: _____

I do not have:

A skin disease or allergy which prohibits the use surface electrodes on the abdomen:

(please initial box) **YES** ☐ **NO** ☐

A history of a neurological disorder or head injury:

(please initial box) **YES** ☐ **NO** ☐

A history of respiratory or breathing problems:

(please initial box) **YES** ☐ **NO** ☐

A history of urinary incontience:

(please initial box) **YES** ☐ **NO** ☐

A history of any physical condition (fracture, neoplasm) or surgery affecting the movement of the legs or back:

(please initial box) **YES** ☐ **NO** ☐

An episode of low back, pelvic or hip pain in the last year that prevented me from going to work, participating in my recreational activites, or required me to seek medical attention:

(please initial box) **YES** ☐ **NO** ☐

A history of being told that I have scoliosis, spinal bifida, spondylolithesis or a compression fracture in my back? :

(please initial box) **YES** ☐ **NO** ☐

Any condition that prevents me from lifting my legs:

(please initial box) **YES** ☐ **NO** ☐

I am:

Currently experiencing low back, pelvic or hip pain:

(please initial box) **YES** ☐ **NO** ☐

Currently pregnant:

(please initial box) **YES** ☐ **NO** ☐

A high level athlete (professional, amateur, varsity):

(please initial box) **YES** ☐ **NO** ☐

Signature_____ Date _____

Name of Researcher taking consent: _____

UNIVERSITY OF Southampton
School of Health Professions and Rehabilitation Sciences

APPENDIX 2b: Informed Consent Form for Studies 2, 4 and 5 (Chapter 5, 7 and 8)

CONSENT FORM (Version 1)

Study Title: **Sonographic Characteristics assocaited with Lumbopelvic (Low Back) Pain**

Researcher: **Jackie Whittaker (PhD Candidate)**

Supervisor: **Prof Maria Stokes**

Ethics number: **08-015**

I _____ **(full name in block capitals)** have read the information sheet (dated Version 1) and consent to participate in this study. I understand that I may withdraw my consent and discontinue participation at any time without penalty or loss of benefits to myself. I understand that the data collected as part of this study will be treated confidentially, and that published results of this project will maintain my confidentiality. In signing this consent letter, I am not waving my legal claims, rights, or remedies. A copy of this letter has been offered to me.

I have reviewed and understand the Information for Research Participants Information Sheet and have asked any questions I may have to the researcher taking my consent:

(please initial box) **YES** ☐ **NO** ☐

I give consent to participate in the above study:

(please initial box) **YES** ☐ **NO** ☐

I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected:

(please initial box) **YES** ☐ **NO** ☐

Name of participant (print name).....

Signature of participant.....

Date.....

School of Health Professions and Rehabilitation Sciences, University of Southampton, Highfield Campus, Southampton SO17 1BJ United Kingdom
Tel: +44 (0)23 8059 2142 Fax: +44 (0)23 8059 5301 www.sohp.soton.ac.uk

APPENDIX 3c - Informed Consent and Participant Information Form for Study 3 (Chapter 6)

TITLE OF PROJECT: Electromyography and Sonography Assessment of Abdominal Muscle Function in Individuals with and without Lumbopelvic Pain

PRINCIPAL INVESTIGATORS:

Linda McLean, BScPT, PhD, Associate Professor
School of Rehabilitation Therapy, Queen's University

Jackie Whittaker, BScPT, PhD Candidate
School of Health Sciences, University of Southampton

BACKGROUND INFORMATION:

You are being invited to participate in a research study directed by Dr. Linda McLean which is investigating the value of using ultrasound imaging as an assessment and treatment tool in rehabilitation therapy. One of the investigators will read through this consent form with you, will describe procedures in detail and will answer any questions you may have. This study has been reviewed for ethical compliance by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board.

DETAILS OF THE STUDY:

Purpose of the study:

We are investigating the relationship between the thickness of the abdominal muscles as seen using ultrasound imaging performed during functional activities in individuals with and without lumbopelvic pain, and the level of activation of these muscles as measured using electromyography. The aim of this study is to determine whether thickness changes seen on ultrasound imaging reflect the level of muscle activation during particular tasks. The results of this study will be used to make recommendations about whether or not ultrasound imaging is a valid tool to use in the assessment and treatment motor control dysfunction.

Inclusion and Exclusion Criteria:

You ~~will be considered~~ for this study if you are between 18 and 60 years of age, with or without lumbopelvic pain and can understand instructions provided in English, can lie on your back and lift your leg and can stand and balance on each leg for 1 second.

You will ~~not be considered~~ eligible for this study if you have a condition that restricts you from undergoing a physical assessment of your low back, a body mass index > than 30 kg/m, respiratory dysfunction, a history of congenital lumbar anomilies or surgery to the lumbar region, neurological symptoms, a skin disorder, are unable to follow instructions, are currently pregnant or have been pregnant beyond the first trimester within the past year, or if you are a high level athletes (train for a competitive sport more than 15 hours per week).

Healthy participants will be screened to ensure that they have no history of low back, pelvic, hip or thigh pain in the last year that interfered with work, recreation or required medical attention.

Procedure of the study:

The study will require a one-time, ninety minute session which will take place in a private setting in the Motor Performance Laboratory at the School of Rehabilitation Therapy at Queen's University. Data collection will be performed by the primary investigators Dr. Linda McLean and Jackie Whittaker.

When you first arrive you will undergo a short interview and physiotherapy assessment, complete several questionnaires and perform a short breathing test (air will be gathered through two small 1 cm tubes that will sit inside your nostrils). You will then be asked to lie in a comfortable position on a wooden plinth. Fine wire EMG electrodes will be inserted by Dr. McLean into the abdominal muscles using a sterile technique and ultrasound guidance to ensure proper positioning. These electrodes will be used to measure the activity of your abdominal muscles during the ultrasound assessment.

Before the ultrasound evaluation, you will be instructed how to perform to movement tasks while lying on your back (drawing in your abdomen and lifting your leg while keeping it straight). You will be given a

chance to practice both tasks prior to data collection. You will then be instructed to perform three repetitions of both tasks while a researcher (Jackie Whittaker) records ultrasound images from two locations on your abdomen.

Risks:

There are no known risks associated with ultrasound imaging. It is non-ionizing radiation, so it does not have the same risks that are associated with x-rays or magnetic resonance imaging (MRI). Ultrasound imaging is safely used to image fetuses, so if you happen to be pregnant and do not currently know, the procedure provides no known risks to the fetus. That said, if you know you are pregnant, please do not volunteer to complete this study.

There is some risk of infection associated with the insertion of fine wire electrodes into the abdominal muscles. Single-use, sterile fine wire electrodes will be inserted using single-use, sterile hypodermic needles and sterile techniques, and the skin will be cleaned with isopropyl rubbing alcohol and allowed to dry before each needle is inserted. Because the electrodes will be inserted under ultrasound guidance, and because no major blood vessels or nerves are located within the vicinity of the insertion site, the procedure carries minimal risk of damage to nerves or blood vessels. It is possible that on insertion of the hypodermic needle the skin surface will become irritated, but this irritation normally subsides upon removal of the needle. Participants will be advised to inform the researchers immediately if the wire electrodes cause discomfort beyond the period that the needle is inserted in the muscle. If this is the case, the wires will be removed and replaced.

There is a small risk that, on inserting the needle into the deepest abdominal muscle the tip of the needle might pass through the connective tissue layer and into your abdominal cavity. Because the needle is sterile and very small, if this were to occur, it would carry with it minimal risk of infection but might cause some minor temporary bleeding. It would be clear within seconds if this were the case as no EMG activity would be recorded from the needle, and as such it would be removed.

If you feel discomfort associated with any aspect of the study, please let the researchers know. Remember that you are free to withdraw from the study without consequence at any time.

Benefits:

While you will not benefit directly from this study, results from this study will lead to a better understanding of the utility of using ultrasound imaging to enhance physiotherapy assessment and treatment using ultrasound imaging.

Confidentiality

All information obtained during the course of this study will remain strictly confidential and your anonymity will be protected. Your data will be identified by a subject number only, and not by your name. Only the principal investigators will have access to the information that links your name to your subject number. Computer data files will identify you by the numerical code only. Paper data (your questionnaire) will be stored in a locked filing cabinet and will be available only to the investigators involved in this study. You will not be identified by name in any publication, presentation or report that results from this study.

Voluntary nature of study/Freedom to withdraw or participate:

Your participation in this study is voluntary. You may withdraw from this study at any time without consequence and your withdrawal will not affect any future relationship with the School of Rehabilitation Therapy or any other program at Queen's University.

Withdrawal of subject by principal investigator:

The principle investigators may decide to withdraw you from this study if your status changes and you no longer meet the required inclusion criteria or exhibit an exclusion criterion, as outlined above, or if you are unable to follow the study protocol.

Liability:

In the unlikely event that you are injured as a result of the study procedures, medical care will be provided to you until resolution of the medical problem. By signing this consent form, you do not waive your legal rights nor release the investigator(s) from their legal and professional responsibilities.

SUBJECT STATEMENT AND SIGNATURE SECTION:

I have read and understand the consent form for this study. I have had the purposes, procedures and technical language of this study explained to me. I have been given sufficient time to consider the above information and to seek advice if I chose to do so. I have had the opportunity to ask questions which have been answered to my satisfaction. I am voluntarily signing this form. I will receive a copy of this consent form for my information.

If at any time I have further questions, problems or adverse events, I can contact the faculty supervisor, who is one of the principal investigators:

Dr. Linda McLean at **613-533-6101**

If I am not satisfied with any aspect of my participation in this study, I can contact

Dr. Elsie Culham, Director of the School of Rehabilitation Therapy and Associate Dean, Faculty of Health Sciences at Queen's University at **613-533-6727**.

If I have questions regarding my rights as a research subject I can contact:

Dr. Albert Clark, Chair, Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board at **613-533-6081**

By signing this consent form, I am indicating that I agree to participate in this study.

_____ _____

Signature of Volunteer Date

STATEMENT OF INVESTIGATOR:

I, or one of my colleagues, have carefully explained to the subject the nature of the above research study. I certify that, to the best of my knowledge, the subject understands clearly the nature of the study and demands, benefits, and risks involved to participants in this study.

_____ _____

Signature of Principal Investigator Date

APPENDIX 3a: Participant Characteristics for Studies 1a* and 1b (Chapter 4)

Table 1: Control Participants

Participant	Height (cm)	Weight (kg)	BMI kg/m^2	Age (yrs.)	Sex	Breathing Strategy	$ETCO_2$ (mmHg)	BPM	Parity	NRS	Oswestry (%)	FABQPA	FABQW	IIQ	UDI	Nijmegen
1	169.0	69.0	24.2	39	1	1	35.6	7.7	1	0	0	0	0	0	0	0
2	170.0	66.3	22.9	35	1	1	35.1	13.6	0	0	0	0	0	0	0	0
4	164.0	78.0	29.0	44	2	2	39.5	16.3	0	0	0	0	0	0	0	0
5	182.0	73.0	22.0	26	2	2	40.4	13.1	0	0	0	0	0	0	0	0
8*	163.0	71.0	26.7	31	1	3	37.8	16.1	0	0	0	0	0	0	0	0
9*	161.0	49.1	18.9	29	1	2	36.8	15.6	0	0	0	0	0	0	0	0
10*	156.0	63.0	25.9	43	1	2	35.8	14.8	0	0	0	0	0	0	0	0
11*	172.0	67.0	22.6	19	1	2	40.0	9.8	0	0	0	0	0	0	0	0
12*	176.0	65.5	21.1	24	1	1	37.4	10.5	0	0	0	0	0	0	0	0
13*	162.0	67.5	25.7	24	1	2	35.2	17.4	0	0	0	0	0	0	0	0
15*	195.0	92.80	24.70	31	2	2	37.6	16.6	0	0	0	0	0	0	0	0
16*	172.0	82.9	28.0	22	2	1	42.6	11.5	0	0	0	0	0	0	0	0
Average	170.2	70.4	24.3	30.6	4 males		37.8	13.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard Deviation	10.6	10.8	3.0	8.2			2.4	3.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Participant in study 1a (Chapter 4)

BPM = breaths per minutes, cm = centimetres, $ETCO_2$ = End tidal Carbon Dioxide, FABQPA = Fear Avoidance Beliefs Questionnaire - Physical Activity Subscale, FABQW = Fear Avoidance Beliefs Questionnaire- Work Subscale, IIQ - Incontinence Impact Questionnaire, , kg = kilograms, mmHG = millimetres of mercury, NRS = Numerical Rating Scale, yrs. = years, UDI = Urogenital Distress Inventory

Sex: Female = 1, Male = 2

Breathing Pattern: Lateral Costal and Abdominal = 1, Abdominal = 2, Apical = 3, Apical and Abdominal = 4

APPENDIX 3b: Participant Characteristics for Studies 2*, 4 and 5 (Chapters 5, 7 and 8)

Table 1: Control Participants

Participant	Height (cm)	Weight (kg)	BMI kg/m^2	Age (yrs.)	Sex	Breathing Strategy	$ETCO_2$ (mmHg)	BPM	Parity	NRS	Oswestry (%)	FABQPA	FABQW	IIQ	UDI	Nijmegen
1*	164.0	54.0	20.1	52	1	1	37.9	13.6	0	0	0	0	0	0	0	13
9	160.0	59.9	23.4	46	1	1	35.3	8.2	1	0	0	0	0	0	0	21
10	163.5	61.2	22.8	47	1	1	36.3	23.7	0	0	0	0	0	0	6	11
11	180.0	77.6	24.0	39	2	1	39.3	13.2	0	0	0	0	0	0	0	0
17*	158.5	54.4	21.5	39	1	2	37.8	16.1	0	0	0	0	0	19	17	0
21	182.0	73.0	22.0	26	2	2	40.4	13.1	0	0	0	0	0	0	0	0
22	169.0	69.0	24.2	39	1	2	35.8	7.7	1	0	0	0	0	0	0	0
23	164.0	78.0	29.0	44	1	2	39.5	16.3	0	0	0	0	0	0	0	0
24	163.0	71.0	26.7	31	2	2	37.8	16.1	0	0	0	0	0	0	0	0
25	161.0	49.1	18.9	29	1	2	36.8	15.6	0	0	0	0	0	0	0	0
26	156.0	63.0	25.9	43	1	2	35.8	14.8	0	0	0	0	0	0	0	0
27	172.0	67.0	22.6	19	1	1	40.0	9.8	0	0	0	0	0	0	0	0
28	176.0	65.5	21.1	24	1	1	37.4	10.5	0	0	0	0	0	0	0	0
29	162.0	67.5	25.7	24	1	1	35.0	18.0	0	0	0	0	0	0	0	0
30	195.0	92.8	24.7	31	2	2	37.6	16.6	0	0	0	0	0	0	0	0
31	172.0	82.9	28.0	22	2	1	42.6	11.5	0	0	0	0	0	0	0	0
38*	162.5	67.0	25.4	33	1	2	35.0	9.3	1	0	0	0	0	0	6	9
40*	172.0	60.3	20.4	53	1	1	39.9	12.4	2	0	0	0	0	0	6	8
43*	167.0	63.0	22.6	39	1	1	40.2	11.6	1	0	0	0	0	0	0	6
52	178.0	75.0	23.7	42	2	1	38.3	13.2	0	0	0	0	0	0	0	3
55*	168.0	64.8	23.0	42	1	2	35.4	9.6	2	0	0	0	0	0	0	2
60*	170.0	65.3	22.6	31	1	1	39.1	10.0	0	0	0	0	0	0	6	18
61*	155.0	63.5	26.4	46	1	1	38.5	9.6	1	0	0	0	0	0	0	12
63*	172.0	62.5	21.1	31	1	2	34.6	13.6	0	0	0	0	0	0	0	3
68	170.0	66.3	22.9	35	1	2	41.4	13.6	0	0	0	0	0	0	0	0
Average	168.5	66.9	23.5	36.3	6 males		37.9	13.1	0.4	0.0	0.0	0.0	0.0	0.8	1.6	4.2
Standard Deviation	9.0	9.4	2.5	9.4			2.2	3.6	0.6	0.0	0.0	0.0	0.0	3.8	3.8	6.3

* Participant in study 2 (Chapter 5)

BPM = breaths per minutes, cm = centimetres, $ETCO_2$ = End tidal Carbon Dioxide, FABQPA = Fear Avoidance Beliefs Questionnaire - Physical Activity Subscale, FABQW = Fear Avoidance Beliefs Questionnaire- Work Subscale, IIQ - Incontinence Impact Questionnaire, , kg = kilograms, mmHG = millimetres of mercury, NRS = Numerical Rating Scale, yrs. = years, UDI = Urogenital Distress Inventory
Sex: Female = 1, Male = 2
Breathing Pattern: Lateral Costal and Abdominal = 1, Abdominal = 2, Apical = 3, Apical and Abdominal = 4

Table 2: Lumbopelvic Pain Participants

Participant	Height (cm)	Weight (kg)	BMI kg/m^2	Age (yrs.)	Sex	Breathing Strategy	$ETCO_2$ (mmHg)	BPM	Parity	NRS	Oswestry (%)	FABQPA	FABQW	IIQ	UDI	Nijmegen	Length of Pain (yrs.)	Clinical Pattern	Compression Pattern
2	168.0	88.9	31.5	54	1	2	35.4	12.4	2	5	20	7	12	4.7	5.6	22	1.0	1	2
3*	159.0	49.9	19.7	45	1	2	37.0	13.3	2	2	10	3	11	9.5	27.8	15	15.0	1	2
4	178.0	79.0	24.9	49	2	1	35.3	16.2	0	7	18	10	0	0	0	5	2.0	2	2
7	172.0	94.3	31.9	48	1	2	36.3	10.7	2	7	26	10	27	0	5.6	22	0.8	1	2
8	186.0	94.3	27.3	59	2	2	38.4	12.2	0	4	32	12	27	0	0	7	0.9	2	2
12	173.0	66.7	22.3	32	1	2	40.1	14.4	0	3	14	10	21	0	5.6	11	1.0	2	2
13*	166.5	72.6	26.0	59	1	2	37.5	14.1	3	7	50	19	38	0	44.4	20	6.0	1	2
14	161.0	52.7	20.4	50	1	2	35.8	10.3	2	4	18	12	0	0	5.6	7	4.0	2	1
15	172.0	65.8	22.2	47	1	2	35.0	15.3	1	3	34	12	35	0	22.2	19	5.0	1	2
16*	164.0	53.5	19.9	39	1	2	36.8	12.3	0	4	28	14	0	0	16.7	20	14.0	1	2
18	170.0	79.8	27.6	42	2	2	35.4	17.3	0	3	10	13	17	0	0	11	2.0	1	2
32*	160.0	60.3	23.6	39	1	2	40.2	13.3	1	5	16	8	13	0	0	12	15.0	2	2
33*	171.0	74.4	25.4	53	1	1	42.2	13.4	1	2	2	0	0	0	16.6	15	1.5	1	2
35*	164.0	69.8	26.0	47	1	2	42.0	13.2	2	2	16	13	2	0	16.7	23	15.0	1	2
41	170.0	73.0	25.3	42	2	2	43.3	12.0	0	3	6	5	0	0	5.6	2	0.8	2	2
42*	176.0	73.2	23.6	42	1	2	36.2	12.4	0	6	32	13	4	0	11.1	15	20.0	2	2
44*	168.0	69.4	24.6	54	1	2	35.2	12	0	1	10	24	19	0	5.6	9	5.0	1	3
46*	169.0	58.5	20.5	57	1	2	35.7	6.5	1	3	18	3	2	14.3	33.3	15	10.0	1	1
48	169.0	70.0	24.5	55	1	2	38.4	7.5	2	4	28	12	14	4.8	16.7	21	4.0	1	2
49	177.0	79.4	25.3	50	2	2	37.6	12.7	0	4	28	24	30	0	11.1	13	2.0	2	3
50	165.0	57.6	21.2	37	1	1	38.4	16.5	0	5	12	9	0	0	0	8	3.0	2	2
53	175.0	75.0	24.5	45	1	2	37.6	5	0	3	14	0	0	9.5	27.8	27	5.0	1	2
56	163.0	63.1	23.7	29	1	1	38.1	11.5	0	4	6	15	19	0	11.1	6	2.5	1	2
62	163.0	56.2	21.2	35	1	1	35.4	11.2	0	3	12	4	0	0	5.6	9	2.0	1	2
65	162.5	43.7	16.5	54	1	2	41.4	10	0	3	38	4	24	0	11.1	13	4.0	1	3
Average	168.9	68.8	24.0	46.5	5 males		37.8	12.2	0.8	3.9	19.9	10.2	12.6	1.7	12.2	13.9	5.7		
Standard Deviation	6.4	13.2	3.5	8.3			2.5	2.9	1.0	1.6	11.5	6.3	12.5	3.9	11.6	6.5	5.7		

* Participant in study 2 (Chapter 5)

BPM = breaths per minutes, cm = centimetres, $ETCO_2$ = End tidal Carbon Dioxide, FABQPA = Fear Avoidance Beliefs Questionnaire - Physical Activity Subscale, FABQW = Fear Avoidance Beliefs Questionnaire- Work Subscale, IIQ - Incontinence Impact Questionnaire, , kg = kilograms, mmHG = millimetres of mercury, NRS = Numerical Rating Scale, yrs. = years, UDI = Urogenital Distress Inventory
Sex: Female = 1, Male = 2
Breathing Pattern: Lateral Costal and Abdominal = 1, Abdominal = 2, Apical = 3, Apical and Abdominal = 4
Clinical Pattern: Insufficient = 1, Excessive = 2
Compression Pattern: General = 1, Anterior = 2, Posterior = 3

APPENDIX 3c: Participant Characteristics for Study 3 (Chapter 6)

Table 1: Control Participants

Participant	Height (cm)	Weight (kg)	BMI kg/m^2	Age (yrs.)	Sex	Parity	NRS	Oswestry (%)	FABQPA	FABQW	IIQ	UDI	Nijmegen
1	177.0	75.0	23.9	50	1	3	0	0	0	0	0	0	9
2	167.0	69.0	24.7	24	1	0	0	0	0	0	0	0	5
3	163.0	65.0	24.5	23	1	0	0	0	0	0	0	0	7
5	163.0	63.5	23.9	35	1	0	0	0	0	0	9.6	27.9	12
7	180.0	71.7	22.1	24	1	0	0	0	0	0	0	0	4
8	173.0	81.7	27.3	26	2	0	0	0	0	0	0	0	0
11	166.0	74.0	26.9	42	1	1	0	0	0	0	0	0	2
Average	169.9	71.4	24.8	32.0	1 male	0.6	0.0	0.0	0.0	0.0	1.4	4.0	5.6
Standard Deviation	6.8	6.2	1.8	10.6		1.1	0.0	0.0	0.0	0.0	3.6	10.5	4.1

cm = centimetres, FABQPA = Fear Avoidance Beliefs Questionnaire - Physical Activity Subscale, FABQW = Fear Avoidance Beliefs Questionnaire- Work Subscale, IIQ - Incontinence Impact Questionnaire, , kg = kilograms, NRS = Numerical Rating Scale, yrs. = years, UDI = Urogenital Distress Inventory
Sex: Female = 1, Male = 2

Table 2: Lumbopelvic Pain Participants

Participant	Height (cm)	Weight (kg)	BMI kg/m^2	Age (yrs.)	Sex	Parity	NRS	Oswestry (%)	FABQPA	FABQW	IIQ	UDI	Nijmegen	Length of Pain (yrs.)	Clinical Pattern	Compression Pattern
9	1.70	56.7	19.6	22	1	0	4	20	17	13	0	0	6	3	2	3
13	1.68	68.0	24.1	23	1	0	5	10	22	15	0	0	2	5	1	3
14	1.75	74.0	24.2	23	2	0	2	4	0	0	0	0	0	0.46	2	1
15	1.62	63.0	24.0	26	1	0	1	8	12	21	0	0	1	0.46	1	1
16	1.70	69.0	23.9	49	1	3	4	14	6	8	0		12	3	1	2
17	1.65	84.4	31.0	45	1	0	3	22	6	9	0	0	12	10	2	2
18	1.73	65.0	21.7	20	1	0	3	8	17	20	0	0	0	4.5	1	3
Average	1.7	68.6	24.1	29.7	1 male	0.4	3.1	12.3	11.4	12.3	0.0	0.0	4.7	3.8		
Standard Deviation	0.0	8.8	3.5	12.0		1.1	1.3	6.7	7.8	7.3	0.0	0.0	5.4	3.3		

cm = centimetres, FABQPA = Fear Avoidance Beliefs Questionnaire - Physical Activity Subscale, FABQW = Fear Avoidance Beliefs Questionnaire- Work Subscale, IIQ - Incontinence Impact Questionnaire, , kg = kilograms, mmHG = millimetres of mercury, NRS = Numerical Rating Scale, yrs. = years, UDI = Urogenital Distress Inventory
Sex: Female = 1, Male = 2
Breathing Pattern: Lateral Costal and Abdominal = 1, Abdominal = 2, Apical = 3, Apical and Abdominal = 4
Clinical Pattern: Insufficient = 1, Excessive = 2
Compression Pattern: General = 1, Anterior = 2, Posterior = 3

University of Southampton

School of Health Professions and Rehabilitation Sciences

Participant Information: Sonographic Characteristcs of the Abdominal & Pelvic Floor Muscles

You are invited to take part in a research project. Before you decide it is important for you to understand what the research is about. Please take time to read the following information and feel free to ask us if there is anything that is not clear. This document tells you:

- The purpose of this study and what will happen to you if you take part.
- Detailed information concerning what the study is about, how it will be carried out and any potential risks.

- **What is the purpose of the study?**

The purpose of this study is to determine if ultrasound imaging (the technique used to look at unborn babies) can be used to measure changes in the size of the abdominal muscles and the shape of the bladder. As these muscles are important for supporting the spine and protecting against back pain and urinary incontinence, we want to learn if ultrasound imaging can assist with assessment and directing treatment of individuals with these problems.

- **Why have I been chosen?**

If you have been contacted it is because you have expressed an interest in taking part in the study, which we advertised in and around the University of Southampton.

- **Do I have to take part?**

No you do not have to take part; it is entirely your decision. If you do, you will be asked to sign a consent form but will still be free to withdraw at any time without giving a reason for doing so.

- **What will happen to me if I take part?**

You will be asked to come to the School of Health Professions and Rehabilitation Sciences, at the University of Southampton for one appointment of approximately 1.5 hours. We will provide you with precise directions and an appointment time that suits both yourself and the researcher.

During this appointment you will be asked to complete a questionnaire, undergo a short physiotherapy assessment and perform several breathing tests (i.e. breathing into a tube similar to a snorkel) and movement tasks (i.e. lifting your leg while lying on your back). During these tests a researcher will record the behaviour of your abdominal and pelvic floor muscles by taking ultrasound images from various places on your abdomen, and from several small electrodes (electromyography) attached to the abdomen with adhesive. Air will also be gathered through two small 1 cm tubes that will sit inside your nostrils.

- **What do I have to do?**

We ask that 1 hour prior to your visit you fully empty your bladder and then drink approximately 500ml (1 cup) of water. We ask that you refrain from further emptying your bladder or drinking more fluid until after your visit. We also ask that you bring appropriate clothing to allow you to move about comfortably.

On arrival you will be asked to fill out a consent and screening form, this will be followed by a physiotherapy assessment during which you will be asked; to sit while your leg reflexes are tested, to perform several resisted muscle contractions (3 seconds), assume a slump position of your spine, stand on one leg and lift the other, lie on your back and lift one leg, and then the other, and sit quietly for a 5 minute breathing test. Following this you will be asked to perform several breathing tests (i.e. breathing into a tube) and movement tasks (i.e. lifting your leg or drawing in your lower abdomen) while electrical activity and ultrasound images of

your abdominal muscles, and shape of the bladder, are recorded, via the electrodes and ultrasound probe on your abdomen. A test will be done prior to attaching any of the electrodes to your skin to ensure that you have no reaction to the adhesive. This will involve a small amount of the tape being applied to your skin.

- **What is being tested?**

We are trying to see if ultrasound imaging can be uset to detect changes in the behavior of the abdominal wall muscles, as well as the shape of the bladder, in a normal population during various activities. This is part of a larger study in which we are investigating the potential role of ultrasound imaging in detecting these changes in people with low back pain. Ultimately the goal is to determine if ultrasound imaging can enhance the traditional physiotherapy assessment.

- **Who will perform the tests?**

All the ultrasound data will be collected by Jackie Whittaker who is a MPhil/PhD candidate in the School of Health Professions and Rehabilitation Sciences at the University of Southampton. Ms. Whittaker has 7 years of ultrasound imaging experience and has completed course work on the topic with the Burwin Institute of Diagnostic Medical Ultrasound in Canada.

- **What are the possible risks, side effects or disadvantages of taking part?**

Ultrasound Imaging - There are no known biological effects caused by exposure to ultrasound imaging however, there is a remote possibility that some may be identified in the future. To minimize any risk the investigator will apply the ultrasound in a prudent manner keeping your exposure to a minimum.

Skin Allergies - There is the possibility that you could be allergic or react to the adhesive used to attach the electrodes to your skin. To avoid this we ask you to think carefully and report any allergies to creams or tape you have used in the past. Even if you have no history of skin problems a skin test will be performed before applying the electrodes. If you have a history of skin allergies or react to the skin test (i.e. the skin becomes itchy, red or hot) it will not be possible for you to take part in this study. If you do proceed and are sensetive to the electrodes your skin could itch, become hot, or a redness and small fluid bubbles may appear but this ***rarely*** happens. If it does we will stop the study and ask you to contact your GP for advice.

Physical Activity – The activites we will ask you to do are not strenous and do not involve vigourous movements however, there is a very remote possibilty that they will result in some physical discomfort. If at any time you feel pain or discomfort you will be asked to notify the researcher and the study will be stopped. Note that sufficient rest periods will be given between activities.

- **How will my confidentially be maintained?**

On entry to the study you will be assigned a code number that will be used to identify you throughout. Your name, contact information, and code number, will be kept in a secure file cabinet to whicih only investigators will have access. Neither your name or any other identifying characteristics will be included in the results of this study.

If you have any questions, please contact Jackie Whittaker
(j.l.whittaker@soton.ac.uk) or Professor Maria Stokes (m.stokes@soton.ac.uk
Tel: 02380 596868)

UNIVERSITY OF Southampton
School of Health Professions and Rehabilitation Sciences

PARTICIPANT INFORMATION SHEET

Study Title: **Sonographic Characteristics associated with Lumbopelvic (Low Back) Pain**

Researcher: **Jackie Whittaker (PhD Candidate)** Supervisor: **Prof Maria Stokes**

Ethics number: **08-015**

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

You are invited to take part in a research project. Before you decide it is important for you to understand what the research is about. Please take time to read the following information and feel free to ask if there is anything that is not clear. This document tells you:

- The purpose of this study and what will happen to you if you take part.
- Detailed information concerning what the study is about, how it will be carried out and any potential risks.

What is the purpose of the study?
The purpose of this study is to determine if ultrasound imaging (the technique used to look at unborn babies) can identify differences in how the abdominal muscles contract and the shape / location of the bladder in persons with low back pain and in those without. The goal is to learn if ultrasound imaging can assist with assessment and direction of treatment of individuals with low back pain.

Why have I been chosen?
If you have been contacted it is because you have expressed an interest in taking part in the study.

Do I have to take part?
No you do not have to take part; it is entirely your decision. If you do, you will be asked to sign a consent form but will still be free to withdraw at any time without giving a reason for doing so. If you are currently undergoing physiotherapy treatment withdrawal will in no way interfere with this.

What will happen to me if I take part?
You will be asked to come to Whittaker Physiotherapy Consulting in Surrey, for two appointments (90 and 30 minutes in length respectively) approximately one week apart. You will be provided with precise directions and appointment times that suit both yourself and the researcher.

During the first appointment you will be asked to complete several questionnaires, undergo a short interview and physiotherapy assessment, perform a breathing test (air will be gathered through two small 1 cm tubes that will sit inside your nostrils) and lie on your back while you perform a breathing and two movement tasks (e.g. draw in your lower abdomen and lift your leg while lying on your back) and the researcher records ultrasound images from various locations on your abdomen. During the second appointment you will be asked to lie on your back while the researcher gathers 9 ultrasound images from same locations on your lower abdomen as during the first visit.

What do I have to do?
We ask that 1 hour prior to both visits you fully empty your bladder and then drink approximately 500ml (1 cup) of water. We ask that you refrain from further emptying your bladder or drinking more fluid until your visit. We also ask that you bring appropriate clothing (shorts or loose fitting track pants and loose top) to allow you to move about comfortably.

During the first visit you will be asked to fill out consent and screening forms as well as several questionnaires. This will be followed by a physiotherapy assessment during which you will be asked; to sit while your leg reflexes are tested, to perform several resisted muscle contractions (3 seconds), assume a slump position of your spine, stand on one leg and lift the other, lie on your back and lift one leg at a time, and sit quietly for a 5 minute breathing test. Following this you will be asked to lie on your back while several ultrasound images are taken from various locations on your lower abdomen while you perform a breathing and two movement tasks (e.g. draw in your lower abdomen and lift your leg while lying on your back). Finally you will be asked to fully empty your bladder after which several final ultrasound images will be taken.

During the second visit you will be asked lie on your back while 9 ultrasound images are taken from the same locations on your lower abdomen as the first visit.

What is being tested?
We are trying to see if ultrasound imaging can detect changes in how the abdominal wall muscles contract, as well as the shape and location of the bladder, in individuals with low back pain compared to those without during various clinical tests. Ultimately the goal is to determine if ultrasound imaging can enhance the traditional physiotherapy assessment and treatment.

Who will perform the tests?
All the ultrasound data will be collected by Jackie Whittaker who is an experienced physiotherapist (qualified 15 years) and a PhD candidate in the School of Health Professions and Rehabilitation Sciences at the University of Southampton, UK. Ms. Whittaker has 7 years of ultrasound imaging experience and has completed course work on the topic with the Burwin Institute of Diagnostic Medical Ultrasound in Canada.

Are there any benefits in my taking part?
There is no direct benefit to participants however you will be assisting the research team in adding to the current body of knowledge which may assist others with low back pain in the future.

What are the possible risks, side effects or disadvantages of taking part?
Ultrasound Imaging - There are no known biological effects caused by exposure to ultrasound imaging. However, there is a remote possibility that some may be identified in the future. To minimize any risk the investigator will apply the ultrasound in a prudent manner keeping your exposure to a minimum amount of time

Physical Activity – The activites we will ask you to do are not strenous and do not involve vigourous movements. However, there is a very remote possibilty that they could cause some physical discomfort. If at any time you feel pain or discomfort you will be asked to notify the researcher and the study will be stopped. Note that sufficient rest periods will be given between activities.

How will my confidentially be maintained?
On entry to the study you will be assigned a code number that will be used to identify you throughout. Your name, contact information, and code number, will be kept in a secure file cabinet to which only investigators will have access. Neither your name or any other identifying characteristics will be included in publication of the results of this study.

If you have any questions, please contact Jackie Whittaker
(j.l.whittaker@soton.ac.uk Tel: +1 604 535 5268)

APPENDIX 5a: Screening Form for Study 1 (Chapter 4)

University of Southampton

School of Health Professions and Rehabilitation Sciences

Screening Form – Sonographic Characteristics of the Abdominal and Pelvic Floor Muscles.

Name: _____ Date: _____

Height: _____cm Weight: _____Kgs

Age: _____yrs Male / Female (circle one)

Please answer the following questions to the best of your ability. Your answers will be used only to determine whether it is safe and appropriate for you to participate in this research.

	YES	NO
1. Have you ever had a previous episode of low back, pelvic, hip, or leg pain that has caused you to seek medical care (profile), result in lost work, or inability to perform recreational activities?		
2. Do you currently have low back, pelvic, hip or leg pain? 2a. If yes, are you seeking medical care for this episode of pain? 2b. If yes, have you had to miss work or stop your recreational activities?		
3. If you currently have low back/pelvic pain have you had these symptoms for longer than 3 months? (If you do not have low back or pelvic pain – answer "no")		
4. If you currently have low back/pelvic pain have you noticed your symptoms travel into your thighs, lower legs, or feet? (If you do not have low back or pelvic pain – answer "no")		
5. Do you have a history of surgery to your abdomen, lower back, pelvis or hip?		
6. Do you have a history of scoliosis, spinal bifida in your back?		
7. Do you have a history of fracture or tumor in you lower back, pelvis or hips?		
8. Are you between 18-65 years of age?		

	YES	NO
9. Do you have a chronic disease that you currently manage (for example: diabetes, multiple sclerosis, stroke, cardiovascular disease, asthma)?		
10. Are you currently pregnant? (If you are male please answer N/A)		
11. Have you been pregnant in the past? (If you are male please answer N/A) 11a. If yes how many times have you been pregnant? _____. 11b. If yes how many times have you given birth? _____. 11c. If yes how many vaginal deliveries have you had? _____. 11d. If yes how many cesarean sections have you had? _____. 11e. If yes what is the date of your last delivery? _____.		
12. Do you have any skin disease or allergy?		
13. Do you have a history of respiratory or breathing problems?		
14. Do you have a history of urinary incontinence?		
15. Are you a high level (professional, amateur or varsity) athlete?		
16. Is there any reason you believe you are not ready to perform a test that requires you to lie on your back and lift one straight leg in off the table?		
17. Are you currently involved as a subject in another research study?		

UNIVERSITY OF Southampton
School of Health Professions and Rehabilitation Sciences

SCREENING FORM (Version 1)

Study Title: **Sonographic Characteristics associated with Lumbopelvic (Low Back) Pain**

Researcher: **Jackie Whittaker (PhD Candidate)**

Supervisor: **Prof Maria Stokes** Ethics number: **08-015**

****

Subject Code: 047. **Date: _____ (mm/dd/yy)**

Height: _____cm **Weight: _____Kgs**

Age: _____yrs **Male / Female** (circle one)

Please answer the following questions to the best of your ability. Your answers will be used only to determine whether it is safe and appropriate for you to participate in this research.

	YES	NO
1. Have you had an episode of low back, pelvic, hip, or leg pain in the last year that has caused you to seek medical care (profile), result in lost work, or inability to perform recreational activities?		
2. Do you currently have low back, pelvic, hip or leg pain? 2a. If yes, are you seeking medical care for this episode of pain? 2b. If yes, have you had to miss work or stop your recreational activities?		
3. If you currently have low back/pelvic pain have you had these symptoms for longer than 6 weeks? (If you do not have low back or pelvic pain – answer "N/A")		
4. If you currently have low back/pelvic pain have you noticed your symptoms travel into your thighs, lower legs, or feet? (If you do not have low back or pelvic pain – answer "N/A")		
5. Do you have a history of surgery to your abdomen, lower back, pelvis or hip?		

	YES	NO
6. Do you have a history of scoliosis, spinal bifida in your back?		
7. Do you have a history of fracture or tumour in you lower back, pelvis or hips?		
8. Are you between 18-50 years of age?		
9. Do you have a chronic disease that you currently manage (for example: diabetes, multiple sclerosis, stroke, cardiovascular disease, asthma)?		
10. Are you currently pregnant? (If you are male please answer N/A)		
11. Have you been pregnant in the past? (If you are male please answer N/A) 11a. If yes, how many times have you been pregnant? _____. 11b. If yes, how many times have you given birth? _____. 11c. If yes, how many vaginal deliveries have you had? _____. 11d. If yes, how many caesarean sections have you had? _____. 11e. If yes, what was the date of your last delivery? _____.		
12. Do you have any skin disease or allergy?		
13. Do you have a history of respiratory or breathing problems?		
14. Do you have a history of urinary incontinence?		
15. Are you a high level (professional, amateur or varsity) athlete?		
16. Is there any reason you are not capable of lying on your back and lifting your leg off the table without bending it at the knee or balancing on one leg?		
17. Are you currently involved as a subject in another research study?		

APPENDIX 5c: Screening Form for Study 3 (Chapter 6)

Study Title: Electromyography and Sonography Assessment of Abdominal Muscle Function in Individuals with and without Lumbopelvic Pain

Primary Investigator: Linda McLean, BScPT, PhD, Associate Professor, School of Rehabilitation Therapy, Queen's University.

Co-investigator: Jackie Whittaker BScPT, PhD Candidate, School of Health Sciences, University of Southampton.

Ethics number:

Subject Code: _____ **Date:** _____ **(mm/dd/yy)**

Height: _____**cm** **Weight:** _____**Kgs**

Age: _____**yrs** **Male / Female** (circle one)

Please answer the following questions to the best of your ability. Your answers will be used only to determine whether it is safe and appropriate for you to participate in this research.

	YES	NO
1. Have you had an episode of low back, pelvic, hip, or leg pain in the last year that has caused you to seek medical care (profile), result in lost work, or inability to perform recreational activities?		
2. Do you currently have low back, pelvic, hip or leg pain? 2a. If yes, are you seeking medical care for this episode of pain? 2b. If yes, have you had to miss work or stop your recreational activities?		
3. If you currently have low back/pelvic pain have you had these symptoms for longer than 6 weeks? (If you do not have low back or pelvic pain – answer "N/A")		
4. If you currently have low back/pelvic pain have you noticed your symptoms travel into your thighs, lower legs, or feet? (If you do not have low back or pelvic pain – answer "N/A")		
5. Do you have a history of surgery to your abdomen, lower back, pelvis or hip?		
	YES	NO
6. Do you have a history of scoliosis, spinal bifida in your back?		

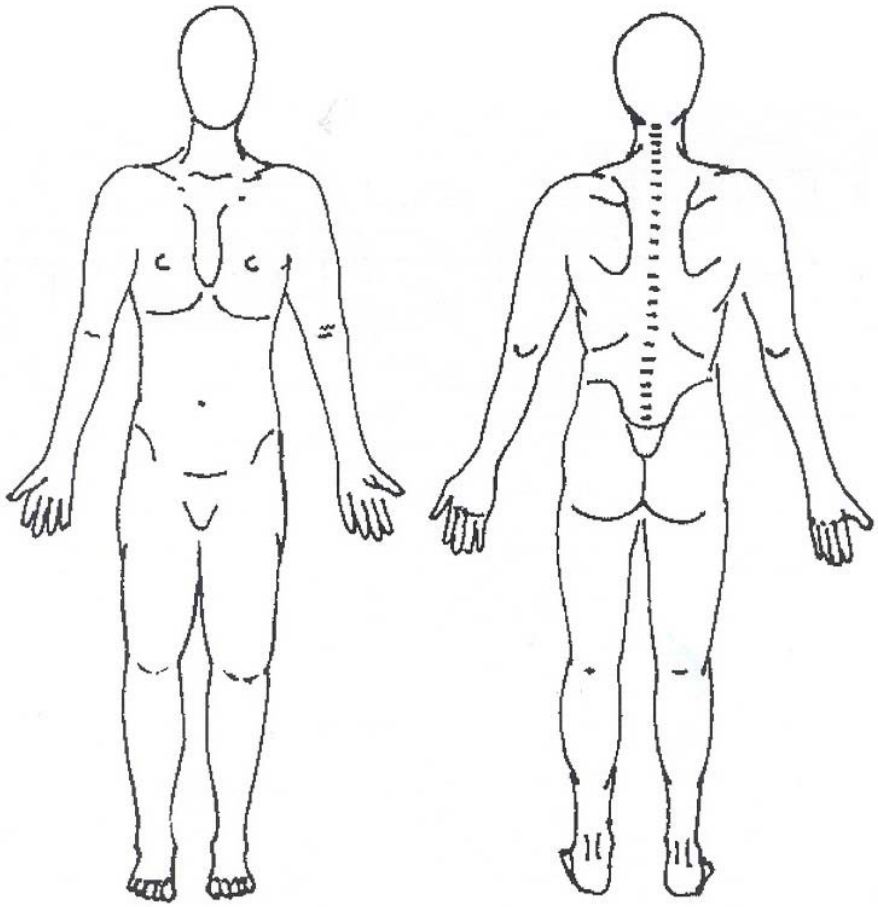
7. Do you have a history of fracture or tumour in you lower back, pelvis or hips?		
8. Are you between 18-50 years of age?		
9. Do you have a chronic disease that you currently manage (for example: diabetes, multiple sclerosis, stroke, cardiovascular disease, asthma)?		
10. Are you currently pregnant? (If you are male please answer N/A)		
11. Have you been pregnant in the past? (If you are male please answer N/A) 11a. If yes, how many times have you been pregnant? _____. 11b. If yes, how many times have you given birth? _____. 11c. If yes, how many vaginal deliveries have you had? _____. 11d. If yes, how many caesarean sections have you had? _____. 11e. If yes, what was the date of your last delivery? _____.		
12. Do you have any skin disease or allergy?		
13. Do you have a history of respiratory or breathing problems?		
14. Do you have a history of urinary incontinence?		
15. Are you a high level (professional, amateur or varsity) athlete?		
16. Is there any reason you are not capable of lying on your back and lifting your leg off the table without bending it at the knee or balancing on one leg?		
17. Are you currently involved as a subject in another research study?		

Pain Diagram and Pain Rating

Subject code #:_____ Date:_____/_____/_____
mm dd yy

Please use the diagram below to indicate the symptoms you have experienced over the past 24 hours. Use the key to indicate the type of symptoms.

Key: Pins and Needles = 000000 Stabbing = / / / / / /
Burning = xxxxxx Deep Ache = zzzzzz



Please rate your current level of pain on the following scale (check one):

0 1 2 3 4 5 6 7 8 9 10
(no pain) (worst imaginable pain)

Please rate your worst level of pain in the last 24 hours on the following scale (check one):

0 1 2 3 4 5 6 7 8 9 10
(no pain) (worst imaginable pain)

Please rate your best level of pain in the last 24 hours on the following scale (check one):

0 1 2 3 4 5 6 7 8 9 10
(no pain) (worst imaginable pain)

MODIFIED OSWESTRY LOW BACK PAIN DISABILITY QUESTIONNAIRE

Section 1: To be completed by subject

Subject code#:_____ Age:_____ Date:_____

Occupation:_____ Number of days of back pain:_____(this episode)

Section 2: To be completed by subject

This questionnaire has been designed to give your therapist information as to how your back pain has affected your ability to manage in every day life. Please answer every question by placing a mark on the line that best describes your condition today. We realize you may feel that two of the statements may describe your condition, but **please mark only the line which most closely describes your current condition**.

Pain Intensity

_____The pain is mild and comes and goes.
_____The pain is mild and does not vary much.
_____The pain is moderate and comes and goes.
_____The pain is moderate and does not vary much.
_____The pain is severe and comes and goes.
_____The pain is severe and does not vary much.

Personal Care (Washing, Dressing, etc.)

_____I do not have to change the way I wash and dress myself to avoid pain.
_____I do not normally change the way I wash or dress myself even though it causes some pain.
_____Washing and dressing increases my pain, but I can do it without changing my way of doing it.
_____Washing and dressing increases my pain, and I find it necessary to change the way I do it.
_____Because of my pain I am partially unable to wash and dress without help.
_____Because of my pain I am completely unable to wash or dress without help.

Lifting

_____I can lift heavy weights without increased pain.
_____I can lift heavy weights but it causes increased pain
_____Pain prevents me from lifting heavy weights off of the floor, but I can manage if they are conveniently positioned (ex. on a table, etc.).
_____Pain prevents me from lifting heavy weights off of the floor, but I can manage light to medium weights if they are conveniently positioned.
_____I can lift only very light weights.
_____I can not lift or carry anything at all.

Walking

_____I have no pain when walking.
_____I have pain when walking, but I can still walk my required normal distances.
_____Pain prevents me from walking long distances.
_____Pain prevents me from walking intermediate distances.
_____Pain prevents me from walking even short distances.
_____Pain prevents me from walking at all.

Sitting

_____Sitting does not cause me any pain.
_____I can only sit as long as I like providing that I have my choice of seating surfaces.
_____Pain prevents me from sitting for more than 1 hour.
_____Pain prevents me from sitting for more than 1/2 hour.
_____Pain prevents me from sitting for more than 10 minutes.
_____Pain prevents me from sitting at all.

Section 2 (con't): To be completed by subject

Standing

_____I can stand as long as I want without increased pain.
_____I can stand as long as I want but my pain increases with time.
_____Pain prevents me from standing more than 1 hour.
_____Pain prevents me from standing more than 1/2 hour.
_____Pain prevents me from standing more than 10 minutes.
_____I avoid standing because it increases my pain right away.

Sleeping

_____I get no pain when I am in bed.
_____I get pain in bed, but it does not prevent me from sleeping well.
_____Because of my pain, my sleep is only 3/4 of my normal amount.
_____Because of my pain, my sleep is only 1/2 of my normal amount.
_____Because of my pain, my sleep is only 1/4 of my normal amount.
_____Pain prevents me from sleeping at all.

Social Life

_____My social life is normal and does not increase my pain.
_____My social life is normal, but it increases my level of pain.
_____Pain prevents me from participating in more energetic activities (ex. sports, dancing, etc.)
_____Pain prevents me from going out very often.
_____Pain has restricted my social life to my home.
_____I have hardly any social life because of my pain.

Traveling

_____I get no increased pain when traveling.
_____I get some pain while traveling, but none of my usual forms of travel make it any worse.
_____I get increased pain while traveling, but it does not cause me to seek alternative forms of travel.
_____I get increased pain while traveling which causes me to seek alternative forms of travel.
_____My pain restricts all forms of travel except that which is done while I am lying down.
_____My pain restricts all forms of travel.

Employment/Homemaking

_____My normal job/homemaking activities do not cause pain.
_____My normal job/homemaking activities increase my pain, but I can still perform all that is required of me.
_____I can perform most of my job/homemaking duties, but pain prevents me from performing more physically stressful activities (ex. lifting, vacuuming)
_____Pain prevents me from doing anything but light duties.
_____Pain prevents me from doing even light duties.
_____Pain prevents me from performing any job or homemaking chores.

Section 3: To be completed by physiotherapist/researcher

SCORE:_____ or _____%

Subject code #:_____ **Date:**_____/_____/____
mm dd yy

Here are some of the things other people have told us about their pain. For each statement please circle the number from 0 to 6 to indicate how much physical activities such as bending, lifting, walking or driving affect or would affect your back pain.

	Completely Disagree			Unsure			Completely Agree
1. My pain was caused by physical activity.	0	1	2	3	4	5	6
2. Physical activity makes my pain worse.	0	1	2	3	4	5	6
3. Physical activity might harm my back.	0	1	2	3	4	5	6
4. I should not do physical activities which (might) make my pain worse.	0	1	2	3	4	5	6
5. I cannot do physical activities which (might) make my pain worse.	0	1	2	3	4	5	6

The following statements are about how your normal work affects or would affect your back pain.

	Completely Disagree			Unsure			Completely Agree
6. My pain was caused by my work or by an accident at work.	0	1	2	3	4	5	6
7. My work aggravated my pain.	0	1	2	3	4	5	6
8. I have a claim for compensation for my pain.	0	1	2	3	4	5	6
9. My work is too heavy for me.	0	1	2	3	4	5	6
10. My work makes or would make my pain worse.	0	1	2	3	4	5	6
11. My work might harm by back.	0	1	2	3	4	5	6
12. I should not do my regular work with my present pain.	0	1	2	3	4	5	6
13. I cannot do my normal work with my present pain.	0	1	2	3	4	5	6
14. I cannot do my normal work until my pain is treated.	0	1	2	3	4	5	6
15. I do not think that I will be back to my normal work within 3 months.	0	1	2	3	4	5	6
16. I do not think that I will ever be able to go back to that work.	0	1	2	3	4	5	6

FABQPA (2,3,4,5): _____/24 FABQW (6,7,9,10,11,12,15): _____/42

Subject code#:_____ _____/_____/_____
mm dd yy

Incontinence Impact Questionnaire

Has urine leakage affected your: ("X" one for each question)

	Not at all	Slightly	Moderately	Greatly
1. Ablility to do household chores (cooking, housecleaing, laundry)?	☐	☐	☐	☐
2. Physical recreation such as walking swimming or other exercise?	☐	☐	☐	☐
3. Entertainment activities (movies, concerts, etc.)?	☐	☐	☐	☐
4. Ability to travel by car or bus more than 30 minutes from home?	☐	☐	☐	☐
5. Participation in social activities outside your house?	☐	☐	☐	☐
6. Emotional health (nervousness, depression, etc.)?	☐	☐	☐	☐
7. Feeling frustrated?	☐	☐	☐	☐

Urogenital Distress Inventory

Do you exerience, and if so,
How much are you bothered by: ("X" one for each question)

	Not at all	Slightly	Moderately	Greatly
1. Frequent urination?	☐	☐	☐	☐
2. Urine leakage related to the feeling of urgency?	☐	☐	☐	☐
3. Urine leakage related to physical activity, coughing, or sneezing?	☐	☐	☐	☐
4. Small amounts of urine leakage drops?	☐	☐	☐	☐
5. Difficulty emptying your bladder?	☐	☐	☐	☐
6. Pain or discomfort in the lower abdominal or genital area?	☐	☐	☐	☐

1. Do you have any uncontrolled leakage of gas, liquid, or solid stool?

___ Yes ___ No

If yes, mark which apply

____ gas
____ liquid stool
____ solid stool

2. On a scale of 0 to 100, where zero represents death and 100 represents perfect health, please indicate how you would rate your current state of health.

___ ___ ___ Number from 0 – 100

NIJMEGEN VENTILATION QUESTIONNAIRE

Circle the score that best describes the frequency of the symptom.

SYMPTOM	NEVER	SELDOM	SOMETIMES	OFTEN	VERY OFTEN
Chest Pain	0 1		2	3	4
Feeling Tense	0 1		2	3 4	
Blurred Vision	0	1	2	3 4	
Dizziness	0	1	2	3 4	
Confusion or loss of touch with reality	0	1	2	3 4	
Fast or deep breathing	0	1	2	3 4	
Shortness of breath	0	1	2	3 4	
Tightness across the chest	0	1	2	3 4	
Bloated sensation in the stomach	0	1	2	3 4	
Tingling in fingers and hands	0	1	2	3 4	
Difficulty in breathing or taking a deep breath	0	1	2	3 4	
Stiffness or cramps in fingers and hands	0	1	2	3 4	
Tightness around the mouth	0	1	2	3 4	
Cold hands or feet	0	1	2	3 4	
Palpitation in the chest	0	1	2	3 4	
Anxiety	0	1	2	3 4	

SCORE: _____/64

ID#:_____ DATE:_____

APPENDIX 7a: Motion analysis data from the LAW and SSP imaging sites with induced transducer orientation (Study 1a, Chapter 4, Whittaker et al 2009)

LAW imaging site motion anaysis data (degrees)

Subject ID	XZ 5°	XZ 10°	XZ -5°	XZ -10°	YZ 5°	YZ 10°	YZ -5°	YZ -10°	ZZ 5°	ZZ 10°	ZZ -5°	ZZ -10°
8	1.65	2.40	1.46	0.08	1.92	1.41	0.64	1.71	6.72	12.36	0.60	2.66
9	3.47	5.33	5.37	6.35	1.10	1.94	2.58	2.26	6.75	11.13	4.23	6.16
10	0.16	0.81	0.15	0.05	1.48	1.34	0.84	0.65	4.50	9.57	3.88	7.73
11	1.05	2.26	0.86	1.58	4.35	0.68	11.77	2.64	6.20	9.38	2.56	5.00
12	0.24	0.21	0.41	0.50	0.31	0.27	2.73	4.04	4.44	10.70	1.99	6.63
13	1.49	1.68	0.58	0.14	0.15	0.50	3.08	3.26	6.06	10.65	3.62	5.39
14	0.41	0.32	2.47		0.48	0.17	3.49		1.48	3.41	5.78	
16	0.75	1.54	3.08	3.38	2.35	1.11	3.93	0.87	8.36	11.20	3.48	5.86

Subject ID	XY 5°	XY 10°	XY -5°	XY -10°	YY 5°	YY 10°	YY -5°	YY -10°	ZY 5°	ZY 10°	ZY -5°	ZY -10°
8	0.24	2.57	6.75	7.08	0.73	3.06	3.98	8.17	0.87	0.12	2.75	2.01
9	2.16	3.93	1.08	3.85	2.51	4.43	1.26	6.82	3.60	3.46	3.00	3.27
10	2.44	3.47	6.88	10.92	2.01	2.75	0.63	1.96	1.66	5.10	1.00	6.49
11	7.39	8.98	1.58	1.72	0.99	6.99	2.41	1.33	0.74	1.64	0.94	1.18
12	3.70	8.38	4.39	5.38	4.21	3.41	1.75	2.55	3.12	5.06	4.44	2.06
13	5.68	10.26	1.80	4.87	0.59	0.69	3.74	7.96	0.57	3.83	4.21	2.94
14	4.09	2.84	10.74	12.98	4.42	7.26	1.85	5.48	6.04	5.97	8.65	4.96
16	0.95	5.59	3.23	4.67	0.30	0.68	4.34	6.43	1.92	0.37	4.84	5.84

Subject ID	XX 5°	XX 10°	XX -5°	XX -10°	YX 5°	YX 10°	YX -5°	YX -10°	ZX 5°	ZX 10°	ZX -5°	ZX -10°
8	8.05	11.77	8.89	14.36	3.31	7.06	4.30	5.69	2.68	6.13	1.66	2.03
9	10.55	16.25	6.07	10.01	6.16	7.97	0.02	1.35	0.69	0.43	2.52	4.21
10	3.76	4.90	1.57	3.22	0.08	4.47	6.13	7.60	0.04	0.91	1.36	2.16
11	5.80	15.69	10.74	12.92	5.74	11.81	2.04	7.31	5.51	13.46	6.13	6.36
12	1.78	6.14	6.76	8.90	5.41	6.17	0.00	0.55	3.53	2.59	3.62	3.64
13	4.15	8.63	1.23	10.66	6.40	9.33	0.54	5.08		1.61	5.02	6.37
14	8.14	16.23	4.85	11.64	2.83	5.85	1.52	1.35	2.78	6.81	3.36	0.14
16	10.29	15.98	4.60	10.96	9.11	13.83	1.34	0.54	1.71	2.13	1.21	3.17

SSP imaging site motion anaysis data (degrees)

Subject ID	XZ 5°	XZ 10°	XZ -5°	XZ -10°	YZ 5°	YZ 10°	YZ -5°	YZ -10°	ZZ 5°	ZZ 10°	ZZ -5°	ZZ -10°
8	6.94	9.14	14.18	15.38	4.51	4.55	7.98	7.90	3.90	2.57	18.81	25.07
9	2.85	6.78	6.84	1.72	5.96	3.35	4.69	3.62	0.63	0.97	7.66	2.46
10	1.21	2.10	5.96	3.41	3.47	3.92	5.77	3.52	4.20	6.25	4.84	8.06
11	5.92	8.30	13.83	14.00	2.25	2.00	5.42	6.33	2.24	1.12	21.01	25.34
12	2.70	7.62	8.49	10.76	0.93	0.20	1.27	0.10	0.05	0.11	12.40	17.36
13	4.92	3.23	7.98	7.87	0.88	3.16	6.37	8.50	0.70	3.71	8.80	14.73
14	2.94	4.08		0.17	1.60	1.90		1.54	0.33	4.84		5.15
16	2.82	2.26	10.11	10.74	0.06	0.27	2.83	4.72	0.89	5.67	13.87	17.28

Subject ID	XY 5°	XY 10°	XY -5°	XY -10°	YY 5°	YY 10°	YY -5°	YY -10°	ZY 5°	ZY 10°	ZY -5°	ZY -10°
8	1.07	1.37	4.02	3.23	8.66	12.93	4.32	5.97	0.23	3.09	0.50	1.57
9	2.53	1.00	5.41	3.93	3.21	2.29	11.49	11.61	1.81	0.27	6.05	2.55
10	8.25	9.71	14.36	16.12	9.83	13.43	1.45	3.92	0.39	1.80	1.99	1.65
11	1.54	2.64	4.15	5.24	3.62	1.19	13.79	17.74	0.25	0.67	0.73	2.00
12	0.21	0.70	2.79	1.01	3.28	4.27	14.16	14.77	2.01	2.39	2.41	2.14
13	1.05	1.41	1.26	2.23	6.02	10.78	9.88	11.06	1.67	2.30	1.19	4.20
14	0.44	2.46		13.48	5.70	11.07		13.62	1.07	0.90		10.67
16	0.73	5.38	3.96	2.90	5.61	10.32	10.64	16.57	0.88	9.61	6.43	2.76

Subject ID	XX 5°	XX 10°	XX -5°	XX -10°	YX 5°	YX 10°	YX -5°	YX -10°	ZX 5°	ZX 10°	ZX -5°	ZX -10°
8	9.12	15.90	16.05	23.33	4.51	5.32	1.44	3.36	3.25	2.78	10.52	11.90
9	2.28	10.38	9.19	16.55	2.94	4.72	14.94	16.83	5.82	10.13	0.30	2.11
10	11.60	16.78	5.50	11.44	3.07	1.80	1.35	9.25	0.01	1.96	4.44	7.83
11	1.51	6.20							5.40	5.94	11.92	12.75
12	7.71	11.86	2.78	8.35	3.05	5.19	2.19	0.77	1.81	3.65	1.75	2.51
13	3.81	15.41	13.09	22.22	3.13	0.99	3.91	0.82	1.23	5.89	5.88	8.61
14	9.96	15.33	13.53	23.79	6.46	8.45	8.37	9.58	13.00	12.05	3.99	1.83
16	11.33	23.57	14.94	24.23	5.98	8.77	3.80	1.21	8.98	13.53	3.10	9.22

Subject ID	XZt 0	XZt NP	XZt VAL	XZt IP	Yzt 0	YZt NP	YZt VAL	YZt IP	ZZt 0	ZZt NP	ZZt VAL	ZZt IP	ZtZt 0	ZtZt NP	ZtZt VAL	ZtZt IP
8	0	1.11	3.36	1.82	0	1.21	0.28	5.49	0	0.76	4.41	0.05	0	6.70	12.85	5.98
9	0	1.71	3.06	1.21	0	1.21	3.68	1.72	0	1.38	3.93	1.24	0	5.48	14.63	6.21
10	0				0				0				0			
11	0	0.32	1.84		0	1.70	3.47		0	1.15	0.47		0	3.80	13.23	
12	0	0.36	2.00	1.87	0	0.84	2.22	0.31	0	0.16	0.09	2.92	0	2.91	16.66	2.89
13	0	0.12	2.10	1.55	0	2.17	2.43	3.99	0	1.17	1.51	2.34	0	4.54	10.11	8.66
14	0	4.97	1.75	3.74	0	7.48	4.24	1.87	0	3.12	1.76	2.33	0	14.67	9.67	4.43
16	0	0.94	1.78	3.70	0	0.68	3.74	9.75	0	1.97	0.76	2.56	0	2.09	8.60	7.17

X = x axis (+ = clockwise, - = counter clockwise rotation). Y = y axis (+ = cranial, - = caudal tilt), Z = z axis (+ = medial, - = lateral tilt), Zt = z translation (inward and outward pressure
NP = no inward transducer pressure, VAL = valsalva (outward transducer motion), IP (inward transducer pressure)
XZ 5° = x axis motion seen when attempting to move the transducer 5° about the Z axis (5° medial tilt).
The first letter = axis corresponding to the motion described, the second = axis about which the transducer was being induced.
Data corresponding to motion about the axis that was being induced.
Values not induced in analysis due to incomplete data
Positive values
Negative values

APPENDIX 7b: USI measurements of Transverus Abdominis thickness and bladder base position before and during induced changes in transducer orientation (Study 1a, Chapter 4, Whittaker et al 2009)

Transversus Abdominis thickness measurements (cm).

	Transducer position (degrees and primary axis of induced motion)																		
Subject ID	0° X	5° X	10° X	minus 5° X	minus 10° X	0° Y	5° Y	10° Y	minus 5° Y	minus10° Y	0° Z	5° Z	10° Z	minus 5° Z	minus10° Z	0Zt	no pressure	valsalva	↑ pressure
8	0.16	0.16	0.16	0.15	0.15	0.16	0.17	0.17	0.16	0.14	0.18	0.16	0.19	0.19	0.18				
9	0.32	0.32	0.38	0.38	0.35	0.31	0.34	0.34	0.33	0.33	0.31	0.28	0.32	0.36	0.36				
10	0.24	0.27	0.27	0.28	0.26	0.23	0.23	0.26	0.26	0.26	0.27	0.23	0.25	0.27	0.28				
11	0.38	0.38	0.45	0.38	0.34	0.33	0.38	0.44	0.46	0.38	0.38	0.35	0.38	0.40	0.40		no data		
12	0.28	0.25	0.26	0.28	0.27	0.25	0.28	0.27	0.28	0.27	0.28	0.28	0.27	0.28	0.28				
13	0.22	0.19	0.18	0.22	0.23	0.22	0.21	0.27	0.24	0.25	0.23	0.23	0.23	0.25	0.27				
14	0.44	0.50	0.54	0.44	0.50	0.50	0.45	0.36	0.35	0.39	0.42	0.43	0.50	0.51					
16	0.35	0.32	0.32	0.35	0.34	0.33	0.31	0.35	0.29	0.24	0.34	0.29	0.32	0.38	0.34				

Anterior / posterior (perpendicular distance from the top of the USI image to a reference point on the bladder base) sagittal bladder base measurements (cm).

	Transducer position (degrees and primary axis of induced motion)																		
Subject ID	0° X	5° X	10° X	minus 5° X	minus 10° X	0° Y	5° Y	10° Y	minus 5° Y	minus10° Y	0° Z	5° Z	10° Z	minus 5° Z	minus10° Z	0Zt	no pressure	valsalva	↑ pressure
8	10.24	10.40	10.24	10.08	10.29	9.77	9.72	9.87	9.87	10.08	9.99	10.08	9.93	10.03	10.03	9.87	10.12	10.97	9.04
9	7.90	7.96	8.20	7.09	6.65	7.72	7.60	7.60	7.84	7.88	7.72	7.72	7.76	7.57	7.72	7.92	8.36	9.51	7.49
10	8.57	7.29	7.29	7.86	7.91	8.86	7.71	7.86	8.86	9.00	8.95	9.14	9.24	8.81	8.00				
11						6.82	6.82	6.82	7.16	7.23	6.94	7.06	6.94	7.06	7.06				
12	9.50	9.27	9.27	9.64	9.34	10.34	10.40	10.50	10.18	9.91	9.5	9.59	9.80	9.70	9.48	9.43	9.86	10.34	9.21
13	11.73	11.73	11.31	12.02	12.02	11.38	11.52	12.16	11.80	11.95	11.73	11.95	12.59	11.95	12.09	11.95	12.59	13.58	11.80
14	7.03	6.90	6.93	6.60	6.33	7.50	7.03	7.00		6.83	7.53	6.60	6.37		6.50	7.70	8.10	8.63	6.60
16	6.55	6.78	6.94	6.63	6.75	6.94	6.86	6.98	6.82	6.59	6.67	6.90	6.86	6.47	6.47	6.82	7.41	7.88	6.31

Cranial / Caudal (perpendicular distance from the side of the USI image to a reference point on the bladder base) sagittal bladder base measurements (cm).

	Transducer position (degrees and primary axis of induced motion)																		
Subject ID	0° X	5° X	10° X	minus 5° X	minus 10° X	0° Y	5° Y	10° Y	minus 5° Y	minus10° Y	0° Z	5° Z	10° Z	minus 5° Z	minus10° Z	0Zt	no pressure	valsalva	↑ pressure
8	10.24	10.40	10.24	10.08	10.29	9.77	9.72	9.87	9.87	10.08	9.99	10.08	9.93	10.03	10.03	9.87	10.12	10.97	9.04
9	7.90	7.96	8.20	7.09	6.65	7.72	7.60	7.60	7.84	7.88	7.72	7.72	7.76	7.57	7.72	7.92	8.36	9.51	7.49
10	8.57	7.29	7.29	7.86	7.91	8.86	7.71	7.86	8.86	9.00	8.95	9.14	9.24	8.81	8.00				
11						6.82	6.82	6.82	7.16	7.23	6.94	7.06	6.94	7.06	7.06				
12	9.50	9.27	9.27	9.64	9.34	10.34	10.40	10.50	10.18	9.91	9.5	9.59	9.80	9.70	9.48	9.43	9.86	10.34	9.21
13	11.73	11.73	11.31	12.02	12.02	11.38	11.52	12.16	11.80	11.95	11.73	11.95	12.59	11.95	12.09	11.95	12.59	13.58	11.80
14	7.03	6.90	6.93	6.60	6.33	7.50	7.03	7.00		6.83	7.53	6.60	6.37		6.50	7.70	8.10	8.63	6.60
16	6.55	6.78	6.94	6.63	6.75	6.94	6.86	6.98	6.82	6.59	6.67	6.90	6.86	6.47	6.47	6.82	7.41	7.88	6.31

Measurements that were not used in anaysis due to incomplete data

X = x axis (+ = clockwise, - = counter clockwise rotation). Y = y axis (+ = cranial, - = caudal tilt), Z = z axis (+ = medial, - = lateral tilt), Zt = z translation (inward and outward pressure)

APPENDIX 7c: Ultrasound Transducer Motion during RESP, ADIM & ASLR Manoeuvres; Raw Data (Study 1b, Chapter 4, Whittaker et al 2010)

X (AP) AXIS ROTATION - CW & CCW Motion (degrees)

Task	ASLR												RESP				ADIM			
Imaging Site	LAW				LA				SSP				LAW				LAW			
Repetition	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
s1uvn	2.52	2.46	2.27	2.41		2.43	3.09	2.76	4.94		2.69	3.81	0.64	1.26		0.95			0.24	0.24
s2uvn	2.36	3.63	2.30	2.77	2.76	2.94	1.34	2.34	2.29	3.91	3.91	3.37	1.25	0.97	0.96	1.06	1.98	1.69	1.97	1.88
s4uvn	2.86	2.08	1.52	2.15	0.64	0.56	1.17	0.79	2.45	3.82	2.70	2.99	3.05	3.94	4.28	3.76	1.38	2.46		1.92
s5uvn	1.00	2.61	3.17	2.26	1.20	0.81	0.69	0.90	2.02	2.81		2.41	5.27	2.83	4.28	4.13	0.39	1.42	0.46	0.75
s8uvn	1.74	3.29	1.77	2.27	2.22	2.73	1.91	2.29	4.94	6.44	6.06	5.81	0.86	0.30	1.50	0.88	1.33	1.28	1.73	1.45
s9uvn	3.37	2.52	3.00	2.96	6.12	4.96	4.77	5.29	19.35	13.84	14.19	15.79	4.57	2.58	4.04	3.73		2.54	3.77	3.15
s10uvn		0.82	1.42	1.12	0.54	0.47	0.50	0.50	1.12	1.15	0.75	1.01	3.17	2.97	4.03	3.39	0.73	1.66	2.59	1.66
s11uvn	2.49	0.75	1.64	1.63	2.11	2.56	2.10	2.25	7.71	4.19	6.38	6.09	0.95	1.33	3.17	1.82	0.71	0.46	0.87	0.68
s12uvn	2.49	3.06	3.32	2.96	1.90	2.12	2.54	2.19	10.17	7.77	5.00	7.65	1.17	1.55	4.66	2.46	0.66	0.48	0.85	0.66
s13uvn	0.79	0.97	0.93	0.90	1.94	1.52	0.81	1.42	2.44	2.37	2.63	2.48	1.45	2.05	1.90	1.80	0.45	1.44	1.10	1.00
s16uvn	2.62	2.05	2.00	2.23					5.53	8.41	4.04	5.99	1.63	1.48	1.13	1.41	1.06	1.47	2.16	1.56
	0.75	3.63	0.69	2.15	0.47	6.12	1.37	2.07	0.75	19.35	4.04	5.22	0.30	5.27	1.24	2.31	0.24	3.77	0.81	1.36
	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean

Y (LR) AXIS ROTATION - Motion to head or feet (degrees)

Task	ASLR												RESP				ADIM			
Imaging Site	LAW				LA				SSP				LAW				LAW			
Repetition	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
s1uvn	1.04	1.61	1.31	1.32		2.58	4.48	3.53	1.74		1.38	1.56	1.40	2.73		2.07			1.55	1.55
s2uvn	4.34	6.38	3.08	4.60	3.28	3.10	2.65	3.01	1.60	4.18	1.81	2.53	2.72	3.23	3.97	3.31	6.10	6.37	5.72	6.06
s4uvn	4.01	4.14	3.55	3.90	2.69	3.00	1.67	2.45	2.73	1.55	1.34	1.87	2.31	2.34	2.04	2.23	3.02	1.63		2.33
s5uvn	2.88	2.42	6.49	3.93	4.47	4.14	3.62	4.07	1.47	1.29		1.38	4.91	6.53	2.51	4.65	0.55	1.74	1.11	1.13
s8uvn	1.59	2.61	4.59	2.93	3.74	2.89	2.04	2.89	5.52	2.65	4.63	4.27	0.83	0.91	2.72	1.49	2.99	1.98	1.60	2.19
s9uvn	1.09	1.48	1.67	1.41	10.28	5.89	4.45	6.87	8.15	8.28	9.92	8.78	7.00	5.85	1.24	4.70		4.36	1.58	2.97
s10uvn		3.60	3.18	3.39	5.18	4.51	4.47	4.72	1.84	2.05	2.30	2.06	3.05	3.03	3.60	3.23	6.89	2.65	3.92	4.49
s11uvn	2.85	2.11	1.34	2.10	2.37	1.09	3.38	2.28	2.34	1.22	2.43	2.00	1.92	2.44	4.36	2.90	1.67	2.22	2.33	2.07
s12uvn	1.97	1.63	1.25	1.62	2.52	1.73	1.22	1.82	4.11	2.40	1.36	2.63	7.22	4.65	6.98	6.28	3.30	1.76	4.21	3.09
s13uvn	2.54	1.03	2.51	2.03	1.70	1.54	0.95	1.40	1.81	0.75	0.94	1.17	2.75	2.30	2.74	2.60	2.62	1.77	1.71	2.04
s16uvn	2.98	1.29	2.18	2.15					3.00	1.65	1.61	2.09	3.88	2.23	3.33	3.15	2.00	1.70	0.91	1.53
	1.03	6.49	1.14	2.67	0.95	10.28	1.61	3.30	0.75	9.92	2.16	2.76	0.83	7.22	1.39	3.33	0.55	6.89	1.45	2.68
	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean

Z (CC) AXIS ROTATION - Motion to right or left (degrees)

Task	ASLR												RESP				ADIM			
Imaging Site	LAW				LA				SSP				LAW				LAW			
Repetition	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
s1uvn	6.89	7.11	5.91	6.64		6.13	5.61	5.87	8.37		4.18	6.27	0.56	1.73		1.15			0.87	0.87
s2uvn	6.05	5.20	5.12	5.46	6.00	6.91	6.36	6.42	3.16	5.85	6.31	5.11	1.11	1.53	1.42	1.35	1.10	1.36	2.12	1.53
s4uvn	2.68	2.86	2.98	2.84	2.58	2.83	2.79	2.73	3.82	4.06	2.98	3.62	3.09	4.61	4.54	4.08	1.13	0.95		1.04
s5uvn	3.19	3.53	4.62	3.78	3.14	4.06	4.10	3.77	3.79	4.62		4.21	1.58	1.96	2.86	2.13	0.82	1.11	0.97	0.97
s8uvn	5.11	5.78	3.72	4.87	3.80	4.97	4.99	4.59	7.40	8.39	6.96	7.59	0.98	1.13	1.83	1.31	2.24	1.79	1.44	1.82
s9uvn	7.12	4.32	3.71	5.05	11.03	8.72	10.87	10.20	23.21	13.92	18.22	18.45	4.04	2.95	3.66	3.55		3.11	3.38	3.24
s10uvn		2.46	2.47	2.46	2.81	2.30	2.44	2.52	2.27	2.74	2.17	2.39	2.41	3.39	2.93	2.91	1.90	1.74	1.17	1.60
s11uvn	3.80	3.23	2.87	3.30	6.11	6.72	5.68	6.17	12.37	7.27	7.46	9.03	0.96	1.46	1.52	1.31	1.54	0.93	1.25	1.24
s12uvn	4.82	4.36	3.69	4.29	2.05	3.71	3.32	3.03	10.87	8.24	9.11	9.41	5.26	1.38	2.72	3.12	1.19	0.72	2.11	1.34
s13uvn	2.29	2.61	3.29	2.73	3.59	2.07	3.32	2.99	3.31	3.87	4.08	3.75	1.80	1.32	1.15	1.43	0.47	1.54	1.11	1.04
s16uvn	6.11	5.76	5.44						8.10	10.31	6.70	8.37	1.33	1.00	2.05	1.46	0.77	1.41	0.91	1.03
	2.29	7.12	1.36	4.14	2.05	11.03	2.40	4.83	2.17	23.21	4.45	7.11	0.56	5.26	1.06	2.16	0.47	3.38	0.67	1.43
	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean

Z (CC) AXIS Translation - Inward and Outward Probe Base Motion (mm)

Task	ASLR												RESP				ADIM			
Location	LAW				LA				SBLD				LAW				LAW			
Repetition	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean	1	2	3	Mean
s1uvn	7.12	7.99	9.45	8.19	4.37	5.23	8.22	5.94	5.56	6.41	5.76	5.91	4.97	5.27	4.95	5.06	2.61	2.46	4.64	3.23
s2uvn	8.65	8.47	9.35	8.82	3.31	3.00	6.78	4.36	3.41	3.27	2.78	3.16	4.17	8.95	6.48	6.53	8.63	11.59	7.61	9.27
s4uvn	7.79	13.83	7.83	9.82	7.02	7.52	6.45	7.00	2.74	3.79	1.95	2.83	4.82	5.68	7.75	6.08	5.42	6.13	5.32	5.62
s5uvn	2.95		3.92	3.43	7.13	9.44	7.92	8.16	3.40	1.58	3.33	2.77	7.52	6.92		7.22	0.76	1.25	1.22	1.08
s8uvn	11.23	10.78	11.07	11.03	4.48	3.70	4.05	4.08	4.53	2.65	2.13	3.10	3.09	1.94	2.39	2.47	3.75	3.00	1.70	2.82
s9uvn	9.62	8.65	9.80	9.36	8.97	6.75	6.84	7.52	14.73	6.77	10.19	10.56	11.69	5.88	2.55	6.71		7.40	5.76	6.58
s10uvn	3.36	3.23	3.12	3.23	13.01	7.61	6.94	9.19	1.73	1.67	0.69	1.36	8.85	7.34	12.31	9.50	3.58	3.69	2.59	3.29
s11uvn	10.63	11.36	5.18	9.05	7.98	4.98	5.10	6.02	2.89	0.67	1.65	1.74	1.89	5.02	3.42	3.44	2.78	6.97	3.95	4.57
s12uvn	12.48	12.83	12.63	12.65	7.58	9.94	12.04	9.85	2.37	2.39	2.28	2.34	11.79	10.37	9.71	10.62	1.69	1.49	2.42	1.87
s13uvn	7.76	5.16	5.90	6.27	5.90	4.34	5.31	5.18	2.88	2.17	1.95	2.33	5.78	6.26	5.34	5.79	1.28	3.03	5.02	3.11
s16uvn	9.67	7.53	6.70	7.97		1.65	2.96	2.30	0.86	1.55	1.56	1.32	3.28	1.58	2.84	2.57	4.04	4.22	4.03	4.10
	2.95	13.83	2.90	8.17	1.65	13.01	1.96	6.73	0.67	14.73	2.68	3.40	1.58	12.31	2.60	6.00	0.76	11.59	2.31	4.14
	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean	MIN	MAX	S.D	Mean

Trials that were not used in the analysis due to incomplete data

ADIM = Abdominal Drawing in Manoeuvre, AP = Anterior posterior, LR left right, ASLR = Active Straight Leg Raise Test, CC = Cranial Caudal, CW = clockwise, CCW = counter clockwise. LA = Linea Alba imaging site, LAW = Lateral abdominal wall imaging site, MAX = maximum value, MIN = Minimum value, RESP = Respiratory task, SSP = Sagittal supra-pubic imaging site, S.D. = standard deviation,

APPENDIX 8a: Day 1 and 2 Ultrasound Imaging Measurements of Rectus Abdominis, External Oblique, Internal Oblique, Transversus Abdominis Thickness and Inter-recti Distance Supine Rest (Study 2, Chapter 5).

Participant	Rectus Abdominis (cm)					External Oblique (cm)					Internal Oblique (cm)					Transversus Abdominis (cm)					Inter-recti Distance (cm)				
CONTROL	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2
1	0.79	0.81		0.82	0.77	0.52	0.51	0.53	0.51	0.51	0.67	0.68	0.69	0.65	0.67	0.38	0.38	0.38	0.35	0.41					
17	0.78	0.80	0.81	0.89	0.87	0.33	0.31	0.30	0.29	0.27	0.53	0.53	0.55	0.41	0.45	0.29	0.27	0.31	0.22	0.21	0.57	0.59	0.51	0.59	0.49
38	0.91	0.92		0.86	0.85	0.36	0.29	0.33	0.31	0.32	0.72	0.77	0.70	0.77	0.77	0.20	0.25	0.26	0.26	0.27					
40	0.91	0.93	0.96	0.74	0.79	0.32	0.31	0.32	0.31	0.32	0.46	0.46	0.47	0.46	0.48	0.24	0.24	0.23	0.26	0.21	0.64	0.56	0.57	0.90	0.71
43	0.80	0.79	0.79	0.81	0.82	0.26	0.26	0.25	0.27	0.27	0.43	0.45	0.45	0.49	0.51	0.20	0.21	0.19	0.19	0.16					
55	0.90	0.92	0.91	0.92	0.92	0.33	0.30	0.31	0.31	0.33	0.48	0.44	0.44	0.47	0.47	0.26	0.26	0.23	0.22	0.21	1.92	2.06	2.01	2.03	1.88
60	0.69		0.73	0.71	0.74	0.29	0.29	0.32	0.34	0.32	0.37	0.39	0.39	0.41	0.39	0.22	0.19	0.18	0.15	0.15	0.20	0.24	0.20	0.23	0.22
61	1.00	1.04	1.02	1.03	1.04	0.62	0.60	0.62	0.52	0.48	0.67	0.65	0.67	0.69	0.60	0.28	0.30	0.26	0.25	0.24	1.11	1.17	1.13	0.74	0.73
63	0.89	0.92	0.86	0.96	0.94	0.30	0.28	0.26	0.29	0.30	0.54	0.51	0.52	0.56	0.58	0.20	0.23	0.21	0.22	0.22	1.11	1.09	1.10	0.90	0.91
LPP																									
3	0.84	0.84	0.84	0.62	0.61	0.47	0.56	0.56	0.52	0.57	0.67	0.66	0.65	0.72	0.70	0.50	0.45	0.54	0.42	0.46	0.74	0.66	0.57	0.70	0.61
13	0.75	0.75	0.75	0.83	0.84	0.28	0.21	0.22	0.23	0.31	0.58	0.55	0.60	0.58	0.63	0.38	0.32	0.28	0.33	0.30	1.61	1.49	1.58	0.88	0.84
16	0.81	0.78	0.78	0.77	0.77	0.32	0.28	0.28	0.27	0.28	0.40	0.39	0.38	0.36	0.37	0.24	0.23	0.25	0.22	0.21	0.48	0.82	0.50	0.48	0.46
32	0.85	0.88	0.81	0.87	0.88	0.35	0.32	0.30	0.31	0.27	0.46	0.45	0.43	0.52	0.54	0.22	0.19	0.19	0.22	0.24	0.56	0.46	0.48	0.24	0.46
33	0.92	0.95	0.95	1.00	0.96	0.40	0.38	0.40	0.42	0.43	0.50	0.55	0.55	0.56	0.57	0.18	0.19	0.23	0.20	0.17	0.76	0.88	0.75	0.34	0.30
35	0.70	0.67	0.66	0.70	0.68	0.25	0.22	0.21	0.23	0.21	0.37	0.42	0.38	0.41	0.45	0.22	0.20	0.21	0.23	0.22	3.17	2.54	2.71	1.78	2.21
42	0.64	0.74		0.81	0.76	0.35	0.35	0.36	0.38	0.36	0.55	0.57	0.59	0.59	0.59	0.27	0.27	0.29	0.27	0.28					
44	0.62	0.66	0.67	0.58	0.61	0.30	0.30	0.29	0.29	0.27	0.36	0.38	0.39	0.37	0.37	0.20	0.19	0.20	0.19	0.22	1.21	1.43	1.46	0.64	0.56
46	0.41	0.44	0.43	0.52	0.53	0.37	0.34	0.33	0.37	0.32	0.39	0.34	0.34	0.38	0.34	0.26	0.23	0.24	0.21	0.20	3.38	2.69	3.07	4.03	4.47

APPENDIX 8a: Day 1 and 2 Ultrasound Imaging Measurements of Rectus Abdominis, External Oblique, Internal Oblique, Transversus Abdominis Thickness and Inter-recti Distance ASLR Leg Hold (Study 2, Chapter 5).

Participant	Rectus Abdominis (cm)					External Oblique (cm)					Internal Oblique (cm)					Transversus Abdominis (cm)					Inter-recti Distance (cm)		
CONTROL	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3
1	0.82	0.80		0.82	0.74	0.51	0.52	0.52	0.50	0.51	0.80	0.78	0.81	0.74	0.72	0.36	0.32	0.34	0.35	0.39			
17	0.69	0.71	0.71	0.85	0.86	0.34	0.32	0.31	0.29	0.27	0.51	0.54	0.54	0.43	0.47	0.32	0.28	0.29	0.24	0.23	0.59	0.47	0.60
38	0.92	0.97		0.88	0.85	0.33	0.32	0.33	0.32	0.34	0.90	0.90	0.76	1.02	1.00	0.33	0.32	0.28	0.36	0.38			
40	0.94	1.02	1.01	0.81	0.83	0.31	0.33	0.32	0.31	0.31	0.56	0.58	0.56	0.59	0.57	0.22	0.25	0.22	0.23	0.21	0.66	0.59	0.54
43	0.72	0.78	0.80	0.78	0.77	0.23	0.22	0.20	0.24	0.24	0.46	0.47	0.46	0.48	0.50	0.22	0.24	0.21	0.22	0.20			
55	0.99	0.97	0.97	0.92	0.92	0.31	0.30	0.30	0.33	0.33	0.45	0.48	0.48	0.49	0.49	0.30	0.23	0.26	0.24	0.25	1.94	2.02	2.01
60	0.71		0.73	0.73	0.77	0.28	0.29	0.34	0.30	0.29	0.44	0.44	0.46	0.44	0.43	0.23	0.22	0.24	0.20	0.21	0.26	0.24	0.23
61	1.13	1.07	1.06	1.03	1.04	0.57	0.59	0.61	0.52	0.49	0.72	0.66	0.75	0.72	0.63	0.41	0.34	0.29	0.31	0.29	0.98	0.95	0.90
63	0.79	0.82	0.82	0.87	0.88	0.27	0.26	0.25	0.28	0.28	0.56	0.55	0.56	0.60	0.63	0.28	0.25	0.31	0.30	0.27	1.19	1.18	1.13
LPP																							
3	0.81	0.79	0.82	0.57	0.58	0.50	0.55	0.54	0.57	0.52	0.76	0.69	0.68	0.78	0.75	0.40	0.48	0.50	0.46	0.46	0.72	0.56	0.79
13	0.79	0.88	0.89	0.89	0.89	0.34	0.30	0.33	0.28	0.26	0.68	0.77	0.80	0.65	0.83	0.27	0.29	0.28	0.32	0.38	0.86	0.81	0.84
16	0.78	0.75	0.79	0.77	0.76	0.34	0.27	0.30	0.33	0.31	0.41	0.40	0.41	0.39	0.39	0.28	0.28	0.34	0.23	0.22	0.64	0.58	0.40
32	0.87	0.88	0.84	0.89	0.89	0.26	0.31	0.28	0.29	0.28	0.55	0.53	0.51	0.63	0.59	0.20	0.19	0.19	0.24	0.20	0.64	0.56	0.42
33	0.98	0.99	0.99	1.03	1.02	0.35	0.33	0.42	0.37	0.49	0.60	0.59	0.65	0.66	0.57	0.20	0.20	0.21	0.21	0.18	0.55	0.61	0.68
35	0.70	0.68	0.66	0.72	0.67	0.23	0.22	0.22	0.24	0.21	0.51	0.51	0.54	0.58	0.59	0.28	0.25	0.26	0.32	0.26	2.48	2.81	2.22
42	0.64	0.72		0.81	0.81	0.35	0.35	0.35	0.37	0.36	0.55	0.54	0.54	0.56	0.60	0.31	0.30	0.31	0.29	0.33			
44	0.71	0.76	0.78	0.68	0.72	0.27	0.26	0.28	0.23	0.25	0.44	0.47	0.47	0.46	0.44	0.22	0.22	0.22	0.29	0.26	1.18	0.95	1.10
46	0.43	0.45	0.43	0.54	0.55	0.33	0.39	0.39	0.35	0.32	0.49	0.44	0.47	0.46	0.51	0.30	0.34	0.34	0.25	0.26	2.81	2.47	1.97

APPENDIX 8b: Day 1 and 2 Ultrasound Imaging Measurements of Rectus Abdominis, External Oblique, Internal Oblique, Transversus Abdominis Thickness and Inter-recti Distance Crook Ly Rest (Study 2, Chapter 5).

Participant	Rectus Abdominis (cm)					External Oblique (cm)					Internal Oblique (cm)					Transversus Abdominis (cm)					Inter-recti Distance (cm)		
CONTROL	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3
1	0.78	0.68		0.82	0.80	0.37	0.43		0.44	0.43	0.51	0.58		0.60	0.60	0.26	0.22		0.27	0.31	0.61	0.57	0.52
17	0.96	0.85	0.81	0.85	0.85	0.29	0.29	0.24	0.28	0.26	0.42	0.44	0.47	0.40	0.40	0.20	0.20	0.24	0.15	0.20	0.35	0.32	0.30
38	0.91	0.97		0.91	0.87	0.30	0.29		0.28	0.28	0.75	0.72		0.81	0.81	0.25	0.29		0.27	0.30	0.54	0.53	0.49
40	0.89	0.88	0.89	0.94	0.94	0.38	0.35	0.35	0.36	0.32	0.50	0.50	0.51	0.49	0.48	0.21	0.20	0.24	0.25	0.19	1.17	1.09	1.07
43	0.78	0.76		0.86	0.86	0.28	0.28		0.31	0.32	0.50	0.50		0.54	0.52	0.27	0.23		0.18	0.23	0.79	0.79	0.77
55	0.87	0.83	0.86			0.30	0.34	0.34	0.32	0.33	0.42	0.43	0.48	0.33	0.46	0.22	0.24	0.26	0.20	0.20	2.15	2.12	2.16
60	0.76	0.81	0.77	0.81	0.75	0.26	0.31	0.30	0.31	0.35	0.42	0.38	0.39	0.38	0.39	0.21	0.24	0.23	0.22	0.24	0.54	0.60	0.54
61	1.07	1.06	1.02	1.09	1.09	0.64	0.63	0.64	0.47	0.44	0.64	0.65	0.65	0.60	0.58	0.28	0.33	0.31	0.33	0.31	2.12	2.23	1.70
63	1.07	1.06	1.02	1.09	1.09	0.36	0.35	0.36	0.36	0.34	0.52	0.52	0.55	0.57	0.57	0.20	0.23	0.26	0.29	0.24	0.67	0.60	0.65
LPP																							
3	0.67	0.72	0.70	0.59	0.61	0.27	0.26	0.26	0.29	0.29	0.32	0.30	0.32	0.35	0.40	0.26	0.32	0.29	0.27	0.29	0.60	0.64	0.64
13	0.70	0.71	0.67	0.74	0.70	0.41	0.41	0.40	0.32	0.35	0.63	0.63	0.65	0.51	0.49	0.30	0.23	0.29	0.31	0.27	2.44	2.45	2.43
16	0.83	0.84	0.85	0.82	0.83	0.32	0.32	0.32	0.30	0.28	0.39	0.37	0.37	0.32	0.40	0.23	0.22	0.23	0.26	0.23	0.47	0.40	0.62
32	0.90	0.90	0.93	0.91	0.88	0.36	0.31	0.32	0.33	0.38	0.47	0.51	0.50	0.47	0.53	0.23	0.24	0.22	0.20	0.23	0.38	0.40	0.41
33	0.94	0.94	0.92	0.85	0.88	0.40	0.38	0.41	0.44	0.42	0.49	0.52	0.53	0.51	0.48	0.28	0.26	0.27	0.20	0.23	0.38	0.39	0.37
35	0.73	0.70	0.64	0.70	0.67	0.20	0.18	0.21	0.26	0.27	0.38	0.39	0.41	0.42	0.42	0.21	0.21	0.21	0.23	0.21	2.39	2.37	2.24
42	0.81	0.81		0.82	0.83	0.35	0.36		0.41	0.41	0.53	0.57		0.64	0.61	0.29	0.27		0.31	0.31	0.83	0.73	0.68
44	0.66	0.66	0.69	0.63	0.65	0.19	0.19	0.17	0.21	0.19	0.37	0.37	0.40	0.40	0.42	0.20	0.23	0.25	0.28	0.28	1.22	1.26	1.18
46	0.46	0.44	0.54	0.51	0.55	0.30	0.35	0.31	0.30	0.30	0.34	0.36	0.33	0.32	0.32	0.28	0.28	0.23	0.25	0.25	2.30	2.39	2.23

APPENDIX 8b: Day 1 and 2 Ultrasound Imaging Measurements of Rectus Abdominis, External Oblique, Internal Oblique, Transversus Abdominis Thickness and Inter-recti Distance ADIM Hold (Study 2, Chapter 5).

Participant	Rectus Abdominis (cm)					External Oblique (cm)					Internal Oblique (cm)					Transversus Abdominis (cm)					Inter-recti Distance (cm)		
CONTROL	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3	Day 2/1	Day 2/2	Day1/1	Day 1/2	Day1/3
1	0.82	0.63		0.84	0.78	0.41	0.42		0.44	0.45	0.53	0.58		0.59	0.59	0.42	0.40		0.37	0.41			
17	0.79	0.83	0.82	0.80	0.84	0.23	0.26	0.22	0.24	0.21	0.43	0.45	0.51	0.38	0.40	0.36	0.34	0.43	0.28	0.28	0.28	0.28	0.26
38	0.85	0.94		0.88	0.82	0.31	0.30		0.26	0.28	0.75	0.67		0.80	0.81	0.38	0.41		0.39	0.42			
40	0.86	0.93	0.92	0.86	0.95	0.37	0.35	0.38	0.35	0.33	0.51	0.48	0.48	0.46	0.46	0.35	0.34	0.32	0.28	0.28	1.01	0.95	0.93
43	0.78	0.73		0.85	0.85	0.25	0.27		0.20	0.25	0.49	0.52		0.58	0.56	0.36	0.39		0.31	0.34			
55	0.44	0.43	0.46			0.29	0.31	0.35	0.34	0.34	0.53	0.50	0.53	0.34	0.46	0.47	0.42	0.42	0.38	0.41	1.68	1.69	1.67
60	0.71	0.68	0.71	0.75	0.71	0.30	0.33	0.32	0.33	0.38	0.41	0.43	0.38	0.38	0.48	0.37	0.37	0.40	0.31	0.32	0.52	0.58	0.48
61	1.06	1.03	1.05	1.04	1.02	0.52	0.61	0.70	0.51	0.52	0.69	0.66	0.66	0.64	0.66	0.42	0.43	0.44	0.45	0.48	2.08	2.18	1.69
63	0.85	0.89	0.88	0.87	0.87	0.29	0.30	0.30	0.26	0.25	0.63	0.61	0.62	0.62	0.62	0.39	0.34	0.41	0.45	0.43	0.68	0.62	0.66
LPP																							
3	0.68	0.66	0.65	0.57	0.59	0.28	0.28	0.23	0.28	0.27	0.36	0.30	0.36	0.38	0.39	0.32	0.43	0.39	0.36	0.40	0.51	0.48	0.48
13	0.61	0.62	0.64	0.67	0.71	0.46	0.42	0.39	0.28	0.34	0.63	0.58	0.58	0.56	0.52	0.55	0.45	0.29	0.48	0.50	2.69	2.68	2.55
16	0.81	0.81	0.81	0.84	0.82	0.32	0.32	0.36	0.25	0.28	0.34	0.38	0.28	0.33	0.35	0.49	0.42	0.43	0.40	0.27	0.56	0.48	0.38
32	0.87	0.87	0.89	0.93	0.96	0.35	0.30	0.33	0.34	0.37	0.48	0.54	0.46	0.48	0.55	0.29	0.31	0.35	0.34	0.36	0.28	0.32	0.31
33	0.92	0.92	0.91	0.83	0.88	0.36	0.37	0.36	0.39	0.42	0.52	0.57	0.55	0.55	0.56	0.29	0.29	0.37	0.27	0.30	0.33	0.41	0.40
35	0.62	0.70	0.64	0.58	0.69	0.16	0.20	0.21	0.23	0.27	0.47	0.45	0.44	0.37	0.40	0.32	0.31	0.34	0.47	0.49	0.33	0.36	0.28
42	0.82	0.82		0.78	0.82	0.35	0.36		0.41	0.42	0.53	0.59		0.59	0.56	0.35	0.35		0.40	0.40			
44	0.64	0.64	0.64	0.66	0.61	0.19	0.17	0.19	0.21	0.20	0.38	0.37	0.35	0.43	0.40	0.31	0.38	0.44	0.43	0.42	1.21	1.18	1.23
46	0.44	0.43	0.46	0.53	0.56	0.30	0.33	0.32	0.31	0.31	0.30	0.35	0.29	0.27	0.27	0.38	0.38	0.37	0.37	0.37	2.20	2.31	2.19

APPENDIX 8c: Day 1 and 2 Ultrasound Imaging Measurements Bladder and Bladder Base Motion during an ADIM (Study 2, Chapter 5).

Participant	Bladder (cm)															Bladder Base (cm)															Bladder Base (relative to the bladder; cm)														
	Day1/1			Day 1/2			Day1/3			Day2/1			Day 2/2			Day1/1			Day 1/2			Day1/3			Day2/1			Day 2/2			Day1/1			Day 1/2			Day1/3			Day2/1			Day 2/2		
CONTROL	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T
1	0.35	0.07	0.05	0.35	0.10	0.10	0.52	0.16	0.15	0.29	0.15	0.14	0.18	0.15	0.23	-0.22	-0.29	-0.09	-0.18	-0.34	-0.05	-0.09	-0.34	-0.14	-0.15	-0.23	-0.12	-0.08	-0.32	-0.05	0.07	-0.15	-0.21	0.09	-0.19	-0.34	0.18	-0.25	-0.24	0.00	-0.06	-0.21	0.10	-0.09	-0.15
17	0.27	0.30	0.27	0.34	0.23	0.15	0.30	0.22	0.18	0.07	0.11	0.19	0.09	0.07	0.14	-0.01	0.39	0.22	0.11	0.39	0.17	0.07	0.34	0.30	-0.05	0.32	0.39	0.10	0.19	0.19	0.19	-0.64	-0.17	0.33	-0.53	-0.18	0.31	-0.63	-0.24	0.46	-0.31	-0.11	0.23	-0.59	-0.20
38	0.18	0.05	0.09	0.19	0.09	0.14				0.14	0.18	0.10	0.31	0.22	0.23	-0.11	0.04	0.24	-0.09	0.07	0.11				-0.12	0.15	0.12	-0.10	0.07	0.03	0.20	-0.24	0.12	0.09	-0.18	0.06				0.24	-0.13	0.03	0.07	-0.20	0.17
40	0.70	0.35	0.20	0.28	0.30	0.16	0.61	0.40	0.23	0.36	0.18	0.11	0.36	0.18	0.11	-0.32	-0.38	-0.15	-0.36	-0.20	-0.13	-0.34	-0.41	-0.07	-0.18	-0.28	-0.15	-0.15	-0.35	-0.05	0.19	-0.24	-0.21	0.03	-0.17	-0.24	0.05	-0.31	-0.22	0.03	-0.23	-0.20	0.13	-0.10	-0.23
43	0.15	0.15	0.14	0.13	0.20	0.16				0.32	0.20	0.25	0.40	0.27	0.17	-0.12	-0.25	-0.12	-0.09	-0.16	-0.13				-0.09	-0.16	-0.13	-0.09	-0.24	-0.09	0.17	-0.14	-0.04	0.09	-0.07	-0.12				0.11	-0.18	-0.09	0.11	-0.06	-0.15
55	0.16	0.20	0.18	0.08	0.24	0.29	0.22	0.17	0.23	0.20	0.20	0.14	0.28	0.27	0.00	-0.03	0.03	0.13	-0.03	-0.03	0.06	-0.06	0.03	0.14	-0.05	0.07	0.24	-0.03	0.04	0.32	0.06	-0.27	-0.13	0.06	-0.32	-0.09	0.03	-0.23	-0.18	0.10	-0.23	-0.13	0.42	-0.27	-0.13
60	0.27	0.04	0.06	0.41	0.24	0.07	0.55	0.17	0.13	0.53	0.15	0.12	0.35	0.10	0.10	-0.12	-0.33	-0.16	-0.20	-0.23	-0.11	-0.18	-0.45	-0.28	-0.15	-0.21	-0.09	-0.12	-0.37	-0.41	0.20	-0.24	-0.33	0.13	-0.33	-0.46	0.23	-0.25	-0.42	0.32	-0.29	-0.46	0.20	-0.25	-0.31
61	0.11	0.10	0.09	0.17	0.08	0.70	0.03	0.10	0.06	0.06	0.16	0.11	0.15	0.13	0.05	-0.12	-0.23	-0.03	0.00	-0.06	0.03	0.03	-0.09	0.06	-0.13	0.23	0.16	-0.33	-0.27	0.13	-0.17	-0.27	-0.14	-0.13	-0.15	-0.09	-0.06	-0.23	-0.05	-0.16	-0.09	0.05	-0.10	-0.18	-0.18
63	1.48	0.48	0.25	1.30	0.55	0.18				0.35	0.48	0.11	0.50	0.65	0.18	-0.32	-0.67	-0.54	-0.24	-0.64	-0.44				-0.19	-0.35	-0.67	-0.25	-0.55	-0.65	0.22	-0.49	-0.94	0.24	-0.50	-0.88				0.16	-0.47	-0.74	0.13	-0.40	-0.87
LPP																																													
3	0.16	0.26	0.28	0.09	0.30	0.32	0.28	0.32	0.20	0.57	0.11	0.17	0.40	0.20	0.29	-0.25	-0.15	0.09	-0.20	-0.08	0.17	-0.17	-0.23	0.12	-0.23	-0.12	0.12	-0.37	-0.08	0.04	0.13	-0.53	-0.45	0.15	-0.46	-0.38	0.08	-0.43	-0.41	0.25	-0.58	-0.44	0.16	-0.54	-0.43
13	0.50	0.20	0.17	0.37	0.12	0.16	0.36	0.12	0.12							-0.11	-0.35	0.15	0.00	-0.41	0.07	-0.11	-0.42	0.09							-0.04	0.25	0.18	-0.17	0.30	0.13	-0.02	0.26	0.06						
16	0.27	0.20	0.18	0.26	0.13	0.21	0.15	0.24	0.33	0.17	0.12	0.23	0.50	0.15	0.21	-0.25	-0.38	0.20	-0.31	-0.19	0.24	-0.40	-0.26	0.16	-0.38	-0.05	0.25	-0.39	-0.25	0.12	0.15	-0.39	-0.48	0.36	-0.27	-0.38	0.27	-0.29	-0.36	0.03	-0.64	-0.52	0.12	-0.50	-0.38
32	0.15	0.28	0.16	0.57	0.33	0.12	0.75	0.33	0.18	0.36	0.22	0.24	0.40	0.47	0.18	-0.38	-0.28	0.22	-0.42	-0.46	0.24	-0.32	-0.43	0.32	-0.46	-0.25	0.25	-0.24	-0.30	0.21	-0.22	-0.54	-0.29	-0.29	-0.63	-0.33	-0.23	-0.54	-0.23	-0.23	-0.57	-0.24	-0.13	-0.43	-0.26
33	0.11	0.11	0.13	0.37	0.13	0.27	0.18	0.09	0.11	0.06	0.08	0.14	0.14	0.16	0.22	0.08	0.05	-0.08	0.14	0.08	-0.22	0.21	0.18	-0.12	-0.04	-0.02	-0.18	-0.02	-0.02	-0.14	0.00	0.07	0.11	-0.28	0.11	0.26	-0.18	0.19	0.15	-0.38	0.03	0.08	-0.08	0.05	0.08
35	0.94	0.27	0.16	0.15	0.21	0.22	0.26	0.20	0.21	0.79	0.30	0.05	1.08	0.11	0.17	-0.62	-1.03	-0.16	-0.52	-1.15	-0.25	-0.69	-1.06	-0.47	-0.62	-1.08	-0.21	-0.71	-1.25	-0.25	0.35	-0.16	-0.42	0.41	-0.07	-0.51	0.67	-0.15	-0.52	0.38	-0.24	-0.66	0.27	-0.17	-0.55
42	0.10	0.09	0.10	0.03	0.06	0.05				0.27	0.03	0.03	0.35	0.14	0.22	-0.10	-0.10	-0.05	-0.10	-0.24	-0.07				-0.22	-0.20	-0.02	-0.24	-0.30	-0.08	-0.07	-0.14	-0.07	-0.07	-0.05	-0.16				-0.04	-0.08	-0.11	-0.06	-0.11	-0.08
44	0.15	0.16	0.11	0.61	0.25	0.08	0.55	0.34	0.13	0.18	0.09	0.12	0.21	0.04	0.06	-0.57	-0.53	-0.07	-0.61	-0.42	0.00	-0.56	-0.56	-0.16	-0.55	-0.45	-0.07	-0.48	-0.33	-0.10	-0.24	-0.11	-0.17	-0.07	-0.14	-0.14	-0.03	-0.19	-0.26	0.00	-0.07	-0.07	-0.17	-0.31	-0.20
46	0.27	0.12	0.16	0.77	0.21	0.22	0.44	0.23	0.19	0.06	0.03	0.07				-0.40	-0.24	0.16	-0.27	-0.16	0.10	-0.36	-0.32	0.06	0.17	-0.06	-0.08				-0.10	-0.39	-0.11	0.02	-0.22	-0.27	-0.10	-0.37	-0.18	-0.02	0.00	0.00			

APPENDIX 8c: Day 1 and 2 Ultrasound Imaging Measurements Bladder and Bladder Base Motion during an ASLR (Study 2, Chapter 5).

Participant	Bladder (cm)									Bladder Base (cm)									Bladder Base (relative to the bladder; cm)								
	Day1/1			Day 1/2			Day1/3			Day1/1			Day 1/2			Day1/3			Day1/1			Day 1/2			Day1/3		
CONTROL	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T	X	Y	T
1	0.63	0.41	0.25	0.38	0.26	0.16				0.25	-0.07	-0.02	0.12	-0.07	-0.09				0.25	0.19	0.09	0.16	0.06	-0.09			
17	0.10	0.21	0.13	0.07	0.22	0.06	0.55	0.28	0.26	-0.15	0.01	0.03	-0.09	-0.25	0.09	-0.27	-0.19	0.00	0.25	0.06	0.06	0.14	0.08	0.02	0.14	-0.02	-0.04
38	0.69	0.26	0.11	0.65	0.46	0.08				-0.17	-0.23	-0.13	-0.13	-0.33	-0.17				0.21	-0.11	-0.39	0.12	-0.28	-0.54			
40	0.40	0.31	0.13	0.42	0.31	0.06	0.38	0.36	0.16	0.02	0.00	0.00	-0.02	0.00	0.02	0.00	-0.02	-0.05	0.15	-0.23	-0.23	0.07	-0.07	-0.33	0.02	-0.17	-0.14
43	0.47	0.34	0.15	0.66	0.60	0.29				-0.34	-0.34	-0.38	-0.40	-0.38	-0.36				0.00	-0.15	-0.11	-0.03	-0.11	-0.13			
55	0.93	0.54	0.14	0.88	0.51	0.29	0.89	0.66	0.27	-0.55	-0.42	-0.55	-0.39	-0.55	-0.58	-0.23	-0.57	-0.76	-0.60	-0.19	-0.57	-0.56	-0.24	-0.33	-0.67	-0.28	-0.41
60	0.54	0.30	0.02	0.64	0.39	0.00	0.52	0.12	0.09	-0.12	-0.21	-0.21	-0.28	-0.37	-0.33	-0.19	-0.35	-0.12	-0.05	-0.23	-0.17	-0.07	-0.31	-0.25	0.05	-0.29	-0.35
61	0.17	0.12	0.25	0.21	0.25	0.25	0.36	0.25	0.27	-0.03	-0.17	0.11	-0.23	-0.30	0.12	-0.06	-0.13	0.20	0.29	-0.04	0.04	0.06	-0.23	-0.02	0.26	0.00	0.00
63	0.36	0.25	0.14	0.28	0.19	0.10	0.39	0.25	0.20	-0.08	-0.18	-0.16	-0.08	-0.29	-0.23	-0.10	-0.12	-0.14	0.14	-0.09	-0.39	0.08	-0.09	-0.24	0.10	-0.32	-0.29
LPP																											
3	0.19	0.06	0.10	0.15	0.05	0.14				-0.04	0.00	0.09	-0.21	-0.08	0.09				0.11	-0.08	-0.16	0.04	-0.22	-0.18			
13	1.55	0.21	0.36	0.91	0.26	0.40	1.83	0.32	0.21	-0.38	-1.40	-0.13	-0.31	-1.59	-0.08	-0.38	-1.62	-0.28	0.19	-0.38	-0.56	0.55	-0.29	-0.53	0.24	-0.28	-0.74
16	0.51	0.35	0.04	0.53	0.33	0.05	0.45	0.16	0.17	-0.17	0.10	0.12	-0.07	-0.02	0.11	0.22	0.00	0.08	0.15	-0.02	0.00	0.23	0.00	-0.02	0.27	-0.05	0.05
32	1.54	1.53	0.09	1.34	1.04	0.24	1.53	1.56	0.19	-0.60	-1.27	-1.17	-0.76	-1.09	-0.98	-0.54	-1.21	-1.13	0.06	-0.59	-0.81	0.21	-0.57	-0.87	0.04	-0.65	-1.15
33	0.70	0.58	0.16	0.57	0.45	0.06	0.60	0.30	0.22	-0.63	-0.98	-0.43	-0.47	-0.77	-0.30	-0.52	-0.63	-0.27	0.37	-0.37	-0.50	0.23	-0.50	-0.43	0.03	-0.42	-0.32
35	0.38	0.51	0.07	0.40	0.35	0.12	0.25	0.07	0.21	-0.41	-0.49	-0.29	-0.28	-0.67	-0.42	-0.38	-0.53	-0.31	0.11	0.09	0.06	0.13	0.06	0.03	0.36	0.26	-0.12
42	0.46	0.38	0.21	0.48	0.43	0.16				-0.33	-0.30	-0.45	-0.37	-0.32	-0.49				-0.02	-0.59	-0.46	0.09	-0.55	-0.43			
44	0.66	0.61	0.38	1.15	1.09	0.49	1.01	1.10	0.33	-0.25	-1.15	-1.04	-0.32	-1.27	-1.27	-0.49	-1.00	-1.27	-0.57	-0.21	-0.59	-0.63	-0.36	-0.90	-0.34	-0.26	-0.74
46	0.68	0.49	0.21	0.87	0.69	0.25	0.77	0.58	0.13	-0.35	-0.56	-0.54	-0.33	-0.77	-0.55	-0.48	-0.53	-0.43	-0.21	0.29	-0.89	-0.03	-0.30	-0.93	0.15	-0.49	-1.29

Appendix 9a: ASLR Cross-correlation co-efficient and Time lag data for Participants in Study 3 (Chapter 6)								
Participant	**RA**		**EO**		**IO**		**TrA**	
	Correlation	**Time lag**	**Correlation**	**Time lag**	**Correlation**	**Time lag**	**Correlation**	**Time lag**
Control	**(r value)**	**(s)**	**(r value)**	**(s)**	**(r value)**	**(s)**	**(r value)**	**(s)**
1	0.16	1.18	0.26	1.94	0.23	1.47	0.35	-1.00
2	0.16	5.70	0.25	-2.53	0.21	-2.53	0.52	-2.53
3	0.32	-2.18	0.27	-3.47	0.32	-3.47	0.42	-3.47
5	0.27	0.24	0.26	5.76	0.27	5.76	0.18	5.76
7	0.21	-1.06	0.34	2.94	0.28	2.94	0.35	2.94
8			0.13	-1.88	0.13	5.53	0.33	5.82
11	0.19	-0.18						
LPP								
9	0.22	2.35	0.27	0.41	0.23	0.41	0.29	0.41
13	0.31	2.35	0.26	-0.82	0.56	-0.82	0.36	-0.82
14	0.17	1.59	0.23	0.76	0.37	0.76	0.32	0.76
15	0.19	0.65	0.33	-0.47	0.34	2.41	0.24	3.59
16	0.51	2.35	0.23	-0.76	0.30	-0.76	0.26	-0.76
17	0.41	-0.65	0.31	1.71	0.29	1.71	0.25	1.71
18	0.17	-0.76	0.25	-1.76	0.29	-1.76	0.42	-1.76

ASLR = active straight leg raise, EO = external oblique, IO = internal oblique, RA = rectus abdominins, s = seconds, TrA = transversus abdominins

Appendix 9a: ADIM Cross-correlation and Time lag data for Participants in Study 3 (Chapter 6)								
Participant	**RA**		**EO**		**IO**		**TrA**	
	Correlation	**Time lag**	**Correlation**	**Time lag**	**Correlation**	**Time lag**	**Correlation**	**Time lag**
Control	**(r value)**	**(s)**	**(r value)**	**(s)**	**(r value)**	**(s)**	**(r value)**	**(s)**
1			0.38	-3.18	0.36	-3.18	0.42	-3.18
2	0.16	1.12						
3	0.35	-5.76						
5	0.48	-5.23	0.42	-1.41	0.62	-1.41	0.47	-1.41
7								
8	0.34	10.58	0.17	-0.24	0.29	-0.24	0.24	-0.24
11	0.17	3.65	0.22	3.06	0.29	3.06	0.26	3.06
LPP								
9	0.22	0.06	0.39	-3.18	0.39	-3.18	0.48	-3.18
13	0.27	7.64	0.45	-0.76	0.45	-0.76	0.56	-0.76
14			0.44	4.76	0.44	4.76	0.40	4.76
15	0.22	-0.12	0.26	2.88	0.26	2.88	0.40	2.88
16	0.56	-1.41	0.33	0.53	0.33	0.53	0.42	0.53
17	0.20	-1.12	0.28	-4.59	0.28	-4.59	0.34	-4.59
18	0.49	1.82	0.31	6.17	0.31	6.17	0.15	6.17

ADIM = abdominal drawing in manoeuvre, EO = external oblique, IO = internal oblique, RA = rectus abdominins, s = seconds, TrA = transversus abdominins

```
% measures every second frame and calculates fascial thickness between EO
% and IO as well as IO and TrA. The results for the fascial measurements
% are apended to the 'Results' varialbe i.e. columns 4 and 5.

clear all;
close all;
s=pwd;

Y1=122;
Y2=650;

X1=150;
X2=800;


% Use this line to set the default directory for data files if this is not
% the same as the directory in which program is installed

%cd('C:\Matlab\Ultrasonic images')

% Prompt operator for file to be anaysed:

[ImageA,Pathname]=uigetfile('*.avi','Select file to be analysed');

[vid] = mmread([Pathname ImageA]); %New line for mmread
% fileinfo = aviinfo([Pathname ImageA]); %commented out as mmread is
%     now used

% Work out number of frames in file:

% NumFrames=fileinfo.NumFrames;


% Ensure root units are pixels and get the size of
% the screen:
    set(0,'Units','pixels') ;
    scnsize = get(0,'ScreenSize');

S=input('Please enter start frame');
F=input('Please enter last frame');
Fl=ceil((F-S)/2);

mov = vid.frames(S); %New line for mmread
% mov = aviread([Pathname ImageA],S); %commented out as mmread is
%     now used

cross=5.0;

fig = figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize(3)/6 4*scnsize(4)/6]);
```

```
Maximize(fig);
image(mov.cdata(Y1:Y2,X1:X2,:))
title(ImageA)
hold on

% Image calibration
scale=ginput(2);
yscale=abs((scale(2,2)-scale(1,2)));
ystep=yscale;


%plotting measurement line
[xselect,yselect] = ginput(1);
x1=round(xselect);
y(1,1) = yselect;
plot( [x1 x1],[0 380],'g','LineWidth',.5);


    for J=1:6;
        [xselect(J), yselect(J)]=ginput(1);
        plot( [xselect(J)-cross xselect(J)+cross],[yselect(J)↙
yselect(J)],'g','LineWidth',.5);

    end

y(1,1:6)= yselect;
close all

S = S+2;

    for N=1:Fl;
        mov = vid.frames(S); %New line for mmread
%         mov = aviread([Pathname ImageA],S); %commented out↙
as mmread is
%     now used
        fig = figure('Position',[scnsize(3)/6 scnsize(4)/6↙
4*scnsize(3)/6 4*scnsize(4)/6]);
        Maximize(fig);
        image(mov.cdata(Y1:Y2,X1:X2,:))
        hold on

        plot( [x1 x1],[0 380],'g','LineWidth',.5);

            for J=1:6;
                [xselect(J), yselect(J)]=ginput(1);
                plot( [xselect(J)-cross xselect(J)+cross],↙
[yselect(J) yselect(J)],'g','LineWidth',.5);
            end

        y(N+1,1:6)= yselect;

        close all

        S=S+2;

    end
```

```
    y = (y).*(1/ystep);

    Results=[y(:,2)-y(:,1),y(:,4)-y(:,3),y(:,6)-y(:,5),y(:,3)-↙
y(:,2),y(:,5)-y(:,4)];

    [f p]=uiputfile;

    xlswrite([p f],Results);
```

```
% measures every second frame and calculates thickness of RA as well as the
% superior and inferior fascia. Values for thickness are exported to excel,
% column one is for RA, column two is the superior fascia and column three
% in the inferior fascia

clear all;
close all;
s=pwd;

Y1=122;
Y2=650;

X1=150;
X2=800;


% Use this line to set the default directory for data files if this is not
% the same as the directory in which program is installed

%cd('C:\Matlab\Ultrasonic images')

% Prompt operator for file to be anaysed:

[ImageA,Pathname]=uigetfile('*.avi','Select file to be analysed');

[vid] = mmread([Pathname ImageA]); %New line for mmread
% fileinfo = aviinfo([Pathname ImageA]); %commented out as mmread is
%     now used

% Work out number of frames in file:

% NumFrames=fileinfo.NumFrames;


% Ensure root units are pixels and get the size of
% the screen:
    set(0,'Units','pixels') ;
    scnsize = get(0,'ScreenSize');

S=input('Please enter start frame');
F=input('Please enter last frame');
Fl=ceil((F-S)/2);

mov = vid.frames(S); %New line for mmread
% mov = aviread([Pathname ImageA],S); %commented out as mmread is
%     now used

cross=5.0;
```

```
fig = figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize↙
(3)/6 4*scnsize(4)/6]);
Maximize(fig);
image(mov.cdata(Y1:Y2,X1:X2,:))
title(ImageA)
hold on

% Image calibration
scale=ginput(2);
yscale=abs((scale(2,2)-scale(1,2)));
ystep=yscale;


%plotting measurement line
[xselect,yselect] = ginput(1);
x1=round(xselect);
y(1,1) = yselect;
plot( [x1 x1],[0 380],'g','LineWidth',.5);


    for J=1:4;
        [xselect(J), yselect(J)]=ginput(1);
        plot( [xselect(J)-cross xselect(J)+cross],[yselect(J)↙
yselect(J)],'g','LineWidth',.5);

    end

y(1,1:4)= yselect;
close all

S=S+2;

    for N=1:Fl;
        mov = vid.frames(S); %New line for mmread
%         mov = aviread([Pathname ImageA],S); %commented out↙
as mmread is
%     now used
        fig = figure('Position',[scnsize(3)/6 scnsize(4)/6↙
4*scnsize(3)/6 4*scnsize(4)/6]);
        Maximize(fig)
        image(mov.cdata(Y1:Y2,X1:X2,:))
        hold on

        plot([x1 x1],[0 380],'g','LineWidth',.5);

            for J=1:4;
                [xselect(J), yselect(J)]=ginput(1);
                plot( [xselect(J)-cross xselect(J)+cross],↙
[yselect(J) yselect(J)],'g','LineWidth',.5);
            end

        y(N+1,1:4)= yselect;

        close all

        S=S+2;
```

```
end

y = (y).*(1/ystep);

Results=[y(:,3)-y(:,2),y(:,2)-y(:,1),y(:,4)-y(:,3)];

[f p]=uiputfile;
xlswrite([p f],Results);
```

APPENDIX 10a: Correlation Values for Chapter 7 Analysis (Study 4)

Variable	Correlation with Muscle	Correlation with CT	Correlation with IRD
BMI	r = 0.43*	r = 0.60*	r_s = 0.19
Age	r = -0.12	r = 0.30	r_s = 0.35
Gender	r = 0.52*	r = 0.13	r_s = -0.03
Parity	r = -0.30	r = -0.03	r_s = 0.21
Pain (NPRS score)	r = -0.027	r = 0.54*	r_s = 0.34
Length of pain	r = -0.28	r = 0.36	r_s = 0.51*
Oswestry Score	r = -0.09	r = 0.58*	r_s = 0.43*

*Statistically significant ($p < 0.05$)

CT = connective tissue, IRD = inter-recti distance, r = Pearson's r, r_s = Spearman's rho

```
% %Program to identify frames in movie where switch is pressed.  This
% version of the code will analyse all of the avi files in one directory.
% The operatory simply needs to select one file in the directory containing
% the files to be analysed.

% This version is adapted to allow for a range of different switch signals
% This verison works by looking for changes in pixels in two bands either
% side of the mean switch position. Works best with event signals that are
% quick vs. slow changing.Within 30 frames.

clear all;
close all;
s=pwd;

%  Store current path

home_dir=pwd;

% Prompt operator for a file in directory to be anaysed:

    [ImageA,Pathname]=uigetfile('*.avi','Select file in directory containimg files to be analysed');


%     Read directory of avi files in chosen directory and find number...
%         of files in directory

    av_files = dir([Pathname '*.avi']);
    number_of_files = size(av_files,1);

%     Start main loop reading files in turn

    for Ifile=1:number_of_files

        FnameA=av_files(Ifile,1).name
        fileinfo = aviinfo([Pathname FnameA]);

% Work out number of frames in file:

        NumFrames=fileinfo.NumFrames;

%      NumFrames=200; %this line can be used to overide the number of frames
%      analysed


% Set up parameters that control operation of trace analysis routine
```

```
    ytop=500;       % y value of top of region searched for↙
ymean
    ybottom=600;    % y value of bottom of region searched for↙
ymean
    yband_lower_limit=10;       % lower limit of band used for↙
searching for deflected trace
    yband_upper_limit=30;      % upper limit of band used for↙
searching for deflected trace
    Frameoffset=5;  % difference in frame numbers used for↙
calculating change in pixel count
    xleft=161;      % x value of left of region analysed
    xright=792;     % x value of right of region analysed

    dist = zeros(1,ybottom-ytop+1);
    mov = aviread([Pathname FnameA],101); % frame 101 analysed↙
to find mean  y value of trace

    for xpos=161:792;
        [C,I]=max(mov.cdata(ytop:ybottom,xpos,2)-mov.cdata↙
(ytop:ybottom,xpos,3)); %designed to exclude white pixels

        if (C>30) % designed to catch green pixels
            dist(I)=dist(I)+1;
        else
        end
    end

 %    Calculate the ymean value (actually mode):
    [C,I]=max(dist);
      ymean=ytop+I-1;

%   Now analyse all frames to find frames where switch events↙
are present
%   (determined by significant number of green pixels↙
(pixelcount) in bands
%   away from ymean)

       pixelcount=zeros(1,NumFrames);

%     Read in each frame in turn

    for N=1:NumFrames;

        mov = aviread([Pathname FnameA],N);

%     Start locating event signals by looking for bright green↙
pixels in bands outside ymean +-yband_lower_limit
%     use difference of pixel colours to
%     differentiate bright green signals from white

        for x=xleft:xright;
            for y=ymean-yband_upper_limit:ymean-↙
yband_lower_limit;
                pixelcol=mov.cdata(y,x,2)-mov(1).cdata(y,x,3);↙
% designed to reject white
                    if pixelcol >80;  % designed to catch↙
```

```
bright green
                        pixelcount(N)=pixelcount(N)+1;
                    else
                    end
            end
            for y=ymean+yband_lower_limit:↙
ymean+yband_upper_limit;
                pixelcol=mov.cdata(y,x,2)-mov(1).cdata(y,x,3);
                    if pixelcol >80;
                        pixelcount(N)=pixelcount(N)+1;
                    else
                    end
            end
        end

    end

% set up npulse to keep count of the number of frames where↙
the change in
% pixelcount is greater than threshold

    npulse=0;

    for N=1:NumFrames-Frameoffset;
       pixel_count_difference(N)=pixelcount(N+Frameoffset)-↙
pixelcount(N);
    end

    [C,I]=max(pixel_count_difference);
    threshold=0.33*C    %threshold is set at a fraction of the↙
maximum pixel count difference (0.33 to start with)

    clear Iframe Ievent Iextract


%   Store the frame numbers of frames with a pixel change↙
greater than
%   'threshold' in Iframe

    for N=1:NumFrames-Frameoffset;

        if pixel_count_difference(N) >= threshold;
            npulse=npulse+1;
%             Iframe(npulse)=N;
            Iframe(npulse)=N + Frameoffset;
        else
        end
    end

%   plot out pixel_count_difference to show changes and enable↙
operator to
%   identify problems if correct number of events are not↙
detected

    figure;
    plot(pixel_count_difference);
```

```
% set up npulse2 to keep count of the number of events↙
detected

    npulse2=0;

% Check for no events

    if npulse==1
            npulse2=1;
            Ievent(1)=Iframe(1);

            disp(' WARNING: no switch events were detected')
    else
    end


        if npulse > 1
            npulse2=1;

            % Locate event signals
            Ievent(1)=Iframe(1);

%   Work through frames in Iframe, rejecting those which occur↙
within 20 frames of an earlier event

            for N=2:npulse
                if (Iframe(N)-Ievent(npulse2))>=30
                    npulse2=npulse2+1;
                    Ievent(npulse2)=Iframe(N);
                else
                end
            end
        else
        end

%     Display the switch event frame numbers
     Ievent


%   calulate the frame numbers of the frames to be extracted

        if npulse2==8

            Iextract(1)=ceil((Ievent(2)+Ievent(3))/2);
            Iextract(2)=Ievent(3);
            Iextract(3)=ceil((Ievent(5)+Ievent(6))/2);
            Iextract(4)=Ievent(6);
            Iextract(5)=ceil((Ievent(8)+NumFrames)/2);

            Iextract

%     Display frames corresponding to extracted images.↙
Uncomment
%     this next section in order to display images.
```

```
%         for N=1:5;
%             figure;
%             mov = aviread([Pathname FnameA],Iextract(N));
%             image(mov.cdata(:,:,:))
%         end

%   write data to file

            k = strfind(FnameA, '.avi');
            save([Pathname FnameA(1:k-1) '.txt'],'ymean','Ievent', 'Iextract', '-ascii');


        else

            disp(' WARNING: 8 switch events were not detected')

        end


    end



 % Check for correct number of events and plot switch event frames
%  Uncomment this next section in order to display images.

%     if npulse2 == 8
%
%         for N=1:npulse2;
%             figure;
%             mov = aviread([Pathname FnameA],Ievent(N)+5);
%             image(mov.cdata(:,:,:))
%         end
%     else
%     end
```

```
% Program to identify manually annalyse frames.  Assumes frames have
% already been identified and data is stored in .txt file

% This program also measures the fasica thickness between IO and EO, and IO
% and TrA, and TrA and abdominal space. The results for these measures are apended to the 'Results'
% variable i.e. columns 4 and 5 and 6.

clear all;
close all;
s=pwd;

Y1=103;
Y2=550;

X1=250;
X2=800;


% Use this line to set the default directory for data files if this is not
% the same as the directory in which program is installed

%cd('C:\Matlab\Ultrasonic images')

% Prompt operator for file to be anaysed:

    [ImageA,Pathname]=uigetfile('*.avi','Select file to be analysed','multiselect','on');

    if length(ImageA)>35;
        b=1;
    else
        b=length(ImageA);
    end


for a=1:b;

    if length(ImageA)>35;
        FnameA=ImageA;
    else
        FnameA=ImageA{a};
    end

    fileinfo = aviinfo([Pathname FnameA]);

% Work out number of frames in file:

        NumFrames=fileinfo.NumFrames;

%      NumFrames=200; %this line can be used to overide the number of frames
%      analysed
```

```
% Load data on selected frames from corresponding .txt file

        k = strfind(FnameA, '.avi');
        s = importdata([Pathname FnameA(1:k-1) '.txt']);
        yswitch = s(1);
        Ievent = s(2:9);
        Iextract = s(10:14);

% Ensure root units are pixels and get the size of
% the screen:
    set(0,'Units','pixels') ;
    scnsize = get(0,'ScreenSize');


    mov = aviread([Pathname FnameA],1);

%%% Old calibration    %%%
%     image(mov.cdata(:,:,:));
%     tickliney=mov(1).cdata(1:652,795,1);
%     ylocations=find(tickliney>120);
%     ystep=mean(diff(ylocations));
%     ticklinex=mov(1).cdata(603,1:800,1);
%     xlocations=find(ticklinex>120);
%     xstep=mean(diff(xlocations));
%
%     yscale=((Y1:1:Y2)-140).*(1/ystep);


    N=1;
    cross=5.0;

    mov = aviread([Pathname FnameA],Iextract(N));
    figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize(3)↙
/6 4*scnsize(4)/6])
    image(mov.cdata(Y1:Y2,X1:X2,:))
    hold on

%     user_entry = input('Enter first measurement');

%%% New calibration   %%%
    scale=ginput(2);
    yscale=abs((scale(2,2)-scale(1,2)));
    ystep=yscale;


    [xselect,yselect] = ginput(1);
    x1=round(xselect);
    y(1,1) = yselect;
    plot( [x1 x1],[0 380],'g','LineWidth',.5);

    for J=1:7;
        [xselect(J), yselect(J)]=ginput(1);
       plot( [xselect(J)-cross xselect(J)+cross],[yselect(J)↙
yselect(J)],'g','LineWidth',.5);
```

```
        title(FnameA)
    end
    y(1,1:7)= yselect;

    for N=2:5;
        mov = aviread([Pathname FnameA],Iextract(N));
        figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize↙
(3)/6 4*scnsize(4)/6])
        image(mov.cdata(Y1:Y2,X1:X2,:))
        hold on

        plot( [x1 x1],[0 380],'g','LineWidth',.5);

            for J=1:7;
                [xselect(J), yselect(J)]=ginput(1);
                plot( [xselect(J)-cross xselect(J)+cross],↙
[yselect(J) yselect(J)],'g','LineWidth',.5);
                title(FnameA)
            end

        y(N,1:7)= yselect;

    end

    y = (y).*(1/ystep);
%     figure;
%     plot (y);

Results=[y(:,2)-y(:,1),y(:,4)-y(:,3),y(:,6)-y(:,5),y(:,3)-y(:,↙
2),y(:,5)-y(:,4),y(:,7)-y(:,6)];



    x1=x1+420;
    k = strfind(FnameA, '.avi');
    xlswrite([Pathname FnameA(1:k-1) '_LAWb'],Results);

    close all
end
```

```
% Program to identify manually annalyse frames.  Assumes frames have
% already been identified and data is stored in .txt file. Also calcultaes
% the thickness of the superior and inferior fascia

clear all;
close all;
s=pwd;

Y1=103;
Y2=550;

X1=250;
X2=800;


% Use this line to set the default directory for data files if this is not
% the same as the directory in which program is installed

%cd('C:\Matlab\Ultrasonic images')

% Prompt operator for file to be anaysed:

    [ImageA,Pathname]=uigetfile('*.avi','Select file to be analysed','multiselect','on');

    if length(ImageA)>35;
        b=1;
    else
        b=length(ImageA);
    end


for a=1:b;

    if length(ImageA)>35;
        FnameA=ImageA;
    else
        FnameA=ImageA{a};
    end


    fileinfo = aviinfo([Pathname FnameA]);

% Work out number of frames in file:

        NumFrames=fileinfo.NumFrames;

%      NumFrames=200; %this line can be used to overide the number of frames
%      analysed


% Load data on selected frames from corresponding .txt file
```

```
        k = strfind(FnameA, '.avi');
        s = importdata([Pathname FnameA(1:k-1) '.txt']);
        yswitch = s(1);
        Ievent = s(2:8);
        Iextract = s(9:13);

% Ensure root units are pixels and get the size of
% the screen:
    set(0,'Units','pixels') ;
    scnsize = get(0,'ScreenSize');


    mov = aviread([Pathname FnameA],1);

%%% Old calibration    %%%
%     image(mov.cdata(:,:,:));
%     tickliney=mov(1).cdata(1:652,795,1);
%     ylocations=find(tickliney>120);
%     ystep=mean(diff(ylocations));
%     ticklinex=mov(1).cdata(603,1:800,1);
%     xlocations=find(ticklinex>120);
%     xstep=mean(diff(xlocations));
%
%     yscale=((Y1:1:Y2)-140).*(1/ystep);



    N=1;
    cross=5.0;

    mov = aviread([Pathname FnameA],Iextract(N));
    figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize(3)↙
/6 4*scnsize(4)/6])
    image(mov.cdata(Y1:Y2,X1:X2,:))
    hold on

%     user_entry = input('Enter first measurement');


    %%% New calibration   %%%
    scale=ginput(2);
    yscale=abs((scale(2,2)-scale(1,2)));
    ystep=yscale;


    [xselect,yselect] = ginput(1);
    x1=round(xselect);
    y(1,1) = yselect;
    plot( [x1 x1],[0 380],'g','LineWidth',.5);
    title(FnameA)

    for J=1:4;
        [xselect(J), yselect(J)]=ginput(1);
       plot( [xselect(J)-cross xselect(J)+cross],[yselect(J)↙
yselect(J)],'g','LineWidth',.5);
```

```
    end
    y(1,1:4)= yselect;

    for N=2:5;
        mov = aviread([Pathname FnameA],Iextract(N));
        figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize↙
(3)/6 4*scnsize(4)/6])
        image(mov.cdata(Y1:Y2,X1:X2,:))
        hold on

        plot( [x1 x1],[0 380],'g','LineWidth',.5);
        title(FnameA)
            for J=1:4;
                [xselect(J), yselect(J)]=ginput(1);
                plot( [xselect(J)-cross xselect(J)+cross],↙
[yselect(J) yselect(J)],'g','LineWidth',.5);
            end

        y(N,1:4)= yselect;

    end

    y = (y).*(1/ystep);
%     figure;
%     plot (y);

Results=[y(:,3)-y(:,2), y(:,2)-y(:,1), y(:,4)-y(:,3)];


    x1=x1+420;
    k = strfind(FnameA, '.avi');
    xlswrite([Pathname FnameA(1:k-1) '_RA'],Results);

    close all
end
```

```
% Program to identify manually annalyse frames.  Assumes frames have
% already been identified and data is stored in .txt file. To be used with
% mmread

clear all;
close all;
s=pwd;

Y1=203;
Y2=650;

X1=250;
X2=800;


% Use this line to set the default directory for data files if this is not
% the same as the directory in which program is installed

%cd('C:\Matlab\Ultrasonic images')

% Prompt operator for file to be anaysed:

    [ImageA,Pathname]=uigetfile('*.avi','Select file to be analysed','multiselect','on');

    if length(ImageA)>35;
        b=1;
    else
        b=length(ImageA);
    end


for a=1:b;

    if length(ImageA)>35;
        FnameA=ImageA;
    else
        FnameA=ImageA{a};
    end

   vid = mmread([Pathname FnameA]); % New line for mmread
%     fileinfo = aviinfo([Pathname FnameA]); %commented out as mmread is
%     now used

% Work out number of frames in file:

%         NumFrames=fileinfo.NumFrames;

%      NumFrames=200; %this line can be used to overide the number of frames
%      analysed
```

```
% Load data on selected frames from corresponding .txt file

        k = strfind(FnameA, '.avi');
        s = importdata([Pathname FnameA(1:k-1) '.txt']);
        yswitch = s(1);
        Ievent = s(2:9);
        Iextract = s(10:14);

% Ensure root units are pixels and get the size of
% the screen:
    set(0,'Units','pixels') ;
    scnsize = get(0,'ScreenSize');


%     mov = aviread([Pathname FnameA],1);

%%% Old calibration    %%%
%     image(mov.cdata(:,:,:));
%     tickliney=mov(1).cdata(1:652,795,1);
%     ylocations=find(tickliney>120);
%     ystep=mean(diff(ylocations));
%     ticklinex=mov(1).cdata(603,1:800,1);
%     xlocations=find(ticklinex>120);
%     xstep=mean(diff(xlocations));
%
%     yscale=((Y1:1:Y2)-140).*(1/ystep);



    N=1;
    cross=5.0;
    mov = vid.frames(Iextract(N)); %New line for mmread
%     mov = aviread([Pathname FnameA],Iextract(N)); %commented↙
out as mmread is
%     now used
    figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize(3)↙
/6 4*scnsize(4)/6])
    image(mov.cdata(Y1:Y2,X1:X2,:))
    hold on

%     user_entry = input('Enter first measurement');


    %%% New calibration   %%%
    scale=ginput(2);
    xscale=abs((scale(2,1)-scale(1,1)));
    xstep=xscale;


%     [xselect,yselect] = ginput(1);
%     x1=round(xselect);
%     y(1,1) = yselect;
%     plot( [x1 x1],[0 380],'g','LineWidth',.5);
%     title(FnameA)
```

```
    for J=1:2;
        [xselect(J), yselect(J)]=ginput(1);
        plot( [xselect(J) xselect(J)],[yselect(J)-cross↙
yselect(J)+cross],'g','LineWidth',.5);
        title(FnameA)
    end
    x(1,1:2)= xselect;

    for N=2:5;
         mov = vid.frames(Iextract(N)); %New line for mmread
%         mov = aviread([Pathname FnameA],Iextract(N)); %↙
commented out as mmread is
%     now used
        figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize↙
(3)/6 4*scnsize(4)/6])
        image(mov.cdata(Y1:Y2,X1:X2,:))
        hold on

%         plot( [x1 x1],[0 380],'g','LineWidth',.5);
        title(FnameA)
            for J=1:2;
                [xselect(J), yselect(J)]=ginput(1);
                plot( [xselect(J) xselect(J)],[yselect(J)-↙
cross yselect(J)+cross],'g','LineWidth',.5);
            end

        x(N,1:2)= xselect;

    end

    x = (x).*(1/xstep);
%     figure;
%     plot (y);

    Results=[x(:,2)-x(:,1)];


%     x1=x1+420;
    k = strfind(FnameA, '.avi');
    xlswrite([Pathname FnameA(1:k-1) '_IntRecDis'],Results);

    close all
end
```

Appendix 11a: Summary of Correlation Analyses of Abdominal Wall Parameters Study 5 (Chapter 8)

Parameter		External Oblique % Δ Thickness								Internal Oblique % Δ Thickness								Transversus Abdominis % Δ Thickness								Rectus Abdominis % Δ Thickness								Inter-recti Distance % Δ Width							
Task		ASLR				ADIM				ASLR				ADIM				ASLR				ADIM				ASLR				ADIM				ASLR				ADIM			
Phase		LL-PR	LH-PR	LR-PR	PoR-PR	ADIM-PR	H-PR	RI-PR	Po-PR	LL-PR	LH-PR	LR-PR	PoR-PR	ADIM-PR	H-PR	RI-PR	Po-PR	LL-PR	LH-PR	LR-PR	PoR-PR	ADIM-PR	H-PR	RI-PR	Po-PR	LL-PR	LH-PR	LR-PR	PoR-PR	ADIM-PR	H-PR	RI-PR	Po-PR	LL-PR	LH-PR	LR-PR	PoR-PR	ADIM-PR	H-PR	RI-PR	Po-PR
BMI	r	-.358	-.242	-.198	-.142	-.035	.037	.027	.031	-.127	-.186	-.205	.225	-.126	-.237	-.255	-.394	-.110	-.019	-.080	.095	-.100	-.260	-.134	-.009	-.139	.125	.140	.115	.095	.131	-.169	.130	-.128	-.039	-.026	.177	.268	-.058	.082	.125
	p	.011	.091	.168	.326	.808	.801	.852	.829	.380	.195	.152	.116	.384	.098	.074	.005	.448	.898	.581	.512	.491	.069	.352	.951	.398	.447	.395	.485	.569	.434	.309	.436	.401	.801	.866	.245	.131	.747	.649	.490
Age	r	-.041	.020	-.027	-.057	-.016	.172	.161	-.176	.264	.323	.193	.098	-.006	-.143	-.177	.019	-.146	-.106	-.198	-.186	-.052	-.236	-.059	.029	.294	.527	.481	.130	-.069	-.007	.104	-.026	-.262	-.236	-.060	.223	.145	-.162	.046	.255
	p	.778	.892	.851	.695	.911	.232	.265	.222	.064	.022	.180	.500	.968	.321	.218	.897	.311	.463	.167	.195	.721	.098	.683	.839	.069	.001	.002	.429	.680	.967	.533	.879	.082	.119	.697	.142	.420	.369	.801	.153
Gender	r	.020	.007	.034	-.031	.000	-.050	.021	-.079	.041	.023	.181	.428	-.268	-.245	-.195	-.164	-.069	-.083	-.024	.114	-.026	.035	.047	.116	-.057	.067	.091	.274	-.205	-.030	.037	.133	-.178	-.100	-.211	-.217	-.005	.019	-.018	.179
	p	.889	.960	.813	.830	.999	.728	.885	.587	.776	.874	.209	.002	.060	.086	.175	.256	.635	.564	.866	.429	.860	.811	.747	.421	.730	.685	.581	.091	.218	.859	.825	.426	.243	.515	.164	.152	.979	.918	.922	.320
Parity	r	-.085	.082	-.105	-.078	-.037	.168	.116	-.025	.126	.238	.080	.048	.138	.052	.036	-.046	.125	-.043	-.077	-.156	-.026	-.106	.043	.076	.382	.313	.190	-.160	.070	-.097	.177	.139	-.102	-.115	.003	.246	-.007	-.138	.145	.131
	p	.556	.572	.468	.589	.800	.245	.423	.865	.385	.096	.583	.739	.340	.718	.806	.752	.388	.769	.595	.278	.855	.466	.769	.599	.017	.052	.246	.330	.675	.562	.287	.405	.503	.450	.987	.103	.968	.444	.421	.468
NPRS	r	-.220	.076	-.004	-.136	.116	.289	.311	.154	.171	.076	-.106	.014	.068	-.181	-.183	-.018	-.419	-.334	-.392	-.441	-.061	-.163	.014	.072	.082	.141	.120	.177	-.118	-.102	-.226	-.114	-.166	-.095	.039	.126	.318	.063	.146	.370
	p	.124	.598	.976	.347	.423	.042	.028	.285	.235	.598	.463	.925	.640	.209	.204	.899	.002	.018	.005	.001	.676	.258	.923	.621	.620	.392	.467	.282	.482	.541	.172	.496	.275	.534	.800	.408	.071	.727	.417	.034
Oswestry	r	-.243	.074	-.007	-.234	.133	.243	.275	-.009	.273	.173	-.039	.053	.030	-.180	-.241	-.029	-.379	-.342	-.372	-.440	-.103	-.216	-.028	.029	.226	.359	.255	.294	-.057	-.140	-.113	-.053	-.095	-.148	.071	.169	.099	-.123	-.015	.205
	p	.089	.611	.962	.102	.358	.090	.053	.950	.055	.229	.788	.716	.838	.211	.091	.842	.007	.015	.008	.001	.477	.132	.845	.844	.166	.025	.117	.069	.735	.400	.499	.752	.534	.331	.644	.266	.582	.496	.932	.252
PainLength	r	.225	.286	.234	.074	.092	.077	.287	-.081	.196	.229	.127	-.079	.245	.058	-.055	.171	-.370	-.244	-.280	-.377	-.082	-.219	-.077	-.070	.101	.158	.078	.046	.033	-.014	.038	.200	-.174	-.262	-.156	-.023	.205	.015	-.001	.259
	p	.117	.044	.102	.608	.524	.595	.043	.578	.173	.110	.380	.585	.087	.691	.706	.235	.008	.088	.049	.007	.573	.126	.594	.629	.539	.336	.638	.781	.846	.932	.820	.228	.252	.083	.305	.880	.252	.934	.997	.145

ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg rasie test, BMI = body mass index, H = ADIM hold, LH = leg hold, LL = leg lift, LR = leg release, NPRS = numerical pain rating scale, p = p=value, Po = post ADIM rest, PoR = post leg lift rest, PR = pre-leg lift rest, r = Pearson's correlation coefficient, RI = ADIM release,

Appendix 11b: Summary of Correlation Analyses of Bladder Base Parameters, Study 5 (Chapter 8)

Task		ASLR																ADIM																	
Phase		**LL-PR**						**LH-PR**						**RL-PR**				**Po-PR**						**ADIM-PR**				**H-PR**				**RL-PR**				**Po-PR**			
Parameter		GBB			RBB			GBB			RBB			GBB			RBB	GBB			RBB			GBB			RBB			GBB			RBB			GBB			RBB		
BMI	r	.166	-.063	-.081	-.052	-.053	.060	-.068	.053	.044	.038	-.054	-.026	.042	.029	.127	-.178	.029	-.041	.145	-.061	.021	.120	.145	-.061	.289	.054	.051	.017	-.083	-.064	.059	.088	.095	.024	-.004	.067	-.097	-.148	.014	-.332	-.165	-.142	.008	-.061	-.100	.041	.008	-.061
	p	.250	.664	.575	.718	.716	.677	.640	.716	.763	.793	.711	.858	.773	.839	.380	.216	.843	.777	.314	.673	.887	.407	.314	.673	.079	.746	.760	.917	.621	.704	.725	.599	.569	.885	.983	.688	.562	.377	.934	.042	.322	.396	.961	.715	.550	.808	.961	.715
Age	r	.453	-.004	-.241	-.095	.010	-.051	.163	-.017	.043	.272	.056	-.200	.168	.066	.075	.009	.018	.048	.021	.075	.111	.096	.021	.075	-.118	.140	.259	.096	-.045	.019	-.020	.184	.016	-.045	.174	.306	-.213	.038	.166	-.181	.192	.176	.190	.132	.082	.155	.190	.132
	p	.001	.980	.092	.512	.947	.725	.258	.906	.768	.056	.698	.163	.243	.648	.606	.949	.902	.739	.885	.603	.442	.506	.885	.603	.479	.401	.116	.568	.790	.909	.903	.268	.926	.789	.297	.061	.198	.820	.320	.277	.247	.292	.253	.429	.626	.352	.253	.429
Gender	r	-.045	-.175	-.127	-.154	-.228	.060	.222	.217	.136	.227	-.039	-.042	-.033	-.024	.187	.084	.297	.215	.284	.335	.259	.185	.284	.335	-.125	-.432	-.290	-.167	.048	.343	.066	.026	.050	.125	-.321	-.294	.091	-.002	.012	-.067	-.095	.217	-.019	-.126	.129	-.076	-.019	-.126
	p	.759	.223	.379	.285	.112	.680	.121	.130	.345	.113	.788	.771	.820	.870	.195	.564	.036	.134	.046	.017	.070	.198	.046	.017	.455	.007	.078	.315	.773	.035	.693	.878	.763	.456	.049	.073	.585	.990	.943	.688	.571	.191	.911	.450	.439	.651	.911	.450
Parity	r	.042	.220	.165	.257	.302	-.049	-.100	-.180	.004	.008	.159	.118	.052	-.067	-.069	.133	.017	.045	-.175	-.276	-.120	-.108	-.175	-.276	-.030	.422	.282	.165	-.040	-.194	.110	.022	-.072	-.164	.397	.317	-.219	-.102	-.051	.156	.312	-.002	.120	.217	.019	.135	.120	.217
	p	.773	.125	.252	.072	.033	.733	.490	.212	.979	.958	.271	.413	.719	.645	.632	.357	.908	.759	.223	.052	.407	.454	.223	.052	.856	.008	.087	.322	.813	.244	.513	.894	.666	.324	.014	.052	.187	.541	.760	.350	.056	.991	.473	.190	.909	.421	.473	.190
NPRS	r	.208	-.164	-.295	-.299	-.116	.198	-.101	-.283	-.196	.175	-.069	-.220	.318	.238	.033	-.156	-.155	-.160	.122	.107	.181	.169	.122	.107	.044	-.027	-.067	-.035	-.074	.125	.062	-.072	-.129	-.055	-.076	-.073	.050	-.115	.017	-.108	-.269	-.157	.061	.066	-.091	-.030	.061	.066
	p	.147	.256	.038	.035	.423	.169	.486	.046	.172	.225	.633	.124	.025	.096	.820	.279	.282	.266	.398	.461	.210	.240	.398	.461	.793	.873	.689	.835	.657	.456	.710	.667	.440	.743	.649	.663	.765	.494	.920	.517	.103	.346	.715	.692	.587	.860	.715	.692
Oswestry	r	.396	-.217	-.306	-.181	-.038	.165	-.037	-.158	-.033	.242	-.151	-.254	.284	.120	.092	-.174	-.052	-.083	.037	.038	.132	.124	.037	.038	.039	.117	.015	-.169	-.139	.018	.048	-.042	-.081	-.043	.062	.092	-.048	.073	.088	-.109	-.101	-.053	.158	.218	-.082	.154	.158	.218
	p	.004	.131	.031	.208	.793	.251	.801	.274	.822	.091	.294	.076	.045	.408	.524	.226	.722	.566	.797	.793	.362	.391	.797	.793	.817	.485	.927	.311	.404	.913	.774	.801	.629	.799	.711	.582	.774	.664	.600	.513	.547	.751	.342	.189	.625	.357	.342	.189
Pain Length	r	.260	-.146	-.182	-.145	.046	.053	-.185	-.221	-.225	.034	-.167	-.184	.274	.273	-.044	-.410	-.295	-.233	-.117	-.166	-.032	.003	-.117	-.166	-.105	.262	.211	.068	.008	-.194	-.059	-.020	.054	-.024	.276	.267	-.162	-.003	.014	-.092	.043	.219	-.115	-.014	.061	.164	-.115	-.014
	p	.068	.311	.206	.314	.749	.715	.200	.123	.116	.815	.246	.201	.054	.055	.762	.003	.037	.104	.418	.250	.826	.983	.418	.250	.531	.112	.203	.687	.960	.242	.723	.903	.747	.887	.093	.105	.330	.985	.935	.582	.795	.187	.490	.936	.718	.325	.490	.936

ADIM = abdominal drawing in manoeuvre, ASLR = active straight leg rasie test, BMI = body mass index, GBB = global bladder base position, H = ADIM hold, LH = leg hold, LL = leg lift, LR = leg release, NPRS = numerical pain rating scale, p = p=value, Po = post ADIM rest, PoR = post leg lift rest, PR = pre-leg lift rest, r = Pearson's correlation coefficient, RBB = relative bladder base position, RI = ADIM release,

Appendix 11c: Summary of ADIM Significance Testing (ANCOVA[ł] and ANOVA), Study 5 (chapter 8)		
Dependent Variable	**F - value**	**p-value**
[ł]EO ADIM-prerest % change	.450	.506
[ł]EO ADIM H-prerest % change	1.144	.290
[ł]EO ADIM RL-presrest % change	4.303	*.044
[ł]EO ADIM Post-prerest % change	.635	.430
[ł]IO ADIM-prerest % change	.437	.512
[ł]IO ADIM H-prerest % change	.051	.822
[ł]IO ADIM RL-prerest % change	.008	.928
[ł]IO ADIM Post-prerest % change	2.177	.147
[ł]TrA ADIM-prerest % change	.602	.442
[ł]TrA ADIM H-prerest % change	1.651	.205
[ł]TrA ADIM RL-prerest % change	.797	.377
[ł]TrA ADIM Post-prerest % change	.338	.564
[ł]RA ADIM-prerest % change	.375	.544
[ł]RA ADIM H-prerest % change	.256	.616
[ł]RA ADIM RL-prerest % change	.147	.704
[ł]RA ADIM Post-prerest % change	.042	.839
IRD ADIM-prerest % change	1.152	.292
IRD ADIM H-prerest % change	.111	.741
IRD ADIM RL-prerest % change	.154	.698
IRD ADIM Post-prerest % change	5.880	.022
Bladder ADIM GBB X	.413	.525
Bladder ADIM GBB Y	.259	.614
Bladder ADIM GBB T	.003	.954
Bladder ADIM H GBB X	.000	.986
Bladder ADIM H GBB Y	.121	.730
Bladder ADIM H GBB T	.074	.787
Bladder ADIM RL GBB X	.020	.889
Bladder ADIM RL GBB Y	.089	.767
Bladder ADIM RL GBB T	1.446	.237
Bladder ADIM PoR GBB X	.121	.730
Bladder ADIM PoR GBB Y	.334	.567
Bladder ADIM PoR GBB T	.114	.738
Bladder ADIM RBB X	.009	.923
Bladder ADIM RBB Y	.016	.899
Bladder ADIM RBB T	.021	.885
Bladder ADIM H RBB X	.446	.508
Bladder ADIM H RBB Y	.450	.506
Bladder ADIM H RBB T	.236	.630
Bladder ADIM RL RBB X	1.116	.298
Bladder ADIM RL RBB Y	2.908	.097
Bladder ADIM RL RBB T	.005	.945
Bladder ADIM PoR RBB X	.709	.405
Bladder ADIM PoR RBB Y	.121	.730
Bladder ADIM PoR RBB T	.334	.567

* Statistically significant; ADIM = abdominal drawing in manoeuvre, EO = external oblique,GBB = global bladder base, IO = internal oblique, IRD = inter-recti distance, H - manoeuvre hold, PoR = post manouevre rest,RA = rectus abdominis, RBB = relative bladder base, RL = manoeuvre release, T = trajectory plane, TrA = transversus abdominins, X = cranial caudal plane, Y = ventral dorsal plane

Appendix 11d: Summary of ASLR Significance Testing (ANCOVA[ŧ] and ANOVA), Study 5 (chapter 8)		
Dependent Variable	**F - value**	**p-value**
[ŧ]EO ASLR LL-prerest % change	.565	.456
[ŧ]EO ASLR LH-prerest % change	1.469	.232
[ŧ]EO ASLR RL-prerest % change	.196	.660
[ŧ]EO ASLR Post-prerest % change	1.255	.269
[ŧ]IO ASLR LL-pre-rest % change	1.127	.294
[ŧ]IO ASLR LH - presrest % change	.038	.846
[ŧ]IO ASLR RL-pre-rest % change	.629	.432
[ŧ]IO ASLR Post-preprest % change	.079	.780
[ŧ]TrA ASLR LL-pre-rest %	14.653	*.000
[ŧ]TrA ASLR LH-pre-rest % change	5.111	*.029
[ŧ]TrA ASLR RL-pre-rest %change	4.109	*.049
[ŧ]TrA ASLR Post-pre-rest % change	7.640	*.008
[ŧ]RA ASLR LL-prerest %	.112	.740
[ŧ]RA ASLR LH-prerest % change	.000	.999
[ŧ]RA ASLR RL-prerest % change	.668	.420
[ŧ]RA ASLR Post-prerest % change	.955	.336
IRD ASLR LL-presrest % change	.008	.930
IRD ASLR LH-prerest % change	.017	.898
IRD ASLR RL-prerest % change	.259	.615
IRD ASLR Post-prerest % change	.061	.806
Bladder ASLR LL GBB X	5.091	*.029
Bladder ASLR LL GBB Y	1.766	.190
Bladder ASLR LL GBB T	5.772	*.020
Bladder ASLR LH GBB X	.561	.458
Bladder ASLR LH GBB Y	3.137	.083
Bladder ASLR LH GBB T	2.466	.123
Bladder ASLR RL GBB X	6.366	*.015
Bladder ASLR RL GBB Y	4.521	*.039
Bladder ASLR RL GBB T	.625	.433
Bladder ASLR PoR GBB X	.414	.523
Bladder ASLR PoR GBB Y	.350	.557
Bladder ASLR PoR GBB T	.879	.353
Bladder ASLR LL RBB X	4.987	*.030
Bladder ASLRLL RBB Y	.606	.440
Bladder ASLR LL RBB T	1.106	.298
Bladder ASLR LH RBB X	1.362	.249
Bladder ASLR LH RBB Y	.691	.410
Bladder ASLR LH RBB T	4.050	.050
Bladder ASLR RL RBB X	5.147	*.028
Bladder ASLR RL RBB Y	2.120	.152
Bladder ASLR RL RBB T	1.882	.176
Bladder ASLR PoR RBB X	.674	.416
Bladder ASLR PoR RBB Y	.414	.523
Bladder ASLR PoR RBB T	.350	.557

* Statistically significant; ASLR = active straight leg raise, EO = external oblique,GBB = global bladder base, IO = internal oblique, IRD = inter-recti distance, LH = leg hold, PoR = post manouevre, RA = rectus abdominis, RBB = relative bladder base, RL = manoeuvre release, T = trajectory plane, TrA = transversus abdominins, X = cranial caudal plane, Y = ventral dorsal plane

```
%%% Uses 'mmread' function to open and display avi file

clear all;
close all;
s=pwd;



% Prompt operator for file to be anaysed:

    [ImageA,Pathname]=uigetfile('*.avi','Select file to be analysed','multiselect','on');

    if length(ImageA)>35;
        b=1;
    else
        b=length(ImageA);
    end


for a=1:b;

    if length(ImageA)>35;
        FnameA=ImageA;
    else
        FnameA=ImageA{a};
    end

   vid = mmread([Pathname FnameA]); % New line for mmread
%     fileinfo = aviinfo([Pathname FnameA]); %commented out as mmread is
%     now used
%     NumFrames=fileinfo.NumFrames;


% %     obj = mmreader([Pathname FnameA]); % mmreader funciton used as avi is used due to missing codec on Martin's PC
% %     vidframes = read(obj); % Obtaining video frames
% %
% %
% %     NumFrames=get(obj, 'numberOfFrames'); % Getting number of frames
% %
% %     for i = 1 : NumFrames % Creating a struct containing movie data
% %         mov(i).cdata = vidframes(:,:,:,i);
% %         mov(i).colormap = [];
% %     end
% %

% Load data on selected frames from corresponding .txt file

        k = strfind(FnameA, '.avi');
        s = importdata([Pathname FnameA(1:k-1) '.txt']);
        yswitch = s(1);
        Ievent = s(2:9);
```

```
        Iextract = s(10:14);



% Ensure root units are pixels and get the size of
% the screen:
    set(0,'Units','pixels') ;
    scnsize = get(0,'ScreenSize');

    N=1;
    cross=5.0;




% Calibration. Calibrate X axis first
    h = figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize↙
(3)/6 4*scnsize(4)/6]);
    Maximize(h)

    mov = vid.frames(Iextract(N)); %New line for mmread
%     mov = aviread([Pathname FnameA],Iextract(N)); %commented↙
out as mmread is
%     now used
    image(mov.cdata); %Comment out if using mmreader

    % %      image(mov(N).cdata) % For use with 'mmreader'↙
function

    title('Image Calibration')
    hold on

    scale_x = ginput(2);
    xscale = abs((scale_x(2,1) - scale_x(1,1)));
    xstep = xscale;

    scale_y = ginput(2);
    yscale = abs((scale_y(2,2) - scale_y(1,2)));
    ystep = yscale;

    scale = [xstep ystep];

    close all


  for N = 1:5; %Analyse each frame in turn

    n = Iextract(N); %Obtaining relevant frame

    h = figure('Position',[scnsize(3)/6 scnsize(4)/6 4*scnsize↙
(3)/6 4*scnsize(4)/6]);
    Maximize(h)

    mov = vid.frames(Iextract(N)); %New line for mmread
%     mov = aviread([Pathname FnameA],Iextract(N)); %commented↙
out as mmread is
```

```
%     now used
    image(mov.cdata); %Comment out if using mmreader

    % %    image(mov(n).cdata) % For use with mmreader↙
function

    hold on


    [x1,y1] = ginput(1);
    x1 = round(x1);
    plot([200 800], [y1 y1],'g','LineWidth',.5);
    plot(x1,y1,'g*')
    xselect(1,:) = x1;
    yselect(1,:) = y1;

    [x2,y2] = ginput(1);
    y2 = round(y2);
    plot([x2 x2],[0 500],'g','LineWidth',.5);
    plot(x2,y2,'g*')
    xselect(2,:) = x2;
    yselect(2,:) = y2;

    [x3,y3] = ginput(1);
    plot(x3,y3,'g*')
    xselect(3,:) = x3;
    yselect(3,:) = y3;

    [x4,y4] = ginput(1);
    plot(x4,y4,'g*')
    xselect(4,:) = x4;
    yselect(4,:) = y4;

    [x5,y5] = ginput(1);
    plot(x5,y5,'g*')
    xselect(5,:) = x5;
    yselect(5,:) = y5;


    Coord(:,N) = [x1 y1 x2 y2 x3 y3 x4 y4 x5 y5];

    px = [xselect(3,:); xselect(4,:)];
    py = [yselect(3,:); yselect(4,:)];

    poly = polyfitn(px,py,1); % linear fit through the 2↙
points at the extremes of the baldder base

    x = linspace(xselect(3), xselect(4)); % Create a series of↙
x axis data of 100 samples from left most edge ti right most↙
edge of bladder base

    polyvals = polyvaln(poly,x); % Obtaining the y values of↙
polyfit with respect to x

    plot(x,polyvals,'r','LineWidth',1)
```

```
    xc = ((x).*(1/xstep))*-1;
    xline(:,N) = xc; % x axis data stored for each frame in↙
turn

    yc = (polyvals).*(1/ystep);
    yline(:,N) = yc; % y axis data stored for each frame in↙
turn

    xpntc = (xselect(5,:)*(1/xstep))*-1;
    xpnt (:,N) = xpntc; % single point
    ypntc = yselect(5,:)*(1/ystep);
    ypnt (:,N) = ypntc; %single point

    X1 = xline(1,N);
    X2 = xline(100,N);

    Y1 = yline(1,N);
    Y2 = yline(100,N);

    ang(:,N) = (atand((Y2-Y1)./(X2-X1)))*-1;

    pnt_int_x(:,N) = xselect(2,:) - xselect(5,:); %Distance of↙
point from intersection in the x axis
    pnt_int_x(:,N) = pnt_int_x(:,N).*(1/xstep);

    pnt_int_y(:,N) = yselect(5,:) - yselect(2,:); %Distance of↙
point from intersection in the y axis
    pnt_int_y(:,N) = pnt_int_y(:,N).*(1/ystep);

    pnt_int_v(:,N) = sqrt(pnt_int_x(:,N).^2 + pnt_int_y(:,N).↙
^2); %Vector distance of point from intersection in the x axis



  end

  for j = 1:4; %distances for each of the 100 samples and↙
point wiht respect to inital frame

      xdisl(:,j) = xline(:,1) - xline(:,j+1,:); % X distance↙
line has travelled in x axis with respect to the first frame
      ydisl(:,j) = yline(:,1) - yline(:,j+1,:); % Y distance↙
line has travelled in y axis with respect to the first frame

      vecl(:,j) = sqrt(xdisl(:,j).^2 + ydisl(:,j).^2); %↙
vector distance line has travelled with respect to the first↙
frame

      xdisp(:,j) = xpnt(:,1) - xpnt(:,j+1); % X Distance↙
single point has travelled wrt first frame
      ydisp(:,j) = ypnt(:,1) - ypnt(:,j+1); % Y Distance↙
single point has travelled wrt first frame

      vecp(:,j) = sqrt(xdisp(:,j).^2 + ydisp(:,j).^2); %↙
vector distance point has travelled with respect to the first↙
frame
```

```
  end

  axdisl = mean(xdisl); % average distances for whole line
  aydisl = mean(ydisl);
  avecl = mean(vecl);

  warning('off','MATLAB:xlswrite:AddSheet');
  h = waitbar(0,'Saving file...');
  xlswrite([Pathname FnameA(1:k-1) '.xls'],xdisl,'X distance↙
of line');
  waitbar(1/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],ydisl,'Y distance↙
of line');
  waitbar(2/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],vecl,'Vector↙
distance of line');
  waitbar(3/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],axdisl,'Average X↙
distance of line');
  waitbar(4/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],aydisl,'Average Y↙
distance of line');
  waitbar(5/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],avecl,'Average↙
vector distance of line');
  waitbar(6/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],xdisp,'X distance↙
of point');
  waitbar(7/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],ydisp,'Y distance↙
of point');
  waitbar(8/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],vecp,'Vector↙
distance of point');
  waitbar(9/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],ang,'Angle of↙
line');
  waitbar(10/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],pnt_int_x,'Point to↙
intersection X axis');
  waitbar(11/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],pnt_int_y,'Point to↙
intersection Y axis');
  waitbar(12/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],pnt_int_v,'Point to↙
intersection Vector');
  waitbar(13/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],Coord,'Coordinates↙
of points');
  waitbar(14/15,h);
  xlswrite([Pathname FnameA(1:k-1) '.xls'],scale,'X and Y↙
calibration values');
  waitbar(15/15,h);

  close(h);
```

```
end
```

```
function polymodel = polyfitn(indepvar,depvar,modelterms)
% polyfitn: fits a general polynomial regression model in n dimensions
% usage: polymodel = polyfitn(indepvar,depvar,modelterms)
%
% Polyfitn fits a polynomial regression model of one or more
% independent variables, of the general form:
%
%   z = f(x,y,...) + error
%
% arguments: (input)
%  indepvar - (n x p) array of independent variables as columns
%        n is the number of data points
%        p is the dimension of the independent variable space
%
%        IF n == 1, then I will assume there is only a
%        single independent variable.
%
%  depvar   - (n x 1 or 1 x n) vector - dependent variable
%        length(depvar) must be n.
%
%        Only 1 dependent variable is allowed, since I also
%        return statistics on the model.
%
%  modelterms - defines the terms used in the model itself
%
%        IF modelterms is a scalar integer, then it designates
%           the overall order of the model. All possible terms
%           up to that order will be employed. Thus, if order
%           is 2 and p == 2 (i.e., there are two variables) then
%           the terms selected will be:
%
%              {constant, x, x^2, y, x*y, y^2}
%
%           Beware the consequences of high order polynomial
%           models.
%
%        IF modelterms is a (k x p) numeric array, then each
%           row of this array designates the exponents of one
%           term in the model. Thus to designate a model with
%           the above list of terms, we would define modelterms as
%
%           modelterms = [0 0;1 0;2 0;0 1;1 1;0 2]
%
%        If modelterms is a character string, then it will be
%           parsed as a list of terms in the regression model.
%           The terms will be assume to be separated by a comma
%           or by blanks. The variable names used must be legal
%           matlab variable names. Exponents in the model may
%           may be any real number, positive or negative.
%
```

```
%           For example, 'constant, x, y, x*y, x^2, x*y*y'
%           will be parsed as a model specification as if you
%           had supplied:
%           modelterms = [0 0;1 0;0 1;1 1;2 0;1 2]
%
%           The word 'constant' is a keyword, and will denote↙
a
%           constant terms in the model. Variable names will↙
be
%           sorted in alphabetical order as defined by sort.
%           This order will assign them to columns of the
%           independent array. Note that 'xy' will be parsed↙
as
%           a single variable name, not as the product of x↙
and y.
%
%        If modelterms is a cell array, then it will be taken
%           to be a list of character terms. Similarly,
%
%           {'constant', 'x', 'y', 'x*y', 'x^2', 'x*y^-1'}
%
%           will be parsed as a model specification as if you
%           had supplied:
%
%           modelterms = [0 0;1 0;0 1;1 1;2 0;1 -1]
%
% Arguments: (output)
%  polymodel - A structure containing the regression model
%        polymodel.ModelTerms = list of terms in the model
%        polymodel.Coefficients = regression coefficients
%        polymodel.ParameterVar = variances of model↙
coefficients
%        polymodel.ParameterStd = standard deviation of model↙
coefficients
%        polymodel.R2 = R^2 for the regression model
%        polymodel.RMSE = Root mean squared error
%        polymodel.VarNames = Cell array of variable names
%           as parsed from a char based model specification.
%
%        Note 1: Because the terms in a general polynomial
%        model can be arbitrarily chosen by the user, I must
%        package the erms and coefficients together into a
%        structure. This also forces use of a special↙
evaluation
%        tool: polyvaln.
%
%        Note 2: A polymodel can be evaluated for any set
%        of values with the function polyvaln. However, if
%        you wish to manipulate the result symbolically using
%        my own sympoly tools, this structure can be converted
%        to a sympoly using the function polyn2sympoly.
%
%        Note 3: When no constant term is included in the↙
model,
%        the traditional R^2 can be negative. This case is
%        identified, and then a more appropriate computation
```

```
%        for R^2 is then used.
%
% Find my sympoly toolbox here:
% http://www.mathworks.↙
com/matlabcentral/fileexchange/loadFile.do?↙
objectId=9577&objectType=FILE
%
% See also: polyvaln, polyfit, polyval, polyn2sympoly, sympoly
%
% Author: John D'Errico
% Release: 2.0
% Release date: 2/19/06

if nargin<1
  help polyfitn
  return
end

% get sizes, test for consistency
[n,p] = size(indepvar);
if n == 1
  indepvar = indepvar';
  [n,p] = size(indepvar);
end
[m,q] = size(depvar);
if m == 1
  depvar = depvar';
  [m,q] = size(depvar);
end
% only 1 dependent variable allowed at a time
if q~=1
  error 'Only 1 dependent variable allowed at a time.'
end

if n~=m
  error 'indepvar and depvar are of inconsistent sizes.'
end

% Automatically scale the independent variables to unit↙
variance
stdind = sqrt(diag(cov(indepvar)));
if any(stdind==0)
  warning 'Constant terms in the model must be entered using↙
modelterms'
  stdind(stdind==0) = 1;
end
% scaled variables
indepvar_s = indepvar*diag(1./stdind);

% do we need to parse a supplied model?
if iscell(modelterms) || ischar(modelterms)
  [modelterms,varlist] = parsemodel(modelterms,p);
  if size(modelterms,2) < p
    modelterms = [modelterms, zeros(size(modelterms,1),p -↙
size(modelterms,2))];
  end
```

```
elseif length(modelterms) == 1
  % do we need to generate a set of modelterms?
  [modelterms,varlist] = buildcompletemodel(modelterms,p);
elseif size(modelterms,2) ~= p
  error 'ModelTerms must be a scalar or have the same # of↙
columns as indepvar'
end
nt = size(modelterms,1);

% check for replicate terms
if nt>1
  mtu = unique(modelterms,'rows');
  if size(mtu,1)<nt
    warning 'Replicate terms identified in the model.'
  end
end

% build the design matrix
M = ones(n,nt);
scalefact = ones(1,nt);
for i = 1:nt
  for j = 1:p
    M(:,i) = M(:,i).*indepvar_s(:,j).^modelterms(i,j);
    scalefact(i) = scalefact(i)/(stdind(j)^modelterms(i,j));
  end
end

% estimate the model using QR. do it this way to provide a
% covariance matrix when all done. Use a pivoted QR for
% maximum stability.
[Q,R,E] = qr(M,0);

polymodel.ModelTerms = modelterms;
polymodel.Coefficients(E) = R\(Q'*depvar);
yhat = M*polymodel.Coefficients(:);

% recover the scaling
polymodel.Coefficients=polymodel.Coefficients.*scalefact;

% variance of the regression parameters
s = norm(depvar - yhat);
if n > nt
  Rinv = R\eye(nt);
  Var(E) = s^2*sum(Rinv.^2,2)/(n-nt);
  polymodel.ParameterVar = Var.*(scalefact.^2);
  polymodel.ParameterStd = sqrt(polymodel.ParameterVar);
else
  % we cannot form variance or standard error estimates
  % unless there are at least as many data points as
  % parameters to estimate.
  polymodel.ParameterVar = inf(1,nt);
  polymodel.ParameterStd = inf(1,nt);
end

% R^2
% is there a constant term in the model? If not, then
```

```
% we cannot use the standard R^2 computation, as it
% frequently yields negative values for R^2.
if any((M(1,:) ~= 0) & all(diff(M,1,1) == 0,1))
  %we have a constant term in the model, so the
  % traditional %R^2 form is acceptable.
  polymodel.R2 = max(0,1 - (s/norm(depvar-mean(depvar)) )^2);
else
  % no constant term was found in the model
  polymodel.R2 = max(0,1 - (s/norm(depvar))^2);
end

% RMSE
polymodel.RMSE = sqrt(mean((depvar - yhat).^2));

% if a character 'model' was supplied, return the list
% of variables as parsed out
polymodel.VarNames = varlist;

% ==================================================
% ============== begin subfunctions ================
% ==================================================
function [modelterms,varlist] = buildcompletemodel(order,p)
%
% arguments: (input)
%  order - scalar integer, defines the total (maximum) order
%
%  p     - scalar integer - defines the dimension of the
%          independent variable space
%
% arguments: (output)
%  modelterms - exponent array for the model
%
%  varlist - cell array of character variable names

% build the exponent array recursively
if p == 0
  % terminal case
  modelterms = [];
elseif (order == 0)
  % terminal case
  modelterms = zeros(1,p);
elseif (p==1)
  % terminal case
  modelterms = (order:-1:0)';
else
  % general recursive case
  modelterms = zeros(0,p);
  for k = order:-1:0
    t = buildcompletemodel(order-k,p-1);
    nt = size(t,1);
    modelterms = [modelterms;[repmat(k,nt,1),t]];
  end
end

% create a list of variable names for the variables on the fly
varlist = cell(1,p);
```

```
for i = 1:p
  varlist{i} = ['X',num2str(i)];
end


% ================================================
function [modelterms,varlist] = parsemodel(model,p);
%
% arguments: (input)
%  model - character string or cell array of strings
%
%  p     - number of independent variables in the model
%
% arguments: (output)
%  modelterms - exponent array for the model

modelterms = zeros(0,p);
if ischar(model)
  model = deblank(model);
end

varlist = {};
while ~isempty(model)
  if iscellstr(model)
    term = model{1};
    model(1) = [];
  else
    [term,model] = strtok(model,' ,');
  end

  % We've stripped off a model term. Now parse it.

  % Is it the reserved keyword 'constant'?
  if strcmpi(term,'constant')
    modelterms(end+1,:) = 0;
  else
    % pick this term apart
    expon = zeros(1,p);
    while ~isempty(term)
      vn = strtok(term,'*/^. ,');
      k = find(strncmp(vn,varlist,length(vn)));
      if isempty(k)
        % its a variable name we have not yet seen

        % is it a legal name?
        nv = length(varlist);
        if ismember(vn(1),'1234567890_')
          error(['Variable is not a valid name: ''',vn,''''])
        elseif nv>=p
          error 'More variables in the model than columns of↙
indepvar'
        end

        varlist{nv+1} = vn;

        k = nv+1;
```

```
      end
      % variable must now be in the list of vars.

      % drop that variable from term
      i = strfind(term,vn);
      term = term((i+length(vn)):end);

      % is there an exponent?
      eflag = false;
      if strncmp('^',term,1)
        term(1) = [];
        eflag = true;
      elseif strncmp('.^',term,2)
        term(1:2) = [];
        eflag = true;
      end

      % If there was one, get it
      ev = 1;
      if eflag
        ev = sscanf(term,'%f');
        if isempty(ev)
            error 'Problem with an exponent in parsing the↙
model'
        end
      end
      expon(k) = expon(k) + ev;

      % next monomial subterm?
      k1 = strfind(term,'*');
      if isempty(k1)
        term = '';
      else
        term(k1(1)) = ' ';
      end

    end

    modelterms(end+1,:) = expon;

  end

end

% Once we have compiled the list of variables and
% exponents, we need to sort them in alphabetical order
[varlist,tags] = sort(varlist);
modelterms = modelterms(:,tags);
```

```
function ypred = polyvaln(polymodel,indepvar)
% polyvaln: evaluates a polynomial model as a function of its↙
variables
% usage: ypred = polyvaln(polymodel,indepvar)
%
% arguments: (input)
%  indepvar - (n x p) array of independent variables as↙
columns
%        n is the number of data points to evaluate
%        p is the dimension of the independent variable space
%
%        IF n == 1, then I will assume there is only a
%        single independent variable.
%
%  polymodel - A structure containing a regression model from↙
polyfitn
%        polymodel.ModelTerms = list of terms in the model
%        polymodel.Coefficients = regression coefficients
%
%        Note: A polymodel can be evaluated for any set of
%        values with the function polyvaln. However, if you
%        wish to manipulate the result symbolically using my
%        own sympoly tools, this structure should be converted
%        to a sympoly using the function polyn2sympoly.
%
% Arguments: (output)
%  ypred - nx1 vector of predictions through the model.
%
%
% See also: polyfitn, polyfit, polyval, polyn2sympoly, sympoly
%
% Author: John D'Errico
% Release: 1.0
% Release date: 2/19/06

% get the size of indepvar
[n,p] = size(indepvar);
if (n == 1) && (size(polymodel.ModelTerms,2)==1)
  indepvar = indepvar';
  [n,p] = size(indepvar);
elseif (size(polymodel.ModelTerms,2)~=p)
  error 'Size of indepvar array and this model are↙
inconsistent.'
end

% Evaluate the model
nt = size(polymodel.ModelTerms,1);
ypred = zeros(n,1);
for i = 1:nt
  t = ones(n,1);
  for j = 1:p
    t = t.*indepvar(:,j).^polymodel.ModelTerms(i,j);
  end
  ypred = ypred + t*polymodel.Coefficients(i);
end
```

APPENDIX 12A –LINEAR DISCRIMINANT ANALYSIS

12.1 Linear Discriminant Analysis Overview

Linear discriminant analysis (LDA) is a method of projecting high–dimensional data onto a lower-dimensional space in a way that best separates the data (Kamvar 2002). For example, imagine that there is a group of 50 individuals, and that each individual in the group either has LPP (w_1) or does not (w_2). Further, that 116 features (including both sonographic and non-sonographic variables) about each of these individuals is known. Accordingly, each individual could be represented as a data point which is described by its 116 features. Graphically one could imagine that to plot the location of all 50 data points based on their 116 features would require a multi-dimensional space. Linear discriminant analysis is a technique that can take a set of high-dimensional data points, where each data point belongs to either class w_1 (i.e. participants with LPP), or class w_2 (i.e. healthy participants), and project them onto two-dimensional space such that the line, (or linear discriminant) that best separates the classes can be calculated (Figure 12.1; Kamvar 2002). Moreover, LDA projects the data in the transformed space in a way that simultaneously maximises the overall between class variance, while minimizing the within class variance, which ultimately results in maximizing the value of the linear discriminant, or Rayleigh quotient [$J(w)$].

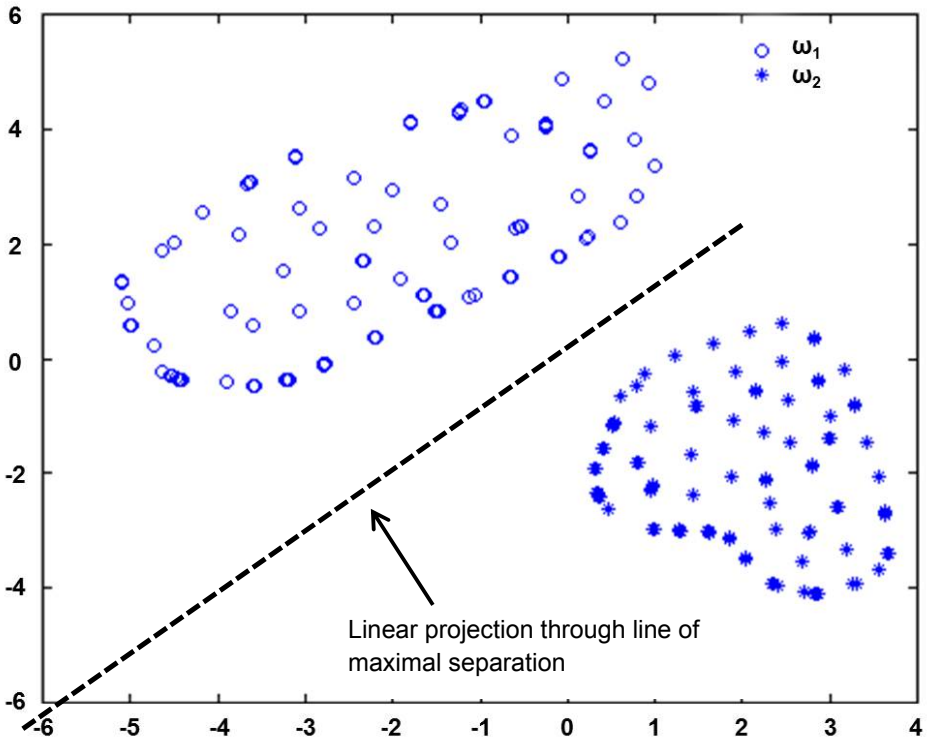


Figure 12a.1: Illustration of data points from two classes (w_1 and w_2) plotted in two dimensional space such that the overall between class variance is maximised and the within class variance is minimized, (modified from Kamvar 2002).

Linear discriminant analysis was first described in 1936 (Fisher, 1936) and has been used in a variety of areas of research for over last 70 years (Astephen and Deluzio 2005; Alvarenga et al. 2010). There are two main areas were LDA is useful (Kamvar 2002). The first is for the purposes of classifying a data point. That is, given the value of 116 features about an individual, a data point representing that individual could be plotted, and depending on if that data point fell to the left or right of some decision point (linear discriminant) the individual could be classified as having LPP or not. The second purpose of LDA, and the one that relates to the secondary analyses in chapter 9, is feature selection. That is, of the 116 features that are known about an individual, which feature, or combination of features, are the most useful in discriminating between the classes of data points. Put more generally, which linear combinations of variables best discriminate between two or more groups (i.e. healthy individuals and those with LPP).

12.2 Fisher Linear Discriminant Analysis

The form of LDA that was used in the analyses outline in chapter 9 was Fisher's linear discriminate analysis (FLDA). This form of LDA does not make the assumption of normally distributed classes, nor equal class covariances (Balakrishnama and Ganapathirju 2000). There are several steps required in order to measure the maximal separation between classes of data, an example of the technique, provided by Dr Peter Worsley is described here (Worsley 2011).

In this example taken from Fisher's (1936) original paper, a transform matrix $\boldsymbol{w}$ is sought, such that the sample $\boldsymbol{x_i}$ can be projected into 1-dimensional space as

$$z_i = w^T x_i, \qquad i = 1,2, \dots l.$$

The matrix w is computed by simultaneously maximising the overall separation between centres of the $\boldsymbol{m}$ classes, and minimizing the sum of the within class scatter in the transformed space of dimension $\boldsymbol{q}$. This involves maximising the Rayleigh quotient

$$J(w) = \frac{w^T \sum_b w}{w^T \sum_w w}$$

where $\boldsymbol{\Sigma_b}$and $\boldsymbol{\Sigma_w}$ denote the between and within class covariant matrices, which are defined as;

$$\sum\nolimits_b = \sum_{i=1}^{m} (\boldsymbol{u}_i - \boldsymbol{u})(\boldsymbol{u_i} - \boldsymbol{u})^T$$

and

$$\sum_w = \sum_{i=1}^{m} \sum_{x_j \in S_i} (x_j - \boldsymbol{u}_i)(x_j - \boldsymbol{u}_i)^T$$

where $\boldsymbol{u}$ denotes the global centre of all the samples, and $\boldsymbol{u}_i$ denotes the centre of class $\boldsymbol{i}$. To maximise the Rayleigh quotient $\boldsymbol{J}(\boldsymbol{w})$, the transformation matrix $\boldsymbol{w}$ is computed by solving the eigenvalue problem

$$\sum_b w = \Omega \sum_w w,$$

where $\boldsymbol{\Omega}$ denotes the diagonal matrix of the eigenvalues. The magnitude of each eigenvalue is a measure of the discriminatory power of the projection along the corresponding eigenvector. In order to obtain a good classification between groups, data should present with a small within-class and a large between class covariant (Figure 12.2).

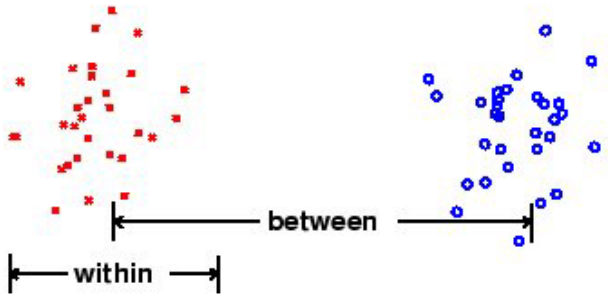


Figure 12a.2: Example of within and between class covariance.

The analyses outlined in chapter 9 used LDA to find the variables or features which offered the highest discrimination between LPP and healthy participants. It is important to note that LDA performs an optimal separation and further techniques are required to incorporate known errors in the variables and uncertainty in the classification process.

APPENDIX 12b: The Rank Order, Individual, and Combined Linear Discriminant of the 116 variables of the Large Database.

Rank	Feature	$J(w)$ value	Cumulative $J(w)$ value	Feature Category	Feature Description
1	Compression Pattern	0.4195	0.4195	Clinical	Pattern of compression that normalised the ASLR test
2	Pain	0.1202	0.6299	Self-report	Numerical Pain Rating Scale Score
3	Function	0.0621	0.6433	Self-report	Oswestry Disability Score
4	FABQPA	0.0544	0.6580	Self-report	Fear Avoidance Belief Questionnaire (Physical Activity Sub-set) Score
5	Nijmegen	0.0235	0.6853	Self-report	Nijmegen (Hypocapnia) Questionnaire Score
6	FABQW	0.0212	0.7386	Self-report	Fear Avoidance Belief Questionnaire (Work Sub-set) Score
7	Total Nfascia	0.0183	0.7465	Sonographic	% contribution of PMCT to abdominal wall thickness
8	Total NAWRESTTh	0.0183	0.7465	Sonographic	% contribution of muscle to abdominal wall thickness
9	UDI	0.0160	0.8955	Self-report	Urogenital Distress Index
10	Age	0.0139	0.9028	Participant	Age in years
11	Pain length	0.0137	0.9140	Self-report	Length of Pain in years
12	TrA ASLRLL ChP	0.0131	0.9207	Sonographic	% change in TrA thickness at ASLR leg lift
13	iRA Nfascia	0.0120	0.9604	Sonographic	% contribution of inferior RA PMCT to total PMCT thickness
14	TrA Nresting	0.0085	0.9632	Sonographic	% contribution of TrA to total abdominal muscle thickness
15	TrA ASLR PoR ChP	0.0078	0.9669	Sonographic	% change in TrA thickness at ASLR post manoeuvre
16	IRD resting	0.0074	1.0015	Sonographic	Inter-recti distance width (cm)
17	sRA Nfascia	0.0066	1.0043	Sonographic	% contribution of superior RA PMCT to total PMCT thickness
18	TrA ASLR RL ChP	0.0054	1.0050	Sonographic	% change in TrA thickness at ASLR manoeuvre release
19	SBLD ASLR RL PGX	0.0053	1.0059	Sonographic	change in GBB cranial/caudal position at ASLR manoeuvre release (cm)
20	Breathing Strategy	0.0050	1.0421	Clinical	predominate supine breathing pattern
21	EO ADIM R ChP	0.0049	1.0721	Sonographic	% change in EO thickness at ADIM manoeuvre release
22	SBLD ASLR LL PGT	0.0048	1.0954	Sonographic	change in GBB trajectory position at ASLR manoeuvre release (cm)
23	TrA ASLR LH ChP	0.0047	1.1074	Sonographic	% change in TrA thickness at ASLR leg hold
24	RA Nresting	0.0043	1.2001	Sonographic	% contribution of RA to total abdominal muscle thickness
25	SBLD ASLR RL PRX	0.0043	0.0129	Sonographic	change in RBB cranial/caudal position at ASLR manoeuvre release (cm)
26	SBLD ASLR LL PGX	0.0042	0.0127	Sonographic	change in GBB cranial/caudal position at ASLR leg lift (cm)
27	Total NLAW REST Th	0.0042	0.0129	Sonographic	% contribution of EO, IO and TrA to total abdominal muscle thickness
28	SBLD ASLR LL PRX	0.0042	0.0130	Sonographic	change in RBB cranial/caudal position at ASLR leg lift (cm)
29	SBLD ASLR RL PGY	0.0038	0.0132	Sonographic	change in GBB ventral/dorsal position at ASLR manoeuvre release (cm)
30	TrA ADIM H ChP	0.0036	0.0133	Sonographic	% change in TrA thickness at ADIM hold
31	SBLD ASLR LH PRT	0.0034	0.0134	Sonographic	change in RBB trajectory position at ASLR leg hold (cm)
32	SBLD ASLR RL BGX	0.0030	0.0135	Sonographic	change in GBB cranial/caudal position at ASLR manoeuvre release (cm)
33	SBLD ASLR LH PGY	0.0026	0.0136	Sonographic	change in GBB ventral/dorsal position at ASLR leg hold (cm)
34	IO ASLR LL ChP	0.0026	0.0137	Sonographic	% change in IO thickness at ASLR leg lift
35	Parity	0.0025	0.0137	Participant	Parity
36	SBLD ASLR RL BGT	0.0021	0.0138	Sonographic	change in GBB trajectory position at ASLR manoeuvre release (cm)
37	SBLD ASLR LH PGT	0.0021	0.0139	Sonographic	change in GBB trajectory position at ASLR leg hold (cm)
38	EO ADIM H ChP	0.0020	0.0140	Sonographic	% change in EO thickness at ADIM hold
39	SBLD ASLR RL PRY	0.0018	0.0140	Sonographic	change in RBB ventral/dorsal position at ASLR release manoeuvre (cm)
40	EO Nresting	0.0017	0.0141	Sonographic	% contribution of EO to total abdominal muscle thickness
41	SBLD ASLR RL PRT	0.0016	0.0141	Sonographic	change in RBB trajectory position at ASLR manoeuvre release (cm)
42	SBLD ASLR LL PGY	0.0015	0.0142	Sonographic	change in GBB ventral/dorsal position at ASLR leg lift (cm)
43	BMI	0.0014	0.0142	Participant	Body mass index (kg/m^2)
44	EO ASLR PoR ChP	0.0013	0.0143	Sonographic	% change in EO thickness at ASLR post manoeuvre
45	Weight	0.0013	0.0143	Participant	(kilograms)
46	IO ASLR LH ChP	0.0012	0.0143	Sonographic	% change in IO thickness at ASLR leg hold
47	SBLD ASLR LH PRX	0.0011	0.0144	Sonographic	change in RBB cranial/caudal position at ASLR leg hold (cm)
48	IO ASLR RL	0.0011	0.0145	Sonographic	IO thickness at ADIM pre-manoeuvre (cm)
49	TrA ADIM PrR	0.0010	0.0145	Sonographic	TrA thickness at ADIM post-manoeuvre (cm)
50	IO ADIM PoR ChP	0.0010	0.0145	Sonographic	% change in IO thickness at ADIM post-manoeuvre
51	SBLD ASLR LL PRT	0.0009	0.0145	Sonographic	change in RBB trajectory position at ASLR leg lift (cm)
52	TrA ADIM R ChP	0.0009	0.0146	Sonographic	% change in TrA thickness at ADIM manoeuvre release
53	RA ASLR RL ChP	0.0009	0.0146	Sonographic	% change in RA thickness at ASLR manoeuvre release
54	IO ASLR PrR	0.0009	0.0147	Sonographic	IO thickness at ASLR pre-manoeuvre (cm)
55	EO ASLR LH ChP	0.0008	0.0147	Sonographic	% change in EO thickness at ASLR leg hold
56	IO ASLR PoR	0.0008	0.0147	Sonographic	IO thickness at ASLR post-manoeuvre (cm)
57	BPM	0.0008	0.0148	Clinical	Breaths per minute
58	SBLD ASLR PoR PGT	0.0007	0.0148	Sonographic	change in GBB trajectory position at ASLR post-manoeuvre (cm)
59	TrA ADIM ChP	0.0007	0.0148	Sonographic	% change in TrA thickness at ADIM onset
60	IIQ	0.0006	0.0148	Self-report	Incontinence Impact Questionnaire
61	EOIO Nfascia	0.0006	0.0149	Sonographic	% contribution of PMCT layer between EO and IO to total PMCT thickness
62	SBLD ASLR LH PRY	0.0006	0.0149	Sonographic	change in RBB ventral/dorsal position at ASLR leg hold (cm)
63	SBLD ASLR PoR PRX	0.0006	0.0149	Sonographic	change in RBB cranial/caudal position at ASLR post-manoeuvre (cm)
64	TrA ADIM PoR	0.0005	0.0149	Sonographic	TrA thickness at ADIM post-manoeuvre (cm)
65	SBLD ASLR RL PGT	0.0005	0.0149	Sonographic	change in GBB trajectory position at ASLR manoeuvre release (cm)
66	SBLD ASLR LL PRY	0.0005	0.0149	Sonographic	change in RBB ventral/dorsal position at ASLR leg lift (cm)
67	TrA ASLR PoR	0.0005	0.0150	Sonographic	TrA thickness at ASLR post-manoeuvre (cm)
68	TrA ASLR LL	0.0005	0.0150	Sonographic	TrA thickness at ASLR leg lift (cm)
69	IO ADIM H ChP	0.0005	0.0151	Sonographic	% change in IO thickness at ADIM hold
70	SBLD ASLR LH PGX	0.0005	0.0151	Sonographic	change in GBB cranial/caudal position at ASLR leg hold (cm)
71	TrA ASLR RL	0.0005	0.0151	Sonographic	TrA thickness at ASLR manoeuvre release (cm)
72	EO ADIM R	0.0004	0.0151	Sonographic	EO thickness at ADIM manoeuvre release (cm)
73	TrA ASLR PrR	0.0004	0.0151	Sonographic	TrA thickness at ASLR pre-manoeuvre (cm)
74	IO ASLR LH	0.0004	0.0151	Sonographic	IO thickness at ASLR leg hold (cm)
75	TrA ADIM	0.0004	0.0152	Sonographic	TrA thickness at ADIM onset (cm)
76	TrA ADIM H	0.0004	0.0152	Sonographic	TrA thickness at ADIM hold (cm)
77	SBLD ASLR PoR PGX	0.0003	0.0152	Sonographic	change in GBB cranial/caudal position at ASLR post-manoeuvre (cm)
78	SBLD ASLR PoR PRY	0.0003	0.0152	Sonographic	change in RBB ventral/dorsal position at ASLR post-manoeuvre (cm)
79	IO ADIM R ChP	0.0003	0.0152	Sonographic	% change in IO thickness at ADIM manoeuvre release
80	SBLD ASLR PoR PGY	0.0003	0.0152	Sonographic	change in GBB ventral/dorsal position at ASLR post-manoeuvre (cm)
81	SBLD ASLR PoR PRT	0.0003	0.0153	Sonographic	change in RBB trajectory position at ASLR post-manoeuvre (cm)
82	LAW Nfascia	0.0003	0.0153	Sonographic	% contribution of LAW PMCT layers to total PMCT thickness
83	EO ASLR LL	0.0003	0.0153	Sonographic	EO thickness at ASLR leg lift (cm)
84	EO ASLR PoR	0.0002	0.0153	Sonographic	EO thickness at ASLR post-manoeuvre (cm)
85	EO ASLR LL ChP	0.0002	0.0153	Sonographic	% change in EO thickness at ASLR leg lift
86	EO ADIM ChP	0.0002	0.0153	Sonographic	% change in EO thickness at ADIM onset
87	EO ADIM H	0.0002	0.0153	Sonographic	EO thickness at ADIM hold (cm)
88	IO ADIM ChP	0.0002	0.0153	Sonographic	% change in IO thickness at ADIM onset
89	TrA ASLR LH	0.0002	0.0154	Sonographic	TrA thickness at ASLR leg hold (cm)
90	IO ASLR LL	0.0002	0.0154	Sonographic	IO thickness at ASLR leg lift (cm)
91	TrA ADIM PoR ChP	0.0001	0.0154	Sonographic	% change in TrA thickness at ADIM post-manoeuvre
92	IO Nresting	0.0001	0.0154	Sonographic	% contribution of IO to total abdominal muscle thickness
93	IO ADIM H	0.0001	0.0154	Sonographic	IO thickness at ADIM hold (cm)
94	IO ADIM R	0.0001	0.0154	Sonographic	IO thickness at ADIM manoeuvre release (cm)
95	SBLD ASLR RL BGY	0.0001	0.0154	Sonographic	change in GBB ventral/dorsal position at ASLR manoeuvre release (cm)
96	EO ASLR PrR	9.47E-05	0.0154	Sonographic	EO thickness at ASLR pre-manoeuvre (cm)
97	EO ASLR RL	9.36E-05	0.0154	Sonographic	EO thickness at ASLR manoeuvre release (cm)
98	Gender	9.35E-05	0.0154	Participant	Gender
99	IOTrA Nfascia	6.80E-05	0.0154	Sonographic	% contribution of PMCT layer between IO and TrA to total PMCT thickness
100	Total AWCT Th	5.51E-05	0.0154	Sonographic	total abdominal wall muscle and PMCT thickness (cm)
101	IO ADIM PrR	4.88E-05	0.0154	Sonographic	IO thickness at ADIM pre-manoeuvre (cm)
102	EO ASLR RL ChP	3.44E-05	0.0154	Sonographic	% change in EO thickness at ASLR manoeuvre release
103	EO ADIM	2.92E-05	0.0154	Sonographic	EO thickness at ADIM onset (cm)
104	IO ASLR PoR ChP	2.82E-05	0.0154	Sonographic	% change in IO thickness at ASLR post-manoeuvre
105	TrAP Nfascia	2.60E-05	0.0154	Sonographic	% contribution of inferior TrA PMCT to total PMCT thickness
106	Height	2.45E-05	0.0154	Participant	Height (meters)
107	IO ADIM	2.14E-05	0.0154	Sonographic	IO thickness at ADIM onset (cm)
108	EO ASLR LH	1.85E-05	0.0154	Sonographic	EO thickness at ASLR leg hold (cm)
109	EO ADIM Po R	1.58E-05	0.0154	Sonographic	EO thickness at ADIM post-manoeuvre (cm)
110	EO ADIM PoR ChP	9.10E-06	0.0154	Sonographic	% change in EO thickness at ADIM post-manoeuvre
111	EO ADIM PrR	6.44E-06	0.0154	Sonographic	EO thickness at ADIM pre-manoeuvre (cm)
112	IO ADIM PoR	5.89E-06	0.0154	Sonographic	IO thickness at ADIM post-manoeuvre (cm)
113	IO ASLR RL ChP	4.75E-06	0.0155	Sonographic	% change in IO thickness at ASLR manoeuvre release
114	ETCO2	2.02E-06	0.0155	Clinical	End tidal Carbon Dioxide (mmHg)
115	TrA ADIM R	1.21E-06	0.0155	Sonographic	TrA thickness at ADIM manoevre release (cm)
116	ANTAW Nfascia	5.41E-08	0.0155	Sonographic	% contribution of RA PMCT to total PMCT thickness

ADIM = Abdominal drawing in manoeuvre, ASLR = Active straight leg raise test, cm = centimeter, EO = exernal oblique, GBB = global bladder base, IO = internal oblique, $J(w)$ = linear discriminant, LAW = lateral abdominal wall, mmHg = millimeters of Mercury, PMCT = perimuscular connective tissue, RA = rectus abdominins, RRB = relative bladder base,TrA = transversus abdominis, % = percent

APPENDIX 12c: The Rank Order, Individual, and Combined Linear Discriminant of the 38 variables of the Small Database.

Rank	Feature	*J(w)* value	Cumulative *J(w)* value	Feature Category	Feature Description
1	Compression Pattern	0.4195	0.4195	Clinical	Pattern of compression that normalised the ASLR test
2	Pain	0.1202	0.6299	Self-report	Numerical Pain Rating Scale Score
3	Function	0.0621	0.6433	Self-report	Oswestry Disability Score
4	FABQPA	0.0544	0.6580	Self-report	Fear Avoidance Belief Questionnaire (Physical Activity Sub-set) Score
5	Nijmegen	0.0235	0.6853	Self-report	Nijmegen (Hypocapnia) Questionnaire Score
6	FABQW	0.0212	0.7386	Self-report	Fear Avoidance Belief Questionnaire (Work Sub-set) Score
7	Total Nfascia	0.0183	0.7465	Sonographic	% contribution of PMCT to abdominal wall thickness
8	Total NAWRESTTh	0.0183	0.7465	Sonographic	% contribution of muscle to abdominal wall thickness
9	UDI	0.0160	0.8955	Self-report	Urogenital Distress Index
10	Age	0.0139	0.9028	Participant	Age in years
11	Pain length	0.0137	0.9140	Self-report	Length of Pain in years
12	TrA ASLRLL ChP	0.0131	0.9207	Sonographic	% change in TrA thickness at ASLR leg lift
13	TrA ASLR PoR ChP	0.0078	0.9220	Sonographic	% change in TrA thickness at ASLR post manoeuvre
14	IRD resting	0.0074	0.9596	Sonographic	Inter-recti distance width (cm)
15	TrA ASLR RL ChP	0.0054	0.9599	Sonographic	% change in TrA thickness at ASLR manoeuvre release
16	SBLD ASLR RL PGX	0.0053	0.9612	Sonographic	change in GBB cranial/caudal position at ASLR manoeuvre release (cm)
17	Breathing Strategy	0.0050	0.9949	Clinical	predominate supine breathing pattern
18	EO ADIM R ChP	0.0049	1.0107	Sonographic	% change in EO thickness at ADIM manoeuvre release
19	SBLD ASLR LL PGT	0.0048	1.0337	Sonographic	change in GBB trajectory position at ASLR manoeuvre release (cm)
20	TrA ASLR LH ChP	0.0047	1.0379	Sonographic	% change in TrA thickness at ASLR leg hold
21	RA Nresting	0.0043	1.1279	Sonographic	% contribution of RA to total abdominal muscle thickness
22	SBLD ASLR RL PRX	0.0043	0.0123	Sonographic	change in RBB cranial/caudal position at ASLR manoeuvre release (cm)
23	SBLD ASLR LL PGX	0.0042	0.0124	Sonographic	change in GBB cranial/caudal position at ASLR leg lift (cm)
24	Total NLAW REST Th	0.0042	0.0125	Sonographic	% contribution of EO, IO and TrA to total abdominal muscle thickness
25	SBLD ASLR LL PRX	0.0042	0.0126	Sonographic	change in RBB cranial/caudal position at ASLR leg lift (cm)
26	SBLD ASLR RL PGY	0.0038	0.0126	Sonographic	change in GBB ventral/dorsal position at ASLR manoeuvre release (cm)
27	SBLD ASLR LH PRT	0.0034	0.0124	Sonographic	change in RBB trajectory position at ASLR leg hold (cm)
28	Parity	0.0025	0.0125	Participant	Parity
29	BMI	0.0014	0.0126	Participant	Body mass index (kg/m^2)
30	Weight	0.0013	0.0126	Participant	(kilograms)
31	BPM	0.0008	0.0126	Clinical	Breaths per minute
32	IIQ	0.0006	0.0127	Self-report	Incontinence Impact Questionnaire
33	LAW Nfascia	0.0003	0.0127	Sonographic	% contribution of LAW PMCT layers to total PMCT thickness
34	Gender	9.35E-05	0.0127	Participant	Gender
35	Total AWCT Th	5.51E-05	0.0127	Sonographic	total abdominal wall muscle and PMCT thickness (cm)
36	Height	2.45E-05	0.0127	Participant	(meters)
37	ETCO2	2.02E-06	0.0127	Clinical	End tidal Carbon Dioxide (mmHg)
38	ANTAW Nfascia	5.41E-08	0.0127	Sonographic	% contribution of RA PMCT to total PMCT thickness

ADIM = Abdominal drawing in manoeuvre, ASLR = Active straight leg raise test, cm = centimeter, EO = exernal oblique, GBB = global bladder base, IO = internal oblique, *J(w)* = linear disciminant, LAW = lateral abdominal wall, mmHg = millimeters of Mercury, PMCT = perimuscular connective tissue, RA = rectus abdominins, RRB = relative bladder base,TrA = transversus abdominis, % = percent

APPENDIX13a: A Clinical Example of the use of Ultrasound Imaging to Inform Physiotherapy Treatment and Surgical Referral in a Female Patient with Lumbopelvic Pain.

<table>
<tr><th colspan="4">PERSONAL CONTEXT FACTORS</th></tr>
<tr><td colspan="2">Age: 32 years</td><td colspan="2">Gender: Female</td><td>Employment: Stay at home mom (two children under the age of 3 years)</td></tr>
<tr><td colspan="5">Socio-Economic Status: Middle to upper class</td></tr>
<tr><td colspan="5">Personal Health Practices: The patient was reportedly active participating in two to three Pilates (equipment based) classes, one body rolling class, and four to five thirty minute walks, and one sixty minute swimming class per week. She had a healthy body mass index and was a non-smoker.</td></tr>
<tr><td colspan="5">Interests: Pilates, body rolling, swimming, walking and child rearing.</td></tr>
<tr><th colspan="5">ENVIRONMENTAL CONTEXTUAL FACTORS</th></tr>
<tr><td colspan="5">Living Situation: This patient was married and lived with her husband and two young children (3 years and 18 months) in a three level home.</td></tr>
<tr><td colspan="5">Environment: The patient was a full- time mom and homemaker for her two young children and husband, who was a busy music producer. As her husband travelled she was often left carrying for the children and home for extended periods (6 weeks). She was supported by a part-time nanny and elderly parents who lived close by. Physical activity was a priority and until recently, she had participated in some form 4 – 6 days a week.</td></tr>
<tr><th colspan="5">HEALTH CONDITION</th></tr>
<tr><td colspan="2">Primary Complaint: Right lower back, buttock and lateral hip pain.</td><td colspan="2">Physiotherapy Diagnosis: Failed load transfer through the right lumbopelvic region secondary to insufficiency of the abdominal wall.</td><td>Date of Diagnosis: June, 2010</td></tr>
<tr><td colspan="5">History of Condition: 16 month history of right low back, buttock and lateral hip pain with an insidious onset related to an increase in activity after birth of her second child (nine pounds, 11 ounces). Assuming that the pain would alleviate itself as she strengthened her ‘core’ she had not sought medical attention opting rather to continue with Pilates and swimming. After months of persisting pain, and on the advice of her Pilates instructor, she referred herself to physiotherapy. She stated the last 18 months had been hectic and it was only now that she had time to address her pain.</td></tr>
</table>

Additional Medical History: No history of low back, buttock or hip pain prior to, or with the previous pregnancy or delivery. The patient denied any metabolic disorders, other medical concerns or incontinence. Both pregnancies and deliveries (both Caesarean-section) had been uneventful.
Diagnostic Tests: None had been performed.
Medications: No pharmaceutical management provided although she did report some improvement with the occasional Aleve.
Functional Level/Abilities: Although capable of all the functional demands of daily living, the patient reported a persistent aching sensation and symptom aggravation with weight bearing (WB) activities such as walking (10 minutes), standing (5–10 minutes), kneeling (5 minutes) or any attempt to progress her Pilates routine. Resting in non-WB positions (i.e. sitting) and swimming provided some relief. Numerical Pain Rating Scale (NPRS; 7/10), Roland-Morris Disability Questionnaire (RM; 12/24 and Quebec Back Pain Disability Scale (QBPDS; 35/100).
PATIENT/CLIENT GOALS
1. Elimination of the right lower back, buttock and hip pain. 2. Full pain free return to Pilates, walking, and activities in general. 3. Restoration of her body back to pre-pregnancy functional status, in her words 'Just give me exercises so that I can get my stomach back'.

PHYSIOTHERAPEUTIC ASSESSMENT AND FINDINGS (tests, factors for consideration)

Standing observation revealed obvious sagging of the abdominal wall, thoracolumbar (TL) lordosis, and lumbosacral (LS) flexion associated with posterior rotation of the pelvis and mild external rotation of the right femur. Gross movements of the region were unremarkable with the exception of left trunk side flexion (restricted by a pulling sensation in the right flank, low back, and out side of the hip) and internal rotation of the right hip (restricted by a pulling sensation in the right buttock).

The ability to transfer weight bearing loads through the pelvis was assessed with the one leg standing (OLS)[6, 7] and active straight leg raise (ASLR) tests.[8] Abnormalities were identified with both. The WB portion of the OLS test was positive suggesting use of a motor control strategy that was unable to maintain relative nutation of the sacrum on innominate. The right ASLR test was positive as the patient reported lateral hip pain and more difficulty when lifting the right leg. Further, the addition of compression to the pelvis (specifically through gathering up the abdominal slack) dramatically decreased the pain, and normalized the weight of the leg suggesting an insufficiency of the abdominal wall.

Passive mobility testing of the sacro-iliac joints (SIJ) and passive intervertebral motion testing of the lumbar spine were normal while tests of hip joint accessory motion indicated an extra-articular restriction of internal rotation (likely tone in the external rotator muscles). Passive stability tests of the SIJ's and lumbar spine were normal and due to the hypomobility detected at the hip joint stability tests were not performed. Nerve conduction and

mobility tests were normal. Hypertonicity of the right > left iliocostalis lumborum, ischiococcygeus, as well as right rectus femoris (RF), tensor fascia latae (TFL) and hip external rotators were detected through palpation.

The pattern of presentation suggested an ineffective motor control strategy for vertical load transfer through the right lumbopelvic region. This involved excessive contribution from the muscles that produced TL extension, posterior pelvic rotation (associated LS flexion) and right hip external rotation as well as insufficient contribution from the abdominal wall. With the goal of ascertaining the status of the abdominal wall, the use of ultrasound imaging (USI) to assess muscle function and Linea Alba (LA) width was introduced and consent provided.[13, 15] Ultrasound imaging revealed the resting thickness of the internal oblique (IO), transversus abdominis (TrA) and rectus abdominis (RA) muscles to be discernibly less than published norms,[10] while the inter-recti distance (IRD) or LA was significantly wider (3.5 cm above the umbilicus).[2] The patient was unable to perform a concentric contraction of the TrA [12] and a sub-optimal motor control strategy involving minimal contribution of the IO and TrA, and excessive contribution from the right RF and TFL during the ASLR test was detected.[14] To determine if the abdominal deficiency was due to a lack of TrA contribution the patient was taught a concentric TrA contraction (using USI biofeedback) and the ASLR test repeated while this was held. The ASLR remained positive suggesting both a functional (TrA and/or IO and RA muscles) and structural (LA) component to the abdominal wall deficiency. Further the presence of the structural deficiencies pointed to a poorer prognosis and overall therapeutic outcome.

PHYSIOTHERAPY ISSUES

1. Inability to control loading through the right lumbopelvic region secondary due to an ineffective motor control strategy. Specifically a strategy that involved excessive contribution from the muscles that produce TL extension, posterior pelvic rotation and right hip external rotation as well as insufficient contribution of the abdominal wall muscles (RA, IO and TrA).
2. Inability to control loading of the right lumbopelvic region secondary to a structural deficiency of the Linea Alba.
3. A lack of understanding by the patient as to the impact of pregnancy and child birth on the abdominal wall and the potential associated long-term consequences. Overall the patient exhibited an unrealistic belief system about the recovery.

PHYSIOTHERAPEUTIC INTERVENTIONS (selection and rationale, treatment progression, outcomes/evaluation)

Issue	Therapeutic Goal	Therapeutic Target	Description of Intervention and rationale
1	**1.** Optimize the motor control strategy for load transfer through the right lumbopelvic	**1a.** Decrease the tone and excessive contribution of the hypertonic muscles	The overarching rational for the interventions aimed at optimizing motor control was to employ an approach involving motor learning strategies. Specifically movement exercises with error correction, augmented feedback and part-practice[3] in combination with education and manual techniques (i.e. manual therapy and dry needling) aimed at

	region thereby decreasing pain (decreased NPRS score) and increasing function (decreased RM and QBPDS scores).	during lumbopelvic loading. - Decrease the twitch responses in these muscles. - Improve the ability of the patient to disassociate movement of the TL and LS spine as well as rest in the neutral resting position of the hip, TL, LS spines **1b.** Increase the contribution of the abdominal muscles during loading of the lumbopelvic region. - Increase the resting thickness of the TrA, IO and RA as well as thickness change of the TrA and IO with an ASLR test.	addressing specifics of the presentation. **1a.** A combination of dry needling of the hypertonic muscles followed by active movement exercises aimed at disassociation of the TL and LS spines (i.e. TL flexion with LS extension) first in non-WB, followed by seated then standing positions and finally in functional movements patterns were used to achieve this target. Initially this involved error correction, visual, verbal and proprioceptive feedback. As the experiential understanding of how to differentiate the regions of the spine improved feedback was removed and task difficulty increased. The rationale was that the dry needling would decrease the resting tone of the hypertonic muscles so that new movement patterns could be introduced and practiced. The aim was to create opportunities for the patient to experience different ways to moving during day to day movement patterns so that she could take that experience and apply it outside of therapy sessions. **1b.** This portion of the intervention involved teaching the patient how to perform a sub-maximal isolated contraction of the TrA (USI assisted) and then maintain it during movements aimed at engaging the RA and IO. The rationale was to have the TrA contraction take up as much fascial slack as possible before engaging the RO and IO with exercises aimed at hypertrophy. Due to the patient's interest many of the exercises were modified versions of Pilates maneuvers. Particular focus was placed upon keeping the hypertonic muscles as relaxed as possible as she worked with these exercises. The majority of the 16 week intervention was spent working towards this goal. Over that time the NPRS dropped to as low as 3/10, the RM to 6/24 and the QBPDS to 20/100, the thickness of the IO and TrA did not change however the RA showed improvement (increasing from 0.54 cm to 0.65 cm). There was an obvious decrease in the number and strength of the twitch responses in the hypertonic muscles with the exception of the hip external rotators. In spite of the improvements there was a persisting tendency for the patient to resort to the presenting motor control strategy at higher loads (specifically if the pelvic belt was not used) which was accompanied with pain.
2	**2a.** Compensate for	**2a.** Optimize the use of	The rationale for the interventions aimed at the structural deficit of the LA was to either;

	the structural deficit of the LA as it applies to load transfer through the lumbopelvic region. **2b.** Attempt to decrease the width of the LA. **2c.** Inform the patient's family physician as to the significance of lengthened LA to her pain and ask him to consider referring the patient for surgical consideration	an assistive device (i.e. pelvic belt) that can compensate for the structural deficiency of the LA during weight-bearing loading situations. **2b.** Decrease the width of the LA (or IRD) through a targeted approach of recruiting the muscles that most impact the width of this structure (namely the lateral abdominal wall muscles)[1] **2c.** Engage the patient's family physician in a dialogue about the relevance of the clinical findings on her prognosis. Further to secure a referral to a plastic surgeon for consultation.	take up the slack (see 1b and 2b), mimic the impaired anterior force closure of the pelvis that it was contributing to (see 2a below),[5] and/ or determine if the patient was a candidate for surgical repair (see 2b below). **2a.** This intervention focussed on education about the mechanism of action, application, and use of, a pelvic belt that could enhance the anterior force closure of the pelvis during daily activities and recreational pursuits. Specifically providing the patient with an experiential understanding that she was able to move differently and with less pain when she used the belt. **2b.** There is low level evidence[11] that supports an approach too decreasing IRD through training the TrA and oblique muscles (similar to 1b above) in hopes of adaptive changes to their fascial extensions. Although it was unlikely that the degree of deficit exhibited by this patient (3.5 cm) would respond to this approach IRD was monitored as the patient worked to improve the contribution of the abdominal muscles to her motor control strategies (see 1b). **2c.** Based on the magnitude of the LA deficit and the unlikely impact of a conservative approach (2a and 2b), it was critical that alternative treatment options be investigated. A report outlining the patient's history, assessment findings, proposed treatment plan and a query about determining her suitability for surgical repair of the LA was sent to her physician. It was positively received and the patient referred to a plastic surgeon. A similar report was sent to the surgeon prior to the patient's visit. After the consultation the surgeon contacted me by phone. He stated the patient was an excellent surgical candidate based on traditional criteria however he needed better understand of the role the LA deficit played in her LPP as it was not something he had considered before. I provided a detailed explanation and several scientific references. After reviewing this material he contacted me again indicating that the surgery was elective, as it is considered cosmetic, and not covered under the public system. However, based on our discussion he felt an argument could be made that this case was an acceptation and should be covered by public funds. To assist in making this argument he asked if I could

			write a report, that went into greater depth about the role of the LA and abdominal wall muscles in the development and persistence of LPP. Based on this he was able to argue successfully the need for the surgery and won approval to have it covered by the public system. The time from the first report until approval was granted for public funding was four months during which, there was very little change in the size of the IRD.
3	**3.** Improve the patients' understanding of the impact of pregnancy and child birth on the abdominal wall and the potential associated long-term consequences	**3.** Ensure the patient had a full grasp of the factors contributing to her dysfunction as well as a realistic understanding of her prognosis.	**3.** The rationale for this aspect of the intervention was to educate the patient so that she had a more accurate understanding of the factors contributing to her dysfunction and her prognosis with conservative and surgical management so that if need be, she could make an informed decision of how to proceed. Topics ranged from understanding the role of the abdominal muscles and fascia in load transfer through the pelvis, the impact of the pregnancy on these structures and realistic expectations about the impact of exercise on the muscles and the LA deficit and how this related to the proposed treatment plan and referral for surgical consultation. The patient began treatment with the belief that she could restore her abdomen to pre-partum status with a few exercises. This belief system was slowly challenged and modified with the education provided. After 16 weeks of physiotherapy, and with the funding for the surgery approved, the patient opted to undergo surgical repair of the LA. This surgery took place on November 10, 2011.

DISCHARGE PLANNING

This patient has not been formally discharged, as she is planning on returning to therapy 6 weeks post-surgery. However planning for the post-surgical period has been discussed. Specifically, as the surgeon's instructions are for no, and then very minimal abdominal muscle contraction for 4-6 weeks the patient, her husband, nanny and I spent one session identifying barriers that may arise during this period and potential solutions. A decision was made to employ the nanny full-time for the first 4 weeks and ensure that meal planning and child care is supported for the 5th and 6th week. With the surgeon's approval, the patient will resume sub-maximal concentric TrA contractions at about the 4 week mark and a therapy session has been booked for Dec 22, 2011. As the patient has been an active participant, provided with knowledge about the source of her dysfunction and rationale for all interventions she understands the importance of rehabilitation post-op and is fully committed to the process.

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APPENDIX13b: A Clinical Example of the use of Ultrasound Imaging to Inform Physiotherapy Treatment in a Male Patient with Lumbopelvic Pain.

<table>
<tr><th colspan="4">PERSONAL CONTEXT FACTORS</th></tr>
<tr><td>Age: 22</td><td>Gender: Male</td><td colspan="2">Employment: Full time 3rd year engineering university student (September through April) and research assistant (May through August).</td></tr>
<tr><td colspan="4">Socio-Economic Status: Middle Class</td></tr>
<tr><td colspan="4">Personal Health Practices: The patient referred to himself as a recreational athlete who enjoyed a regular (3/week) gym workout schedule (aerobic and strength training exercises), and a 40 minute weekday cycling commute. He had a healthy body mass index and was a non-smoker.</td></tr>
<tr><td colspan="4">Interests: Recreational snowboarding, running and mountain biking in addition to his regular health practices.</td></tr>
<tr><th colspan="4">ENVIRONMENTAL CONTEXTUAL FACTORS</th></tr>
<tr><td colspan="4">Living Situation: This patient was single and lived with his parents within transit or cycling commute from the university.</td></tr>
<tr><td colspan="4">Environment: The patient was a full- time student and/or research assistant and as such spent the majority of his time commuting (via transit or bicycle), in class, studying or creating and running computer models which translated to considerable walking and sitting. Up until this injury he tried to participate in some form of physical activity daily.</td></tr>
<tr><th colspan="4">HEALTH CONDITION</th></tr>
<tr><td colspan="2">Primary Complaint: Pain and tightness in the right lower back (below waistline), buttock and tailbone.</td><td>Physiotherapy Diagnosis: Fixation of the right sacroiliac joint (SIJ) with associated motor control changes secondary to a traumatic fall.</td><td>Date of Dx: May 2010</td></tr>
<tr><td colspan="4">History of Condition: Onset immediately after a fall onto the right buttock snowboarding 3 months previous. Due to the severity of his pain and fear of a fractured tailbone he had gone to the emergency room that day. X-rays taken were reportedly normal. When the pain had not resolved after four weeks he had seen his family physician, at which time he had a second set of x-rays (also reportedly normal) and referred to physiotherapy. After</td></tr>
</table>

attending six physiotherapy sessions he discontinued treatment (which had consisted of modalities, general stretching and “core stability” exercises) as it had not impacted his pain.
Additional Medical History: No previous history of low back, buttock or hip pain or disorders. The patient reported a severe left ankle sprain 5 years earlier that had required physiotherapy management. He denied metabolic disorders, other medical concerns or incontinence.
Diagnostic Tests: An x-ray of the pelvis and lumbar spine taken the day of the incident and repeated six weeks later were reportedly normal.
Medications: No pharmaceutical management provided although he did report some improvement with the occasional Advil.
Functional Level/Abilities: Although capable of all the functional demands of daily living, the patient reported a persistent aching sensation, symptom aggravation with weight bearing activities like walking (10–15 minutes), standing (5–10 minutes), or cycling, and an inability to commute on his bicycle, run or snowboard without pain since the incident. Non-weight bearing positions (i.e. sitting) provided some relief, particularly if the chair was soft. Numerical Pain Rating Scale (NPRS; 6/10) and a Roland-Morris Disability Questionnaire (RM; 17/24).
PATIENT/CLIENT GOALS
1. Elimination of the lower back, buttock and tailbone pain and tightness. 2. Regardless of two negative x-rays the patient was still concerned that a tailbone fracture had been missed and wanted a third opinion. 3. Full pain free return to walking, running, mountain biking and ultimately snowboarding.

PHYSIOTHERAPEUTIC ASSESSMENT AND FINDINGS (test, factors for consideration)

Standing observation revealed evidence of increase tone in the right thoracolumbar erector spinae, which corresponded to a lordosis extending from L3 – T8. Further, the patient demonstrated a posteriorly rotated pelvis, and externally rotated right femur. Gross movements of the region detected asymmetry with both forward (right rotation at full flexion corresponding to pulling in the right low back and buttock) and backward bending (left rotation at full extension corresponding to a pinching sensation in the right low back). Left side flexion was restricted by a pulling sensation in the right flank, low back and buttock, while right side flexion, although within normal limits, produced a mild binding sensation in the right low back. The ability to transfer weight bearing loads through the pelvis was assessed with the one leg standing (OLS)[4, 5] and active straight leg raise (ASLR) tests.[6] Abnormalities were identified during both. Specifically limited posterior rotation of the right innominate was detected during the non-weight bearing (NWB) portion of the OLS test and the patient had difficulty balancing on the right leg during the weight bearing (WB) portion of the test. During the ASLR test the patient reported that it was more difficult to lift the right leg up off the bed, and the addition of further compression to the pelvis (particularly if applied posteriorly) increased the pain, and weight of the leg.

Passive mobility testing of the SIJ's detected increased stiffness of the vertical arm of right joint compared to the left, with the end feel suggestive of a joint fixation. Passive intervertebral motion testing of the lumbar spine revealed irritability to posterior inferior motion of the right L5 zygapophyseal articular surface on S1. Passive accessory intervertebral motions at this segment were more abrupt then the left, and the end feel suggested restriction due to increased muscle tone. Mobility testing of the right hip detected a decrease in flexion and internal rotation. Tests of hip joint accessory motion indicated an articular restriction of flexion (likely anterior impingement) and an extra-articular restriction of internal rotation (likely tone in the external rotator muscles). Due to the hypomobility detected at the SI, lumbar and hip joints stability tests were not performed. Nerve conduction tests were normal, while nerve mobility tests indicated a slight decrease in the mobility of the right sciatic nerve (detected at the end range of a slump test).[1]

Hypertonicity of the right abdominal wall, iliocostalis lumborum, ischiococcygeus, external rotators of the hip, and right biceps femoris was detected through palpation. Of particular interest was the tenderness provoked with palpation of the insertion of the ischiococcygeus on the inferior lateral angle of the sacrum as the patient reported this as the 'source of pain' and location of the 'potential' fracture site. Sensing the significance of this symptom additional time was spent applying posterior / anterior (PA) pressure to the sacrum and coccyx (which were pain free) vs. palpating the muscle insertion site as well as using a skeletal model and anatomical slides of the pelvic floor muscles (PFMs) from Primal Pictures to give the patient a more visual understanding of the anatomy in the region and that the pain source was at the muscle insertion site vs. 'the tailbone'.

Due to the pattern of presentation it was concluded that there was a fixation of the right SIJ in combination with associated hypertonicity secondary to traumatic fall. Accordingly after educating the patient on the findings and obtaining informed consent a high velocity, low amplitude gap (manipulation) was performed on the right SIJ, followed by dry needling directed at reducing the increased tone in the right iliocostalis lumborum, ischiococcygeus, external rotators (piriformis) of the hip and biceps femoris. On immediate reassessment there was improved mobility of the SIJ during passive and active mobility tests and subsequent passive stability tests were normal suggesting that the passive elements that control the joint were intact. The WB portion of the OLS test was positive (i.e. the patient employed a motor control strategy that was unable to maintain relative nutation of the sacrum on innominate). The ASLR test was positive on the right in that the right leg remained more difficult to lift, although in contrast to the pre-manipulation test, the leg became lighter when compression was provided across the inferior aspect of the pelvis (a force meant to mimic the contribution of the PFMs to force closure of the pelvis) in combination with lengthening of the right thoracolumbar region. Finally, nerve mobility testing continued to indicate decreased freedom of the right sciatic nerve.

PHYSIOTHERAPY ISSUES

1. Inability to control loading of the right SIJ secondary to an ineffective motor control strategy. Specifically a motor control strategy which involved; excessive contribution from the right abdominal wall, iliocostalis lumborum, ischiococcygeus, and external rotators of the hip combined with insufficient contribution from the PFMs.
2. Decreased mobility of the right sciatic nerve likely secondary to the hypertonicity in the piriformis and other external rotators of the hip.
3. A lack of understanding by the patient of the cause of his symptoms, the mechanical implications and the severity of the situation. Overall the patient exhibited an external locus of control with respect to his situation, meaning that he felt he had very little control over it.

PHYSIOTHERAPEUTIC INTERVENTIONS (selection and rationale, treatment progression, outcomes/evaluation)

The first session ended with education on the assessment findings (use of an ineffective movement control strategy for vertical or weight bearing loading of the pelvis), a review for the rationale of the treatment provided, and the treatment plan going forward. This discussion was aimed at improving the patient's understanding of the situation and diminishing his fear (PT issue 3). Further, the patient was shown how to self-release the hypertonicity in his right buttock region by using a soft racquet ball (PT issue 1), as well as how to mobilize the right sciatic nerve in a middle to end range position (PT issue 2). The patient was advised to return in approximately one week at which time we would reassess the situation.

The patient reported an obvious decrease in symptoms (RM = 11/24, a clinically significant change is indicated with a score change of 5) at the second session. On assessment the patient had a positive right ASLR test that normalized with inferior pelvic compression and there remained a mild increase in pain with application of posterior compression aimed at approximating the PSIS's. These findings suggested a deficiency in the force closure of the inferior aspect and either intolerance to, or excessive force closure of the posterosuperior aspect of the pelvis. The hypertonicity in the right abdominal wall, iliocostalis lumborum, ischiococcygeus and external rotators of the hip persisted and there was a small improvement in nerve mobility testing. Treatment proceeded with further dry needling aimed at diminishing hypertonicity of the right iliocostalis lumborum, superficial multifidus, ischiococcygeus, and piriformis followed by educating the patient on how to attend to the tension in those muscles and to relax his thoracolumbar lordosis, posterior pelvic tilt and buttock clenching in a crookly position. Doing so helped decompress the right lumbosacral junction, and allowed space for the right femoral head to begin to re-seat itself within the acetabulum.

To assist in providing a framework for home exercises, and the next step in treatment, it was explained to the patient that the re-education of his movement control strategy for his pelvis was going to involve 'turning off' or decreasing the contribution of some muscles, and then increasing the contribution of others when he moved (PT issue 1). Further, based on the ASLR test it was likely that the muscles that needed to increase their contribution were the PFM's. Correspondingly to help ascertain the status of the patient's PFM's in a non-invasive manner, the concept of using ultrasound imaging (USI) to assess muscle function was introduced and consent provided.[11] USI through an abdominal imaging site confirmed a sub-

optimal motor control strategy involving straining of the diaphragm and abdominal wall muscles which resulted in bladder decent during a right ASLR,[8] and revealed that the patient was unable to produce an isolated concentric contraction of the PFM's, instead demonstrating again, a straining strategy associated with a posterior pelvic tilt. Through education and use of USI as biofeedback, a concentric contraction of the PFM was achieved over a short period of time. This was then practiced in conjunction with USI feedback in an attempt to solidify the internal awareness of the contraction and the patient was given somatic cues to focus on independent to the USI that would help him to identify an inaccurate contraction so that it could be practiced at home.

USI of the bladder base during a concentric PFM contraction provided a unique opportunity to visualize coccyx flexion. Consequently this motion, and the observation that it was not painful, was pointed out in an attempt to further decrease anxiety about a missed tailbone fracture. When the right ASLR test was retested with an isolated PFM contraction the right leg was easier to lift then previously and the bladder remained stationary. Although able to normalize the motor control strategy used during the ASLR test the PFM's fatigued quickly, and there was a tendency to revert back to the straining strategy with an increase in effort. Instructions for home were to continue releasing any persisting hypertonicity in the region through trigger point work with a racquetball followed by sciatic nerve mobilization. The patient was also encouraged to spend time relaxing into a neutral spinal position followed by isolated contractions of the PFMs.

On the third visit the patient reported a further decrease in his symptoms and an improved tolerance for walking and standing (RM = 9/24). On assessment the patient had a positive right ASLR test that normalized with inferior innominate compressor, conscious contraction of the PFM, and lengthening of the right internal oblique (IO). Further, there was no increase in pain associated with posterior compression which approximated the PSIS's. There was less hypertonicity in the right iliocostalis lumborum, ischiococcygeus, and piriformis and nerve mobility testing had normalized. The patient was enthusiastic to confirm the accuracy of the PFM contraction so the session began with a reassessment of this with USI. Imaging revealed a mild isolated concentric contraction of the PFMs that was almost instantaneously accompanied with a straining effort which caused bladder decent. Consequently the USI probe was moved to view the right lateral abdominal wall muscles revealing that when the patient contracted his PFMs there was an associated appropriate co-contraction of the transversus abdominis (TrA) muscle along with a simultaneous inappropriate co-contraction of the right IO. Consequently, dry needling was administered to the trigger points in the right IO followed by breath work emphasizing right lateral costal expansion. At the completion of this the coordination of the PFM contraction was re-assessed, while maintaining the new respiratory strategy and the patient was able to accurately demonstrate a concentric PFM contraction associated with a co-contraction of the TrA and without any straining from the IO. Once the patient felt that he could confidently isolate his PFM, both with feedback from USI, as well as performing it with his eyes closed he was sent home with the goals of controlling the hypertonicity in his right IO through trigger point, respiratory and neutral spine work. He was to continue to practice the PFM contraction, focusing on maintaining the new respiratory strategy, while attempting longer holds and changing postures (supine, sitting, standing etc.).

On the fourth visit the patient continued to report an overall decrease in his symptoms and little to no pain with walking and standing (RM 6/24). Accordingly he was excited to return to recreational activities. On assessment the right ASLR was similar to the left however continued to benefit slightly from lengthening of the right IO indicating some residual hypertonus. The right WB phase of the OLS test was normal (if he concentrated on a concurrent low grade PFM contraction) however there was a tendency to slip into a bit of right hip external rotation as the length of time the one leg stance increased. This indicated a lack of adequate motor control for rotation at the hip joint in more demanding loading situations. The hypertonicity in the right iliocostalis lumborum, ischiococcygeus, external rotators of the hip and right IO had improved significantly. On USI assessment the patient demonstrated an isolated contraction of the PFM associated with a coordinated co-contraction of TrA.

As the motor control of the region was normalizing in low loading situations the focus of treatment turned towards rehabilitation of motor control strategies associated with higher demanding functional activities, and vertical loading situations. Specifically, the patient was progressed through a graduated exercise program based on the concept of maintaining a low grade sub-maximal PFM contraction while controlling motions that required coordination of the other muscles in the lumbopelvic region. This was done first in stable, predictable situations and progressed to less stable, unpredictable, and higher demand tasks. Due to the specific needs (desire to return to running, cycling and snowboarding) of this patient special attention was given to disassociating the right leg from the trunk, right hip rotation control and repetitive vertical loading. In time (7 visits, approximately three months from the initial visit) the patient was able to control loading of the right side of his pelvis and hip during high loading tasks, and returned fully to his recreational activities at which time he was discharged (NPRS 0/10, RM 2/24).

DISCHARGE PLANNING

Discharge planning took place in three stages. The first stage took place at the first visit and set the stage for the entire rehabilitation process. This involved the provision of knowledge about the source of the problem, the mechanical and movement implications, as well as guidance provided towards self-management. The discharge planning continued throughout the entire rehabilitation process in the form of the education that was provided that helped to refine and expand the patients understanding and awareness of his movement behaviors and how they impacted his low back, pelvis and hip, the principles upon which the various interventions were based, and how with this knowledge he could be an active participant in his recovery. The final stage of discharge planning occurred at the last visit and involved a review of the principles upon which the rehabilitation had been based and a discussion about what he had learned and how this would impact how he managed future injuries.

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Rehabilitative Ultrasound Imaging: Understanding the Technology and Its Applications

From an historical perspective, ultrasound imaging (USI) has been used for medical purposes since the 1950s. The primary use of USI continues to be for traditional radiological goals, which consider the morphological characteristics and structural integrity of various organs and tissues. However, as the technology has been embraced as a safe, portable, objective, and relatively inexpensive means of examination, the ingenuity and diversity of applications has extended beyond these realms.

Ultrasound imaging related to musculoskeletal rehabilitation has been developing rapidly since the 1980s. The first report of muscle imaging linked to rehabilitation was in 1968, when Ikai and Fukunaga[63] related the size of the upper arm muscles to strength. However, it was the work of Dr Archie Young and colleagues at the University of Oxford in the 1980s that sowed the seeds for the use of USI by physical therapists. A striking finding of their work was how dramatic limb muscle wasting is underestimated with a tape measure.[144] Several studies of the quadriceps muscle followed, including investigation of the effect of knee joint injury, strength-training protocols, and aging on muscle size, and the relationship between muscle size and strength in different populations (see Stokes and Young[122] for a review). This early research used compound B-scanning, which enabled whole cross sections of large muscles to be captured, because the image could be built up as the transducer was moved over the skin. The compound technique, which was expensive, was phased out as a routine tool and replaced by real-time USI (definitions are provided in the **APPENDIX**) both in general medical and musculoskeletal settings.

A recent (1990s) resurgence in the interest of rehabilitative applications of USI has been seen amongst clinical therapists. This stems from a series of studies in which USI was used to detect atrophy of the lumbar multifidus (isolated to the side and spinal level of symptoms) in individuals with acute low back pain (LBP),[51] as well as to determine that recovery of this muscle was not automatic when pain subsided,[49] thus required specific training to reduce risk of future episodes.[47] In addition, these studies

SYNOPSIS: The use of ultrasound imaging by physical therapists is growing in popularity. This commentary has 2 aims. The first is to introduce the concept of rehabilitative ultrasound imaging (RUSI), provide a definition of the scope of this emerging tool in regard to the physical therapy profession, and describe how this relates to the larger field of medical ultrasound imaging. The second aim is to provide an overview of basic ultrasound imaging and instrumentation principles, including an understanding of the various modes and applications of the technology with respect to neuromusculoskeletal rehabilitation and in relation to other common imaging modalities. *J Orthop Sports Phys Ther 2007;37(8):434-449. doi:10.2519/jospt.2007.2350*

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suggested that the biofeedback provided by USI might facilitate the relearning process. Since that time, applications of USI with respect to many other muscles of the trunk and limbs continue to be investigated.[119]

Current applications of USI in rehabilitation essentially fall into 2 distinct areas of musculoskeletal imaging: rehabilitative USI (RUSI) and diagnostic imaging. The former, which is the topic of this special issue, includes evaluation of muscle structure (morphology) and behavior, as well as the use of USI as a biofeedback mechanism. Specifically, this includes the measurement of morphological features (morphometry), such as muscle length, depth, diameter, cross-sectional area, volume, and pennation angles; changes in these features and the impact on associated structures (fascia and organs such as the bladder) with contraction; tissue movement and deformation (eg, high-frame-rate USI and elastography); and qualitative evaluation of muscle tissue density. Alternatively, diagnostic USI involves examining the effects of injury or disease on ligament, tendon, and muscle tissues, which requires different skills and training than those needed for RUSI.[14]

In May 2006, the first international meeting on RUSI was hosted by the US Army-Baylor University Doctoral Program in Physical Therapy in San Antonio, TX. The purpose of the symposium was to develop best practice guidelines for the use of USI for the abdominal, pelvic, and paraspinal muscles, and to develop an international and collaborative research agenda related to the use of USI by physical therapists. At that symposium the participants agreed on the use of the term *RUSI*. In addition, a position statement (below) was created to help define this emerging tool in the field of physical therapy.[128] This statement, along with a visual representation of how the practice of RUSI fits into the larger field of medical USI, was endorsed by delegates (**FIGURE 1**):

"RUSI is a procedure used by physical therapists to evaluate muscle and related soft tissue morphology and function during exercise and physical tasks. RUSI is used to assist in the application of therapeutic interventions aimed at improving neuromuscular function. This includes providing feedback to the patient and physical therapist to improve clinical outcomes. Additionally, RUSI is used in basic, applied, and clinical rehabilitative research to inform clinical practice. Currently, the international community is developing education and safety guidelines in accordance with World Federation for Ultrasound in Medicine and Biology (WFUMB). Dated: 10 May, 2006."[128]

In addition to defining the scope of USI with respect to physical therapy, the position statement and diagram are intended to guide therapists in acknowledging professional boundaries, as ultimately the delegates' goal is to see RUSI accepted within the medical-imaging field. However, as the use of USI (both rehabilitative and diagnostic) by physical therapists is in its infancy, the need to establish training facilities for therapists in conjunction with other imaging disciplines, including their professional bodies, where possible, is recognized as a priority.

This commentary aims to provide an overview of basic USI and instrumentation principles as they relate to RUSI. This will include an introduction to the various modes of imaging, how USI fits with respect to other more commonly known imaging technologies, the type of information that USI applications can provide, how these applications may be of value to the researcher and clinician, as well as potential future lines of investigation.

BASIC PRINCIPLES OF SOUND WAVE PROPAGATION AND INSTRUMENTATION

This section is intended to provide a basic understanding of the principles that underlie USI. The generic characteristics of USI units and the physical properties of sound wave propagation will be discussed. As a complete appraisal of these topics is not possible in this forum, the reader is encouraged to refer to more thorough resources for further discussion.[73,138]

The Physical Properties of Sound

Ultrasound is defined as sound with a frequency greater than 20 000 Hz, which is the upper limit of the range registered by the human ear. USI uses sound waves primarily in the range of 3.5 to 15 MHz. Ultrasound waves behave according to

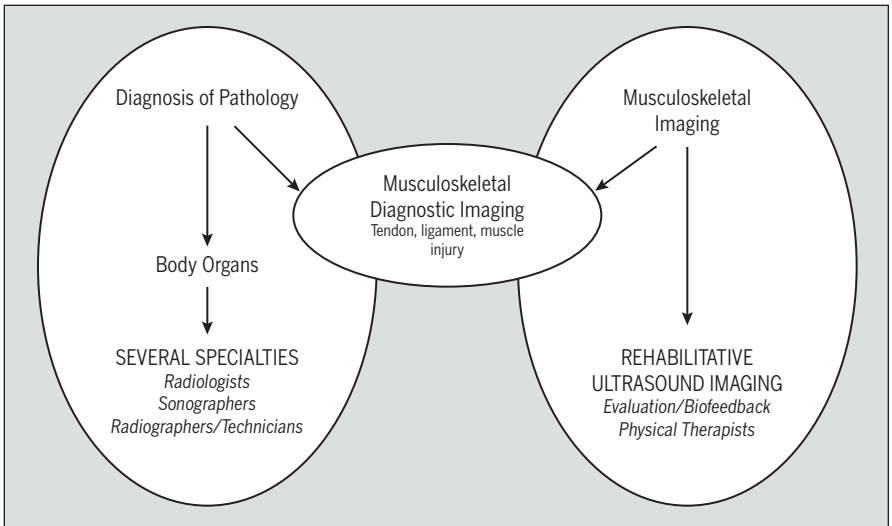

FIGURE 1. Fields of medical ultrasound imaging. Reproduced from Teyhen (2006)[128] with permission. Adapted from Stokes (2005)[118] with permission from University of Southampton.

principles that apply to all sound waves, which at the most fundamental level are mechanical waves that travel via particle vibration. Specifically, the source of a sound creates oscillatory vibrations that affect particles in the medium that lies adjacent to it. These particles, in turn, affect their adjacent particles, and so on. This process is referred to as wave propagation.[81] How far a sound wave propagates and whether an echo is produced depends on the strength of the sound source, the properties of the media through which the sound has to travel, and the number, shape, and properties of the objects it encounters.[73] These behaviors can be summarized by the principles of penetration and attenuation.

Penetration Penetration refers to the ability of sound to travel (depth) and is influenced by the intensity (strength or loudness), frequency, and speed of a sound wave. The intensity of an ultrasound wave refers to the rate at which energy is delivered per unit area and is determined by the total power output (W) of an ultrasound transducer, divided by its area (cm^2), and is expressed in units of mW/cm^2. As the intensity of an ultrasound wave increases, so does the depth it can penetrate, the strength of the echo that it can generate, and the potential it has to induce biological effects (heat and cavitation) within the tissues it is traveling through.

Frequency is defined as the number of oscillations that a wave undergoes in 1 second and is expressed in hertz (Hz). The higher the frequency of sound, the less the emerging wave will diverge. Due to their relatively high frequency, ultrasound waves are cohesive and can be used to selectively expose a target area. The frequency of an ultrasound wave is determined in the construction of the transducer assembly. As a general rule, the lower the frequency of a sound wave the farther it will penetrate.

The speed at which an ultrasound wave travels is determined by the density and stiffness of the structure or medium it is traversing. The more rigid the media the faster sound will travel through it. The average speed at which sound travels through soft tissue is 1540 m/s, which is similar to the velocity that it would travel through water (1485-1526 m/s).[85] Fat is less stiff than most soft tissue. Hence sound traverses it at a slightly slower speed (1450 m/s). Muscle and bone are stiffer and consequently sound propagates faster through them (1585 m/s and 3500m/s, respectively).

Attenuation As an ultrasound wave propagates, it encounters changes in tissue densities, or interfaces. Each tissue or medium has a characteristic resistance to sound referred to as acoustic impedance. This value is dependent upon the density of the medium and the speed at which sound can travel through it. At each interface between media of dissimilar impedance, an ultrasound wave will react and lose energy. Consequently, the energy within a sound wave decreases as it penetrates, until it is completely dispersed. This phenomenon, referred to as attenuation, occurs through the processes of reflection, scattering, refraction, and absorption. Although the first 3 processes contribute to the dispersion of an ultrasound wave, most of its energy is absorbed by the surrounding tissue in the form of heat.[73]

When a sound wave encounters an interface, the portion that is reflected back to its source is referred to as "reflection" and serves as the basis for image formation. The strength of a reflection depends on the size of the reflecting medium, the roughness of its surface, the incident angle of the sound wave, and the difference in impedance of the 2 media that create the interface.[73] The more regular the surface, the greater the difference in impedance between tissues and the more perpendicular the incidence angle; hence the greater the reflection and brighter (more white) the interface appears within the ultrasound image. An obvious example of this is the interface between bone and muscle (**FIGURE 2**). Not only is there a significant difference in the impedance of these 2 tissues, but bone attenuates a high percentage of the incident sound wave and, consequently, obscures the view of deeper structures.

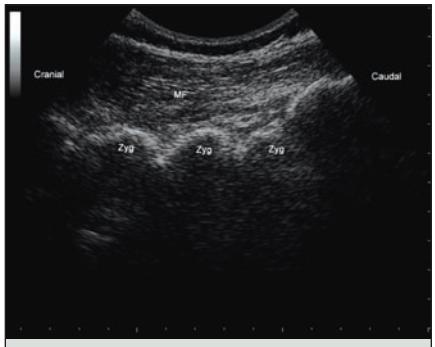

FIGURE 2. A parasagittal ultrasound image of the multifidus (MF) muscle in the plane of the zygapophyseal joints (Zyg). Note the increased echogenicity at the muscle-bone interface. Reproduced with permission Whittaker 2007.[142]

A sound wave can also scatter or refract when it encounters an interface between heterogeneous media. If, for instance, the structures that comprise an interface are very small, portions of the wave will be scattered. Those portions that travel back to the transducer are used in image formation, while those that scatter (the majority) are not. Alternatively, if there is either a significant difference in the speed that sound can travel though the 2 tissues or if the interface is not at a right angle to the ultrasound wave, the wave will change its direction when it crosses the boundary. This is referred to as refraction and it too can be a detriment to image formation through production of positional errors.

The practical implication of attenuation is that it limits penetration and consequently the depth of the images that can be generated.[73] Attenuation and frequency have a direct relationship: the higher the frequency of an ultrasound wave, the greater the attenuation and the more shallow its penetration. Conversely, the more attenuation, the more reflection and the better the detail resolution (ability to show detail) demonstrated in the ultrasound image. Consequently, the choice of frequency used for an imaging application will be dependent upon the depth of the region or structures of interest. Higher frequencies (7.5-10.0 MHz) are more valuable for ex-

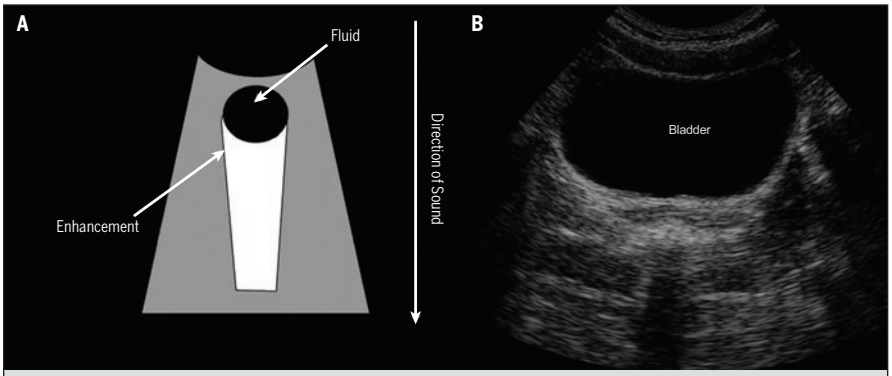

FIGURE 3. (A) Depiction of the enhancement of a region deep to a fluid-filled structure. Enhancement occurs as there is less attenuation of the propagating sound wave as it travels through a fluid-filled structure. (B) A transverse ultrasound image demonstrating enhancement of the midline pelvic floor structures deep to the bladder. Reproduced with permission Whittaker 2007.[142]

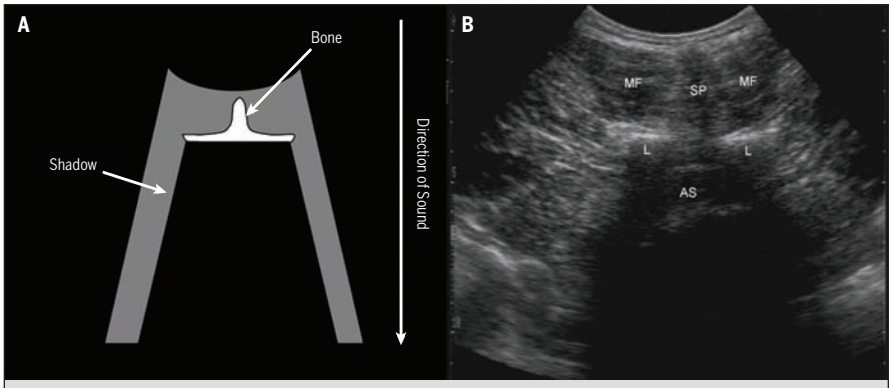

FIGURE 4. (A) Depiction of how an acoustic shadow forms behind a strongly attenuating (hyperechoic) structure such as bone. (B) A transverse ultrasound image demonstrating acoustic shadowing (AS) caused by the posterior elements of a lumbar vertebra. Abbreviations: L, lamina; MF, multifidus; SP, spinous process. Reproduced with permission Whittaker 2007.[142]

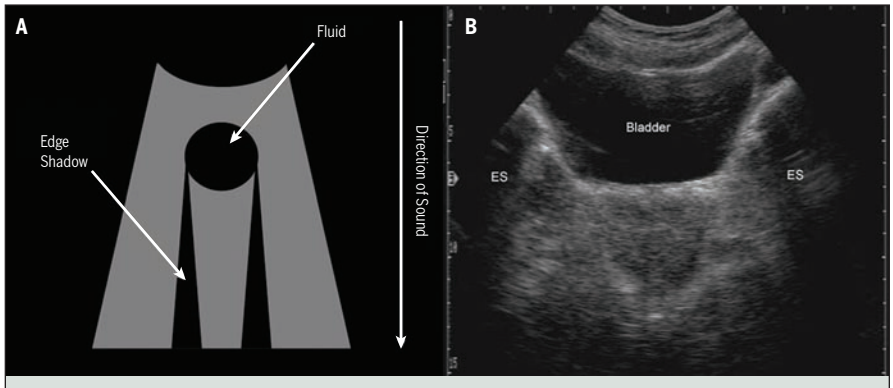

FIGURE 5. (A) Depiction of an edge shadow produced when a sound wave is refracted (bent) around the edges of a fluid filled structure. (B) A transverse ultrasound image demonstrating edge shadowing (ES) caused by the bladder. Reproduced with permission Whittaker 2007.[142]

amining superficial structures (superficial muscles, ligament, and tendons) and lower frequencies (3.5-5.0 MHz) for deeper structures (deeper muscles, the bladder, and contents of the abdominal/pelvic cavities). As a general rule, the highest frequency transducer that can image an area of interest should be used.[138]

Artifact USI devices generate images based upon several assumptions: sound travels in straight lines, echoes only originate from objects located in the 2 dimensions of the sound beam, the amplitude of an echo is directly related to the reflecting or scattering properties of the objects it encounters, and the speed at which sound travels through all the tissues is a constant 1540 m/s.[73] If any of these assumptions are violated, incorrect representations of anatomy can occur. These incorrect representations are referred to as "artifacts" and can also be the result of improper equipment operation or imaging technique. Artifacts can be both a help and a hindrance, and result in situations in which structures are either not real, missing, improperly located, or of improper brightness, shape, or size. Those which have a greatest impact on RUSI include enhancement, shadowing, and reverberation.

Acoustic enhancement refers to an increase in the amplitude of the ultrasound echo coming from a structure that lies behind a weakly attenuating structure, such as a fluid-filled cavity (eg, bladder [**FIGURE 3**]).[73] As the ultrasound device assumes that there is uniform attenuation of the ultrasound wave as it propagates, the tissues on the far side of the transmitting structure appear brighter than they should, as they are being exposed with a less attenuated beam. When this occurs, gain settings can be manipulated to compensate.

Acoustic shadowing is the opposite of enhancement. It refers to a reduction in the sound wave echo from structures that lie behind a strongly attenuating structure, such as bone (**FIGURE 4**).[110] Specifically, ultrasound waves hit something that blocks their path and everything behind the blocking structure appears black, as if it were within an "acoustic shadow." A shadow can also occur as a sound beam is refracted (bent) from its original path by passing close to a large, curved, fluid-filled structure (**FIGURE 5**).[43,61]

Reverberation refers to multiple reflections and is a result of ultrasound echoes bouncing between tissue layers and the transducer. Specifically, when an echo from a highly reflective surface that lies parallel to the transducer face returns to the transducer, a portion may be reflected back into the tissue to meet the same interface, where it again is reflected back to the transducer. Due to the time delay of the echoes being registered at the transducer, the depth of that interface is portrayed progressively deeper within the tissue. As the reflective echoes become weaker, the artifact fades out (**FIGURE 6**).

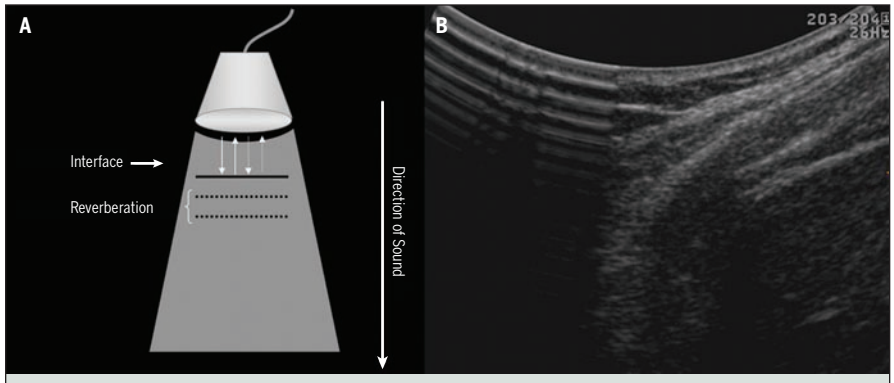

FIGURE 6. (A) Depiction of reverberation which is caused when a portion of the ultrasound echo from a highly reflective surface, lying parallel to the transducer, is reflected back into the tissue to meet the same interface where it again is reflected back to the transducer. The time delay falsely portrays that interface at 1 or more levels deeper in the tissue structure. (B) An ultrasound image demonstrating reverberation (lines on the left side of the image) produced by the interface between the transducer and air at the skin surface (inadequate use of gel).

Instrumentation

A typical USI device is a pulsed-echo (generates a series of short ultrasound waves at regular intervals) instrument consisting of 2 components: a transducer assembly (commonly referred to as a "transducer" or "probe"), and an imaging system. The transducer is responsible for generating ultrasound waves, as well as receiving the ultrasound echoes returning from the tissues and converting them into electrical signals. The imaging system is the component of the technology that receives the electrical signals representing the echo from the transducer and processes them so that they can be displayed as a digital image.

Imaging System A USI system consists of 4 generic components: the beam former, signal processor, image processor, and visual display.[73] In general terms, the beam former is responsible for generating the electrical impulses that drive the transducer assembly, as well as for amplifying and digitizing the electrical signal returning from the transducer assembly that represents the ultrasound echo. The signal processor is responsible for filtering and compressing the electrical signal before the image processor converts the signal into an image presented on the instruments display.[73]

Transducer Assembly (Probe) A transducer assembly houses an array of crystals (transducers), their electrical connections, an acoustic lens, and damping material. By definition, a transducer is a device that converts one form of energy to another.[73] Ultrasound transducers (also referred to as "elements" or "crystals"), commonly a ceramic formulation of lead zirconate titanate, are piezoelectric elements that produce voltage (electrical energy) when deformed by an applied pressure such as a sound wave (acoustic energy).[73] Although not technically accurate, a transducer assembly is generally referred to as simply a transducer or probe (the term transducer will be used throughout this commentary). The arrangement and the operating frequency of the crystal elements, as well as the width of the field of view (in metric) produced, are all taken into consideration when describing a transducer.

The arrangement, or array, of the elements within a transducer can be linear or curved (also referred to as "curvilinear"). A linear transducer contains many small rectangular crystal elements mounted side by side across its face. By triggering the elements sequentially, a rectangular image is built up from many vertical, parallel scan lines with a width that approximates the length of the array.[73] The advantage of a linear array is its wide near field, which is appropriate for imaging small superficial structures (**FIGURE 7**). A curved transducer is similar except that the crystal elements are formed into a curve rather than a straight line, which results in a diverging (pie or sector shaped) image (**FIGURE 8**). The advantages of a curved array is its wide far field, coupled with a small "footprint," which is suitable for imaging deep abdominal structures.

A typical ultrasound transducer produces a range of frequencies around a preferred (maximum efficiency) frequency that is referred to as the "operating frequency" or "resonance frequency." The operating frequency of an ultrasound transducer is predetermined by the thickness of the crystal elements. It is commonplace that a transducer may have 2 distinct operating frequencies (eg, 3.5 and 5.0 MHz, or 7.5 and 10.0 MHz) and, indeed, some are multifrequency.

BRIGHTNESS MODE AND MOTION MODE USI

There are several options (modes) available to display the electrical signal representing the ultrasound echo that returns from the tissues. The most common modes of display employed in rehabilitative settings are "B" (brightness, brilliance) and "M" (motion, movement) modes (b-mode and m-mode, respectively).

B-Mode USI

B-mode displays the ultrasound echo as a cross-sectional grey-scale image and is the mode of display most typically associ-

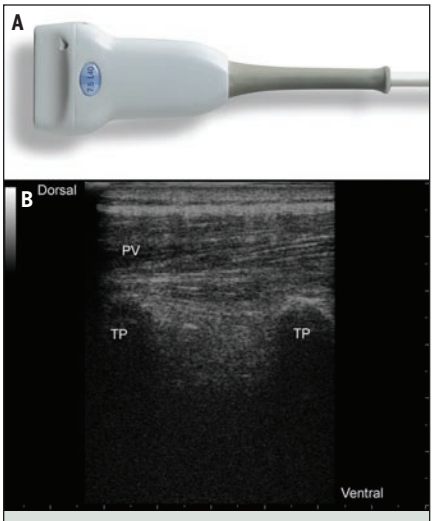

FIGURE 7. (A) A linear array ultrasound transducer. (B) A sagittal ultrasound image of the thoracic spine generated using a 7.5- to 10.0-MHz linear array transducer. Abbreviations: PV, paravertebral musculature; TP, transverse process. Note the linear footprint and the rectangular nature of the image.

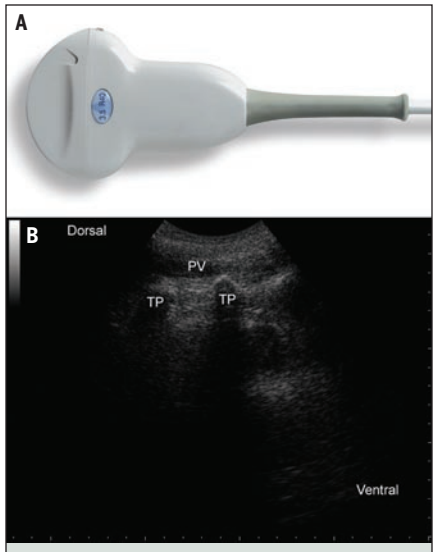

FIGURE 8. (A) A curved or convex array transducer. (B) A sagittal ultrasound image generated from the same location as in Figure 7B, using a 3.5- to 5.0-MHz curved or convex array transducer. Abbreviations: PV, paravertebral musculature; TP, transverse process. Note the curved footprint and the pie or sector nature of the image.

ated with USI (**FIGURE 9A**). B-mode images provide information gathered from the entire length of the transducer and consist of visible dots or pixels of varying degrees of brightness that represent the location and density of structures encountered by the ultrasound beam. The brightness of each pixel depends on the strength of the echo, which in turn is determined by the location and characteristics of the echo-generating structure. The position or plot of a pixel is established by considering the direction of an ultrasound wave when it enters the body, the length of time it takes for the echo to return to the transducer, and the speed at which sound can travel through soft tissue.[138]

In contrast to other modes of display (eg, m-mode), the relatively large field of view available to b-mode, combined with the real-time nature of USI, presents an opportunity to view several structures at once and, if warranted, over time. Consequently, it can be used to depict the morphology (eg, shape, size, composition, and resting state) of a structure (eg, muscle, nerve), the positional relationship of several structures (eg, muscle, nerve, bone, or organs such as the bladder), as well as the characteristics (simultaneous versus independent, or phasic versus sustained increase in muscle thickness) and the influence of a dynamic event, such as a muscle contraction, on structures within the field of view. Hence, it has been speculated that b-mode USI may be able to enhance clinical rehabilitative outcomes by contributing previously unavailable information about the structure and behavior of muscle to the examination process[33,70,105,106,120] and by providing useful feedback about the behavior of muscle during therapeutic interventions.[27,45,93] Furthermore, because of its advantages and capabilities, b-mode USI may have a role to play in basic, applied, and clinical rehabilitative research.[9,20,52,57,88,124]

Clinical Applications of B-Mode USI: Evaluation Although used extensively in the laboratory, the clinical use of b-mode USI and the evidence base supporting it are in their infancy. That said, clinicians may look to related and emerging research to speculate on the kinds of information able to contribute to the examination process.[142]

B-mode USI is well established as a tool for measuring the static architectural features of a muscle, the positional relationships between muscles and/or other structures, as well as changes in these features and relationships over time. For instance, measurements of assorted muscle parameters (length, depth, cross-sectional area) for a wide variety of muscles, including the biceps brachii,[6] masseter,[102] cervical[77] and lumbar[48] multifidus, transversus abdominis,[52] rectus abdominis,[19] rectus femoris,[6] supra and infraspinatus,[65] as well as the vastus lateralis,[107] have been validated through comparison to magnetic resonance imaging (MRI). Furthermore, USI has been used to describe the relationship between the pelvic floor muscles and the bladder wall,[131,133] the bladder neck and symphysis pubis,[106] the bladder neck and anorectal angle,[98,99] as well as the bladder base and the urethrovesical neck.[21] As an extension of this work, investigators have been able to demonstrate acceptable interrater and intrarater reliability for various measurement applications,[18,74,88,117,129] to generate normal reference ranges,[104,105,120] to demonstrate differences in these parameters over time between normal and various patient cohorts[51,100,130,133] as a result of therapeutic interventions,[50] and to investigate the relationship between the size and strength of specific muscles in varied populations.[4,67,88,145,146]

Recently, the role that b-mode USI has played in detecting the presence of muscular degeneration resulting from aging and/or chronic dysfunction has been investigated. As muscular degeneration is associated with a decrease in water and an increase in fat and fibrous content,[10,136] it results in greater echogenicity and a loss in the demarcation of a muscle's architectural features (muscle contour, pennate pattern, and the central tendon).[66,124] Although MRI is considered the gold standard for identifying these changes, examples of these findings have been reported with b-mode USI for several muscles, including the cervical[74] and lumbar[120] multifidus, the rectus ab-

dominis,[19] and the rotator cuff.[124] Furthermore, with the use of a qualitative evaluation tool that has incorporated both the degree of demarcation of architectural characteristics and muscle echogenicity with respect to a reference muscle at a set level of gain, Strobel et al[124] have concluded that b-mode USI is moderately accurate for the detection of significant levels of fatty atrophy in the supraspinatus and infraspinatus muscles when compared against MRI.

B-mode USI has also been used to comment on changes in architectural features of muscle, as well as the positional relationships of muscles or other structures in both normal and patient populations during dynamic events, such as a muscle contraction (voluntary and automatic) or increases in intra-abdominal pressure. Specifically, changes in architectural features of biceps brachii, tibialis anterior, transversus abdominis, and the internal and external oblique muscles have been investigated and compared to the amount of muscle activity present with electromyography (EMG) during voluntary contractions.[57,82] Furthermore, automatic changes in these parameters have also been monitored during specific tasks. For instance, Ferreira et al[33]described changes in the depth and length of the lateral abdominal wall muscles during a lower extremity lifting task, while Kiesel et al[70] have described changes in the depth of the lumbar multifidus with a prone arm lift movement. B-mode display has also been used to monitor the position of the bladder base,[131] the bladder wall,[114,132,133] the bladder neck,[20,106,133] and the anorectal angle[98,99] during voluntary pelvic floor muscles contractions, increases in intra-abdominal pressure (Valsalva maneuver),[130] and lower extremity lifting tasks.[94]

Although this work is valuable and has provided insight into mechanisms of neuromuscular dysfunction, it has also highlighted the limits to the information that USI can provide when considered in isolation. Specifically, as the relationship between actual muscle activity (measured with indwelling EMG) and changes in the architectural features of a muscle (seen with USI) is nonlinear,[53,57] a change in muscular dimensions may or may not indicate an increase in muscle activity. The relationship of these 2 factors is unique to each muscle; however, there is generally a rapid increase in muscle thickness associated with lower levels of muscle activity (approximately less than 25% of maximal voluntary contraction), which tapers as activity increases.[57] The discrepancy exists due to limitations of 2-dimensional imaging and the factors related to the length, pennation pattern, and extensibility of a muscle, as well as to the potential for a change in architecture in the presence of a competing force on the muscle (eg, contraction of an adjacent muscle or an increase in intra-abdominal pressure).[53] Similar issues arise when describing the relative change in position of a structure. Due to these considerations, investigators must take care during both the interpretation and reporting process. Ultimately, investigators must be adequately trained and experienced to be able to detect, reliably measure, and interpret the causes behind a change in one of these previously mentioned parameters. Furthermore, care must be taken to limit reporting to a change in the parameter measured (eg, thickness) and acknowledge that any conclusions regarding muscle activation or the mechanisms behind these changes are an extrapolation of these findings. Nevertheless, if these issues are considered and appropriate care is taken, accurate analysis and measurement are possible.[9,33,52,57,70,104,105,120]

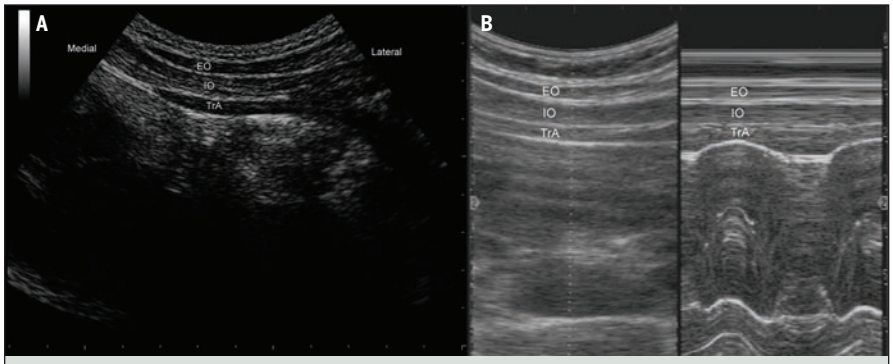

FIGURE 9. (A) A brightness mode (b-mode) image of the lateral abdominal wall. Abbreviations: EO, external oblique; IO, internal oblique; TrA, transversus abdominis. (B) A split-screen image with b-mode on the left and motion mode (m-mode) on the right. The m-mode image represents the information from the dotted line on the b-mode image displayed over time (*x*-axis). Static structures produce straight interfaces while structures that change in thickness or depth (in this case the TrA) create curved interfaces. The increase in depth of the TrA correlates to a contraction. Reproduced with permission Whittaker 2007.[142]

Clinical Applications of B-Mode USI: Biofeedback The importance of coordinated muscle effort (neuromuscular control) has received considerable attention with respect to the rehabilitation of cervical and lumbopelvic dysfunction, as well as incontinence, in recent years. This is due to an accumulation of evidence pointing to altered neuromuscular control in individuals with persistent and recurring symptoms.[5,15,24,56,60,62,126] Moreover, investigations indicate that these deficits do not consistently recover with the resolution of pain[49,51] and are not addressed with traditional exercise programs focused on increasing strength and functional capacity.[125] The extrapolation of this work is that the initial focus of rehabilitation may need to address these motor control alterations through a therapeutic intervention rooted in motor learning.[64,134,135]

As the real-time nature of b-mode USI allows a patient and therapist to view a muscle contraction and its impact on surrounding structures directly, it is a unique tool that may be a novel and previously unavailable resource to the learning process. First, it may serve as a tool that allows a therapist to explain and physically

demonstrate to a patient the subtleties of specific motor control impairment; second, it may serve as a comprehensive form of biofeedback providing knowledge of results and performance and enabling the modification of motor response. Although the literature is unclear as to how this knowledge might enhance motor learning or the permanence of these effects, recent findings[27,45,93,139] suggest that real-time b-mode USI may enhance motor learning.

Research Applications of B-Mode USI Research applications of b-mode USI primarily involve assessment of the morphological characteristics of muscle (length, depth, diameter, cross-sectional area, volume) and changes in these characteristics, and the corresponding effect on associated structures (fascia and organs such as the bladder) with contraction, dysfunction, or therapeutic interventions, in an attempt to provide insight into the mechanisms that underlie alterations in the neuromuscular system. Paramount to the investigative process is the understanding that various factors influence the robustness and reporting of these measurements.

At the most fundamental level, this involves the need for standardization of imaging and measurement procedures. This includes definition of measurement site, definition of muscle borders, as well as matters related to repeated measurements, such as consistent patient positioning (eg, joint angle alters muscle cross-sectional area and length), transducer location, orientation, and inward pressure. Ideally, a repeatable transducer location is achieved through the use of bony or fascial landmarks that serve as standard reference points from which measurements can be taken at different points in time. If such reference points are not available within the ultrasound image, then carefully defined surface transducer locations generic between subjects[33,105,129] or regions of the greatest visualized displacement of a structure (eg, the region of the bladder wall that exhibits the greatest displacement during a pelvic floor muscles contraction)[114,133] may be used. Relocation of the ultrasound transducer can also be aided by external markers (eg, freckles or scars) that can be traced onto a transparent sheet to form a map of the site and stored for future use.[122] Furthermore, the sonographic convention in terms of positioning the ultrasound device on the right side of a supine subject (or left side of a prone subject) is recommended during research applications to aid in standardizing the orientation of the resulting images.[16] However, this protocol may not always be feasible when assessing dynamic functional activities.

To facilitate comparisons between studies and the development of reference data for clinical purposes, it is suggested that future reports related to muscles size and other characteristics include mean, standard deviation, range, and 95% confidence intervals. Moreover, as these values have been found to vary based on gender and body mass index,[105,117,120] comparison between individuals may be enhanced by standardizing the values across subjects by normalizing the postevent by the preevent measurement and expressing this as a percentage.[129]

With respect to statistical analysis, different tests have been used to investigate the reliability of USI measures, most commonly intraclass correlation coefficients (ICC)[115] with standard error of measurement (SEM) and minimal detectable change (MDC).[28] Bland and Altman tests also provide a clinically meaningful measure of the magnitude of agreement (95% limits of agreement) independent of the true variability in the observations.[7] These tests have their individual strengths and weaknesses, and no single test is sufficient to reflect reliability fully.[101,103,115] It is recommended that future studies use all of these methods of analysis to enable comparison between reliability studies.

Although b-mode USI has limitations, it nonetheless appears to provide an opportunity to gather novel information. Hence, future work should focus on determining its clinical utility as both an evaluative and therapeutic tool. Further, investigation should be undertaken into its ability to predict symptomatology, appropriateness for intervention, as well as categorization of subjects into homogeneous cohorts for interventional studies.

M-Mode Ultrasound Imaging

Unlike b-mode, which generates a cross-sectional image of an anatomical region using information gathered from the entire length of the transducer (**FIGURE 9A**), m-mode displays information collected from the midpoint of the transducer as a continuous image over time (as represented as the dotted line on **FIGURE 9B**). With time on the x-axis, and the depth of the underlying anatomical structure on the y-axis, the m-mode image represents changes in thickness, or depth of a structure, over time and is, therefore, referred to as "time-motion" mode. For example, the image in **FIGURE 9B** displays the change in thickness of the transversus abdominis muscle from a resting to contracted state over time.

Investigators have found m-mode USI to be a reliable technique to measure muscle thickness.[9,69,82] Further, changes in muscle thickness measured by m-mode have been correlated to those generated by b-mode.[82,137] McMeeken et al[82] found acceptable agreement between the 2 display modes for measuring changes in thickness of the lateral abdominal wall muscles. The intrarater ICC value for b-mode was 0.989, for m-mode 0.981, and the between-mode reliability was 0.817.

M-mode also provides an opportunity to assess the depth of a structure over time and allows for the calculation of the relative timing of muscular thickness changes. For example, Mittal et al[86] used m-mode USI to assess the temporal relationships between circular and longitudinal muscle contractions during esophageal peristalsis. More applicable to physical therapy, Vasseljen et al[140] used high-frame-rate m-mode USI to detect the onset of lumbar multifidus

activity associated with limb motion, while Bunce et al[8,9] found that m-mode USI was able to assess functional components of the lateral abdominal muscles during treadmill walking.

Until recently, m-mode has been a mode of display used almost exclusively in echocardiography to assess the structure and motion of the myocardium and the heart valves.[34,87,143] Specifically, it has been used to assess morphological and functional changes in the myocardium during isometric exercise[12] and endurance training,[38,42,112] as well as comparison of these changes between different populations (athletes,[96] nonathletes,[96] and obese individuals[116]) and as a function of age.[97]

In addition to the above applications, m-mode USI has been used to assess pulmonary function, specifically diaphragm excursion, motility, and paralysis.[2,32,39,78,113] Furthermore, it has been found to be beneficial in assisting and guiding treatment in those with muscular dystrophy. Researchers assessing diaphragmatic motion using m-mode USI have found that gender, body mass index, waist circumference, and age influence the amount of excursion.[68] These findings highlight the need to further assess the effects of these variables on measurement of muscular function when using m-mode for RUSI.

Although the use of m-mode USI in the assessment of muscle behavior is relatively new,[8,9,69,82,140] it appears to have the potential to provide unique information. Specifically, it may assist investigators in describing changes in the function of the lateral abdominal wall, posterior spinal, and pelvic floor muscles associated with dysfunction.

HIGH-FRAME-RATE USI

Conventional m-mode ultrasound images are constructed from data updated approximately 25 to 50 times per second. Although these frame rates are capable of detecting deformation (thickness) and changes in the depth of a muscle, they are not high enough to provide information related to the normal anticipatory response demonstrated by certain muscles[23,54,60,89] and the loss of this response with dysfunction.[24,55,58,79] In fact, to be able to record anticipatory muscle response (defined as a contraction occurring from 100 milliseconds before and up to 50 milliseconds after activation of a prime mover[3,59,89]), frame rates need to be on the order of 500 frames per second.[140]

Although intramuscular EMG is considered the gold standard for evaluating onset of muscle activity, high-frame-rate m-mode USI is a promising noninvasive alternative, as it allows for the visualization of the onset of deformation of muscle as it starts to contract. For instance, Vasseljen et al[140] demonstrated that high-frame-rate m-mode USI, captured at 500 frames per second, has comparable accuracy (when based on averaged values of repeated trials) to intramuscular EMG in detecting the onset of lumbar multifidus activity in healthy individuals. The superficial location of multifidus and the use of a high-frequency (12-MHz) transducer made the high frame rate and ultimately the investigation possible.

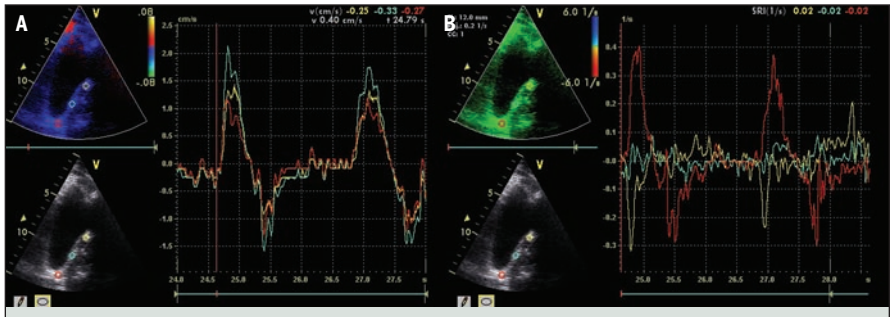

FIGURE 10. (A) Tissue velocity imaging. In the bottom left of the figure is a grayscale brightness mode ultrasound image of the bladder base during subsequent pelvic floor contractions. It is used to navigate and localize 3 measuring points (red, green, and yellow circles). Above this is the same image with tissue velocity analyzed via colour Doppler for the 3 sites. By plotting the velocity (cm/s) of the sites (*x*-axis) against time (*y*-axis), it can be determined that in this example there is no difference in velocity between the points. Scanner: Vivid 7, GE-Vingmed Ultrasound, Horten, Norway. Note the bladder is sparingly filled to better demonstrate displacement. (B) Strain rate imaging. Strain rate analyses (the rate by which strain occurs) of the same data involve plotting the strain rate period (1/s) against time (s). In this example strain rate differs at the 3 sites. The tissue marked by the yellow point has a negative strain rate, indicating that the tissue is compressed at the beginning of the contraction. The tissue marked by the red point initially exhibits a positive strain rate, indicating elongation; it then exhibits a negative strain rate indicating compression. The tissue marked by the green point undergoes mild compression and elongation (Scanner: Vivid 7, GE-Vingmed Ultrasound, Horten, Norway).

High-frame-rate m-mode USI, alongside methods such as tissue Doppler, falls into a category of imaging aimed at investigating tissue deformation, motion, and strain. As indicated above, high-frame-rate m-mode USI can be used to detect the onset of muscle deformation, as it shortens and thickens with a contraction. In contrast, tissue Doppler can be used to calculate tissue strain and strain rates,[44] as well as tissue velocity (**FIGURE 10**). Both deformation and velocity imaging can be derived from conventional ultrasound or tissue Doppler data; however, strain and strain rate require postprocessing.

Limitations of high-frame-rate USI vary across scanning devices. In general, the limitations of high-frame-rate m-mode are similar to b-mode in that they detect the earliest onset of motion induced by muscle contraction, whether as a result of actual contraction or the displacement of surrounding tissue. Furthermore, although contraction of a muscle produces displacement in 3 dimensions, m-mode applications are only capable of providing information about movement towards or away from the transducer.[53]

Although the majority of studies employing high-frame-rate m-mode USI are

focused on describing the cyclic motions and deformation of the heart,[123] developments and experiences in the field of echocardiology hold potential for the description of a variety of parameters related to the contraction of skeletal muscles in rehabilitation. Specifically, research is required to determine whether high-frame-rate m-mode USI is helpful in investigating the location of the onset of a contraction within a muscle, differences in the onset of muscle activity within and between individuals or populations (symptomatic versus asymptomatic), and these at different points in time, as well as the sequence, timing, and patterns of muscle activation. These insights may provide valuable information to our understanding of automatic and voluntary muscle activity.[141]

ELASTOGRAPHY

It is possible to postprocess the electrical signal produced from the echo returning from the tissues to the transducer in such a way as to quantify tissue movement and deformation in response to internal or external mechanical forces.[13,92] In the last decade, several of these techniques (elasticity imaging and speckle tracking), including elastography, have been developed.

Elastography was initially conceived with a goal of quantifying the subjective information conveyed by palpation of harder areas within softer tissues, such as in the clinical detection of tumors (eg, breast, prostate).[17,35] In the classical elastography method, the ultrasound transducer is used to slightly compress the tissue, while a rapid series of successive ultrasound images is acquired. Using cross-correlation methods to postprocess the ultrasound data, displacement and strain images are calculated and represent the amount of movement that small segments of individual A-lines (the electrical signal coming from a single transducer) undergo during the tissue compression.[92] A-line segments with more relative motion correspond to softer tissue (assuming a uniform strain distribution within the tissue).

The technique has since been extended to other applications, including the use of external sources of tissue motion (such as vibration), as well as naturally occurring internal motions (such as breathing, cardiac wall motion, and arterial pulsation).[72,108] Furthermore, increased availability of high-frame-rate USI devices has allowed for the use of handheld transducers, which has simplified the frame-suspended setups used in earlier applications.[71] Due to these advancements, clinical applications have expanded to include the detection of liver fibrosis and deep-vein thrombosis.[36,109] Musculoskeletal applications include the quantification of soft tissue displacement and strain in response to a variety of externally applied mechanical inputs such as tension, compression, and acupuncture needle manipulation.[37,41,76]

To date, tissue elasticity imaging techniques have not been used for rehabilitation purposes; however, they hold potential for the detection of differences in the biomechanical properties of muscle and its associated connective tissue in response to physical tasks. It is important to keep in mind that elastography images do not directly represent tissue elasticity but, rather, tissue displacement and strain. However, in conditions in which local tissue stress can be calculated (or estimated), strain and stress values can be used to map local tissue stiffness.

Although these elastic imaging techniques hold potential for rehabilitation, some practical difficulties need to be overcome. These include access to the raw electrical ultrasound signal (not available on most commercially available USI equipment) and the need for postprocessing of the ultrasound data, which preclude real-time feedback. Despite these limitations, the dynamic spatial mapping of tissue strain over time offers exciting new possibilities for quantifying the behavior of soft tissues in response to externally or internally generated perturbations.

USI VERSUS OTHER IMAGING METHODS

The identification, evaluation, and monitoring of various musculoskeletal disorders is expanding due to technological advancements associated with MRI, CT, and USI. Specifically, new and innovative applications are improving clinical understanding of the underlying mechanisms and sequelae common to musculoskeletal disorders.[11,30,40,47,66,84] As such, it is important to consider how USI and the information that it can provide compares to these other imaging technologies.

MRI, CT, and USI provide insight into various features of the muscular system, both in asymptomatic as well as symptomatic individuals.[31,49,70,77,105,120] In particular, they provide useful qualitative/quantitative measures concerning the muscular system, including the consequential muscular degeneration (atrophy and fatty infiltrate) shown to be common in patients with low back pain,[11,22,47,51,66,75,84,95] neck pain,[1,30,40,74,83] and other peripheral musculoskeletal disorders.[124] Although MRI is considered the gold standard for musculoskeletal imaging, emerging applications of USI and CT are capable of providing insight into in vivo features of the musculoskeletal system. Each imaging method has strengths as well as weaknesses (**TABLE**).

Magnetic Resonance Imaging

MRI, unlike USI, has multiplanar and multislice imaging capabilities. It is considered the gold standard for the evaluation and quantification of soft aqueous muscular degeneration, as it provides reliable measures of degenerative changes in muscle such as fatty infiltration and atrophy.[1,11,30-31,40,52,66,83,84,90,95] There are 2 conventional MRI sequences: T1 and T2 weighted. Images from T1-weighted scans demonstrate excellent anatomical contrast of fat and other soft aqueous tissues (eg, skeletal muscle).[90] Alternatively, T2-weighted scans provide outstanding detail related to the features

of inflammation that are suggestive of neopathological conditions. The drawbacks of MRI remain cost, accessibility, constraints in the number of joints that can be investigated per session, limited real-time imaging capacity, and variable patient tolerance (eg, claustrophobia, metallic implants, pacemaker, and pregnancy).

Computerized Tomography

CT, like MRI but unlike USI, permits multislice imaging and can offer better scan resolution and shorter imaging times than MRI. However, it is not without the inherent risks associated with exposing a patient to ionizing radiation. CT is useful in diagnosing traumatic musculoskeletal injuries, such as fractures, and has been effectively used to evaluate and quantify cross-sectional area of paraspinal musculature in patients with low back pain.[22,75] While CT produces high-quality images, they are dependent on tissue densities in order to provide contrast. When tissue densities between pathologic and adjacent anatomy are similar, contrast media may be required for differentiation, rendering CT inadequate if a patient has a history of contrast reaction.[80]

Ultrasound Imaging

USI, although less sophisticated in terms of resolution than MRI and CT, has advantages as a safe, cost-effective, portable, and clinically accessible method for gathering information about the static characteristics of muscle,[47,51,70,74,105,120,124] as well as muscle behavior during dynamic events.[50,77] As such, it shows promise as a tool in musculoskeletal examination and treatment. Moreover, unlike CT, USI does not expose the patient to ionizing radiation and is well tolerated by patients. A feature unique to USI is its dynamic capability of scanning in real time, which makes it superior to MRI and CT for evaluating mobile structures such as tendons, nerves, and muscles, and it may become an important tool for directing appropriate physical therapy treatment decisions.[127] However, as highlighted throughout this commentary, USI is not without disadvantages and is highly operator dependent. Perhaps the most promising feature of USI is its accessibility and the feasibility for physical therapists to acquire the skills needed to incorporate its use into clinical practice. However, evidence for its use in different applications within rehabilitation is needed before widespread routine clinical use can be promoted.

Comparisons Between Different Imaging Modalities Used in the Assessment of Musculoskeletal Disorders*

	MRI	USI	CT
Cost	Expensive	Inexpensive	Intermediate
Ease of accessibility	Difficult	Easy	Difficult
Ionizing radiation	None	None	Yes
Supports intervention	Yes	Yes	Yes
Operator-dependent	No	Yes	No
Imaging capability			
Planes	Multi	Variable axes to joint surface	Multi
Anatomy			
Muscle	Excellent	Good	Fair
Fat	Excellent	Fair	No role
Tendons and sheaths	Good	Excellent	No role
Ligaments	Good	Excellent	No role
Synovial membrane	Good	Excellent	No role
Bone	Excellent	Good	Good
Cartilage	Good	Excellent	Fair
Inflammation	Excellent	Good	No role
Number of joints/session	Few	Many	Few
Real-time scanning	Cardiac only	Yes	No
Patient tolerance	Variable	Good	Variable

** Adapted from Tan et al[127] with permission.*
Abbreviations: CT, computerized tomography; MRI, magnetic resonance imaging; USI, ultrasound imaging.

FUTURE CONSIDERATIONS

It is unclear whether the evaluation of muscular and motor control abnormalities differs across imaging technologies, muscle, body regions, body side, varying diagnoses, and assorted anthropometric variables. Further, the value of USI from a pathoanatomical and pathophysiological perspective, although under investigation, has yet to be determined. Although innovations in muscular imaging research are enhancing our understanding of muscle dysfunction, degeneration, and control, and slowly influencing clinical practice, there is a need to standardize techniques that are cost effective, reliable, easily accessible, and well tolerated by both patients and clinicians in order to ensure their appropriate use.

Future research efforts should address the diagnostic and prognostic validity of USI in patients with acute musculoskeletal pain and a wide variety of musculoskeletal disorders by comparing USI, MRI, EMG, and perhaps CT results. Randomized control trials are also needed that include comparison of interventions incorporating RUSI to those that do not to examine whether USI biofeedback improves outcomes. Ultimately, such studies could provide appropriate evidence-based evaluation and treatment strategies that incorporate RUSI as an outcomes measure. Routine adoption of RUSI in physical therapy requires appropriate training programs.

CONCLUSION

The goal of this commentary has been to provide an overview of basic USI and instrumentation principles, including an understanding of the various modes and applications of the technology with respect to neuromusculoskeletal rehabilitation and in relation to other common imaging modalities. In doing so, we hope that the reader has gained a greater understanding of the value of this tool both from a clinical as well as an investigative perspective. Although other imaging modalities may be superior in providing some, although not all, of the information available with USI, there is growing access to, and evidence in support of, its use by physical therapists. As such, it is imperative that there is support for further investigation with regard to its potential and also a greater understanding of its limitations, as it is likely that the full significance of USI in relation to rehabilitation has yet to be established.

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APPENDIX

GLOSSARY OF TERMS

Acoustic shadowing—The reduction of sound wave echoes from structures that lie behind a strongly reflecting or attenuating structure (eg, bone)[73]

A-line—An electrical signal corresponding to the scattering and reflection of ultrasound from tissue or other media, generated from a single ultrasound transducer either used alone, or as part of a linear (brightness-mode) array

A-line segment—A small portion of an A-line used in elastography cross-correlation analysis

Artifact—Incorrect representations of anatomy or motion (eg, situations that result in structures that are not real, missing, improperly located, or of inaccurate brightness, shape, or size). Examples include acoustic shadowing, edge shadowing, enhancement, and reverberation[142]

Attenuation—The reduction in the intensity or amplitude of a sound wave, expressed in decibels ($dB/cm^1/MHz^1$) and caused by absorption, scattering, and reflection of the sound wave as it travels. As attenuation increases, penetration decreases[73]

B-mode—Brightness or brilliance mode

Cavitation—Refers to the production and behavior of gas bubbles within a liquid when exposed to the sound wave. This behavior can be variable (eg, oscillation or collapse) and depends upon factors such as the size of the cavity, and the nature of the immediate environment[91]

Doppler imaging—The basic principle of Doppler ultrasound lies in the observation that the frequency of a sound beam reflected back to its source is altered when it encounters a moving object.[138] As the change in frequency is proportional to the velocity of the object, Doppler imaging can be used to display flow (blood) or tissue velocity related information

Echogenic—A structure or material that produces echoes (eg, reflection of ultrasound waves). The more echogenic a structure or substance is, the whiter it will appear within an ultrasound image[142]

Edge (refractile) shadowing—Refers to specific type of acoustic shadow that is generated when a sound wave encounters an object with a curved surface (eg, bladder or cyst). The shadow is observed at the lateral margins of the object where the sound beam contacts the interface at a very oblique angle. As a result of both refraction and reflection, none of the incident sound returns to the transducer from this region and a shadow results

Enhancement—The strengthening of a sound wave echo distal to a weakly attenuating structure (eg, a fluid-filled organ such as the bladder)[73]

Far-field—The bottom half of the ultrasound screen, which represents that part of the body furthest from the ultrasound transducer[142]

Field of view (FOV)—Refers to what is visible on the ultrasound display FOV and is dictated by the shape (curvilinear versus linear) and width of the transducer, as well as the depth setting of the image display. The ultimate depth of the FOV is determined by the frequency of the transducer, the power setting of the ultrasound device, as well as the characteristics of the medium that is being imaged

Frame rate—The number of frames of echo information stored each second[73]

Frequency—The number of oscillations a molecule or a sound wave undergoes in 1 second. Frequency is expressed in Hz[142]: 1 Hz = 1 cycle per second; 1 kHz = 1000 cycles per second; 1 mHz = 1 000 000 cycles per second

Gain—Refers to amplification (expressed in dB) of the echoes returning from the tissues back to the transducer. The degree of amplification is under the voluntary control of the operator[73,142]

Hyperechoic—A structure or substance that is more echogenic (whiter and brighter on the ultrasound screen) than surrounding tissue. The surface of bone and dense fascia are examples of hyperechoic media[142]

Hypoechoic—A structure or substance that is less echogenic (darker on the ultrasound screen) than surrounding tissue. Fluids such as blood and urine are examples of hypoechoic media[142]

Impedance—The resistance that a tissue or medium has to sound. Acoustic impedance depends upon the density of the medium and the speed at which sound can travel through it. It is expressed in rayls[73]

Incidence angle—The angle between the sound coming from the transducer (incident sound) and a line perpendicular to the boundary of a medium[73]

Intensity—The rate at which energy is delivered per unit area.[73] The intensity of an ultrasound wave is determined by the total power output of the transducer (W) divided by its effective radiating area (cm^2) and expressed in units of mW/cm^2

M-mode—Motion mode, sometimes referred to as time-motion (TM) mode

Morphology—The study of form and structure.[25] With respect to muscle, this refers to describing characteristics of its dimensions (eg, cross-sectional area, length, shape ratios, and depth/thickness), as well as tissue composition

Morphometry—The quantitative measurement of form.[111] With respect to muscle, this refers primarily to measurement of its dimensions (eg, cross-sectional area, length, shape ratios, and depth/thickness). Morphometry does not consider tissue composition

Motor control—"An area of study dealing with the understanding of the neural, physical, and behavioral aspects of movement."[111] Relates to the timing, magnitude, and sequencing of muscle activation and relaxation

Motor learning—A set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for motor skill[111]

Muscle behavior—Observable activity or the response of muscle during a specific event or given set of circumstances. The behavior of muscle can be described by changes in its electrical properties over time or architectural characteristics (cross-sectional area, length, depth/thickness, or relationship to adjacent structures)

Muscle cross-sectional area (CSA)—A quantitative 2-dimensional measure of the plane of a structure created by cutting through it transversely.[25] Anatomical CSA refers to the CSA at 90° to the long axis (or direction) of the muscle fibers. Physiological CSA is not measured 90° from the long axis of the muscle fibers. Physiological CSA is commonly generated with rehabilitative ultrasound imaging (RUSI), for instance with muscles that have complex internal architecture such as the lumbar multifidus in which the fascicles pass in a caudal-lateral direction over the vertebrae

Muscle inhibition—Reflex inhibition is the reduction or elimination of muscle activity associated with afferent stimuli from joint receptors that reduce activation of alpha motor neurons in the anterior horn of the spinal cord (eg, reflex inhibition of quadriceps has been demonstrated in the presence of knee joint damage in the absence of pain).[121] Voluntary inhibition refers to an unwillingness to contract a muscle due to pain or fear of pain

Muscle thickness (depth)—A quantitative linear measure from the superficial to deep aspects of a muscle.[26] Baseline or resting thickness refers to the thickness of a muscle in a perceived resting state

Near-field—The top half of the ultrasound screen, which represents that part of the body closest to the ultrasound transducer[142]

Operating frequency—The preferred (maximum efficiency) frequency of operation of a transducer.[73] The operating frequency can also be referred to as the resonance or main frequency

Penetration—Refers to the ability for sound to travel through media, thereby influencing image depth. Penetration is dependent upon the strength (intensity) and frequency of the sound wave, as well as the compressibility of the medium that it travels through. In descriptive purposes, penetration refers to image depth[73,142]

Pixel—An abbreviation of "picture element." A pixel refers to the smallest unit of a digitized, 2-dimensional image. A pixel can be described by its location (a set of x and y coordinates), as well as its brightness[73]

Piezoelectric effect—A phenomenon in which some materials (ceramic, quartz, etc) produce a voltage or electrical current when deformed by an applied pressure, such as sound[73]

Real-time ultrasound imaging (RTUS)—The rapid sequential display of ultrasound images resulting in a moving presentation[73,142]

Reflection—As a sound wave propagates it attenuates (loses energy). Reflection is one form of attenuation and refers to the portion of the sound wave that is reflected back towards the source of the sound. This reflected wave is received and processed to generate an ultrasound image[73,142]

Refraction—Refers to the change in direction of a wave when it crosses a boundary. It comes from the modification of a Latin term meaning "to turn aside"[73]

Resolution—A measure of the ability of an instrument to show detail[138]

Scatter—Describes the generation of secondary waves (fractions) in response to the primary sound wave encountering a rough surface or heterogeneous media. Scattering is often referred to as diffusion[73,142]

Sonography—The term used to describe imaging resulting from ultrasound. The Latin word sonus is sound, and the Greek word graphien is to write[73]

Sound—Mechanical energy that propagates through air, water. or any other matter in an orderly, rhythmic fashion, as determined by the molecular makeup of the transmitting medium[73,138]

Strain—Mechanical deformation of a structure as the result of stress

Strain rate —Strain rate refers to the instantaneous strain (or change in strain) per time unit. The strain rate has the same direction as the strain (eg, negative strain rate during shortening, positive strain during elongation)

Transducer—Any device that converts one form of energy into another. The piezoelectric crystal is a transducer that converts electrical energy into sound energy and vice versa[73]

Transducer assembly (commonly referred to as a transducer)—Consists of the transducer elements, their associated casing, and dampening material[73,138]

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● *Original Contribution*

INDUCED TRANSDUCER ORIENTATION DURING ULTRASOUND IMAGING: EFFECTS ON ABDOMINAL MUSCLE THICKNESS AND BLADDER POSITION

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Abstract—The use of ultrasound imaging (USI) by physiotherapists to assess muscle behavior in clinical settings is increasing. However, there is relatively little evidence of whether the clinical environment is conducive to valid and reliable measurements. Accurate USI measurements depend on maintaining a relatively stationary transducer position, because motion may distort the image and lead to erroneous conclusions. This would seem particularly important during dynamic studies typical of a physiotherapy assessment. What is not known is how much transducer motion can occur before error is introduced. The aim of this study is to shed some light on this question. Eight healthy volunteers (19 to 52 y) participated. USI images were taken of the lateral abdominal wall (LAW) and bladder base (midline suprapubic) at various manually induced transducer orientations (approximately –10 to 10° about 3 axes of rotation), which were quantified by a digital optical motion capture system. Measurements of transversus abdominis (TrA) thickness and bladder base position (cranial /caudal and anterior/posterior) were calculated. Repeated measures analysis of variance was performed to determine if the measurements obtained at the induced transducer orientations were statistically different ($p < 0.05$) from an image corresponding to a reference or starting transducer orientation. Motion analysis data corresponding to measurements that did not differ from reference image measurements were summarized to provide a range of acceptable transducer motion (relative to the pelvis) for clockwise (CW)/counter-clockwise (CCW) rotation, cranial/caudal tilting, medial/lateral tilting and inward/outward displacement. There were no significant changes in TrA thickness measurements if CW/CCW transducer motion was <9° and cranial/caudal or medial/lateral transducer tilting was <5°. Further, there were no significant changes in measurements of bladder base position if CW/CCW transducer motion was <10°, cranial/caudal or medial/lateral transducer tilting was <10° and 8°, respectively and inward/outward motion was <8 mm. These findings provide guidance on acceptable amounts of transducer motion relative to the pelvis when generating measurements of TrA thickness and bladder base position. Future sonographic studies and clinical assessment investigating these parameters could take these findings into account to improve imaging technique reliability. (E-mail: j.l.whittaker@soton.ac.uk)

Key Words: **Bladder position, Transversus abdominis, Ultrasound imaging, Ultrasound transducer, Validity.**

INTRODUCTION AND LITERATURE

There has been a significant increase in the clinical use of ultrasound imaging (USI) by physiotherapists to objectively measure architectural changes of muscle (*e.g.*, thickness and cross-sectional area) and bladder position in both static and dynamic conditions. These applications fall within the scope of rehabilitative ultrasound imaging (RUSI) (Teyhen et al. 2006, Whittaker et al. 2007a). In the lumbopelvic region USI has been used to measure the thickness and/or cross-sectional area of the lateral abdominal wall muscles (transversus abdominis [TrA], internal oblique [IO] and external oblique [EO]) (Rankin et al. 2006, Teyhen et al. 2007, Whittaker et al. 2008), the rectus abdominis (Coldron et al. 2008), the lumbar paraspinal muscles (multifidus and longissimus) (Stokes et al. 2005, 2007) and the position of the bladder base and bladder neck (Thompson et al. 2005; Whittaker et al. 2007b). Imaging has been performed in both static (resting) and dynamic (*e.g.*, active straight-leg raise, abdominal drawing in, respiration, balance tasks, coughing, *etc.*) conditions. Validity of USI as a measurement tool for architectural parameters for some of these muscles has been established through comparison to magnetic

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resonance imaging (MRI) (Hides et al. 1995, 2006) and some aspects of intra/inter-rater and intra/intersession reliability have been established (Hides et al. 2007; Mannion et al. 2008; Teyhen et al. 2005). There is, however, a lack of literature investigating whether the clinical environment is conducive to valid and reliable measurements.

As the position and inward pressure of a USI transducer influences both the location and shape of a structure of interest on a USI image, it is logical to assume that accurate measurement and interpretation will be influenced by changes in its orientation to the body surface (Klimstra et al. 2007). In fact, several authors have alluded to measurement error with changes in transducer orientation. For instance, while measuring supraspinatus and deltoid muscle thickness, Dupont et al. (2001) stated that a variation in transducer angle by 30° (from perpendicular to the body surface) results in a 15% error. They recommended that steps be taken to ensure that the transducer angle remains consistent throughout an imaging study. Herbert and Gandevia (1995), while investigating the pennation angle of brachialis, reported that transducer rotation ''by more than about 5 degrees'' tended to decrease the observed pennation angle of the muscle. Reddy et al. (2001) reported the magnitude and direction of bladder neck motion (inward/outward and ventral/dorsal translation plane) during a strain, cough and pelvic floor contraction, with a sagittal perineal imaging approach. In doing so, they determined and compensated for transducer motion relative to the pubis symphysis (bony landmark). They reported that the transducer/pubic symphysis relationship shifted 70% of the time during a strain, 53.5% of the time during coughing and 20% of the time with a pelvic floor contraction. Further, the shift of this relationship resulted in a percentage error in the calculation of the distance and direction of bladder neck motion.

Clearly, changes in transducer position introduce measurement error for a variety of sonographic parameters. What is not known is the amount of transducer motion that can occur before error is introduced, *i.e.*, the threshold motion. In an attempt to shed some light on this question, measurements of TrA thickness and bladder base position were obtained from images taken at various degrees of manually induced transducer orientation (monitored by a digital optical motion capture system) simulating transducer motion that may be seen during a dynamic imaging study.

MATERIALS AND METHODS

Participants

Eight healthy volunteers (7 female and 1 male) aged 19–52 y were studied. Participants averaged 30.5 ± 10.7 y, 64.5 ± 10.3 kg and had a mean body mass index of 23.7 ± 3.1 kg/m^2. Exclusion criteria included musculoskeletal or neuromuscular disorder affecting the lumbopelvic region, a history of lumbopelvic pain in the last year that required medical attention or resulted in the inability to work or perform recreational activities, a BMI >31 kg/m^2, an inability to follow instructions or a skin disorder. The study was approved by the School of Health Professions and Rehabilitation Sciences Ethics Committee, University of Southampton, UK. All subjects gave written informed consent to participate in the study.

Procedure for ultrasound imaging

An USI system (MyLab 25, Biosound Esaote Inc, Indianapolis IL, USA) with a 5.0-MHz (40-mm footprint) transducer (lateral and axial resolution of 1.0 and 0.93 mm, respectively) was used to generate brightness (B)-mode images, with subjects lying in a supine position. Images were taken from two sites: transversely on the right anterolateral aspect of the abdomen halfway between the iliac crest and inferior border of the rib cage to produce an image of the lateral abdominal wall (LAW) muscles (Fig. 1a) and sagittally over the midline of the abdomen just superior to the pubic symphysis to produce a sagittal image of the bladder base (BB) (Fig. 2a). All imaging procedures were performed by one operator (JLW).

Reference images of the LAW, before manipulation of transducer orientation for each axes and plane, were obtained when the transducer was perpendicular to the body surface and the medial to lateral placement was such that the anteromedial border of TrA was approximately 2 cm from the medial edge of the image. Care was taken to keep the fascial boundaries between the muscle layers in a horizontal orientation on the scanner's screen (Fig. 1b) (Teyhen et al. 2007, Whittaker et al. 2008). Reference sagittal images of the bladder were obtained once the proximal end of the transducer was angled towards the subject's head until the entire outline of the bladder was visible (Fig. 2b). In an attempt to standardize bladder volume, subjects were asked to void one hour before the session, drink 500 mL of water and not void again until after the session (Thompson et al. 2005, 2007). Once either the lateral abdominal wall or bladder reference image was generated, the location through the longitudinal axis of the transducer on the abdomen was marked with a black pen to assist in transducer relocation.

Procedure for motion analysis

A six-camera digital optical motion capture system (Vicon 460, Oxford, UK) was chosen to monitor motion of both the bony pelvis and USI transducer throughout data collection because it has superior accuracy for measuring angles and provides information about the angle of rotation of a segment around three axes (compared with just one when using an inclinometer or

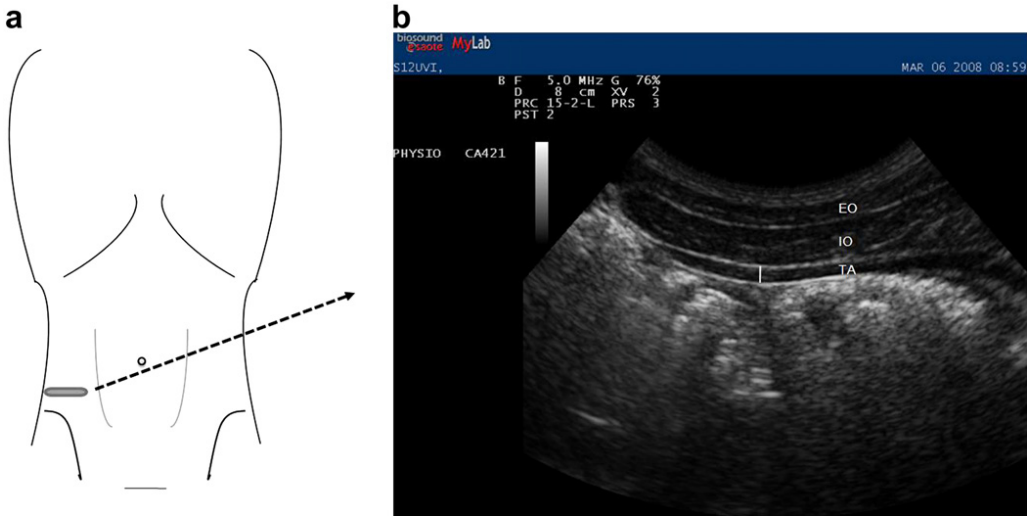

Fig. 1. (a) Lateral abdominal wall (LAW) transducer imaging site. (b) Transverse ultrasound image of the right lateral abdominal wall showing the thickness of the transversus abdominis muscle defined as the perpendicular distance between the muscles' superficial and deep fascial boundaries. EO = external oblique; IO = internal oblique; TA = transversus abdominis.

goniometer). The six cameras were set up to provide a capture volume (approximately $2 \times 2 \times 2$ m) that enabled a mean camera residual <1 mm. A kinematic model to define the pelvis and USI transducer segments to determine the rotation and position of the transducer, with respect to the pelvis, was developed and written in Vicon Bodybuilder software (Oxford, UK). Full details of the kinematic model, including its accuracy, which was determined to be within 1°, are described elsewhere (in preparation). Retro-reflective markers (14 mm in diameter) were applied bilaterally to the anterior and posterior superior iliac spine (ASIS and PSIS, respectively) and iliac tubercles of all subjects. A static standing trial was captured for participant calibration. The PSIS markers were placed in the local coordinate frame of the segment formed by the ASIS and iliac tubercle markers. The two PSIS markers were then removed and participants assumed a supine lying position (Fig. 3). During USI imaging trials, virtual PSIS markers were created and placed within the local reference frame of the segment formed by ASIS and iliac tubercle markers.

The pelvic segment was formed and local axes defined following the standard used for gait analysis (Kadaba et al. 1990). The line pointing from left to right

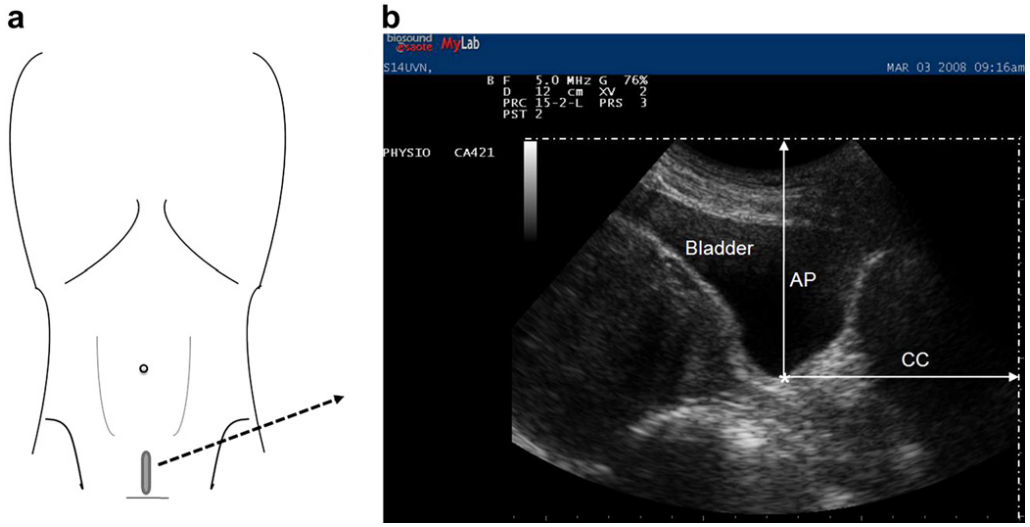

Fig. 2. (a) Midline suprapubic (BB) transducer imaging site. (b) Sagittal ultrasound image of the bladder showing the perpendicular anterior/posterior (AP) distance and the cranial/caudal (CC) distance from the top of the USI image and the side of the USI image, respectively, to a reference point (*; the most inferior border of the bladder) on the bladder base.

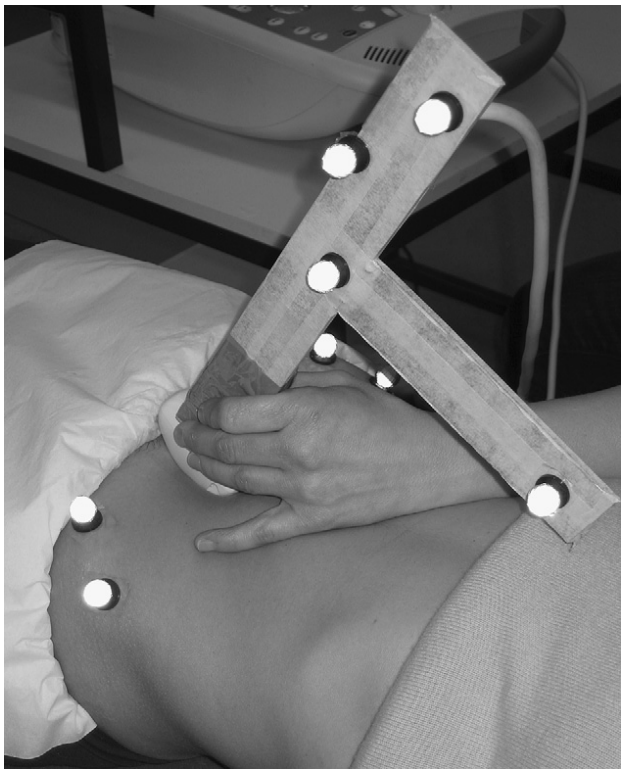

Fig. 3. Experimental setup for imaging at the sagittal bladder imaging site. Note the retro-reflective markers on the ASISs, iliac tubercles and wand attached to the ultrasound transducer.

ASIS markers formed the y-axis, the line pointing forward from PSIS to ASIS formed the x-axis and the line perpendicular to these axes, pointing cranially (following the right hand rule) formed the z-axis. A wand with retro-reflective markers was attached to the USI transducer such that motion of the transducer could be resolved into X (clockwise/counter clockwise; CW/CCW), Y (cranial/caudal tilt of the proximal end of the transducer) and Z (medial/lateral tilt of the proximal end of the transducer) components, as well as the scalar distance of the transducer's wand origin marker to the right ASIS marker for LAW trials (Fig. 4) or the midpoint between the right and left ASIS for BB trials (Fig. 5). Euler angle calculations with rotation order X, Y, Z were used to calculate relative change in transducer angle throughout the USI scanning trials, with respect to the pelvic segment.

Procedure for inducing transducer angle/motion

Before manipulating the orientation of the transducer at either the LAW or BB imaging site, a reference USI image was taken and the position of the transducer relative to the pelvis was recorded (by the motion analysis system). This reference image and corresponding transducer orientation (defined as 0°) served as the basis from which all induced transducer positions about that axis were compared. This procedure was repeated before inducing motion for every axis and the one plane on interest. Because our goal was to mimic transducer motion that may occur during a dynamic study in a clinical environment, the transducer was moved manually approximately 5° and 10° in both a positive and negative direction about each axis (x, y and z). With respect to inducing inward and outward motion of the transducer (only at the BB transducer location), the operator first increased the inward pressure (from that of the reference position), then all inward pressure was released and finally the subject was asked to perform a moderate Valsalva (a breath-hold accompanied with bearing down) maneuver which caused the transducer to move even further outwards. CW and CCW motions were induced with the help of a transparency template placed on the skin, with both the longitudinal axis of the transducer (0°), as well as lines corresponding to +5, +10, −5 and −10° marked

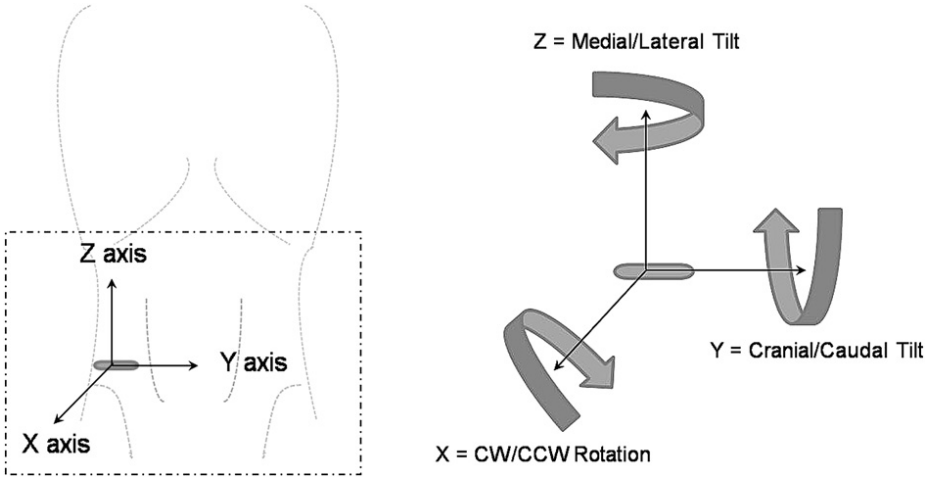

Fig. 4. Axes and associated motions for induced transducer motion at the lateral abdominal wall imaging site. CW = clockwise; CCW = counter-clockwise.

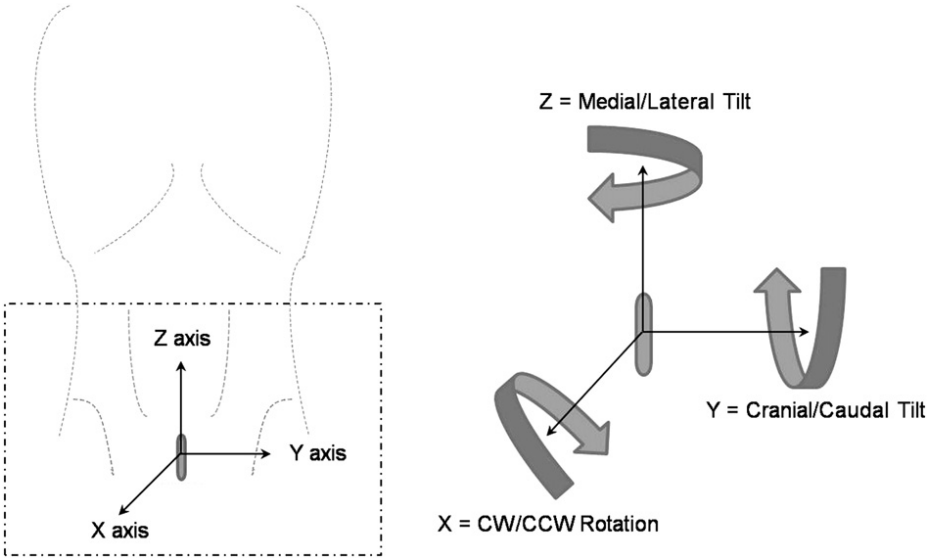

Fig. 5. Axes and associated motions for induced transducer motion at the sagittal bladder imaging site. CW = clockwise; CCW = counter-clockwise.

on it. Cranial/caudal and medial/lateral tilt of the proximal end of the transducer was induced with the help of a goniometer. The actual transducer angles and inward/outward translation achieved (including out-of-plane motion) were confirmed later by the motion analysis data and are reported in the Results section. Ultrasound images and transducer positions were recorded for 15 different transducer orientations at the LAW location and 19 different transducer orientations at the BB location for each participant (5 each about the x, y and z axis and 4 associated with inward /outward motion) (Table 1).

Data analysis

Descriptive statistics (mean, standard deviation and range) relating to the amount of transducer motion (relative to the pelvis) that occurred around all three axes and along the one plane of interest (inward/outward motion) during changes in transducer orientation were calculated.

Ultrasound images were captured, stored and measured offline on a laptop computer using National Institutes of Health (Bedthesda, MD, USA) ImageJ software (V 1.38 t) (http://rsb.info.nih.gov/nih-image/). TrA thickness was calculated as the perpendicular distance between the muscle's superficial and deep fascial boundaries in the middle of the image or TrA (Fig. 1b). The accepted convention of defining the boundaries of the muscle as the last hypoechoic pixel before the fascial layers was used (Teyhen et al. 2007; Whittaker et al. 2007). For the bladder base, the perpendicular anterior/posterior (AP) distance from the top of the USI image to a reference point (the most inferior border of the bladder) on the bladder base (Fig. 2b), and the perpendicular cranial/caudal (CC) distance from the side of the USI image to the same point (Fig. 2b) were calculated for all bladder images.

Descriptive statistics were calculated for each USI measurement arising from all images taken during manipulation of the transducer around a particular axis (*e.g.*, x). Repeated measures analyses of variance (ANOVA) were then performed using SPSS software, version 15.0 (Chicago, IL, USA) for each pool of measurements or datasets (*e.g.*, TrA) to determine whether the values were statistically different from the reference image data ($p < 0.05$). For datasets in which a statistically significant difference resulting from the changes in the transducer orientation was identified, the data corresponding from the two outer transducer positions (the so-called −10 and +10° positions) were removed and the ANOVA recalculated on the smaller dataset (*i.e.*, the so-called

Table 1. Summary of approximate induced transducer positions

Imaging site	x axis rotation (CW/CCW)					y axis rotation (cranial/caudal)					z axis rotation (medial/lateral)					z axis translation (inward/outward)				Total
LAW	−10	−5	0	5	10	−10	−5	0	5	10	−10	−5	0	5	10					15
BB	−10	−5	0	5	10	−10	−5	0	5	10	−10	−5	0	5	10	Pin	0	Pno	Val	19

CW/CCW = clockwise/counter-clockwise; LAW = lateral abdominal wall imaging site; BB = bladder imaging site; Pin = inward pressure; Pno = no inward pressure; Val = voluntary Valsalva maneuver.

−5 and +5° positions). The motion data corresponding to the images that showed no significant difference ($p > 0.05$) in the measurement of the USI parameter were then summarized to provide a range of acceptable transducer motion (relative to the pelvis) for changes in orientation resulting from CW/CCW motion, CC tilting, medial/lateral tilting and inward/outward motion of the transducer.

RESULTS

In total, 111 transducer orientations and associated USI images of the TrA, and 143 transducer orientations and associated USI images of bladder base, from eight subjects, were used in the analysis. Vicon camera data was unavailable for 18 (7%) induced transducer orientations and the USI images associated with these missing motion analysis data were excluded from analysis.

A summary of the descriptive statistics (mean ± standard deviation, range) for transducer motion relative to the pelvis for the two transducer positions during the various conditions are summarized in Table 2. At the LAW imaging site, the actual ranges for induced tilt of the transducer in the different planes of motion were: −16.3 to 16.2° of CW/CCW; −8.2 to 7.3° of CC and −5.8 to 8.4° of medial/lateral tilt. At the BB site, −23.6 to 24.2° of CW/CCW, −13.4 to 16.8° of CC, −25.3 to 12.8° of medial/lateral tilt and −8.7 to 16.7 mm of inward and outward motion of the transducer was induced. An attempt was made to approximate changes in transducer orientation in one direction at a time. However, because it is unlikely that transducer motion will occur about only one axis or in one plane at a time during a dynamic study in a clinical environment, we purposely permitted out-of-plane motion and reported it in Table 2. Consequently, a greater amount of induced motion about one axis may have occurred during a condition in which motion was being induced about another axis. For example, a greater value of CC and medial/lateral transducer motion (at the BB imaging site) was seen during the condition concerned with inducing CW/CCW transducer rotation.

A summary of the descriptive statistics (mean ± standard deviation, range) for measurements of TrA thickness and bladder base position, before and after changes in transducer orientation are found in Tables 3 and 4, respectively. The reference values (0°) for TrA thickness averaged 3.0 ± 0.9 mm. The average percent change in AP bladder base position ranged from 0.6% during CC tilting to 4.7% during inward and outward motion of the transducer. The average percent change in CC bladder base position ranged from 1.1% during CW/CCW tilt to 3.5% during inward and outward motion of the transducer.

None of the datasets corresponding with TrA thickness measurements during the induced transducer conditions were found to be statistically different ($p > 0.05$) to the reference image measurement. In addition to providing ranges of acceptable transducer motion, this result suggests that the operator likely maintained some degree of consistency, with respect to inward/outward pressure (which was not monitored at this imaging site) during the data collection. Further, only the datasets for the AP bladder base measurement during induced inward/outward transducer motion and the CC bladder base measurement during induced CW/CCW transducer motion were found to be significantly different ($p < 0.05$) to the reference image measurement. Consequently, it can be concluded that it is unlikely that transducer motion (as summarized in Table 5) will introduce error into measurements of TrA thickness and bladder base position.

DISCUSSION

This appears to be the first study that has attempted to establish guidance for acceptable (threshold) amounts of transducer motion for generating reliable measurements of TrA thickness and bladder base position (see Table 5 for a summary) during a clinical simulation. Although the absolute values of the USI parameters (*i.e.*, TrA

Table 2. Summary of actual induced ultrasound transducer orientation

Condition		x axis rotation (CW/CCW) Degrees (mean ± SD, range)		y axis rotation (cranial/caudal) degrees (mean ± SD, range)		z axis rotation (medial/lateral) degrees (mean ± SD, range)		z axis translation (inward/outward) mm (mean ± SD, range)
LAW	**X**	8.6 ± 4.4 (−16.3 – 16.2)	X	*5.0 ± 3.3 (−13.0 –10.3)*	X	*1.5 ± 1.5 (−3.1 –5.4)*		
	Y	*4.7 ± 3.6 (−11.8 –13.8)*	**Y**	3.3 ± 2.4 (−8.2 –7.3)	Y	*2.6 ± 2.8 (−2.4 –11.8)*		
	Z	*3.3 ± 2.8 (3.4 – 13.5)*	Z	*3.2 ± 2.1 (−8.7 – 5.8)*	**Z**	4.5 ± 2.1 (−5.8 –8.4)		
BB	**X**	14.0 ± 8.2 (−23.6 – 24.2)	X	*4.0 ± 4.2 (−16.1 –2.5)*	X	*6.6 ± 4.2 (−15.4 –1.7)*	X	*2.0 ± 1.3 (−3.4 –5.0)*
	Y	*9.9 ± 13.7 (−9.3 –16.8)*	**Y**	8.8 ± 4.7 (−13.4 –16.6)	Y	*3.5 ± 2.4 (−8.0 –8.50)*	Y	*2.9 ± 2.4 (−4.4 –3.1)*
	Z	*6.1 ± 4.2 (−13.5 –12.8)*	Z	*2.5 ± 2.5 (−10.7 – 3.1)*	**Z**	7.8 ± 7.7 (−25.3 –6.3)	Z	*1.7 ± 1.2 (−4.4 – 3.1)*
	Zt		Zt		Zt		**Zt**	8.1 ± 4.4 (−8.7 –16.7)

The bold font represents the primary axis about which the transducer was being manipulated. The normal font represents the associated out of plane motion. LAW = lateral abdominal wall imaging site; BB = sagittal bladder imaging site; CW = clockwise; CCW = counter-clockwise.

Table 3. Transversus abdominis thickness measurements for induced transducer orientation about the x, y and z axes

	TrAX (CW/CCW)	TrAY (cranial/caudal)	TrAZ (medial/lateral)
Avg. reference value (mm)	3.0 ± 0.9	2.9 ± 10	3.0 ± 0.8
Avg. induced value (mm)	3.1 ± 1.1	3.0 ± 0.8	3.1 ± 0.9
Avg. change (mm)	0.1 ± 0.4	0.4 ± 0.6	0.04 ± 0.4
Avg. % change	3.3	1.5	3.1

TrA = TrA thickness defined as the perpendicular distance between the muscles superficial and deep fascial boundaries.
No significant differences ($p > 0.05$) were found.

thickness) investigated are consistent with values published previously (Rankin et al. 2006), it may be useful to determine if the threshold amounts of acceptable transducer motion are in line with previously reported indicators of statistical and clinically significant changes for these parameters. Indicators of statistical significance include standard error of measurement (SEM) and minimum detectable change (MDC) (Portney and Watkins 1999). However, statistical significance does not necessarily translate to clinical significance, which is defined as the change that must take place in a patient's score to become a score typical of the normal population (Jacobsen et al. 1984).

The SEM is a reliability measure of response stability and is calculated by estimating the standard error in a set of repeated scores (Portney and Watkins 1999). The MDC represents the smallest difference or change that would be statistically significant when comparing repeated measures of a particular parameter. There are several studies that provide these statistics for TrA thickness (Hides et al. 2007; Kiesel et al. 2007; Mannion et al. 2008; Norasteh et al. 2007; Springer et al. 2006; Teyhen et al. 2005) and displacement of the bladder base during various maneuvers (*i.e.*, pelvic floor muscle contraction) (Sherburn et al. 2005; Thompson et al. 2005, 2007), but none that have done so for resting bladder base position.

Published SEM values for repeated measurements of TrA (resting) thickness in supine vary from 0.1–0.45 mm (Hides et al. 2007; Kiesel et al. 2007; Mannion et al. 2008; Norasteh et al. 2007; Springer et al. 2006; Teyhen et al. 2005). Kiesel et al. (2007) reported a MDC of 0.30 mm for thickness measures of TrA thickness (in supine), suggesting that changes <0.30 mm are not statistically significant. Our findings of induced changes of TrA thickness between 0.04–0.4 mm (Table 3) are within these previously reported SEM and MCD values. SEM and MDC values for changes in the position of the bladder base (sagittal suprapubic USI) during a pelvic floor contraction vary from 0.1–0.6 mm and 3.6 mm, respectively (Sherburn et al. 2005; Thompson et al. 2005, 2007). Although the present study was concerned with resting bladder base position measurements at various induced transducer positions, they range from 0.6–4 mm (Table 4) and are in line with the previously reported SEM and MCD values for this parameter during a pelvic floor muscle contraction.

Clinical significance is generally used when interpreting a patient's response to a particular intervention; however, it may be useful in the context of this paper to provide further interpretation of the findings (*i.e.*, Is the change in TrA thickness or bladder base position, resulting from manipulation of transducer orientation, of a magnitude that would be considered clinically significant?). Jacobsen et al. (1984) suggest that a clinically significant change in a score is one that moves the score >2 SD from the mean for the patient group. Teyhen et al. (2009) report the difference in the change in TrA thickness between a patient with lumbopelvic pain (6.4 ± 2.9%) and a normal, healthy cohort (23.7 ± 2.9%) during an active straight-leg raise test. Based on these findings, a clinically significant change would be one that resulted in a 5.8% increase in TrA

Table 4. Sagittal bladder base position measurements for induced transducer orientation about the X, Y, Z axes and Zt plane

	BB APX (CW/CCW)	BB APY (cranial/caudal)	BB APZ (medial/lateral)	BB APZt (inward/outward)
Avg. reference value (cm)	8.6 ± 1.8	8.7 ± 1.7	8.6 ± 1.7	8.7 ± 1.9
Avg. induced value (cm)	8.4 ± 1.8	8.6 ± 1.8	8.6 ± 1.9	9.1 ± 2*
Avg. change (cm)	0.2 ± 0.5	0.06 ± 0.4	0.07 ± 0.5	0.4 ± .8
Avg. % change	2.6	0.6	0.8	4.7
	BB CCX (CW/CCW)	**BB CCY (cranial/caudal)**	**BB CCZ (medial/lateral)**	**BB CCZt (inward/outward)**
Avg. reference value (cm)	11.6 ± 3.9	12.1 ± 4.0	11.3 ± 3.4	11.6 ± 4.1
Avg. induced value (cm)	11.4 ± 4.3*	12.5 ± 3.8	11.0 ± 3.8	12.0 ± 3.8
Ave. change (cm)	0.1 ± 1.6	0.4 ± 0.8	0.3 ± 0.8	0.4 ± 1.2
Ave % change	1.1	3.2	2.6	3.5

BB = sagittal bladder imaging site; AP = the perpendicular distance from the top of the ultrasound image to a reference point on the bladder base; CC = the perpendicular distance from the side of the ultrasound image to a reference point on the bladder base; CW = clockwise; CCW = counter-clockwise.
* Significant difference ($p < 0.05$).

Table 5. Guidelines for acceptable amounts of transducer motion for measurements of TrA thickness and bladder base position

Measurement	CW/CCW motion (degrees)	Cranial/Caudal tilt (degrees)	Medial/Lateral tilt (degrees)	Inward/Outward motion (mm)
TrA	≤9	≤5	≤5	Unknown
BB Base AP	≤14	≤10	≤8	<8 mm
BB Base CC	<10	≤10	≤8	≤8 mm

TrA = TrA thickness defined as the perpendicular distance between the muscles superficial and deep fascial boundaries; BB Base AP = the perpendicular distance from the top of the ultrasound image to a reference point on the bladder base; BB Base CC = the perpendicular distance from the side of the ultrasound image to a reference point on the bladder base; CW = clockwise; CCW = counter-clockwise.

thickness, which is greater than the percent change in thickness reported in the present study (range 1.5 to 3.9%). In regards to bladder base position, Thompson et al. (2007) reported that the change in position of the bladder base during a pelvic floor muscle contraction differed between two patient groups (urge incontinence = 2.6 ± 6.1 mm; stress urinary incontinence = 5.5 ± 5.1 mm) and a normal cohort (5.0 ± 4.9 mm). Based on these findings, a clinically significant change would be one that resulted in a 9.8-mm change in bladder base position, which is greater than the changes reported in the present study (range 0.6 to 4 mm). This suggests that the amount of transducer orientation manipulation in the present study did not produce changes in measurements of TrA thickness or bladder base position that were clinically significant.

Several clinical messages can be drawn from this investigation. Specifically, sonographic studies and clinical assessments investigating TrA muscle thickness and bladder base position should take transducer orientation into account to improve the reliability of the imaging technique. For general guidance, investigators and clinicians are advised to minimize angular motion of the transducer to <10° and inward/outward motion to <8 mm. It is interesting to note that the condition with the greatest amount of induced error across all participants was for measurements of cranial/caudal bladder base position when attempting to induce CW/CCW transducer motion (x-axis). It is clear that, unlike manipulation of the transducer in the other planes, there was significant out-of-plane transducer motion in the other two directions (cranial/caudal and medial/lateral tilt; Table 2), suggesting that there may be a culmination of error when changes in transducer motion occur about several axes. Hence, the data indicate an argument that transducer motion around multiple axis or planes should be minimized.

Several limitations to this study must be acknowledged. Clearly, a more complicated methodology and statistical model are required to provide definitive guidelines for directional threshold values of transducer motion. Specifically, it would be of interest to attempt to initiate transducer motion about only one axis or plane (*i.e.*, inward and outward motion) at a time and determine the influence on specific USI parameters. Because the goal of this investigation was to mimic changes in transducer orientation likely to occur during a dynamic imaging study in an attempt to inform researchers/clinicians and gain pilot data for future investigations, such an endeavor was beyond its scope. Further, it is important to remember that the depth, size and consistency of a structure, as well as the surrounding environment, influence its appearance within a USI image (Kremkau 2002). For instance, transducer motion relative to the body surface results in greater distortion the further (deeper) a structure is from the USI transducer. Hence, care must be taken when generalizing the results of this study to other measurement parameters and under different conditions (*i.e.*, subject position and characteristics, dynamic maneuvers). Keeping these points in mind, it is critical that the guidance reported here remains in context and absolute values are not quoted as being actual threshold levels for acceptable transducer motion for all USI parameters.

Topics for future research include determining the amount of USI transducer motion that occurs when examining other regions of the body and during commonly used clinical maneuvers for examining the lumbopelvic region (*i.e.*, abdominal drawing in and active straight-leg raise test). Furthermore, it would be very useful to confirm that the amounts detected during these maneuvers were less than or consistent with those found in the present study. This will serve to provide a greater context for the use of USI by physiotherapists to assess the behavior of the TrA and changes in the position of the bladder base in a clinical setting.

SUMMARY

The purpose of this study was to shed light on the amount of USI transducer motion that is required before there is a significant error introduced into the measurement of TrA thickness and bladder base position, and in doing so, inform both clinicians and researchers using USI and designing future studies. We have done this by first determining if induced transducer orientation produced a significant difference in specific USI parameters compared with a reference position and then secondly by looking to the previous literature and the SEMs and MDCs reported to date. Our findings suggest that small

amounts of transducer motion (between 5 to 10° of angular and 8 mm on inward/outward motion) may be acceptable without distorting the image and introducing measurement error; however, a larger, more intricate study is required to provide definitive thresholds of movement.

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● *Original Contribution*

ULTRASOUND IMAGING TRANSDUCER MOTION DURING CLINICAL MANEUVERS: RESPIRATION, ACTIVE STRAIGHT LEG RAISE TEST AND ABDOMINAL DRAWING IN

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Abstract—Clinical use of ultrasound imaging by physiotherapists is increasing; however, the clinical setting may be problematic due to variability inherent in the environment. As transducer motion interferes with accurate measurement, this study aimed to measure handheld transducer motion, relative to the pelvis, during a clinical simulation involving typical maneuvers employed in a physiotherapy assessment of the lumbopelvic region. Transducer motion about three axes and through one plane was measured (Vicon, Oxford, UK) on 12 participants during three clinical maneuvers at four abdominal imaging sites. Data were grouped and means used to determine discrepancies in transducer and pelvic motion for each imaging site/maneuver combination. None of the conditions produced large transducer motions relative to the pelvis and all findings were within previously established guidelines for acceptable amounts of transducer motion. These findings suggest that an ultrasound transducer can be held relatively stationary in a clinical setting, for the maneuvers tested. (E-mail: j.l.whittaker@soton.ac.uk) **© 2010 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Abdominal drawing in maneuver, Active straight leg raise, Ultrasound imaging, Ultrasound transducer, Validity.**

INTRODUCTION AND LITERATURE

The term rehabilitative ultrasound imaging (RUSI) has been coined to outline the scope of ultrasound imaging (USI) use by physiotherapists (Teyhen 2006; Whittaker et al. 2007a). Coinciding with the appearance of this term has been an increase in the clinical use of USI by physiotherapists to evaluate the morphology (Stokes and Young 1986; Hides et al. 1995; Stokes et al. 2005; Hides et al. 2007) and behavior of muscle (Hides et al. 2007; Whittaker 2008; Teyhen et al. 2009a, 2009b) as well as to provide biofeedback (Henry and Westervelt 2005; Van et al. 2006; Henry and Teyhen 2007) about muscle behavior during therapeutic exercises. These clinical applications commonly involve measurement of the abdominal wall and lumbar paraspinal muscles (see Stokes et al. 2007 and; Teyhen et al. 2007 for an overview) or bladder position (see Whittaker et al. 2007b for a summary) at rest and during dynamic maneuvers.

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The clinical setting poses unique challenges to objective data collection that are more easily controlled for in a laboratory setting (*i.e.*, variability of environment, time restraints associated with length of patient appointment and the lack of access and feasibility of use of various assistive technologies). This is potentially amplified with studies gathering USI data with a handheld transducer, as accurate interpretation depends upon maintaining a relatively stationary transducer position during an imaging study, as motion can distort the image and lead to erroneous conclusions (Dupont et al. 2001; Reddy et al. 2001; Klimstra et al. 2007). Further, complicating this issue is the dynamic nature of USI studies undertaken during a typical physiotherapy assessment of the lumbopelvic region that result in trunk, abdominal wall or limb motion. For example, physiotherapists commonly gather USI clips during maneuvers that involve either a supine leg lift or drawing in of the abdominal wall. Specifically, the active straight leg raise test (Mens et al. 1999) is a clinical test used to assess the ability of the lumbopelvic region to effectively transfer load (Mens et al. 1999; Hungerford et al. 2004). It involves a patient lying supine and

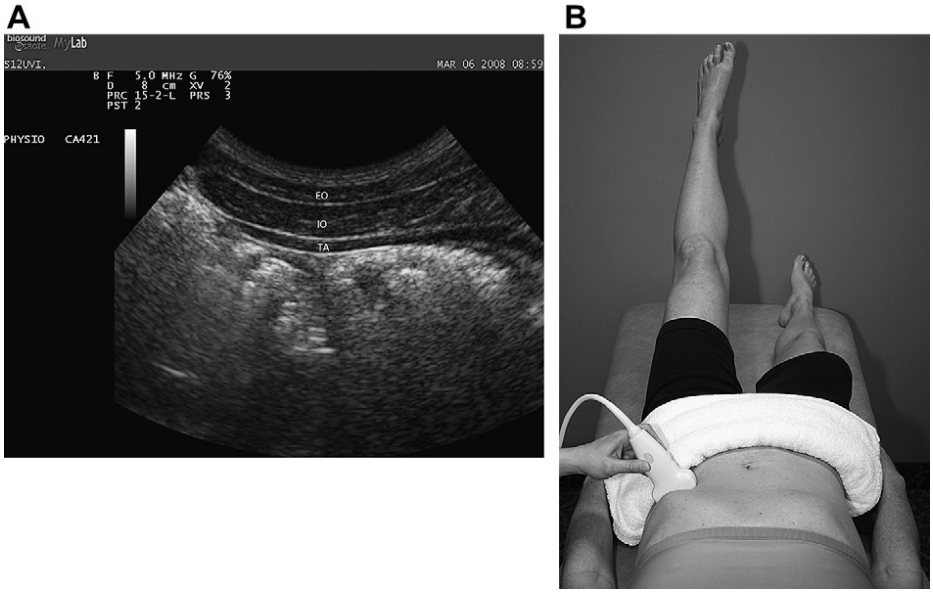

Fig. 1. (A) An ultrasound imaging of the lateral abdominal wall muscles (EO = external oblique; IO = internal oblique; TrA – Transversus Abdominis) taken during a clinical USI study of the lateral abodminal wall muscles during an active straight leg raise test (B).

raising alternate legs five centimeters off the supporting surface without bending their knee (see Fig. 1A). The test is judged to be positive when unilateral pain, discomfort or a feeling of heaviness is experienced. The test has been shown to have a significant association with increased pelvic joint motion (Mens et al. 1999), demonstrates good sensitivity and specificity for detecting lumbopelvic pain and good test re-test reliability (Mens et al. 2001). In contrast, the abdominal drawing in maneuver (Richardson et al. 2004) is a commonly investigated clinical muscle test of the abdominal wall (Richardson and Jull 1995; Teyhen et al. 2005; Stuge et al. 2006; Hides et al. 2006b) as re-education of this motion has been shown to be successful in decreasing low back pain (O'Sullivan et al. 1998; Stuge et al. 2004; Goldby et al. 2006). Ultrasound imaging can be used to monitor the function (thickness) of the abdominal muscles during both maneuvers and investigators have shown that individuals with back pain demonstrate significantly smaller increases in thickness of the internal oblique (IO) and transversus abdominis (TrA) muscles then healthy controls during both tasks (Fig. 1B; Critchley and Coutts 2002; Kiesel et al. 2007; Teyhen et al. 2009a, 2009b).

Aware of the potential source of error resulting from transducer motion during dynamic maneuvers previous investigators have employed elaborate laboratory apparatus (fixed mounts/belts) and imaging postprocessing (Bunce et al. 2002; 2004; Peng et al. 2006; Lovegrove Jones et al. 2009), that are not feasible in a clinical setting, in an attempt to maintain or compensate for transducer (or participant) motion. In contrast, others have neglected to indicate how transducer motion was controlled for, or report that transducer position was maintained manually (Koppenhaver et al. 2009; Teyhen et al. 2009a, 2009b). In keeping with the inconsistency of methodology, it is not surprising that the range of reported reliability estimates for sonographic parameters, such as abdominal wall muscle thickness and bladder base position are widespread. For example reported interclass correlation coefficients of abdominal wall muscle thickness range from 0.26 to 0.92 (Costa et al. 2009) while those for bladder base motion range from 0.51 to 0.98 (O'Sullivan et al. 2002; Thompson et al. 2005; 2007). Although there are many factors that could be influencing the spread of these values (experimental set-up, imaging site, operator expertise, statistical analysis etc.), it is interesting to note that 80% of the correlation coefficients reported for single resting measures were >0.80 while most values for change in thickness, or during maneuvers in which transducer motion was more likely, were <0.70 (Costa et al. 2009). One plausible interpretation of this is that transducer motion during a dynamic event may interfere with accurate interpretation.

In a recent study, the question of how much USI transducer motion can occur before a statistically significant error is introduced into measurements of TrA thickness and bladder base position (from a supra-pubic approach) was investigated (Whittaker et al. 2009). Specifically, repeated measurements of these two parameters were taken from images recorded at various induced

transducer orientations (quantified by digital optical motion capture system; Vicon, Oxford, UK). Motion data corresponding to images that produced measurements statistically equivalent ($p > 0.05$) to values taken from a reference image (0^0 tilt) were summarized to provide a range of acceptable transducer motion about three axes of rotation and one plane of translation (inward and outward transducer motion). The findings, which suggest that small amounts of transducer motion (between 5^o and 10^o of angular and 10 mm of inward/outward) may be acceptable without distorting the image and introducing measurement error, provide objective evidence for previously reported indicators of statistical (standard error of measurement and minimum detectable change) and clinically significant changes for these parameters (Sherburn et al. 2005; Thompson et al. 2005; Hides et al. 2007; Kiesel et al. 2007; 2007; Mannion et al. 2008; Koppenhaver et al. 2009). Keeping these guidelines for acceptable amounts of transducer motion in mind, it is prudent to determine the amount of ultrasound transducer motion that occurs during USI studies typically undertaken during a physiotherapy assessment of the lumbopelvic region. Accordingly, the aim of this study was to investigate the amount of ultrasound transducer motion that occurs during a clinical simulation (*i.e.*, handheld transducer) of a respiratory task, an active straight leg raise test and an abdominal drawing in Maneuver in relation to the bony pelvis as a means to inform clinicians and future investigations. The hypothesis was that small amounts of transducer motion will occur but that they would not exceed previously reported guidelines (Whittaker et al. 2009) for acceptable transducer motion.

MATERIALS AND METHODS

Participants

Twelve healthy volunteers (8 female and 4 male) aged 19 to 44 years were studied. Participants averaged 30.6 ± 8.2 years, 70.4 ± 10.9 kg and had a mean body mass index (BMI) of 24.3 ± 3.0 kg/m^2. Exclusion criteria were musculoskeletal or neuromuscular disorder affecting the lumbopelvic region, a history of lumbopelvic pain in the last year that had required medical attention or resulted in the inability to work or perform recreational activities, a BMI greater than 31 kg/m^2, an inability to follow instructions or a skin disorder. The study was approved by the School of Health Sciences Ethics Committee, University of Southampton, UK. All participants gave written informed consent to participate in the study.

Ultrasound imaging simulation

The purpose of this investigation was to document transducer motion (not sonographic data) during USI studies collected during common clinical maneuvers. An USI system (MyLab 25; Biosound Esaote Inc., Indianapolis IL, USA) with a handheld curvilinear 5.0 MHz (40 mm footprint) transducer was used to simulate USI studies from four abdominal imaging sites while participants performed three common clinical maneuvers; the active straight leg raise test, abdominal drawing in maneuver and a respiratory task (consisting of tidal respiration as well as a forced expiration). The imaging sites included the right lateral abdominal wall transversely on the right anterolateral aspect of the abdomen halfway between the iliac crest and inferior border of the rib cage), the linea alba just inferior to the umbilicus and sagittal and transverse over the midline of the abdomen supra-pubic (Fig. 2).

Motion analysis protocol

A six-camera digital optical motion capture system (Vicon 460; Vicon, Oxford, UK) was used to monitor motion of both the bony pelvis and USI transducer throughout data collection at a sampling frequency of 120 Hz. The six cameras were set up to provide a capture volume (approximately 2 m width × 2 m length × 2 m height) that enabled a mean camera residual (image error) below 1 mm. Retro-reflective markers (14 mm in diameter) were applied bilaterally to the anterior and posterior

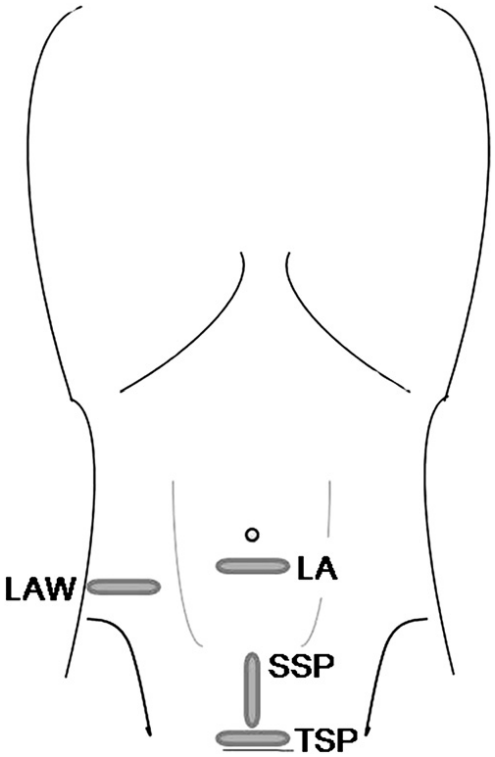

Fig. 2. Location of imaging sites; lateral abdominal wall (LAW), linea alba (LA), saggital and transverse supra-pubic (SPP and TSP, respectively).

superior iliac spine's (ASIS and PSIS, respectively) and iliac tubercles of all participants as well as to a wand that was attached to the ultrasound transducer. A static standing trial was captured for participant calibration. The two PSIS markers were then removed and participants assumed a supine lying position (Fig. 3).

A kinematic model to define the pelvis and USI transducer segments to determine the rotation and position of the transducer with respect to the pelvis was developed and written (by M.B.W.) in Vicon Bodybuilder software (Oxford, UK; see Appendix 1). From this model, the motion of the ultrasound transducer (relative to the pelvis) could be resolved into X (clockwise/counter clockwise; CW/CCW), Y (cranial/caudal tilt of the proximal end of the transducer) and Z (medial/lateral tilt of the proximal end of the transducer) components, as well as the scalar distance (inward and outward motion) of the transducer's wand origin marker to the right ASIS marker for lateral abdominal wall imaging trials, or the midpoint between the right and left ASIS for the linea alba and supra-pubic imaging trials (see Fig. 4).

Experimental procedure

Transducer motion (relative to the pelvis) was recorded as participants performed an active straight leg raise test while a handheld transducer was used to mimic USI data collection at all four imaging sites. Participants also performed a respiratory task and the abdominal drawing in maneuver while the handheld transducer was used to mimic USI data collection at the lateral abdominal imaging site only. Order of task and imaging site were randomly assigned; each maneuver was repeated three times and the data saved for later analysis. All imaging simulations were performed by one operator (J.L.W.) who is a practiced physiotherapist (qualified 17 years) with 9 years of RUSI experience.

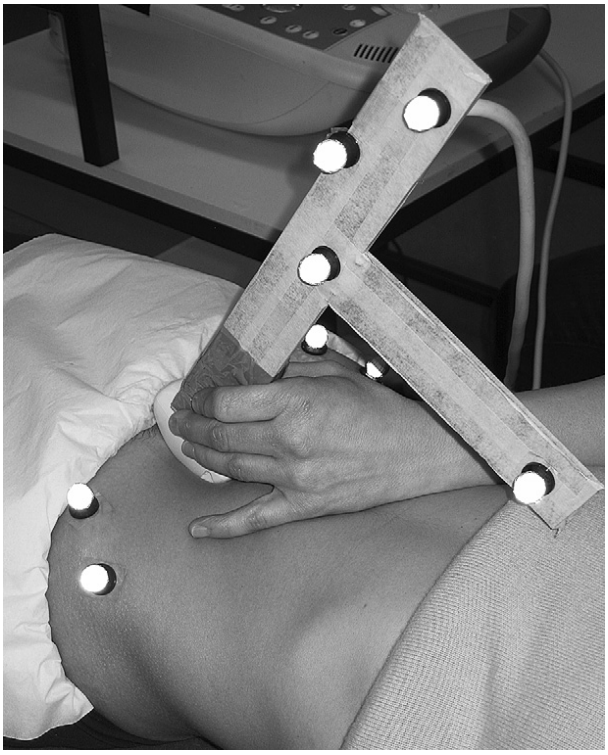

Fig. 3. Experimental set-up for USI at the sagittal supra-pubic imaging site. Note the retro-reflective markers on the ASIS's, iliac tubercle's and wand attached to the ultrasound transducer.

The respiratory and abdominal drawing in tasks were performed from a supine crook lying position and the active straight leg raise test from a fully supine position. Standardized verbal instructions were employed for all participants and a foot switch was used to mark specific events in the timeline of motion data for each task (see Tables 1, 2 and 3). To standardize the requested effort for the forced expiration participants were asked to ''breathe out forcing all the air out of your lungs''. To standardize the height of the leg lift participants were asked to lift their leg until they felt their shin touch a ruler that had been taped to a tripod set at 5 cm above the height of the treatment table. Finally, to standardize the effort for drawing in the abdomen, participants were asked to ''gently draw in your lower abdomen''. When participants were able to consistently perform the maneuver over two consecutive repetitions (as observed on USI), data collection resumed. During data collection participants were asked to replicate a closely as possible the effort of the drawing in during all the abdominal drawing in maneuver trials. This method of standardizing effort has been used by previous investigators (Henry and Westervelt 2005).

Data analysis

Motion data were grouped based upon the imaging site and maneuver performed. Descriptive statistics (mean, standard deviation and range) were used to summarize the amount of transducer motion (relative to the pelvis) that occurred in a clockwise (CW) counter clockwise (CCW; X axis rotation), cranial caudal (Y axis rotation) medial lateral (Z axis rotation) and inward/outward scalar distance for each imaging site/maneuver combination. These values were then compared with the error threshold values obtained from a previous investigation (Whittaker et al. 2009) to assess whether transducer motion during clinical maneuvers would be below that which would cause distortion of the muscle/bladder base image.

RESULTS

In total, 93 lateral abdominal wall (32 active straight leg raise test, 32 respiratory and 29 abdominal drawing in

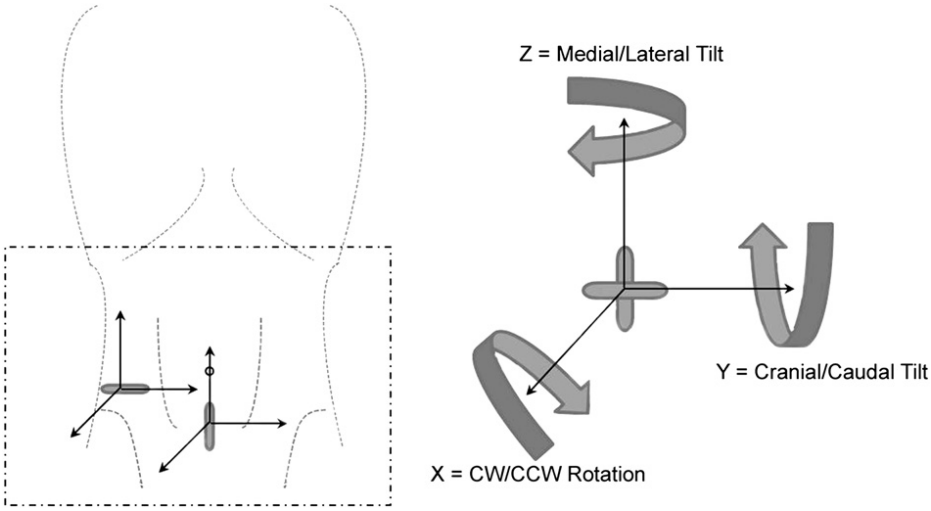

Fig. 4. Axes and associated motions for transducer motion at the lateral abdominal wall imaging and supra-pubic imaging site (CW = clockwise; CCW = counter clockwise). Note the axes and associated motions at the linea alba and transverse supra-pubic imaging site are similar.

maneuver), 29 linea alba, 31 sagittal supra-pubic and 29 transverse supra-pubic motion trials from 11 participants, were used in the analysis. Data from one subject was not included in the analysis, as there was no analogue signal available to determine where the start and end points of the trial were. Of the participants included in analysis, motion data was unavailable for 13 (7%) trails.

Descriptive statistics (mean ± standard deviation, range) for actual transducer motion (relative to the pelvis) for each imaging site and maneuver combination are summarized in Table 4. The condition that resulted in the greatest amount of angular transducer motion was the sagittal supra-pubic imaging site during the leg raise test (2.8 ± 2.2 to 7.1 ± 4.5 degrees) while the least was seen at the lateral wall site during the drawing in maneuver (1.4 ± 0.7 – 2.7 ± 1.5 degrees). The condition that resulted in the greatest amount of inward/outward transducer translation was the lateral wall imaging site during the leg raise test (8.2 ± 2.9 mm) while the least was seen at the sagittal supra-pubic site during the leg raise test (3.4 ± 2.7 mm). In general, the active straight leg raise test was the maneuver that produced the greatest amount of transducer motion (2.1 ± 1.4 to 7.1 ± 4.5 degrees of angular motion and 3.5 ± 2.7 to 8.2 ± 2.9mm of inward/outward translation) while the abdominal drawing in maneuver produced the least (1.4 ± 0.7 to 2.7 ± 1.5 degrees of angular motion and 4.1 ± 2.3mm of inward/outward translation. None of the maneuvers produced large transducer motions relative to the pelvis and all findings were within error threshold guidelines suggesting that an USI transducer can be held relatively stationary in a clinical setting for the maneuvers tested in the hands of an experienced operator (Tables 5 and 6).

DISCUSSION

This appears to be the first systematic study to investigate the amount of handheld ultrasound transducer motion that occurs when undertaking a dynamic USI

Table 1. Protocol used for respiratory trials

Verbal instruction	Event	Event marker
The clip will start as you breathe out	Start of trial	Clip on
Breathe in normally	Inspiration	Peak of inspiration
Breath out normally and hold 5,4,3,2,1,	Expiration	Bottom of expiration
Breathe in normally	Inspiration	Peak of inspiration
Breathe out forcing all the air out of your lungs	Forced expiration	Bottom of expiration
Breathe in normally	Inspiration	Peak of inspiration
Breathe out normally	Expiration	Bottom of expiration
Relax	End of trial	Clip off

Table 2. Protocol for the active straight leg raise test trials

Verbal instruction	Event	Event marker
The clip will start as you breathe out	Start of trial	Clip on
Breathe in normally	Inspiration	Peak of inspiration
Breath out normally and hold 5,4,3,2,1,	Expiration	Bottom of expiration
Lift your leg and hold 5.4.3.2.1	Leg lift	Onset of leg lift
Breathe in normally	Inspiration	Peak of inspiration
Breathe out normally	Expiration	Bottom of expiration
Lower leg as you hold	Lower leg	First contact of leg on bed
Breathe in normally	Inspiration	Peak of inspiration
Breathe out normally	Expiration	Bottom of expiration
Relax	End of trial	Clip off

Table 3. Protocol for abdominal drawing in maneuver trials

Verbal instruction	Event	Event marker
The clip will start as you breathe out	Start of trial	Clip on
Breathe in normally	Inspiration	Peak of inspiration
Breath out normally and hold 5,4,3,2,1,	Expiration	Bottom of expiration
Gently draw in your lower abdomen and hold 5,4,3,2,1	ADIM	Peak of ADIM
Breathe in normally	Inspiration	Peak of inspiration
Breathe out normally and hold 5,4,3,2,1	Expiration	Bottom of expiration
Relax abdomen	Relaxation of Abdomen	Command to release ADIM
Breathe in normally	Inspiration	Peak of inspiration
Breathe out normally	Expiration	Bottom of expiration
Relax	End of trial	Clip off

study of the abdominal wall or bladder base during maneuvers common to a physiotherapy assessment of the lumbopelvic region. A previous investigation (Whittaker et al. 2009) has shown that no statistically significant ($p < 0.05$) changes in measurements of TrA thickness or bladder base position (from a supra-pubic imaging site) occur if transducer motion is kept to less than approximately 5 to 10 degrees of angular or 10 mm of inward/outward motion (Whittaker et al. 2009). The findings of the current study are within these guidelines suggesting that meaningful measurements of abdominal muscle thickness and bladder base position can be made during these maneuvers in a clinical setting, if a similar methodology is employed by a skilled operator.

Clinical messages

Several useful messages can be drawn from this investigation. Although none of the maneuvers produced transducer motions greater than error threshold guidelines, it is not surprising that a greater amount of transducer motion was seen during the more dynamic maneuvers (*i.e.*, leg raise test > forced respiration > abdominal drawing in) suggesting that conscious efforts to control transducer motion during these types of maneuvers may be prudent. In the case of the condition that resulted in the greatest amount of inward/outward transducer motion, the lateral wall imaging site during an active straight leg raise test, it is interesting to note that the majority of the motion occurred at the moment that the leg was raised from the treatment table (Fig. 5). Consequently, it may be relevant for future investigators using this maneuver to specifically concentrate on controlling for inward/outward translation (however, care must be taken not to over compensate and distort the thickness of the abdominal wall through compression) of the transducer at the point of the leg lift. Similarly, in the case of the condition that resulted in the greatest amount of angular transducer motion, the sagittal supra-pubic imaging site during the active straight leg raise test, the majority of the transducer motion occurred at the moment that the leg was raised from the supporting surface in the form of medial or lateral tilting of the proximal end of the transducer. Accordingly, it may be relevant for future investigators employing this maneuver to specifically concentrate on controlling for medial and lateral tilting of the transducer at the point of the leg lift.

An additional clinical message speaks to the utility of transabdominal supra-pubic USI of the bladder base. Generally, the transabdominal approach is commonly dismissed in favor of a transperineal one because it provides no bony landmark from which to standardize measurements during dynamic events (Thompson et al. 2007; Whittaker et al. 2007b). Arguably, the transperineal technique is advantageous in some situations as it provides a direct view of the levator ani muscles,

Table 4. Descriptive statistics of ultrasound transducer motion during RESP, ADIM and ASLR maneuvers

Condition	X (AP) axis rotation (clockwise/counter clockwise) degrees mean ± SD, (range)	Y (LR) axis rotation (cranial/caudal) degrees mean ± SD, (range)	Z (CC) axis rotation (medial/lateral) degrees mean ± SD, (range)	Z translation (inward/outward) mm mean ± SD, (range)
RESP				
LAW	2.3 ± 0.8, (0.3–5.2)	3.3 ± 1.4, (0.8–7.2)	2.2 ± 1.1, (0.6–4.6)	6.0 ± 2.6, (1.6–12.3)
ADIM				
LAW	1.4 ± 0.8, (0.2–3.8)	2.7 ± 1.5, (0.5–6.9)	1.4 ± 0.7, (0.5–3.4)	4.1 ± 2.3, (0.8–11.6)
ASLR				
LAW	2.1 ± 0.7, (0.7–3.3)	2.7 ± 1.1, (1.0–6.5)	4.3 ± 1.4, (2.3–7.1)	8.2 ± 2.9, (3.0–13.8)
LA	2.1 ± 1.4, (0.5–6.1)	3.3 ± 1.6, (1.0–10.3)	4.8 ± 2.4, (2.1–11.0)	6.7 ± 2.0, (1.7–3 0)
SSP	5.2 ± 4.0, (0.8–19.3)	2.8 ± 2.2, (0.7–9.9)	7.1 ± 4.5, (2.2–23.2)	3.4 ± 2.7, (0.7–14.7)
TSP	3.7 ± 2.2, (1.0–8.9)	4.2 ± 2.8, (1.2–10.1)	5.6 ± 2.6, (1.5–11.0)	5.3 ± 3.6, (1.5–17.1)

RESP = respiratory task; ADIM = abdominal drawing in maneuver; ASLR = active straight leg raise test; LAW = lateral abdominal wall imaging site; LA = linea alba imaging site; SSP = sagittal supra-pubic imaging site; TSP = transverse supra-pubic imaging site; AP = anterior posterior; LR = left right; ML = medial lateral; CC = cranial caudal.

Table 5. Comparison of ultrasound transducer motion at the LAW imaging site to error thresholds (Whittaker et al. 2009) during a respiratory task, the ADIM and the ASLR test

	Transducer motion				Error thresholds			
Condition	CW/CCW degrees, mean ± SD	Cranial/caudal degrees, mean ± SD	Medial/lateral degrees, mean ± SD	Inward/outward mm, mean ± SD	CW/CCW degrees	Cranial/caudal degrees	Medial/lateral degrees	Inward/outward Mm
RESP	2.3 ± 0.8	3.3 ± 1.4	2.2 ± 1.1	6.0 ± 2.6	< or = 9	< or = 5	< or = 5	Unknown
ADIM	1.4 ± 0.8	2.7 ± 1.5	1.4 ± 0.7	4.1 ± 2.3				
ASLR	2.1 ± 0.7	2.7 ± 1.1	4.1 ± 1.4	8.2 ± 2.9				

RESP = respiratory task; ADIM = abdominal drawing in maneuver; ASLR = active straight leg raise test; LAW = lateral abdominal wall imaging site; CCW = counter clockwise; CW = clockwise.

facilitating study of their morphology, as well as the pubic symphysis, the bladder neck and ano-rectal angle (Dietz et al. 2001; Morkved et al. 2004; Peng et al. 2007b; Lovegrove Jones et al. 2009). However in contrast to the transabdominal approach, proficiency requires extensive training, measurements are complex and transducer location is both intrusive and may at times interfere with functional maneuvers such as a supine leg raise (Whittaker et al. 2007b). The findings of the present study suggest that contrary to some investigators' beliefs, the transabdominal approach may be capable of rendering meaningful measures of bladder base position during dynamic maneuvers similar to those investigated in this study, in that transducer motion can be kept to a level that will not introduce error into the measurement process.

Limitations

Several limitations to this study must be acknowledged. First, it is likely that the abdominal wall muscles and bladder move independent of the bony pelvis during these dynamic maneuvers. In this investigation, it was assumed that these structures were essentially one for ease of analysis. With that being said the transducer motion seen was within values that have been shown not to produce a statistically significant change in measurements of TrA thickness or bladder base position (Whittaker et al. 2009).

Second, it is well accepted that individuals with pain or dysfunction in the lumbopelvic region employ motor control strategies that differ from healthy participants (O'Sullivan et al. 2002; Beales et al. 2009a; 2009b). For instance Beales et al. (2009b) showed that participants with unilateral chronic pelvic girdle pain adopt a bracing (co-contraction) motor control strategy with their trunk muscles (specifically the external and internal oblique muscles) when performing an active straight leg raise test on their affected side. This bracing strategy was associated with higher levels of intra-abdominal pressure (IAP) and greater pelvic floor depression. Accordingly, the greater abdominal wall muscle contraction and higher levels of IAP seen in individuals with lumbopelvic pain may impart greater USI transducer motion than normal participants during dynamic maneuvers. In an attempt to mimic the co-contraction of the oblique abdominal muscles and increase in IAP seen with lumbopelvic pain, we included a forced expiration in the respiratory trials investigated here. Although the transducer motion seen during the respiratory trials was within the error thresholds previously reported, it would be prudent to include participants with lumbopelvic pain in future investigations.

The goal of this investigation was to inform clinicians and future investigations. Every experimental system is unique and possesses its own measurement properties. Therefore, care must be taken when

Table 6. Comparison of ultrasound transducer motion at the LA, SSP, TSP imaging sites to error thresholds (Whittaker et al. 2009) during the ASLR test

	Transducer motion				Error thresholds			
Condition	CW/CCW degrees, mean ± SD	Cranial/caudal degrees, mean ± SD	Medial/lateral degrees, mean ± SD	Inward/ outward mm, mean ± SD	CW/CCW degrees	Cranial/ caudal degrees	Medial/ lateral degrees	Inward/ outward mm
LA	2.1 ± 1.4	3.3 ± 1.6	4.8 ± 2.4	6.7 ± 2.0	unknown	unknown	unknown	unknown
SSP	5.2 ± 4.0	2.8 ± 2.2	7.1 ± 4.5	3.4 ± 2.7	<10	< or = 10	< or = 8	< or = 8 mm
TSP	3.7 ± 2.2	4.2 ± 2.8	5.6 ± 2.6	5.6 ± 3.6	unknown	unknown	unknown	unknown

LA = Linea Alba imaging site; SSP = sagittal supra-pubic imaging site; TSP = transverse supra-pubic imaging site; ASLR = active straight leg raise test; CCW = counter clockwise; CW = clockwise.

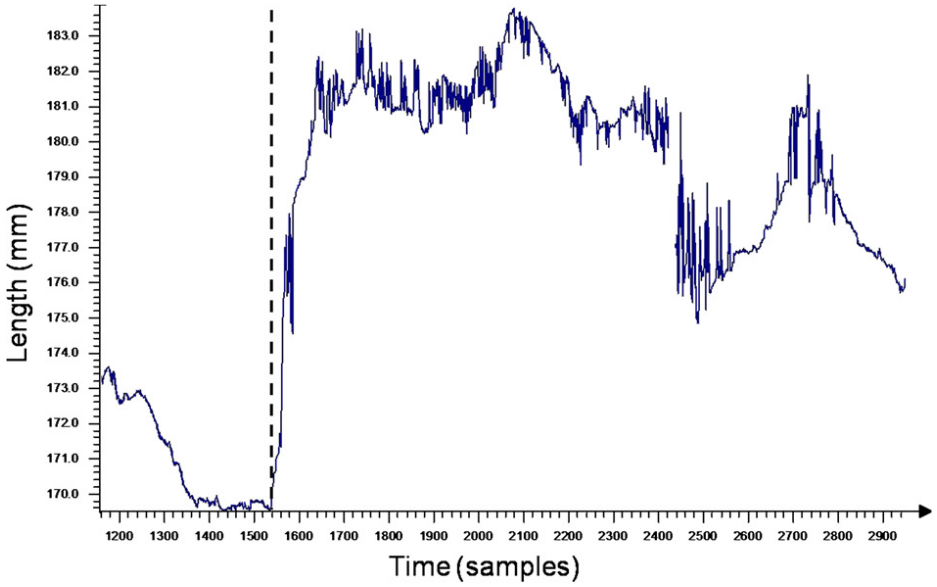

Fig. 5. Ultrasound transducer motion (outward translation) at the lateral abdominal wall imaging site during an active straight leg raise test. Note that the majority of the motion occurs at the moment the leg is lifted from the support surface (dashed line).

generalizing the results of this study to other measurement parameters and under different conditions (*i.e.*, examiner experience, participant position and characteristics, dynamic maneuvers etc.).

SUMMARY

The purpose of this study was to investigate the amount of ultrasound transducer motion that occurs during a clinical simulation of a respiratory task, an active straight leg raise test and an abdominal drawing in maneuver in relation to the pelvis. This has been achieved by documenting the motion of an USI transducer at four abdominal imaging sites during three commonly employed physiotherapy maneuvers. The findings are within previously reported error threshold guidelines suggesting that a transducer can be held relatively stationary in a clinical setting for the maneuvers tested in the hands of an experienced operator in healthy participants.

The areas identified in this article for future research, particularly in patient populations, will serve to provide a greater context for the use of USI by physiotherapists to assess the behavior of the TrA and changes in the position of the bladder base in a clinical setting.

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APPENDIX 1

A kinematic model was developed and written (by MBW) in Vicon Bodybuilder software v3.6 (Vicon Motion Capture System, Oxford UK). Two rigid body segments were formed; the pelvis $_{(PEL)}$ and ultrasound transducer $_{(TRN)}$. As there was no physical connection between the pelvis and ultrasound transducer it was assumed the probe had 6 degrees of freedom (6DOF); rotation about the three cardinal planes (sagittal, coronal and transverse) and translations within all three planes.

During the USI simulation, participants adopted a supine position, making the markers attached to the PSIS, which are commonly used in gait to determine pelvic tilt, uncomfortable for participants and invisible

to the motion capture system cameras. Therefore, a technical reference frame $_{(TPEL)}$ for the pelvis was formed utilizing the iliac crest markers, as follows;

- $Origin_{TPEL}$ = Midpoint between left and right ASIS (APEL)
- Y_{TPEL} = Line pointing from left ASIS marker to right ASIS marker
- X_{TPEL} = Line pointing from the mid-point of the left and right iliac crest markers toward APEL.
- Z_{TPEL} = Line mutually orthogonal to Y_{TPEL} and X_{TPEL} following the right hand rule.

The location of the PSIS markers with respect to $_{TPEL}$ was recorded during a static standing trial. The two PSIS markers were then removed and participants assumed a supine lying position (Fig. 3). During the USI simulation trials virtual PSIS markers were created and located into their position within the $_{TPEL}$ reference frame.

The pelvic segment $_{(PEL)}$ was formed and a local coordinate system, using the convention used in clinical gait analysis (Kadaba et al. 1990), was defined;

- $Origin_{PEL}$ = APEL
- Y_{PEL} = Line pointing from left ASIS to right ASIS
- X_{PEL} = Line pointing from the midpoint of the left and right PSIS markers toward APEL
- Z_{PEL} = Line mutually orthogonal to Y_{PEL} and X_{PEL} following the right hand rule.

A wand with retro-reflective markers (marker names; TRNO, TRN1 and TRN2) was attached to the ultrasound transducer and a local coordinate system for the ultrasound transducer $_{(TRN)}$ was defined. During lateral abdominal wall, linea alba and transverse supra-pubic trials the definition of axes was as follows (Fig. 6A);

- $Origin_{TRN}$ = Point 170 mm from TRNO in the negative X_{TRN} direction
- X_{TRN} = Line pointing from TRNO to TRN1
- Y_{TRN} = Line pointing from TRNO to TRN2
- Z_{TRN} = Line mutually orthogonal to X_{TRN} and Y_{TRN} following the right hand rule.

An Euler angle sequence was used to calculate the three rotations of the $_{TRN}$ segment with respect to the $_{PEL}$ segment, with rotation order;

- X = Clockwise/anticlockwise rotation
- Y' = Cranial/caudal tilt of the transducer probe
- Z'' = Medial/lateral rotation

During sagittal supra-pubic trials the transducer was rotated through 90° and gimbal lock, a phenomenon observed when two differing axes become aligned and prevent measurement of the angle

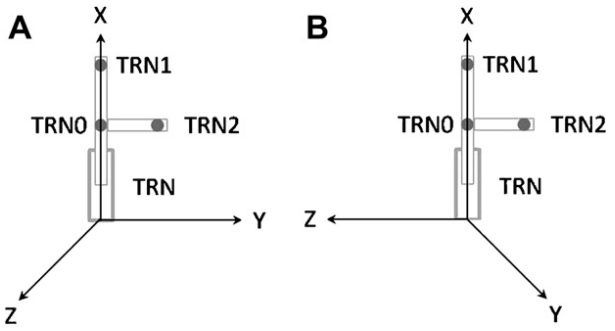

Fig. 6. (A) Axis orientation for the ultrasound transducer $_{(TRN)}$ during lateral abdominal wall, linea alba and transverse supra-pubic trials and (B) during sagittal supra-pubic trials. Markers attached to the transducer wand are labeled TRNO, TRN1 and TRN2.

between these axes, was observed. Consequently, $_{TRN}$ was redefined as (Fig. 6B);

$Origin_{TRN}$ = Point 170mm from TRNO in the negative X_{TRN} direction
X_{TRN} = Line pointing from TRNO to TRN1
Z_{TRN} = Line pointing from TRNO to TRN2
Y_{TRN} = Line mutually orthogonal to X_{TRN} and Y_{TRN} following the right hand rule.

This allowed for the Euler rotation sequence of XY'Z'', which relates to an order of clockwise/counter clockwise (CW/CCW), cranial/caudal tilt of the proximal end of the transducer and medial/lateral tilt of the proximal end of the transducer rotation of the transducer, to be maintained.

The translation between $_{TRN}$ and $_{PEL}$ was calculated as follows;

$$\text{Distance} = \sqrt{(MKR1_x - MKR2_x)^2 + (MKR1_y - MKR2_y)^2 + (MKR1_z - MKR2_z)^2}$$

Where; $MKR1_x$ = X coordinate of marker 1; $MKR2_x$ = X coordinate of marker 2; $MKR1_y$ = Y coordinate of marker 1; $MKR2_y$ = Y coordinate of marker 2; $MKR1_z$ = Z coordinate of marker 1; $MKR2_z$ = Z coordinate of marker 2. During the lateral abdominal wall trials; MKR1 = Left ASIS; MKR2 = TRNO. During the linea alba, sagittal and transverse supra-pubic trials; MKR1 = APEL; MKR2 = TRNO.

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Ultrasound Imaging and Muscle Function

In the past 30 years, increasing numbers of physical therapists have employed conventional grayscale brightness mode (B-mode) ultrasound imaging (USI) to assess components of muscle morphology (the form and structure of muscle) and morphometry (measures of muscle form or size) as a means to speculate on muscle function in both research and clinical settings.[22,24,64,73,79] To that end, the term "rehabilitative ultrasound imaging" (RUSI) was coined as a means to encompass and define these applications.[68] Specifically, RUSI refers to USI procedures used by physical therapists to evaluate the morphology and behavior (morphometry) of muscle and related soft tissues, to provide biofeedback about muscle morphometry during restoration of function, and to carry out research aimed at informing clinical practice.[68,73]

The first to report use of USI for the measurement of muscle size (biceps brachii) was a group at the University of Tokyo in the late 1960s.[29] This trend continued through the 1980s,[5,15,17,76-79] and, by the 1990s, investigative teams were using USI to measure the size and other architectural characteristics of various muscles, including the pelvic floor muscles,[3] masseter,[58] and lumbar multifidus.[22,23] As a decrease in muscle size has been linked to various pathologies and impairments,[16,19] the use of the technology has continued to expand to include investigation of muscles such as the supraspinatus and infraspinatus,[35] rectus femoris,[13] biceps brachii,[2] transversus abdominis (TrA) and internal oblique (IO),[20] rectus abdominis,[8] cervical multifidus,[45] trapezius,[56] rectus femoris, sartorius, and iliopsoas.[53] Other aspects of muscle morphology and function that have been explored with USI include composition,[44,61,66] changes in internal architecture (pennation angles),[48,80] force generation,[13] and muscle activity (ie, electrical activity recorded by electromyography [EMG]).[6,28,34,36,52]

While physical therapists are familiar with therapeutic ultrasound and the underlying physics, they often lack training regarding the principles and instrumentation underlying USI.[32] It is, therefore, critical that they develop a basic understanding of the physics and safety aspects of USI,[71,75] and a clear understanding of the information that it may provide about muscle structure, form, and function, before employing it for either research or clinical applications. Accordingly, specialized training (consistent with the World Health Organization recommendations) is recommended.[73,75] This paper will briefly review how conventional grayscale B-mode ultrasound images are generated and describe the types of information that they can provide, then go on to explore aspects of muscle function that can and cannot be measured by USI.

SYNOPSIS: There is a growing trend in the physical therapy profession to use conventional grayscale brightness (B-mode) ultrasound imaging (USI) as a tool to assess the morphological (form and structure) and morphometric (measures of form) characteristics of muscle, and to use these findings to draw conclusions regarding muscle function. This trend is reflected in numerous published investigations. As many physical therapists may lack training in the principles and instrumentation underlying USI use, it is critical that therapists gain a clear understanding of the information that USI can, and cannot, provide about muscle function before employing the technique for either research or clinical applications. Failure to do so may result in the propagation of inaccurate terminology and beliefs. This paper aims to clarify the role that USI has in the assessment of muscle function, first, by briefly reviewing how conventional grayscale B-mode ultrasound images and clips are generated, and second, by summarizing the types of information that these images can provide. It also discusses the various factors that need to be considered when interpreting a dynamic USI assessment of muscle specifically as it relates to the assessment of muscle function. *J Orthop Sports Phys Ther 2011;41(8):572-580, Epub 7 June 2011. doi:10.2519/jospt.2011.3682*

KEY WORDS: *morphology, morphometry, sonography*

Generation of Conventional Grayscale B-Mode Ultrasound Images

The intention of this section is to briefly review the basic principles that underlie USI image generation as a foundation for the forthcoming discussion. Previous publications have thoroughly covered the

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topic of USI image generation and instrumentation, and readers are encouraged to refer to these for a more complete appraisal of this topic.[42,71,73]

Ultrasound waves are formed when an electrical current is passed across the face of a crystal. In the case of USI, an electrical current is sent to the ultrasound probe, where it is passed across a series of crystals located along the face of the probe and an ultrasound wave is produced. These waves penetrate into the body. How far they travel and how they reflect depends upon the characteristics of the sound wave, which are determined by the current transmitted from the ultrasound unit and the properties of the transducer crystals housed in the transducer assembly or probe, as well as the impedance (resistance) of the tissues that they travel through.[42]

At every tissue interface, sound waves are absorbed, reflected, and/or scattered. When sound energy reflects back to the ultrasound probe, the unit can determine where along the length of the transducer it arrived, how long it has taken to go out and come back, and its amplitude.[71] With B-mode USI, the ultrasound unit uses these 3 parameters to assign the echo from a particular structure a pixel (picture element). The horizontal location of the pixel is determined by the location to which the echo returns along the length of the probe face, while its vertical placement is determined by the amount of time the sound takes to go out and come back. For instance, reflections that return quickly are assumed to be from superficial structures and are placed closer to the top of the image, while those that take a greater amount of time to return are from deeper structures and are placed at the bottom. The brightness of the pixel depends on the strength of the returning echo; the stronger the echo, the whiter, and the weaker the echo, the darker it will appear. This process is repeated over and over until an image is created over the entire screen (**FIGURE 1**). As ultrasound waves are continuously going out and coming back, the image is continuous, with most conventional grayscale USI units updating each pixel 20 to 40 times per second, depending on the frequency of the sound wave.[42]

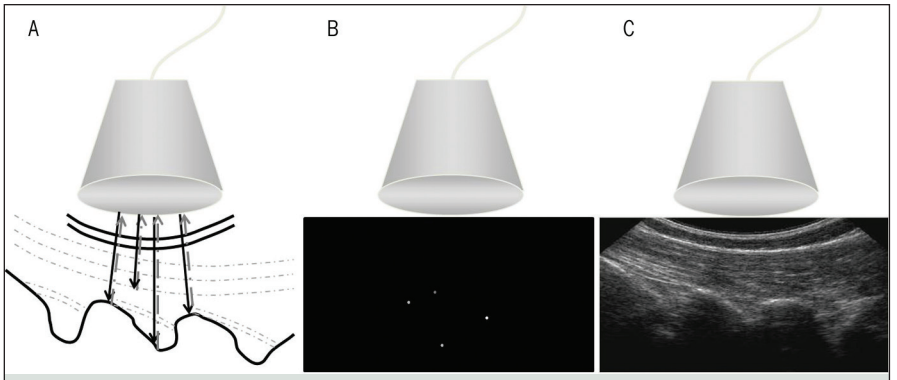

FIGURE 1. Illustration of how a B-mode ultrasound image is generated. (A) Sound waves penetrate into the tissues. At each interface, a portion of the sound wave is reflected back to the transducer. (B) The unit can determine where along the face of the transducer the echo returned, the amount of time it was away, and its amplitude. It uses these 3 parameters to determine the vertical (time) and horizontal (transducer) location of a pixel representing the echo from a particular structure, and the amplitude to determine the brightness. (C) This process is repeated until an ultrasound image is generated.

Generally speaking, the more densely organized the collagen within a tissue, the better it reflects sound, and the whiter the pixels representing it will appear within the image.[71] Structures that do not have collagen (fluids, for example) do not produce a reflection (referred to as "hypoechoic" or "anechoic") and appear black within an ultrasound image (**FIGURE 2A**).[71] Alternatively, bone, which, stated simply, contains densely organized collagen, absorbs, scatters, or reflects 100% of the sound that encounters it and, consequently, appears as a bright white interface within an ultrasound image that is referred to as hyperechoic (**FIGURE 2B**). Muscle is generally well profused with blood and appears hypoechoic (darker), in contrast to the intervening or surrounding fascial layers, which consist of very densely organized collagen (**FIGURE 2C**).

As with any imaging modality, USI units generate images based on several assumptions: that sound only travels in straight lines, echoes only originate from objects located within the 2 dimensions of the sound beam, and sound travels through all tissues at the same speed (1540 m/s).[71] These assumptions are commonly violated, and, consequently, artefact (an incorrect representation of anatomy) is possible.[42] However, with proper equipment operation, imaging technique, and expertise, this can be overcome.

What Information Does Conventional Grayscale Ultrasound Imaging Provide?

Keeping the principles of image generation in mind, it is important to understand that conventional grayscale USI can only provide 2 types of information. The first is information about the echogenicity or reflective properties of a tissue, which is an indicator of its composition or makeup (eg, how much collagen or fluid it contains), and the second is information about the architecture (eg, internal structure, size, and shape) or position of a structure. Recent examples of how researchers have used information about the echogenicity of muscle and the perimuscular tissue obtained with conventional USI to comment on the composition of these structures include an investigation by Strobel et al in 2005[66] that employed USI to detect fatty atrophy of the supraspinatus and infraspinatus, an exploration to detect muscle trigger points in the upper trapezius muscle by Sikdar and colleagues in 2009,[61] and an examination of the perimuscular tissue of the lumbar spine in persons with low back pain (LBP) by Langevin et al in

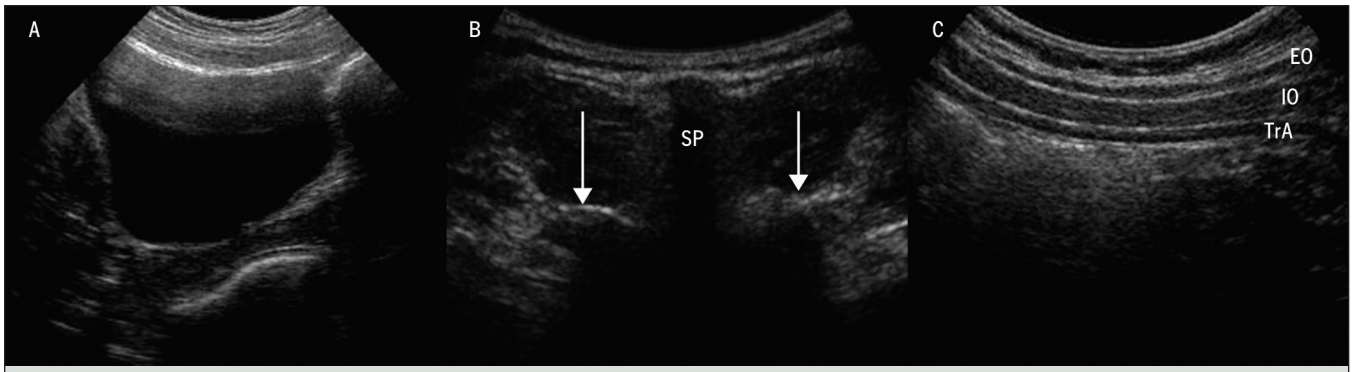

FIGURE 2. (A) An ultrasound image of the bladder. Note the hypoechoic nature (black) of the urine. (B) A transverse ultrasound image of the fifth lumbar vertebrae. Note the brightness of the muscle bone (lamina) interface (arrows). (C) An ultrasound image of the muscle and fascia layers of the lateral abdominal wall. Note that the muscle layers are darker (hypoechoic), while the intervening fascia is brighter (hyperechoic). Abbreviations: EO, external oblique; IO, internal oblique; SP, spinous process; TrA, transversus abdominis.

2009.[44] To date, the most common use of USI in studies by physical therapists has been measurement of the architectural characteristics of muscle, which usually involves measuring parameters such as thickness,[59,60,65] width,[8,65] and cross-sectional area (CSA),[8,43,65] and comparing changes or differences in these parameters between groups of individuals[19,70] or over time—before and after some event (eg, injury)[8] or intervention (eg, training).[25,31]

Is Ultrasound Imaging a Valid Technique for Measuring Muscle Size?

The gold standard for measuring the architectural characteristics of muscle is magnetic resonance imaging (MRI). However, as USI is less expensive and more readily available, many investigators have compared measures taken by the 2 modalities for a number of different muscles to determine the validity of USI for this purpose.[2,35,45,53,56,58] A variety of parameters, ranging from measures of thickness, width, length, and CSA at various anatomical locations, have been considered. Although correlation statistics have reported a range of 0.22 to 0.90, all of the studies reviewed have reported good agreement (greater than 0.80) for at least 1 of the measurement sites investigated and concluded that USI is an accurate method for measuring the muscle parameter of interest. However, it is important to acknowledge that these studies have been conducted almost exclusively in small numbers of young, healthy participants. Further, they were done under static resting conditions, with the exception of the investigations by Raadsheer et al[58] (masseter) and Hides et al[20] (lumbar multifidus). Keeping in mind that muscle parameters are more difficult to measure during dynamic tasks and in older or patient populations, future studies are likely required to validate USI for these conditions and populations. Regardless of these limitations, it is commonly stated in the literature that the validity of USI for measuring muscle morphology is adequate.[21,40,50,63,70,73] In keeping with this commonly held assumption, the next points of consideration are the reliability of USI measurements and, more specifically, what the measured changes in muscle architecture tell us about muscle function.

Is Ultrasound Imaging Reliable for Measuring Muscle Size?

Reliability refers to the extent to which a measurement is consistent and free from error, which is a prerequisite for establishing the usefulness of a measure in making clinical and research decisions.[57] The reliability of USI techniques for measuring various muscles and parameters are reported widely in the literature.[33,39,47,49,55] In general, these studies conclude that USI is a reliable method to measure the muscle parameter of interest. However, as highlighted by Costa et al,[9] using the lateral abdominal wall muscles as an example, the majority of the investigations published prior to 2009, regardless of muscle or parameter, were of low quality (small sample sizes, lack of information about blinding or order of tests, and poorly defined time intervals between tests) and only specific to healthy cohorts. Most of the pre-2009 studies have used standard error of measurement as the agreement parameter. However, few provided confidence intervals or Bland-Altman plots, or calculated minimum detectable change. In general, these studies reported moderate to excellent reliability for single measures of thickness, and poor to good reliability for measures of thickness change. Correlation values (intraclass correlation coefficient) for single measures of muscle thickness have been higher than those for change in thickness. Further, reported intraclass correlation coefficients from studies that included clinical cases were slightly lower than those which used only a healthy cohort. Prior to 2009, no investigations had reported the reliability of between-day measures of the difference in thickness changes, which is important for determining improvement or deterioration in muscle function. A noteworthy study by Koppenhaver et al[39] was published in 2009, that has served as a standard for future USI reliability investigations. Specifically, these investigators

TABLE Summary of Studies Published Comparing Changes in Abdominal Muscle Thickness and EMG Signal Amplitude

Method	Hodges et al[2]	McMeeken et al[4]	John and Beith[3]	Brown and McGill[1]
Muscles investigated	EO, IO, TrA	TrA	EO	EO, IO
Sample	3 healthy subjects	9 healthy subjects	24 healthy subjects	9 healthy subjects
Subject position	Reclined sitting	Supine	Supine	Unsupported sitting
Task	Targeted isometric contractions, % MVC	Ramped abdominal drawing-in	Isometric trunk rotation and ADIM	Ramped abdominal drawing-in
EMG type	Fine-wire EMG	Bipolar needle EMG	Surface EMG	Surface EMG
EMG normalization strategy	Maximum signal from 3 MVCs	Maximum signal from 3 maximal Valsalva maneuvers and 3 ADIMs	Maximum signal from 3 maximum isometric trunk rotations	Maximum signal from modified sit-up/reverse curl with rotations
Imaging site	Parallel to TrA fibers	Parallel to TrA fibers	Parallel to TrA fibers	Parallel to OE, OI, and TrA fibers
Correlation statistic	*r*	R^2	R^2	*r*

Abbreviations: ADIM, abdominal drawing-in maneuver; EMG, electromyography; EO, external oblique; MVC, maximal voluntary contraction; IO, internal oblique; TrA, transversus abdominis.

used the mean of 2 measures[41] to investigate intrarater and interrater reliability in participants with LBP and reported adequate to high reliability for single within-day (0.88-0.94) and between-day (0.80-0.92) thickness measurements of the TrA and multifidus muscles at rest and during contractions.

It is important to remember that reliability is a property of a measurement system that includes the rater, instrument, methodological setup (inclusive of the population being tested), and data analysis processes. If the measurement system for a new investigation differs in at least 1 aspect from a previously published or proven system (eg, new rater or different population), the reliability of the new measurement system must be established prior to any evaluation. Ideally, depending on the way in which the investigators plan to employ the USI technique, this investigation of reliability should include within-day and between-day measurements of both intrarater and interrater (a relatively inexperienced operator compared to an experienced one) reliability in control and case cohorts. Although few studies to date have achieved this standard, various aspects of reliability have been adequately established.

From a clinical perspective, if a therapist is going to rely on USI to monitor changes in muscle size with treatment, it is important that they first determine the reliability of their clinical measurement system. As an alternative to the complex statistical analysis used in research, a simple approach for clinicians to check their reliability is to look at the percentage variability of a number of measures of the same parameter. The bottom line is that, unless individuals demonstrate the reliability of the measurements themselves, they cannot assume that a demonstration of good reliability of a similar measurement by someone else can be relied upon for assessing change over time.

Ultrasound Imaging and Muscle Function

Clearly, when USI is used to visualize a concentric muscle contraction, an increase in muscle thickness and a decrease in muscle length are observed. However, what is the relationship between the pattern and magnitude of change in muscle size and muscle function? One aspect of muscle function that has been compared to change in muscle size is muscle electrical activity, specifically, the relationship between changes in muscle size (measured with USI) and muscle activity (measured with EMG). This association has been investigated in several muscles (lumbar multifidus, tibialis anterior, biceps brachii, and brachialis),[28,36] but most thoroughly in the lateral abdominal wall muscles (5 different occasions by 3 different research groups).[6,14,28,34,52] To date, the findings are clearly inconclusive, with correlation statistics ranging anywhere from 0.14 to 0.93. For instance, McMeeken et al[52] reported a linear relationship between 2 measurements (thickness and EMG signal amplitude) for the TrA (R^2 = 0.87), Hodges et al[28] described a nonlinear relationship (the majority of thickness change occurring within the first 22% of EMG signal amplitude) for the external oblique (EO) (r = 0.23), IO (r = 0.93), and TrA (r = 0.90) muscles, and a more recent study by Brown and McGill[6] found no definitive relationship for the EO (r = 0.22) and IO (r = 0.14) during contraction. The **TABLE** highlights the differences in the methodologies employed in 4 of the lateral abdominal wall investigations that may provide a possible explanation for why these investigations differ in their findings. However, beyond these methodological differences, there is likely a more fundamental reason underlying the lack of a consistent relationship between a change in muscle thickness and muscle activity, which is that many factors, in addition to muscle activity, may influence changes in muscle thickness or size.[27] Specifically, such factors include the resting state (activity and length) of the muscle, the extensibility (compliance)[30] and structure (parallel versus pennate muscle fiber orientation)[6,18] of a

musculotendinous unit, the type of contraction taking place (isometric, concentric, eccentric), the presence of external forces that an expanding muscle must compete against (eg, increases in intra-abdominal pressure[10] or contraction of adjacent muscles[13]), out-of-plane changes,[4] and imaging technique.[38,74]

Consideration of each of the above-mentioned factors and their influence on changes in muscle size is critical when attempting to interpret the findings of a dynamic imaging study. For instance, when a hypothetically normal muscle undergoes a concentric contraction from a true resting state, an increase in thickness and a decrease in length are generally observed (**FIGURE 3A**). However, if the muscle is hypertonic (eg, hypertonic secondary to pain), a similar contraction will result in a smaller change in thickness and length (**FIGURE 3B**). If the starting condition is not taken into consideration, an erroneous conclusion (that a very small increase in thickness equals very little muscle activity) could be made. Similarly, if a musculotendinous unit is stretched out and has an altered length-tension curve (eg, postpartum abdominal wall), a concentric contraction may only result in a relatively small change in thickness and length (**FIGURE 3C**). If the altered compliance of the musculotendinous unit is not taken into consideration and it is assumed that the thickness change is a result of muscle activity alone, it could be incorrectly concluded that there was very little increase in muscle activity due to the very small increase in thickness. Further, it is extremely important to take into account the presence of any forces competing for space with an expanding or contracting muscle. If there is any increase in activity or resistance of an adjacent muscle or fascial/body compartment restraining the muscle from expanding, the same amount of thickness change will not be observed (**FIGURE 3D**). If the presence and influence of these competing forces on the change in thickness of a muscle are not taken into consideration, inaccurate conclusions regarding muscle activity will be made. A recent investigation by Delaney et al,[13] which monitored the change in size, surface EMG signal amplitude, and force generation of the quadriceps muscles during contraction, illustrates this influence of adjacent muscles. Specifically, a minimal (10%) increase in thickness and a moderate decrease in width (30%) of the rectus femoris muscle were observed with a contraction resulting in maximal force generation. The proposed explanation for the potentially unexpected decrease in width was that the 2 adjacent muscles (vastus lateralis and medialis) were competing for space during the contraction and constrained the expansion of the rectus femoris.In addition to factors associated with the myofascial unit, it is also important to consider those associated with interpreting 2-dimensional ultrasound images and the imaging technique itself, specifically, architectural changes occurring outside of the plane of motion being imaged. For example, when the lumbar multifidus contracts concentrically, there is an increase in CSA (**FIGURE 4A**). If this is imaged in a transverse plane, both an increase in thickness and width of this muscle may be observed (**FIGURE 4B**). If, however, the contraction is imaged in a sagittal plane (**FIGURE 4C**), only the increase in thickness is observed, as the width change is occurring outside of the plane being imaged (eg, into and out of the screen). In contrast, if, for some reason, the longissimus muscle, which sits adjacent to the multifidus, protrudes into the multifidus compartment, it may cause the multifidus to decrease in width (as in the example above of the rectus femoris[13]) and increase in depth, due to the anterior and medial bony confines of its compartment within the thoracolumbar fascia (**FIGURE 5A**). Both the increase in thickness and any decrease in width will be detected if this event is imaged in the transverse plane (**FIGURE 5B**). However, only the increase in thickness would be detected if it were being imaged in the sagittal plane (**FIGURE 5C**). Not considering what is happening in the transverse plane may lead to an erroneous conclusion that the increase in thickness seen in the sagittal plane was the result of a multifidus contraction, when, in fact, part of the increase in thickness of the multifidus may be due to the longissimus protruding into it. Finally, it is critical to realize that by simply changing the angle at which the ultrasound transducer is orientated to the skin by more than 10° or greater than 10 mm of inward or outward motion, the thickness of a muscle can be altered.[74]

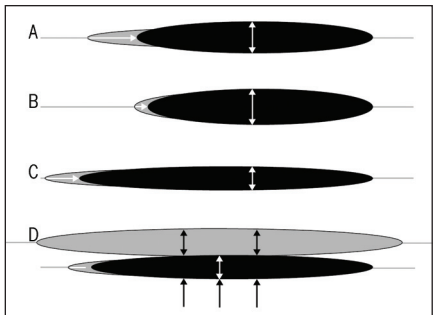

FIGURE 3. An illustration of factors that influence the change in thickness of a muscle. (A) An increase in thickness and decrease in length of a normal muscle (gray, at rest, precontraction; black, active, contracted) during a submaximal concentric contraction. (B) A relatively smaller increase in thickness and decrease in length then seen in a normal muscle, due to increased resting activity (eg, secondary to pain). (C) An increase in the extensibility of the myofascial unit (eg, postpartum). (D) Competing forces, specifically an increase in resistance from an adjacent muscle contracting (2-headed black arrows), and an increase in intra-abdominal pressure (black upward pointing arrows).

Ultimately, the ability to correctly interpret the reasons for, and the magnitude of, a change in muscle size during a dynamic USI study depends on a sound understanding of the technology, the factors that influence changes in muscle shape, as outlined above, and operator experience. In a theoretically ideal situation, in which all of the factors listed above are controlled for, it is likely that the relationship between muscle size and activity would be closely related. In situations where this is not the case, the relationship is not so clear. Therefore, although USI may be a valid and reliable measure of muscle size (in healthy populations),[40] it is not surprising that the literature regarding the relationship be-

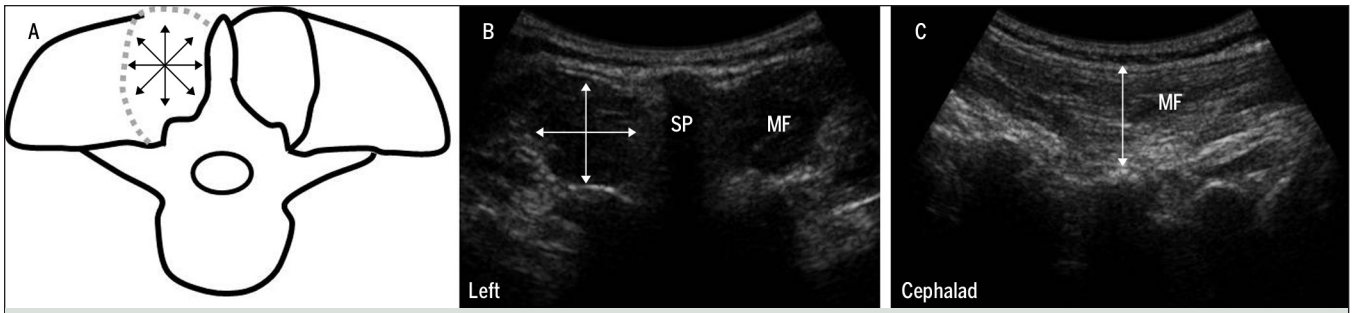

FIGURE 4. (A) An illustration of a multifidus contraction in the transverse plane, resulting in an increase in the cross-sectional area (CSA) of the muscle. (B) A transverse ultrasound image of a multifidus contraction, depicting both an increase in thickness and width associated with the overall increase in CSA. (C) A sagittal ultrasound image of a multifidus contraction, depicting only an increase in thickness of the multifidus, as the increase in width cannot be viewed from this imaging plane. Abbreviations: MF, multifidus; SP, spinous process.

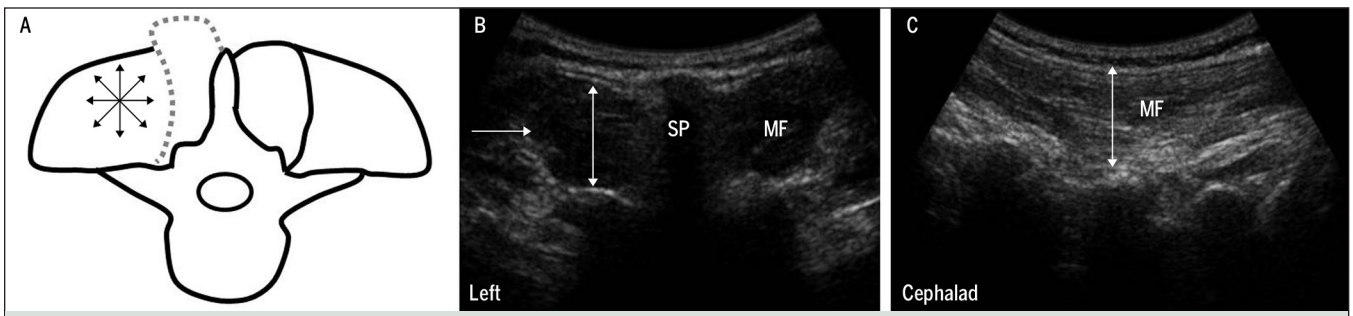

FIGURE 5. (A) An illustration of a longissimus contraction in a transverse plane, resulting in an increase in thickness and decrease in width of the multifidus compartment, due to its bony constraints anterior and medially. (B) A transverse ultrasound image of a longissimus contraction, depicting increase in thickness and a decrease in width of the multifidus. (C) A sagittal ultrasound image of a longissimus contraction, depicting an increase in thickness of the multifidus, as the decrease in width cannot be viewed from this imaging plane. Abbreviations: MF, multifidus; SP, spinous process.

tween increases in muscle activity (EMG) and thickness change (USI) is not conclusive, with changes in muscle size and muscle activity not always demonstrating a direct relationship. Further, it is important to consider that, in addition to not establishing a relationship between USI and EMG measures, these studies have been conducted on small numbers of young, healthy participants in nonclinical environments. Consequently, there is a lack of information regarding this relationship in other populations or during other dynamic maneuvers. Therefore, the validity or ability to use USI to quantify muscle activity is, at best, context dependent. Consequently, the logical conclusion is that USI cannot be used to indiscriminately assess muscle activity.

Distinguishing Between Patient and Healthy Populations With Ultrasound Imaging

A second aspect of muscle function that is increasingly investigated with USI is the comparison of the pattern of architectural change of a muscle, or group of muscles, during a specific task or posture, between control and case populations.[1,37,69,70,72] For example, Teyhen et al[70] monitored the thickness of the IO and TrA muscles in 15 participants with unilateral lumbopelvic pain and 15 age-matched and gender-matched controls, during the performance of an active straight leg raise test. They reported a 24% and 11% increase in TrA and IO thickness, respectively, in the control group, and significantly smaller (6% and 6%, respectively) increases in thickness in the lumbopelvic pain group. Although, for reasons explained above, it would be inappropriate to assume that the smaller change in thickness in the lumbopelvic pain cohort was due solely to a decreased amount of muscle activity, knowing that a 24% and an 11% change in thickness of the TrA and IO, respectively, is expected during an active straight leg raise test is potentially useful. In addition to this example and in keeping with the abdominal wall muscles as an example, investigators have measured thickness, length, and/or CSA in both resting[7,12,54,59,63] and dynamic conditions (eg, abdominal drawing-in maneuver,[11,69] respiration,[1,72] balance, upper limb tasks,[51] and walking tasks) within various (low back, lumbopelvic, and pelvic girdle pain,[67] amputees,[62] postpartum,[8] and healthy) cohorts. These studies provide normal resting values and/or describe patterns of architectural change. Further, similar investigations exist for various other muscles in the body, such as the lumbar and cervical multifidus.[26,37,45,46] Although investigations to identify normal and altered patterns of muscle architectural changes with clinical tests and movement are still in their infancy, the approach appears promising and clinically relevant. However, future research is re-

quired to determine the clinical utility of this approach.

CONCLUSION

Conventional grayscale B-mode USI provides information about the echogenicity or reflective properties of a tissue, as well as the architectural characteristics (eg, size and shape) of a structure. Alterations in muscle echogenicity can assist in the detection of muscle trigger points and fatty fibrous infiltration. Changes in muscle size, although influenced by muscle activity, are an amalgamation of many factors ranging from the resting state of the muscle, the extensibility (compliance) and structure of the musculotendinous unit, the type of contraction taking place, the presence of competing forces, factors associated with interpreting 2-dimensional ultrasound images, and factors associated with imaging technique. As such, thickness changes measured with USI cannot be used indiscriminately as a surrogate measure of muscle activity without uniformly controlling for these confounding factors. Furthermore, it is important that this understanding is reflected in contemporary physical therapy literature. It is, therefore, recommended that changes in muscle size during a dynamic event are reported as such and not as measures of muscle activity. It may be appropriate for future investigations aimed at using USI to provide information about alterations in muscle performance and to focus on identifying normal and altered patterns of architectural change of muscle in various clinical populations and during various tasks. ◉

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