University of Southampton

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS
SCHOOL OF ENGINEERING SCIENCES

Assessment of Short-term Knee Arthroplasty Function using Clinical Measures, Motion Analysis, and Musculoskeletal Modelling

By

Peter Richard Worsley

A thesis submitted in partial fulfilment of the requirement of the degree of:

Doctorate of Philosophy

April 2011

University of Southampton

ABSTRACT

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Life expectancy around the developed world has been consistently increasing over the last century. This has led to an increase in the prevalence of age related pathologies. Joint degeneration in the form of osteoarthritis is a common pathology, which can cause increased pain and loss of function. When necessary, joint surgery is used to replace degenerated articular surfaces, with knee arthroplasty (KA) being the most common. There is, however, a body of evidence to suggest a proportion of patients are not satisfied with their KA, and several physical functional limitations are retained post-operation. This PhD project was designed to quantify short-term KA function and find factors which contribute to post-operative changes in function compared to the healthy population.

In order to achieve functional assessment, measurement techniques were identified to assess different aspects of observed and perceived disability. Twenty healthy and 39 KA participants (31 patients completed pre- and six month post-KA assessments) were recruited for their function to be assessed using clinical measures, questionnaires, motion capture, and musculoskeletal modelling. In addition to these measures, information on the surgery and rehabilitation were also collated. The data collected were reduced by using statistical methods to identify the most discriminatory measures between the healthy and pre-operative patients. These variables provided the basis to classify function and subsequent post-operative changes in function (Dempster-Shafer Theory). Regression analysis determined the factors which affected these changes the most.

The results from this study show that subjective clinical measures of perceived pain and function using questionnaires were the most discriminatory variables. Objective measures of muscle size, range of movement, and joint kinetics/kinematics of activities of daily living also provided discrimination. These data were used to classified participants with an accuracy of between 90-94%. Post-KA patients improved in perceived pain and function. However, objectively there were limited functional gains. The factors that affect post-operative function were identified as pre-operative objective and subjective function (composite function from a body of evidence), and post-operative reported activity levels. Patient satisfaction was correlated with post-operative perceptions of pain and function.

This study has provided a holistic measure of function, building bodies of evidence to observe changes in function. Physical functional limitations remain in six months post-KA patients. This study has highlighted the need for future research to focus on pre-operative function and post-operative activity levels to maximise potential patient outcomes.

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DECLARATION OF AUTHORSHIP

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Acknowledgements

Over the last three years this PhD has provided both challenges and great rewards. Without the help and guidance of family, friends, peers, and supervisors I would not have been able to complete this thesis. I am, and always will be very grateful to be given the opportunity to undertake a PhD. I have gained great experience over the last three years and hopefully this will be the start of a long and happy career in health care research.

My first thanks must go to my family, my parents (Rose and Richard) have provided guidance, motivation, love, and support. My brothers (Adrian and Stephen) who seem perplexed that I am still a student have also contributed in their own way, often giving me a punch and telling me to hurry up. Over the last two years my partner Danielle has also provided a source of love, support, and motivation for me to complete my PhD. Coming home to her after a long day in the office makes all the hard work seem worthwhile. My friends have also always provided both support and welcome relief from the life of a PhD student. PhD life can be lonely, however all of the past and present students in the Bio and Materials office have always provided a warm and friendly environment to work in.

During the PhD I have had assistance from many colleagues and collaborators. First I would like to thank the patients and healthy participants who took part in the study. Collaboration with Southampton General Hospital has been a great experience, with special thanks to surgeons, Professor David Barrett, Mr Chapman-Sheath, and Mr Tice, and their receptionists. During the data collection I had help from Martin Warner and Dr Lucy Knight for which I am very grateful. When I came to analyse the data I had help from both Francis Galloway and Dr Presanth Nair. I also worked in collaboration with Cardiff University and I would like to offer my thanks to Dr Cathy Holt and Dr Gemma Whatling.

The reason why I got into research has to go down to Professor Maria Stokes. Maria will always be an inspiration for what can be achieved in research. When I was looking at PhD opportunities Maria introduced me to Professor Mark Taylor, and then I realised I was really in trouble. I feel very privileged to be co-supervised by Mark and Maria. Mark has expertly nudged me in the right direction to complete this work. Thank you both for your past, present, and hopefully future guidance in research.

Funding support received from the Engineering & Physical Sciences Research Council (EPSRC) and Depuy, a Johnson & Johnson Company was greatly appreciated.

Abbreviations

ACL	-	Anterior Cruciate Ligament
ADL	-	Activities of Daily Living
A-P	-	Anterior-Posterior (translational direction)
BW	-	Body Weight; normalising factor for joint forces
CSA	-	Cross Sectional Area
CT	-	Computed Tomography
DM	-	Direct Method (Optimisation)
DoF	-	Degree of Freedom
D-P	-	Distal-Proximal
(M/L)CL	-	(Medial/Lateral) Collateral Ligament
(A/P)CL	-	(Anterior/Posterior) Cruciate Ligament
FFC	-	Flexion Facet Centres
GOM	-	Global Optimisation Method
I-E	-	Internal-External (rotational axis)
In-vitro -	-	(lit. 'in glass', test tube/Petri dish)
In-vivo	-	(lit. 'in body')
LFDA	-	Linear Fisher Discriminant Analysis
MIS	-	Minimally Invasive Surgery
M-L	-	Medial-Lateral (translational direction)
MRI	-	Magnetic Resonance Imaging
MS	-	Musculoskeletal
NHS	-	National Health Service
OA	-	Osteoarthritis; synonyms: Osteoarthrosis, Arthrosis
PCA	-	Principle Component Analysis
PCL	-	Posterior Crutiate Ligament
RF	-	Rectus Femoris
RoM	-	Range of Motion
SOM	-	Segmental Optimisation Method
T(J/K)A	-	Total (Joint/Knee) Arthroplasty
T(J/K)R	-	Total (Joint/Knee) Arthroplasty
V-V	-	Varus-Valgus (rotational axis)
UKR	-	Unicompartmental Knee Arthroplasty

Chapter 1

Introduction and Motivation

1.1 Motivation

The World Health Organisation (WHO) have published the International Classification of Functioning, Disability, and Health (ICF) [1]. Here the ICF is broken down into subsections including body functions, body structures, activities and participation, and environmental factors. The ICF acknowledges that every human being can experience decrement in health and thereby experience some degree of disability. Within the ICF, function is related to all of the subsections, and any limitation within these sub classifications could be interpreted as reduced function for an individual. For the purposed of this project function will be termed in respect to the ICF recommendations, and measures of function will attempt to incorporate the multi-factorial classification.

Definition of Function: 'Function is a combination of body function, joint function, activity, and quality of life'.

Over the last century the average life expectancy across the developed world has increased [2], leading to further demands on the health care system. As well as an increase in life expectancy there is a trend towards an increase in obesity levels, with over 1 billion individuals currently over weight and 300 million clinically obese [3]. This increase in life expectancy and increase in body weight has resulted in the prevalence of joint degeneration pathologies rising significantly [4]. A common form of this joint degeneration is osteoarthritis (OA) and it is estimated that general OA causes joint pain in 8.5 million people in the UK, and approximately 20% of adults aged 45–64 years have experienced OA pain in their knee. In 1999–2000, 36 million working days were lost because of OA, costing the UK economy nearly £3.2 billion in lost production [5]. Osteoarthritis of the knee is an active disease process involving cartilage destruction, subchondral bone thickening, and new bone formation [6]. Clinical features of OA include considerable pain, frequent instability, and, consequently, often results in physical disability [7, 8]. Treatment for this loss of function normally starts with pain relief and referral to physiotherapy. However if the symptoms persist and get worse, surgery is commonly performed.

Knee arthroplasty (KA) is a procedure of orthopaedic surgery, in which the arthritic or dysfunctional joint surface is replaced with an orthopaedic prosthesis. During KA the artificial surfaces of the joint replacement are shaped in such a way as to allow joint movement similar to that of a healthy natural knee. Although OA is the predominant pathology that results in KA, other indications for surgery include rheumatoid arthritis (RA), avascular necrosis (interruption of the blood supply), infection, and trauma [1]. Advances in the last 25 years have improved the design and surgical approach of KA, resulting in improved short and long term outcomes [2]. There are many different types of surgical approaches and prosthetic designs available to those who are considering a KA and depending on the severity of the changes in the joint and surrounding tissues there are differing levels of surgery. Two of the most common KA procedures are the total (TKA) and unicondylar (UKA). In 2009, over 70,000 knee arthroplasty were conducted in England and Wales [1]. Prevalence in KA within the UK has risen from 20,854 in 2003 [3], to 77,545 in 2009 [1], although this rise in reported prevalence is partly due to the increased reporting rates.

This increase in prevalence has caused a considerable strain on health care systems around the world, and the increase in numbers looks to continue in the coming years. Over recent years there has been a change to the patient demographic undergoing KA, with increasing numbers of younger more active people electing for to receive a KA. This has led to increased patient expectations post-operation [4], and an increase in pressure for the patient to return to normal function in order to contribute to the economy and society. On initial inspection of the data available for TKA and UKA the procedure appears to be successful, with most national registries reporting over 90% survivorship of the prosthesis at 10 years [5], however revision rates after five years in England and Wales have shown a steady increase from 2007-2009 (4.3% to 5.9% of all procedures). Evidence has shown that KA procedure improves health related quality of life (HRQoL), although this assessment has relied on questionnaires measures with limited validity [6].

Currently there is a large investment in research and development of new prosthesis and technologies to enhance post-operative outcomes for patients undergoing KA. Despite this investment there is still an evident gap in function between KA patients and the healthy age matched population [12]. In 2007 Baker et al collated data from 10,000 questionnaires sent to KA patient one year post-operation, from the patients eligible for analysis (8,231) only 8.6% of patients had 'no' or 'hardly any' problems with their KA [7]. Previous reports have described levels of satisfaction after primary TKA ranging between 67% and 89% [7, 8]. Evidence suggests that KA patients experience more difficulty performing numerous daily tasks than the healthy age matched population [9].

Reduced function in KA patients has been assessed using objective clinical measures, which have identified deficits of muscle force [10], proprioception [11], range of motion [12], and compensatory mechanisms during activities of daily living (ADL) [13]. It is clear from the evidence base that function is a multi-factor entity in KA patients with numerous physical and psychological components contributing to an individual's function

figure 1.1). There are also many factors which could affect functional changes from pre- to post-KA including; pre-operative function, operative factors, and rehabilitation input. Current evidence investigating factors which could affect function have been limited by small sample sizes, limited functional assessment methods, and in most cases result in no statistical differences between intervention techniques [14, 15]. In order to direct future practice in KA and to highlight key areas of interest for research a comprehensive evaluation of pre- and post-operative function is needed. Analysis of factors which affect changes in both perceived and measured function could help focus future research and clinical practice.

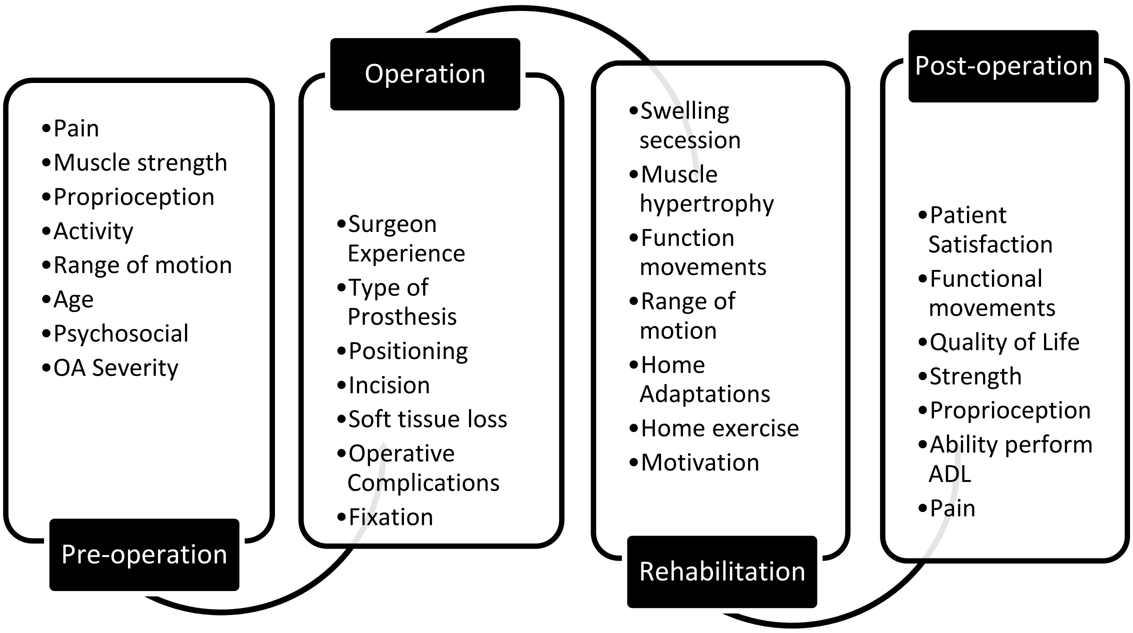


Figure 1.1: Factors which could affect KA function

1.2 Objectives

This thesis will use a standardised non-invasive functional assessment of KA patients both pre- and post-operation. This data will then be compared to that of a age and sex matched cohort of healthy participants. Evidence suggests functional status of KA is a multi-factorial problem, with any number of factors being prominent in an individual's functional gains/losses post KA. The aims of the project were therefore focused on a comprehensive functional assessment method looking at multiple patient perceived and observed outcomes after KA. Data collected will include questionnaire based measures, clinical measures, and analysis of ADL. The data collected will be collated in a multivariate statistical analysis in order to build a comprehensive evaluation of the participants holistic function. The changes in function from pre- to post-operation will then be assessed, and factors which affect the change in function will be analysed. Finally a hierarchy of factors which affect function will be built. By making the assessment a holistic process taking into account many factors which could affect function, the final hierarchy should represent the weighted relationship between one factor and another.

1.3 Aims

1. Identify in the literature factors which affect knee arthroplasty function.
2. Identify a standardized method to assess patient function non-invasively.
3. Compare healthy with pre-operative, and post-operative knee arthroplasty function.
4. Measure functional changes from pre- to post-KA
5. Create a hierarchy of factors which could affect post-operative knee arthroplasty function.
6. Make recommendations for future practice and research.

Chapter 2

Literature Review

2.1 Anatomy and Physiology of the Natural Knee Joint

When describing the human body it can be divided up into orthogonal planes which create the basis for describing movement patterns. These anatomical planes are described in Appendix B, along with common terminology for movement patterns which will be described throughout this thesis.

The knee joint is a condylar joint which satisfies its weight bearing and body propulsion purposes with some of the largest bones and muscles in the human body. It is the largest synovial articulation in the body, with complex movement capabilities. The knee joint is an articulation between the distal end of the femur, the meniscus-bearing proximal surface of the tibia, and the posterior surface of the patella (Figure 2.1). The joint achieves its stability during strenuous activities, mainly through soft tissue structures, e.g. ligaments and tendons. The knee comprises of three separate joints which are located in a single synovial cavity; (1) a condylar joint between the medial condyles of the femur and tibia, (2) a condylar joint between the lateral condyles of the femur and tibia. Combined to create the tibio-femoral joint (TFJ). (3) a sellar joint between the patella and femur, termed the patellofemoral Joint (PFJ) [16].

2.1.1 Bones of the knee joint

The knee joint has three bones; the ***femur***, ***tibia***, and ***patella***. The distal femur flairs into medial and lateral epicondyles, these serve as muscle and ligament attachment sites. Distal to these are two smooth round surfaces, the medial and lateral condyles, separated by a groove called the intercondylar fossa. On the anterior side of the femur, a smooth medial depression called the patellar surface articulates with the patella. The patella, or knee cap, is a roughly triangular shaped sesamoid bone that forms within the tendon of quadriceps femoris (Figure 2.1). The tibia has a broad superior head with two fairly flat articular surfaces, the medial and lateral condyles, separated by a ridge called the intercondylar eminence [16].

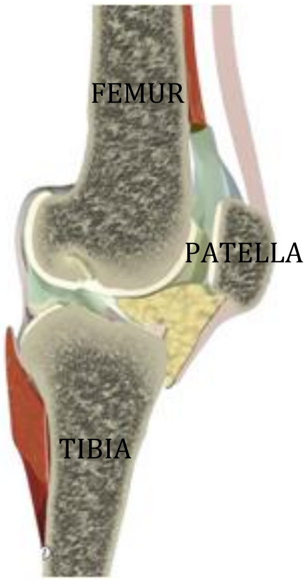


Figure 2.1: Bones of the knee joint. Reproduced from anatomy.tv. Courtesy and copyright Primal Pictures Ltd

2.1.2 The TFJ menisci

The menisci are so called because of their 'half-moon' or miniscal configuration (Figure 2.2), which act as intra-articular discs on the tibial plateau. The function of the menisci at the knee is to increase the congruence between the articular surface of the femur and tibia, participate in weight bearing, aid lubrication, and participate in the locking mechanism of the knee.

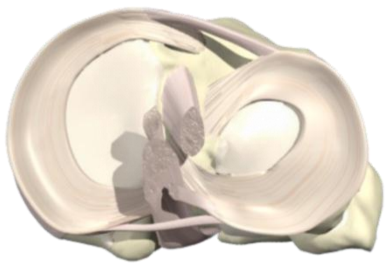
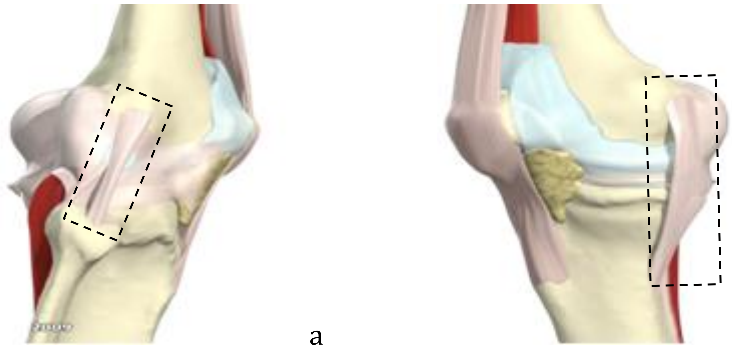


Figure 2.2: Superior view of the menisci on the tibial plateau. Reproduced from anatomy.tv, courtesy and copyright Primal Pictures Ltd

2.1.3 Ligaments and Tendons

The ligaments and tendons within and surrounding the knee joint play a vital role in joint stability in all six degrees of freedom. The two cruciate ligaments provide anterior-posterior (A-P) stability at the TFJ, aided by both quadriceps and hamstring muscles. The anterior cruciate ligament (ACL) provides constraint for the anterior translation of the tibia with respect to the femur. The posterior cruciate ligament (PCL) performs the opposite task (posterior constraint). The two collateral (tibial and fibular collateral ligaments) ligaments provide constraint for medial-lateral (M-L) translation and valgus-varus (V-V) rotation at the TFJ (Figure 2.3).



a b

Figure 2.3 (a). Lateral collateral ligament (LCL) of the knee joint. (b). Medial collateral ligament (MCL) of the knee joint Reproduced from anatomy.tv. Courtesy and copyright Primal Pictures Ltd

The ligamentum patella is the continuation of the tendon of quadriceps femoris. It is a strong, flat band attaching around the apex of the patella, being continuous over the front of the patella with the fibres of quadriceps tendon [16]. This structure provides a strong link for which the quadriceps can use the PFJ as a axis to exert a extension moment about the TFJ.

2.1.4 The Muscles

The muscles surrounding the knee drive movement and stabilise the joint under loading conditions. Muscles work in conjunction with one another as agonists and antagonists, providing an efficient mechanism for driving movement (Table 2.1). Agonist muscles provide a contractile force to drive movement working concentrically (shortening), whilst the antagonist works eccentrically (lengthening) to control movement. For example, quadriceps femoris will drive knee extension whilst hamstrings work eccentrically.

Table 2.1: Muscles surrounding the knee joint

	Muscle	**Description**
Quadriceps	Vastus Lateralis	part of the quadriceps femoris; extends the shank at the knee joint
Quadriceps	Vastus Medialis	part of the quadriceps femoris; extends the shank at the knee joint
Quadriceps	Vastus Intermedialis	part of the quadriceps femoris; extends the shank at the knee joint
Quadriceps	Rectus Femoris	part of the quadriceps femoris; extends the shank at the knee joint; assists hip flexion
	Tensor Fasciae Latea	flexes and abducts and possibly rotates the thigh; supports the femur on the tibia during erect posture
	Sartorious	laterally rotates and abducts the thigh; flexes the shank and rotates medially when the knee is flexed
	Gracilis	adducts the thigh, flexes leg at the knee and rotates it medially
Hamstrings	Biceps Femoris Caput Longum (long head)	flexes the leg at the knee joint and once flexed, rotates the tibia laterally on the femur; extends the thigh at the hip joint and rotates it laterally
Hamstrings	Biceps Femoris Caput Breve (short head)	flexes the leg at the knee joint and once flexed, rotates the tibia laterally on the femur
Hamstrings	Semitendinosus	flexes the leg at the knee joint and once flexed, rotates the tibia medially on the femur: extends the femur at the hip joint
Hamstrings	Semimembranosus	flexes the leg at the knee joint and once flexed, rotates the tibia medially on the femur: extends the femur at the hip joint
	Popliteus	Rotates leg medially, and flexes knee.
	Gastrocnemius	Plantar flexion and supination at the ankle joint, flexion of the knee;

2.1.5 Movements

Concerning movements of the knee, two separate articulations have to be considered: that between the femur and the tibia (TFJ) and that between the patella and the femur (PFJ). TFJ movement mainly consists of primary flexion and extension, along with a smaller degree of anterior-posterior (A-P) translation, and internal-external (I-E) rotation. Secondary knee motions consist of medial-lateral (M-L) translation and valgus-varus (V-V) rotation, although these secondary movements are considered to be minor in a healthy knee joint (Figure 2.4). It is important to remember for both TFJ and PFJ joint articulations there will be considerable inter person variability. There are also large differences between active and passive range of motion (A/PRoM). A higher degree of motion can be accessed through passive manipulation (PRoM), for all of the 6 degrees of freedom. Therefore a more functional assessment of knee RoM is an active test.

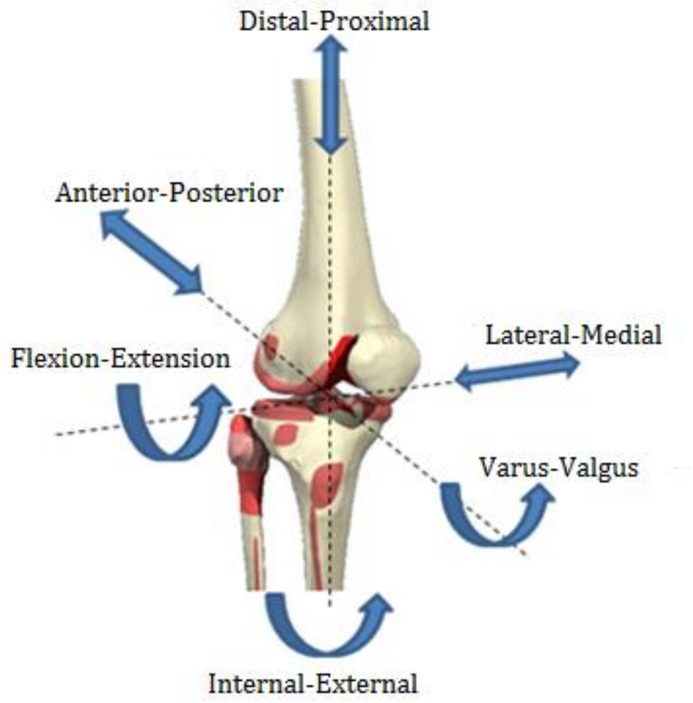


Figure 2.4: Movements of the knee [16] Reproduced from anatomy.tv. Courtesy and copyright Primal Pictures Ltd

In 2005 Freeman and Pinskerova conducted a review of normal TFJ movement. They reviewed data collected from cine-Computed Tomography (CT), fluoroscopy, x-ray, radiographs (RSA), and Magnetic Resonance Imaging (MRI) studies. The review stated that, 'anatomically the point of importance for tibio-femoral movement was the posterior articular surfaces of both the femoral condyles (called the flexion facet centres or FFCs). These can be found from sagittal images and used as femoral landmarks. Using these anatomical landmarks the arc of knee flexion can be subdivided into 3 envelopes' [17];

1. full extension to 10°, perhaps 30°, for 'screw home' or terminal extension.
2. an arc from 10°, perhaps 30°, to approximately 120°, the active flexion arc.
3. 110-120°, full passive flexion

Studies have shown the medial femoral condyle to translate no more than ±1.5mm in the A-P direction whilst weight bearing and non-weight bearing [18]. On the other hand the lateral condyle rolls but also translates in the A-P direction. The lateral femoral condyle has been shown to translate ~15mm posteriorly by a mixture of rolling and sliding, which creates external rotation in the TFJ [19]. At 90° flexion the tibia is free to rotate 20-30° longitudinally without further flexion movement [17].

The surface motion of the PFJ in the frontal plane shows a gliding motion. From full extension to full flexion of the knee, the patella glides caudally approximately 7cm on the femoral condyles. Both the medial and lateral facets of the femur articulate with the patella from full extension to 140° of flexion [20]. Beyond 90° of flexion, the patella rotates externally, and only the medial femoral facet articulates with the patella. At full flexion, the patella sinks into the intercondylar groove. Contact areas increase with an increased amount of knee flexion, and increase pulling force of the quadriceps [20].

2.2 Knee Kinematics and Kinetics during Activities of Daily Living

2.2.1 Introduction

The knee joint withstands various movements (kinematics) and loads (kinetics) during activities of daily living (ADL). Studies have shown the most frequent ADL's are walking (gait), stairs, and sit-stand activities [21]. Other activities which could be more stressful at the knee are also performed during every day living, but are less frequent. Analysis of human movement is key to expand the current knowledge of joint loading and mechanisms of injury and pathology. Many different methods have been used to assess movement during ADL, giving insight into joint kinematics and kinetics. Data published to date can be roughly split into two groups; Predictive models using either inverse or forward dynamic techniques or *in-vivo* telemetrised joint arthroplasty data.

2.2.2 Predictive Modelling

Musculoskeletal (MS) modelling is a major application across the field of biomechanics, which has been used for the assessment of joint replacements and understanding the functional adaptations specific to a design [22]. Inverse MS modelling is a method for computing forces and moments of force (torques) based on the kinematics of a body and the body's inertial properties (mass and moment of inertia) [23]. Typically it uses link-segment models to represent the mechanical behaviour of human limbs. Where given the kinematics of the various parts, inverse dynamics derives the net joint moments, net joint powers, and net joint inter-segmental forces [24]. Muscles can be attached to the segments of the MS model and optimisation methods can be used to derive individual muscle contributions to solve the moments at each joint. Several authors have used inverse dynamics to predict knee joint kinematics and kinetics during gait [25, 26], sit-stand [27], and stairs ascent [25, 28]. Forward dynamic modelling uses muscle and other external forces to derive kinematics, this method offers the user the ability to use deformable structures and model contact stresses in multiple sections of a joint [29]. MS modelling techniques are an attractive option for predicting joint kinematics and kinetics. However, several limitations with the technique remain [30]. A review of MS modelling can be found in Chapter 4.

2.2.3 In-vivo Measurement

D'Lima et al reported the first *in-vivo* measurement of knee forces [31]. Initially the group used the tibial component of a TKA prosthesis with four load cells to measure loading at the TFJ [31]. However, in the most recent papers the force sensing device was modified to measure all components of tibial force (shear and moment) using a posterior cruciate-retaining TKA (Figure 2.5, Zimmer GmbH, Winterthur, Switzerland) [32]. Participants in the studies have been assessed during many different ADL, and at differing stages post TKA.

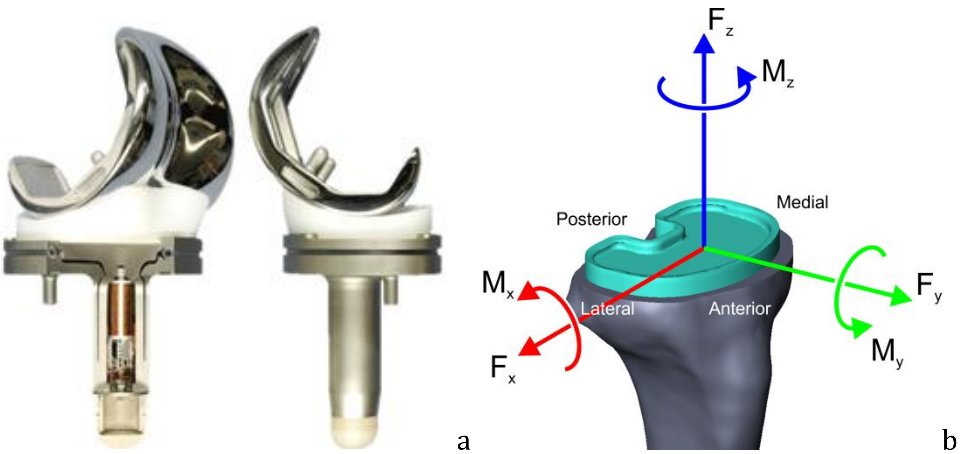


Figure 2.5: (a) Section through the instrumented tibial tray. When the proximal plate is loaded it deforms reversibly. This is measured by six semi-conducting strain gages, data is transferred wirelessly to an external receiver. (b) coordinate system of instrumented tibial component. With permission from www.OrthoLoad.com [33].

D'Lima et al also used the technology on a different implant in 2006 [34], this time is was a cruciate-retaining cemented Sigma PFC implant. Subsequently Heinlein et al and Kutzner et al have increased patient numbers that have been assessed [35, 36]. The TKA used was an INNEX FIXUC (Zimmer GmbH, Winterthur, Switzerland) crutiate sacrificing system with a congruent tibial insert (Figure 2.5). Data from the telemetrised total KA has adopted a 'open source' approach to presenting the data with a website specifically designed to share their findings [33]. This approach to sharing the data now gives the viewer a unique insight into all loading and moments at several joints.

2.2.4 Gait

Gait has been defined as the most frequent ADL [37], this is reflected in the literature, with the majority of studies looking at joint kinematics and kinetics of gait [13]. During gait each lower limb performs a cycle of events which is similar, but performed a half cycle out of phase with the other. When considering gait, it is often easier to break up the pattern observed in different phases. For example, stance phase (foot on floor) and swing phase (foot off floor). Gross knee flexion measured during gait has long been established, with a peak in flexion during early stance phase and a second peak in swing phase (Figure 2.6). During stance phase of gait knee flexion angles range between 0-20°, and during swing phase flexion peaks at approximately 58°. There is evidence to suggest that there is considerable variance in knee flexion angle in the healthy population throughout the gait cycle [38].

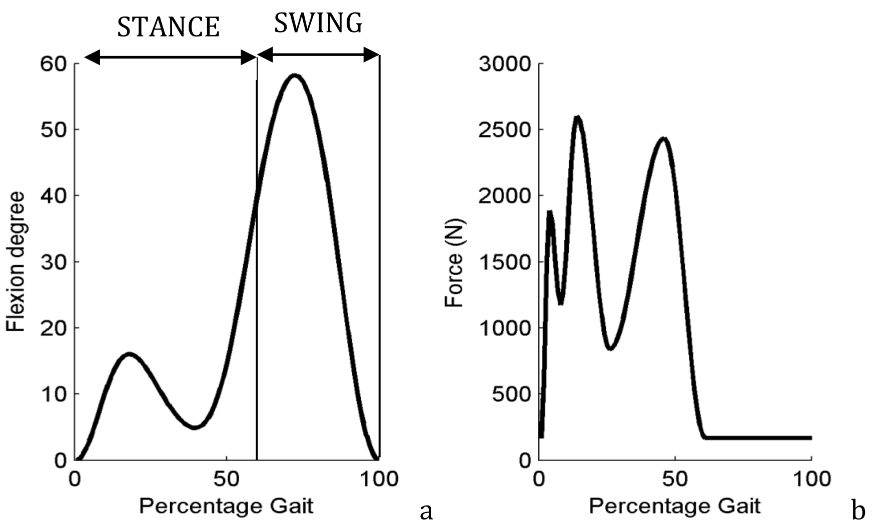


Figure 2.6: ISO Standard 14243-1. (a) Flexion angle, (b) distal-proximal (D-P) reaction force [39]. Reproduced from ISO 14243-1:2002

When considering knee joint forces during gait, methodology and participant population must be carefully considered when interpreting results. Recommended loading patterns can be found in the proposed implant wear test methods by the American Standards for Testing and Materials (ASTM) and International Organisation for Standardization (ISO). The ISO Standard has been used in pre-clinical testing of KA prosthesis. The latest ISO standard for knee simulation (Figure 2.6) has been taken from multiple sources, for which some can be dated back to the early inverse musculoskeletal (MS) modelling work of Morrison [40].

The TFJ forces during gait have been shown to have a double peak during stance phase of gait, and small load during swing phase (Figure 2.6b). Moments about the knee also have been described, with the latest telemetrised data revealing significant variance in magnitude and patterns of moments between TKA patients (Figure 2.7). Although there is significant variance in the force and moments measured using the telemetrised prosthesis it is apparent that the higher magnitudes of knee moments are also seen in the stance phase of gait.

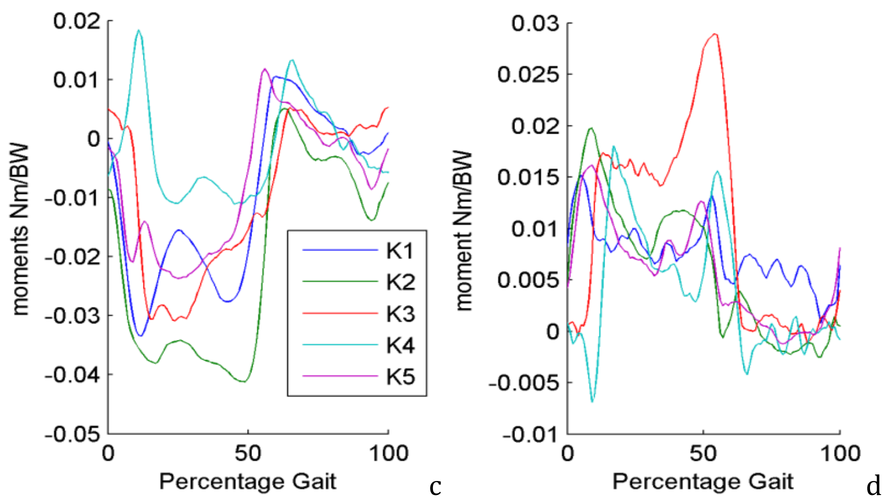


Figure 2.7: (a) varus-valgus (V-V) moment reaction from five TKA patients (k1-5) during gait. (b) flexion-extension moment from five TKA patients during gait with permission from www.OrthoLoad.com [33].

Moments about the knee have been presented in studies using rigid body mechanics [41]. However these models do not include muscles to predict forces and they simply use the force plate and segment inertia properties to predict external moments about the TFJ [42]. Comparison between these predicted external moments and measured internal moments are therefore difficult to make.

The telemetrised data reveals V-V moments from five TKA patients ranged from 0.041Nm/BW valgus to 0.018Nm/BW varus with most of the variance occurring in stance phase of gait. The pattern is similar for all of the patients bar one (K4), which has a reversed moment during early stance (Figure 2.7a). Peak average flexion moment (Figure 2.7b) for the five patients was 0.02Nm/BW (range 0.016-0.029). Finally I-E moment shows the smallest magnitude during the gait cycle, I-E moment ranges from 0.015Nm/BW internal to 0.01Nm/BW external moment [33, 36]. Summarised below are figures from the literature for TFJ forces during the gait cycle, the table highlights the difference in magnitudes of loading when different assessment methods are applied (Table 2.2). The data presented clearly shows that there is a much more open presentation of forces in the telemetrised studies, with few predictive MS modelling studies offering a full breakdown of the forces within the knee. The table also shows clear differences in the magnitudes of predicted and telemetrised measured knee forces, with the predictive MS models showing higher forces at the knee during gait.

Table 2.2: Range of peak knee loading during the gait cycle taken from the literature. [25, 26, 28, 32, 34-36, 39, 43, 44]. One times standard deviation are followed by ± symbol where appropriate. n=number of subjects. NA = data not available

Author	n	Pathology	D-P N/BW	P-A N/BW	L-M N/BW
Telemetrised					
D'Lima et al (2006)	1	TKA	2.17	NA	NA
D'Lima et al (2007)	1	TKA	2.3	0.3	0.3
Heinlien et al (2009)	2	TKA	2.08 - 2.76	-0.29 - 0.28	-0.2-0.21
Kutzner et al (2010)	5	TKA	2.15 - 3.03	-0. 5 - 0.22	-0.32 - 0.25
Predicted					
Morrison (1969)	NA	Healthy	3.0	NA	NA
ISO standard (2002)	1	Healthy	3.3	0.33	NA
Schipplein et al (1991)	15	Healthy	3.16 ± 0.63	NA	NA
Kuster et al (1997)	12	Healthy	3.4 - 3.9	NA	NA
Costigan et al (2002)	35	Healthy	3.7 ± 1.07	0.51 ± 0.16	0.15 ± 0.05
Taylor et al (2004)	4	THA	2.9 - 3.2	0.4 - 0.6	NA
Winby et al (2009)	11	Healthy	3.2-4.9	NA	NA
Shelburne (2006)	1	Healthy	2.7	NA	NA

D-P = distal-proximal. P-A = posterior-anterior. L-M = lateral-medial.

2.2.5 Sit to Stand to Sit

Sit to stand is a commonly performed activity in daily living. It involves a complex sequence of coordinated postural movements utilising centre of gravity to achieve efficiency of movement. Sit to stand has received much less attention than gait in the literature base, with only a few papers publishing knee kinematics and kinetics for this activity [12]. This is despite the fact that the sit to stand activity has been shown to be performed on average sixty times per day (±22) in 140 healthy free-living adults [45]. Knee kinematics during sit to stand generally follow a pattern of going from ~90° flexion to full extension **[46]** and the reverse for stand to sit. Magnitudes in knee flexion will depend on the height of the seat and the position of the pelvis relative to the knees.

The current literature base for the analysis of knee kinetics during the sit to stand task is very limited. There have been very few predictive MS modelling studies of this activity [27], however the most recent data comes from studies of the telemetrised knee prosthesis. Force profiles from the telemetrised data show that there are similar forces during stand to sit and sit to stand activities with average peaks in TFJ force of 2.2N/BW [33]. As with gait, sit to stand predictive MS modelling appears to over predict the total joint loading. Ellis et al predicted peak mean TFJ loading of 4.43N/BW compared to an average of 2.2N/BW measured in the telemetrised data [27, 36]. These findings are summarise in Table 2.3.

Table 2.3 Peak knee loading during sit-stand taken from *in-vivo* literature. [27, 32, 36]. One times standard deviation are followed by ± symbol where appropriate. n=number of subjects.

Author	n	Pathology	D-P N/BW	P-A N/BW	L-M N/BW
In-vivo					
D'Lima et al (2007	1	TKA	2	0.17	~0.2
Kutzner et al (2010)	5	TKA	1.7 - 2.4	-0.52 - 0.22	-0.2 - 0.12
Predicted					
Ellis et al 1984	18	Healthy	4.15-4.85		

Ellis et al also found that there were significant difference in TFJ loading when the arms of the chair were used (reduced) and when the height of the chair was varied (the higher the chair, the lower the forces). The findings of Ellis et al have to be put into the context of the time when they were reported (1984). Data collected using the technology available in the 1980's would result in more noise and potential error, and the MS modelling procedure was more simplistic than that seen in the more recent literature [27].

Between subject variance in telemetrised force and moment measures during sit-stand are higher than that of gait. This highlights that, although sit to stand is a closed chain activity (feet are fixed to the floor) with limited scope for kinematic variance, significant variance can still be seen in kinetics (Figure 2.8).

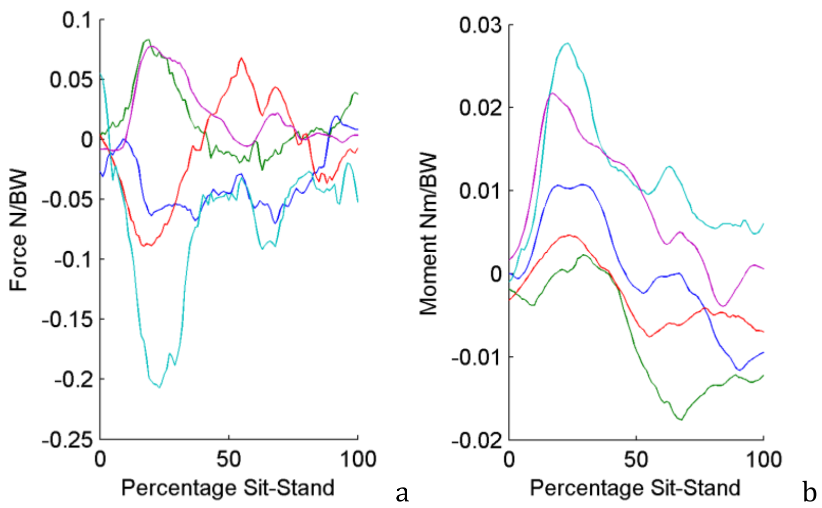


Figure 2.8: (a) M-L from five TKA patients during sit-stand. 2.7.3 (b) V-V moment from five TKA patients during sit-stand with permission from www.OrthoLoad.com [33].

This variance in TFJ loading could have been achieved by differences in posture during the activity, with the centre of mass (COM) of the person performing the activity being a key factor for weight distribution [47]. This change in posture has been shown to be prevalent in TKA patients with shifts in posture to reduce weight bearing (WB) through the operated knee during sit-stand [48]. It has also been found that age had an effect on the postural changes during sit to stand to sit, with decreased anterior translation of the COM in the older population [49].

2.2.6 Stairs

There are many variations of the stair descent/ascent cycle making its description difficult. There are also many combinations to stair configurations (height of step etc) which could modify the pattern of movement. As with the gait cycle the movement pattern during stair activity can be divided into rough phases for the stairs cycle. Stair kinematics have been reported in the literature taken from external marker motion analysis [28].

Higher peak knee flexion angles have been observed in both ascent and descent when compared to gait (~100°), with large deviations in knee flexion across the healthy population **[50]**.

Stair ascent data sets have come from both instrumented prosthesis [32] and inverse dynamic modelling [25, 28]. As with the gait data, predicted forces in the knee joint are considerably higher than that of *in-vivo* literature. This is especially evident in the P-A reaction, with predicted forces being approximately four times greater in the inverse dynamic literature as compared to *in-vivo* measurements, as apparent in Table 2.4.

Table 2.4: Peak knee loading during stairs ascent taken from literature. [25, 28, 32, 35, 36]. One times standard deviation are followed by ± symbol where appropriate.

Author	**n**	**Pathology**	**D-P N/BW**	**P-A N/BW**	**L-M N/BW**
In-vivo					
D'Lima et al (2007)	1	TKA	3	0.26	~0.2
Heinlein et al (2009)	2	TKA	2.92 - 3.06	-0.32 - 0.3	-0.14 - 0.26
Kutzner et al (2010)	5	TKA	2.65 - 3.15	-0.45 - 0.33	-0.26 - 0.26
Predicted					
Taylor et al (2004)	4	THA	4.7 - 5.6	1.1 - 1.5	
Costigan et al (2002)	35	Healthy	3.45 ± 1.12	1.19 ± 0.42	0.13 ± 0.05

2.2.7 Overview of ALD Knee Kinematics and Kinetics

These data sets are difficult to compare for many reasons. Some of the data sets have come from patients who have undergone joint replacement, whether it be a knee [32] or hip [25]. There is evidence to suggest persons who have undergone lower limb arthroplasty have altered ADL kinematics and kinetics [13]. Most studies included in this review have had small sample sizes <10, making it impossible to generalise these findings across the population. Evidence clearly shows the difference between measured *in-vivo* data and predictive simulations, with all of the *in-vivo* tests showing lower forces and moments through the knee joint during gait, sit-stand, and stair activities. However, a comparison between the data sets may not be valid due to the differing population being studied, and the very different techniques employed to assess knee kinetics. When inverse derived knee forces have been directly compared to telemetrised loading data using combined motion capture, force plate, and EMG analysis, an over-prediction of approximately 17% and 52% on the medial and lateral compartment of the TFJ were found [51].

For many years it was assumed that D-P loading in the knee during gait was around 3N/BW, after works from Morrison [40]. However, now that the telemetrised data have been released, loading appears to have been over-estimated in inverse models [32, 35]. Although the telemetrised data is small in sample size, and is only made up of TKA patients it does offer the most thorough source of TFJ kinetic data. From this data it is clear to see that there are changes in the magnitude of forces both between subjects and activities (Figure 2.9).

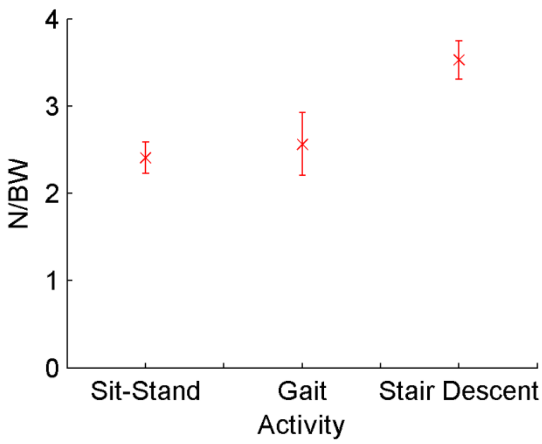


Figure 2.9: Mean peak forces acting about the TFJ during several activities capture with the telemetrised prosthesis with five TKA patients (k1-5) with permission from www.OrthoLoad.com [33]. ±1*standard deviation in error bars.

Resultant forces range from 1-3.5N/BW during the activities assessed showing the knee has to withstand significant forces during ADL [21]. It is of particular note that there was both within and between person variance for all of the activities. The OrthoLoad data showed that the higher the resultant loading during the activity the higher the potential for between participant variance for both force and moment measures [21]. This variance shown in the TKA population could be from a number of factors including adaptation to ADL movement patterns [52] and knee alignment [53]. The variance in knee kinetics presented has to be put into the context of the small sample size (n=5). Loading variance in the general population might be much greater if more subjects were assessed. There is currently a very limited evidence base of healthy TFJ kinetics during ADL making comparison difficult. One of the goals of this thesis will be to provide a set of TFJ kinematics and kinetics of ADL for the healthy older population.*

**Worsley, P, Stokes, M, Taylor, M. Predicted knee kinematics and kinetics during functional activities using motion capture and musculoskeletal modelling in healthy older people. Gait & Posture 2011; 33(2): 268-273.*

2.3 Knee Arthroplasty (KA)

2.3.1 Introduction

Chapter One briefly eluded to the growing incidence and prevalence of KA in the UK and throughout the world. The primary reason for KA is OA (97% of patients in England and Wales in 2009), where cartilage destruction, subchondral bone thickening, and new bone formation [54] causes pain and loss of function [55]. When the damage to the joint and subsequent loss of function is severe surgery can be performed. Depending on the damage to the articular surfaces of the knee and the soft-tissues surround the joint there are varying levels of surgery. Whilst retention of soft and hard tissues would be ideal during the KA surgery, the more conservative options may be less robust and have a higher chance of needing revision. A list of the common KA procedures can be described:

- **Hemiarthroplasty**: replacing the articular surface of one bone (i.e. tibia, femur, or patella).
- **Unicompartmental KA (UKA):** when the damage to the TFJ is confined to one of the knee compartments a unicompartmental KA (UKA) can be used. By replacing one compartment it leaves the bone and ligaments of the rest of the knee intact. This makes UKA an attractive option to take, however results from the joint registers show that revision rates after ten years are relatively high at 10% [5].
- **Total KA (TKA):** when damage to the TFJ and/or PFJ is seen throughout all compartments a TKA procedure it commonly used. This involves bone resection on the tibia, femur, and in some cases the patella. There are many different designs of implant which offer varying levels of soft tissue removal and offer varying conformity between the components (See section 2.3.3).

2.3.2 Patient Details from England and Wales

Joint registers have been compiled in several countries which highlight trends the populations that undergo KA and the type of procedure they are receiving [1, 5]. On closer inspection of the joint registry data from England and Wales there are some clear trends in the population receiving KA. In 2009 there were 77,545 KA procedures in England and Wales, with 57% of those patients being female. Details of these patients from the Nation Joint Registry (NJR) of England and Wales are surmised below (Table 2.5).

Table 2.5: Age, BMI, and sex of the patients who underwent KA in England and Wales in 2009 [1]. SD = standard deviation, IQR = inner quartile range.

	TKA			**UKA**		
	mean	SD	IQR	mean	SD	IQR
Age (years)	70.2	9.3	63.7-77.1	63.8	9.7	57.1-70.6
BMI	30.6	5.2		29.9	5.2	
	Male (%)	Female (%)		Male (%)	Female (%)	
Sex	43	57		51	49	

On average those who had a TKA were older and had a higher proportion of female population that of the UKA population. In 2009 the NJR reported that the majority of patients had a mild disease that is not incapacitating (72%), with less than one percent reporting a life threatening disease prior to the procedure [1].

2.3.3 Surgical Procedure

During surgery exposure of the knee is required to resect bone and soft tissue structures to position and fix the prosthesis. This usually requires an incision through the anterior structures of the knee, which will go through the skin, patella reticular, joint capsule, and muscle belly. The most common approach for a TKA (over 90% in the UK) is the medial parapatella approach [1]. Here the incision is made on the medial aspect of the patella, the incision is made so the patella can be everted and full exposure of the articular surfaces can be achieved with knee flexion. Other surgical approaches are becoming more prevalent with a 19% increase in the use of minimally invasive surgery (MIS) for UKA in England and Wales from 2004-2006 [56]. During MIS the surgeon gains access to the knee joint by the use of a very small arthotomy and without dislocating/everting the patella.

2.3.4 Prosthesis design

During KA bone which has been resected is replaced by prosthetic implant to reform the articular surfaces of the knee. The latest femoral and tibial components are often made of cobalt-chromium (Co-Cr), which provides high strength, biocompatibility, and corrosion resistance. An insert which sits on the tibial component acts as the articulating surface with the femoral component, this is often made of ultra-high molecular weight polyethylene (UHMWPE). Although this surface acts as a low friction, low wear articular surface it has been shown that wear debris can be distributed into the knee joint which can result in the need for revision [57]. In 2007, the NJR for England and Wales found 54 brands of total condylar knee prostheses were used. Prosthetic design can vary considerably, with continual adaptations in design aimed at improving function and life span of the prosthetic components (Figure 2.10).

NexGen (Zimmer) P.F.C. Sigma (Depuy) Oxford Unilateral (BIOMET)

Figure 2.10: Examples of prosthetic design for total KA.

One of the most significant differences between the designs is the tibial insert, which can be constrained (no movement), rotating (rotates around a central peg), or rotating and translating. It is thought that allowing some rotation and translation of the tibial insert against the tibial tray would allow the knee to rotate and translate like a 'normal knee' (see section 2.1.7) thus reducing wear on the insert. Although tibial inserts recorded in total condylar procedures were predominantly fixed bearing (85%) in England and Wales in 2009 [56].

Another key decision when performing TKA is whether to retain or sacrifice the PCL. In nearly all TKA cases the ACL is removed in order to get exposure of the articulating surfaces of the knee and to position the prosthesis appropriately. The MCL and LCL are generally conserved in order to retain the valgus-varus constraint they apply to the knee. Designs that retain (commonly referred to as crutiate-retaining) or sacrifice usually have different design characteristics. Crutiate retaining (CR) implants commonly have less conformity in the sagittal plane, as the PCL serves to restrain sagittal translation (Figure 2.3.1 Nexgen, Zimmer). The PCL sacrificing (CS) designs require more sagittal conformity and often have a cam system in the intercondylar region (Figure 2.3.1 PFC Sigma, DePuy). As the femur flexes and experiences anterior force, the cam system engages to resist the anterior motion. Last year TKA procedures in England and Wales were 72% were CR, 25% were CS, 3% constrained condylar, and less than 1% were hinged replacements [1].

2.3.5 Prosthesis Fixation

In most cases of TKA and UKA the prosthesis is fixed to the underlying bone by cement, although there are a proportion of designs which have cementless fixation. Fixation pegs are often incorporated into the design of the prosthesis to avoid loosening under the forces and torques applied to the implant. The cementless designs often have a porous coating for a better mechanical fixation, and to encourage bone in-growth. The fixation of KA has remained largely unchanged over the last five years. The NJR reported that in 2009, 93% of procedures were cemented, and 7% were uncemented [1].

2.3.6 Rehabilitation

Rehabilitation post KA is focused around strength, range of movement, and functional exercises [58]. Commonly patients will remain in hospital between 4 and 7 days post-operation, patients are encouraged to mobilise on the first day, and progress with frequent treatments from physiotherapists, occupational therapists, and rehabilitation technicians. There are no current national clinical guidelines in the United Kingdom (UK) for the treatment of TKA patients; each hospital has its own similar treatment pathway (Appendix C). Once the patients have met the functional outcomes (usually 0-90° knee flexion, straight leg raise without lag, and ambulation of stairs and level gait) they may or may not receive follow-up rehabilitation.

2.3.7 Failure and Revision

One of the most comprehensive sources of information on revision rates of KA comes from the Swedish Joint Register [5]. It has ten year follow-up data on a number of implants giving a unique picture of long term prosthesis performance. As previously stated (Section 2.3.1) there is a clear difference in ten year revision rates of UKA (10%) and TKA procedures (3.4%). The results from the ten year follow up also indicate that certain implants perform better depending on the pathology (OA vs RA), and have differing reasons for revision [5]. Vince (2003) conducted a review of why knees fail. The review split causes of failure into 9 categories [59];

- Aseptic loosening is one of most common modes of failure, resulting in loss of mechanical interface between bone and prostheses (diagnosed with radiographs).

- Instability in the knee joint is linked to resection of ligaments, mal-alignment of prostheses, and ligament laxity resulting in large translations across the joint and 'unstable' knee sensation during high loading activities.
- Patellar instability related to tibia and femoral mal-rotations . This in turn will affect the extensor (quadriceps) mechanism and cause anterior knee pain.
- 'Mystery Knee' where patients have received a revision for no clear diagnostic reason. The knee is usually painful and problematic for the patient and restricts function.
- Catastrophic wear and breakage (not to be overlaid with aseptic loosening).
- Failure due to sepsis (infection).
- Extensor mechanism rupture.
- 'Stiff knee' where patients range of motion is restricted to the degree that functional activities are not possible.
- Fracture, most commonly in the femur in the supracondylar region.

Failure of the procedure can cause significant discomfort for the patient and will results in further more invasive knee surgery. Surgeons and prosthetic designers are currently researching methods to reduce the risk of failure and this has shown to be successful with patients operated in the last decade having half the risk of revision compared to the decade before [5]. Although KA failure is an important aspect of research, what perhaps is more pertinent is the fact that patients are not achieving functional recovery after their operation (Section 1.1).

2.4 Current Evidence in post-operative KA function

As highlighted in Chapter One evidence suggests there is significant functional deficit post-KA, with a large number of patients having perceived and observed difficulty performing ADL [9]. This is coupled with satisfaction rates that have clear room for improvement [7]. Although perceived function assessment and satisfaction scores are important indicators of post-operative outcome this may or may not relate to objective clinical scores [60]. Studies such as Noble et al [59] highlight the difficulty which patients feel when trying to perform certain activities. However little is known why they experience difficulties, and how these differences can be measured objectively. There are also studies which assess objective changes during ADL, however little attention is given to why the patient adapts ADL movement patterns [13]. Evidence suggests that immediately post-operation patient function decreases, and then improves up to a year post-operation [60], however function never appears to meet that of the healthy age matched population [9]. Many studies have looked at different aspects of function post-operation and studies vary in quality and quantity. It is clear from the findings that post-operative functional deficit is a multifactor problem.

2.4.1 Perceived Function

Patients perception of their ability to perform activities has been shown to be much less than that of the healthy age matched population [9]. In extensive questionnaire studies into KA function there were significant correlations between disease-specific outcome measures (including pain) and satisfaction post-KA [7, 61]. It is of note that the return rates of the more comprehensive questionnaires can be low, and patients who respond to the disease-specific questionnaires tended to be the patients who were less satisfied [61]. Perceived function appears to increase immediately post-KA compared to the pre-operative scores and continues to rise several months after the operation [60]. However, patients retain some perceived functional limitations years after their KA [61], and although improvements in function will rise over the first year these improvements plateau in most cases in the following years post-operation [62]. Although perceived function is a key indicator of patients wellbeing, evidence suggests that there are limitations with questionnaire based methods (Section 3.2).

2.4.2 Pain

Pain is one of the key determinants in a patient deciding to undergo KA, and is therefore one of the most important post-operative outcomes. It has been found that pain in the ipsi- and contralateral knee is one of the most important outcome measures that relates to patient dissatisfaction after TKA [7]. Studies have shown that 27% of patients who have undergone TKA report increased pain in the non-operated knee one year post-operation, and 30% of TKA patients report moderate pain in the contralateral knee within seven years of the operation [63]. Management of pain is an important aspect of post-operative function, and multidisciplinary intervention is seen as the best approach [64]. In all of the studies pain is measured using subjective questionnaires (Section 3.2). Reported pain in the patients may differ depending on the patient specific interpretation of the measure.

2.4.3 Stiffness

Stiffness is a disabling problem following KA with definitions of stiffness varying in the literature. Some studies define stiffness by loss of RoM, 'stiffness after TKA is >10° of extension deficit and/or <95° of flexion in the first six weeks post-operation' [65]. Prevalence of stiffness is wide ranging in the current evidence base, with studies reporting 1.3-5.3% of the TKA population [65, 66]. Patients have reported both pain and diminishing function in association with stiffness [65, 66]. Stiffness after total KA may be attributed to many factors, including limited preoperative motion, a biological predisposition, intra-operative technical problems, poor patient motivation, and inadequate postoperative rehabilitation [67]. Stiffness by definition is a resistance to a given movement, and in this sense clinically a lot of patients feel stiff after lying still or sitting for long periods. Patients often complain of tightness and stiffness in their knee's however this does not always transfer into a loss of range of motion. This relative stiffness across the knee joint would be very hard to assess, but just relying on pure RoM may not highlight the prevalence of knee stiffness in the KA population.

2.4.4 Instability

Instability post KA is difficult to quantify and reports on prevalence are lacking. Instability has been reported in both the PFJ [68] and TFJ [69], although more focus is given to the latter. As with pain and stiffness, instability is hard to measure accurately and reliably. There are several directions in which instability can appear, including V-V, A-P, recurvatum (hyperextension), and global [69]. Vince et al reports that the idea of a patient complaining of instability is not a diagnosis, the experience may have been a 'buckling' or spontaneous yielding of quadriceps with knee flexion. The author argues that true instability is treatable if thoroughly understood [69]. Early instability is has been related to poor alignment of the prosthesis [70], inadequate balancing of the extensor mechanisms, and polyethylene wear [70]. The literature surrounding instability post KA suggests that there are many factors which could contribute to instability and that surgical error maybe one of the most predominant factors [70]. Definition and treatment of instability is varied. The evidence surrounding instability seems to put opinions across about causes and interventions with little evidence to back up their statements. With instability being one of the largest causes of revision, there is surely a need to better understand this problem.

2.4.5 Strength and Inhibition

There is strong evidence showing that after a KA there is an acute and profound postoperative deficit of both quadriceps and hamstrings strength [71], with this strength loss being related to perceived and observed function outcomes [10]. While the reason for quadriceps weakness is not well understood in the KA population, it has been suggested that a combination of muscle atrophy (muscle loss) and neuromuscular activation deficits (inability to contract the muscle) contribute to strength impairments [72]. It has been shown that strength deficits can be severe with some patients producing less than half of their preoperative torque values one month post-operation [72]. While quadriceps strength increases steadily thereafter (isometric improves 10-20% from pre-op), strength rarely returns to that of healthy age matched individuals [71]. But caution must be taken when critiquing the evidence of unilateral weakness, for it is well known that the uninvolved limb may also require a TKR in the following years and therefore have some underlying weakness. Prior to surgery, failure of voluntary muscle activation (voluntary muscle inhibition) has been found to be twice that of healthy adults [72]. There is evidence to show that this voluntary inhibition continues for an extended time after surgery [73]. Assessment of strength in the health care and research setting has its limitations, these will be discussed in Section 3.3.1.

2.4.6 Proprioception

Proprioception is the perception of movement and spatial orientation arising from stimuli within the body itself [11]. Proprioception is commonly measured using either a static test of joint position sense (JPS), or a dynamic trial of balance looking at postural sway (PS). Studies have looked into the effects on decreased joint proprioception both pre- and post-KA [11]. There is mixed and conflicting evidence in this area, confounded by the fact that there has been no standardised measuring tool for proprioception testing. There is some evidence to suggest proprioception does not improve after KA [74], but there is a greater depth of evidence suggesting there are improvements [11, 75]. There is also the mixed evidence for the proprioceptive effects of sacrificing or retaining PCL during surgery [76]. In one of the most recent studies by Isaac et al [11] they compared pre- and post-operative JPS and PS measures. They found an increase in both static and dynamic proprioception post operation, with the larger increase in dynamic proprioception than static. They also found UKA patients improved marginally greater than the TKA group. This study provided a more complete picture of proprioception testing [11] in the KA population.

2.4.7 Psychological Factors

When a person suffers from a longstanding chronic disorder such as OA there may be psychological effects. It has been found that general practitioners (GPs) can overlook the psychosocial and socioeconomic factors associated with OA [77]. There has been mixed results in studies looking into the effects of psychological condition and functional rehabilitation post KA [78]. There is, however, a growing body of evidence to support that psychosocial factors might pre-dispose individuals to adverse pain-related outcomes post TKA [78]. Even though psychological factors are hard to assess, it is important to take them into consideration when assessing overall function. Psychosocial factors may also contribute to changes in ADL performance. If a patient is nervous or apprehensive about using the knee joint, this could result in fear avoidance behaviour during ADL (Section 2.4.9).

2.4.8 Range of Motion (ROM)

Knee RoM has been shown to be a key determinant of overall function, and function specific to stair ascent and gait [79]. However more recent evidence suggests it is less important than pain and stiffness scores post TKA [12]. High flexion outcome (above 125^{o}) was shown to improve stairs ascent, but again had little influence on overall functional outcome [80]. Despite this evidence, prosthetic designs are still striving to produce greater degree of flexion post-operation [81]. RoM can be affected by many difference factors including, pre-operative ROM, component positioning, PCL tightness, instability, prosthetic design, excessive post-operative pain, and poor response to rehabilitation [82]. Measurement of RoM has been shown to be reliable, however some error is common in the process (Section 3.3.3).

2.4.9 Changes to Kinematics and Kinetics during ADL

Altered knee kinematics and kinetics has been shown in many ADL post-KA. Observed changes in gait [13], sit-stand [83], and stair ascent [84] have all been shown in the literature. Evidence suggests that alterations in ADL patterns pre-operation are kept post-operatively [85]. McClelland et al reviewed gait analysis of TKA patients, they found eleven articles from a comprehensive literature search conducted in 2006 [13]. They found a wide range of both assessment techniques and analyses, but all of the studies concluded that the most significant findings were a decreased in knee sagittal range of motion (ROM) and moment during both swing and stance phase. However, they found no research that has investigated the relationship between a reduction in knee RoM during gait and patients functional abilities [13]. Kinematics and kinetics in the other planes of the knee have not been shown to be significantly different compared to the healthy population during gait [86]. Evidence has also identified conservative strategies in TKA patients to manage centre of mass (COM), centre of pressure (COP) [87], and varus moment about the knee [88].

Reduced strength and joint proprioception are thought to cause co-contraction of hamstrings and quadriceps during low flexion ADL. The antagonist hamstring moments potentially counteract the anterior tibial shear and excessive internal tibial rotation induced by the contractile forces of the quadriceps near full knee extension. There have been many studies to show this muscle co-activation increases post KA [89]. But all the studies cited above have very small samples, and the EMG data recorded cannot correlated to force production on the TFJ.

Some authors have combined ADL measures to provide a multivariate analysis of KA function. Statistical methods such as Principle Component Analysis (PCA) and linear discriminative analysis (LDA) techniques are becoming more common in the latest literature (both PCA and LDA techniques discussed in Chapter 5). One of the first authors to utilise PCA analysis on waveform measures of ADL was Deluzio et al, where a relationship between gait adaptations and questionnaire measures was established [90]. Subsequently authors have applied to PCA to pre- and post-operative TKA patients [41], combined clinical measures with PCA analysis [87], and to produce discriminatory statistical models of function [91].

2.5 Factors which could affect post-operative KA function

Current evidence into factors which could affect function are varied in quality and quantity. Most studies do not report comprehensive information on pre-operative factors, operative procedures, and rehabilitation input. This has led to poor outcomes when studies have tried to compare factor which affect function. Listed below are the factors which can affect function and the supporting evidence. In order to examine these factors the KA process can be broken down into three stages;

1. Pre-operation
2. Operation

3. Rehabilitation

Each of these three stages can have multiple contributors to the functional gains/losses in which a patient will go through. Each stage will ultimately be linked to the next and the combination of factors in each stage will contribute to post-operative satisfaction, objective and subjective function. There are other factors to consider which contribute to post-operative function, for example patient motivation and other comorbidities. However the three stages of the KA process highlighted are the factors which could be influenced by changes in practice, these will therefore become the focus of investigation. It is of note that there has been more focus in some areas KA function compared to others. For example a literature search of three commonly used resources (Allied and Complementary Medicine (AMED), EMBASE, Ovid Medline) was conducted using 'knee arthroplasty' as a key word. In addition to the key word 'prosthesis', 'surgical', and 'rehabilitation' were added separately resulting in 6815, 5121, and 1275 hits respectively. This shows that there has been many studies looking into the surgical approach and prosthesis type/design, however rehabilitation seems to lack the depth of evidence base.

2.5.1 Preoperative Factors

It has been found that pre-operative status is one of the main determinants of post-operative function [92]. This implies that if a patient has a low pre-operative function this will lead to a poorer post-operative outcome. Lingard et al assessed over 700 TKA patients looking into knee function questionnaire data from the United Kingdom (UK), the United States (US), and Australia [92]. Patients were assessed pre-operation then one and two years post-operation. They found that post-operative functional status of the patients from the United Kingdom was significantly worse than that of the patients from the other countries and the difference was clinically important at both the one year and two-year follow-up examination ($p<0.05$). Patients who have marked functional limitation, severe pain, low mental health score, and other comorbid conditions before total KA are more likely to have a worse outcome at one year and two years postoperatively. The study also found that the UK patients on average had suffered longer from pain in their knee and had lower knee flexion pre-operation compared to the US and Australia [92]. Pre-operative reduced function could be attributed to a number of different factors, functional limitations can include;

- loss of strength [93],
- reduced proprioception [94],

- increased pain [95],
- loss of balance [96]
- sensorimotor deficit [97].
- reduced RoM [98]

It is of important note for the present study that kinematics of ADL (gait, sit-to-stand, and stairs) are also effected by OA symptoms. Decreased joint loading [99], altered muscular activity [100], and altered knee kinematics and kinetics [42] have been shown to prevalent in OA patients during ADL. Many of these factors highlighted in pre-operative function also limit post-operative outcomes (Section 2.4), suggesting that current KA is not improving these limiting factors sufficiently.

2.5.2 Operative Factors

As highlighted in Section 2.3.3-2.3.4 there are many operative factors which can vary with surgeon or hospital preference. Joint registers from around the world highlight the varying surgical approaches, prosthesis types and fixation methods. Surgeons tend to have the responsibility of educating the patient as to whether the KA intervention is advisable and the potential for functional recovery. Generally the surgeon will decide on the extent of the KA (Section 2.3.1), the surgical approach, the type of prosthesis, and the fixation method. The British Orthopaedic Association (BOA) has released guidelines on best practice for KA, from the clinical assessment through to the surgical technique [101].

The BOA guidelines state that a prosthesis should be chosen through comprehensive evidence based practice, with a ten year follow up as a preferable standard [101]. However a confounding factor for the surgeon is that knee devices with apparently good published results have in the meantime been modified by the manufacturers and the clinically tested design is no longer available. A systematic review into comparisons of prostheses have highlighted the lack of evidence and need for further investigation [102]. Comparisons between fixed and mobile bearing tibial inserts have shown little or no clinical difference between the designs [103]. When comparing cruciate retaining (CR) and cruciate substituting (CS) TKA evidence suggests that there is no difference in post-operative knee scores [102]. Since the review by Jacobs et al [102] evidence has shown that CS designs may have better RoM outcomes post-operation [104]. Studies comparing prosthesis design have been limited by small patient numbers and varied outcome measurements, these confound the ability to combine multiple findings.

When surgical approaches have been compared there has been no conclusive evidence to suggest one approach is better than another [15]. In reviews comparing surgical approaches it is highlighted that factors such as poor study design, lack of true randomization, and blinding affect the integrity of currently available data [15]. Randomised control trials (RCTs) comparing MIS to standard methods show no improvements in patient function [105]. However, misalignment of the KA prosthesis has been shown to alter knee loading [53], increased wear [106], and reduce post-operative function [107]. Degrees of misalignment has been shown vary 5^{o} in the tibial A-P slope, 6^{o} in the tibial coronal plane, and 8^{o} in the femoral coronal plane within the same experienced surgeon [108]. Recently, the use of computer-assisted surgical (CAS) navigation systems have been reported to improve the achievement of bone cuts and implantation with a high degree of precision [109]. However, the systems remain somewhat cumbersome to use and costly to acquire [110]. Although there has been an increase in accuracy of bone cuts, this has not translated in improvements in functional recovery post-operation when comparing CAS with conventional surgical techniques [110].

Fixation methods for KA are cemented (more common) and cementless. Baker et al reported an RCT of the long-term survival of the two methods in 501 primary TKA patients using a press-fit condylar design. They found no significant difference in revision rates over 15 years, with both fixation methods performing well [111]. Previous reports have suggested that clinical outcomes and long-term survival is higher in the cemented fixation [112], however these studies lacked randomisation and had small sample sizes, questioning the validity of their findings compared to Baker et al [111].

2.5.3 Rehabilitative Factors

The National Institute of Health Consensus Panel reports that the use of rehabilitation services is perhaps the most understudied aspect of the peri-operative management of TKA patients [113]. There is very limited evidence base for the efficacy of rehabilitation both prior to [114] and after KA [115]. These findings are compounded due to the low number of patients studied, a high number of dropouts, no matched control populations, different physical training protocols, and the use of limited functional analysis [14]. Lowe et al conducted a systematic review and meta-analysis of physiotherapy exercise post-KA [14]. Only six trials were identified, five of which were included in the meta-analyses. Of these trials assessment techniques varied in quality and quantity making collating the evidence difficult [14]. As highlighted previously (Section 2.5.1) there is a disparity in rehabilitation protocols both within and between different countries. When Lingard et al compared management and care of patients undergoing TKA across the UK, US, and Australia it was found that there were significant differences in the length of acute hospital stay, use of extended care facilities, home physiotherapy, and outpatient therapy in the cohort of hospitals they evaluated [116] (Table 2.6).

Table 2.6: Summary of data collected by Lingard et al looking into management and care of patients who have undergone TKA [116].

Country	No. of Patient	Mean hospital length of stay (days)		Extended care facilities % patients		Home PT, % patients		Outpatient PA, % patients	
		mean	range	mean	range	mean	range	mean	range
UK	423	13	9.7-15.6	0	0-1	3.8	0-10	59	29-89
US	256	4.8	3.9-6.1	43.8	6-83	59.5	28-88	22.3	3-33
Australia	170	8.3	5.7-10.8	35	2-68	7	4-10	66.5	66-67

These findings from Lingard et al are currently limited in significance in current practice as they were recorded in 1997-1998. Current joint registers for the UK show that acute hospital length of stay is now significantly shorter with TKA and UKA patients staying 8.7 and 5.9 days respectively [56]. The registers however give no indication to therapy intervention post-operation. The findings from Lingard et al show how varied therapy input is within the UK, with some hospitals following up 93% of patient with either home or outpatient therapy compared to 31% in another hospital. On average 62.8% of patient received either home or outpatient therapy in the UK, compared to 79.5% and 73.5% in the US and Australia [116]. The lack of standardisation in therapy follow up for patients has the potential to result in differing post-operative outcomes between different hospitals within the UK. With the NHS running on a tight financial budget there is the argument that if there is little or no evidence of the benefits of physiotherapy then it perhaps does not seem cost effective in practice. The previous literature does not suggest that enough quality research has been conducted in this area of KA intervention, so conclusion of the efficacy cannot be formulated.

2.6 Discussion

The overriding limitation with the literature surrounding the factors which could affect KA function is that there is no agreed standardisation of outcome measures for knee replacement. Meta-analysis studies have highlighted this problem with their limited ability to collate data. The data presented in Section 2.4 highlights that post-operative function is a multi-factorial entity, however when studies have tried to assess factors which limit function they normally focus on one outcome measure, for example a questionnaire. In Chapter One function was defined by the ICF guidelines published by the WHO [117]. Here function and disability was described as a combination of physical, mental and environmental factors. By measuring one form of function, for example strength, there is very limited scope to assess the magnitude of changes in this measure on holistic function. The evidence in Section 2.4 highlights that any number of factors can contribute to global function. By comparing one measure to another there is little scope to determine its effect on function, knowing that other factors could be affecting results. The use of exclusion criteria to combat this which negates other co-morbidities will limit the power of a RCTs results on 'real life' outcomes. This has led to studies showing very limited or no statistical differences between groups assessed during RCTs. This is little surprise given the known number of factors which could affect function in KA patients and the variance in patient function pre-operation.

There is a need to assess patients more holistically, taking into account the numerous factors which could affect KA function. Given the ICF guideline function needs to be assessed taking into account physical, mental and environmental factors. Standardised assessment techniques need to measure all of the functional limitations pre-operation, the surgical intervention, and the post-operative rehabilitation. In order for a holistic evaluation of function subjective and objective measures are required to build a picture of global function. To data no research has been conducted which has incorporate this holistic approach, and this could be one of the reasons for limited findings in the current literature. Factors affecting function have been highlighted in the literature, however there seems to be a bias towards research focussing on prosthetic design and surgical approach. In comparison pre-operative function and post-operative rehabilitation factors have had few studies, of which most have limited methodology. Surgical approach and prosthetic design are important factors in the outcome of KA, however there is a clear need to increase the research and development effort in both pre-operative factors and rehabilitation.

Few studies have assessed multiple variables in determining post-operative function [118, 119]. They investigated the determinants of function post TKA [119], using data from questionnaires, medical variables, and surgical variables. Using multiple linear regression they found that baseline function, walking device, walking distance, and comorbid conditions predicted 6 month post op function. Significant findings were achieved however only a small percentage of the variance was explained (R^2=0.2-0.3) between independent variables and post-operative questionnaire scores. The authors concluded that the pre-operative function was the key determinant of post-operative function, but only questionnaire data were taken pre-operatively [118, 119]. These studies are a good step towards a more thorough analysis of function, however there are still variables that the authors did not consider in the regression analysis, for example strength, proprioception, and detailed analysis of ADL. A flow chart of the factors which could affect function has been devised; it provided a platform for the analysis in this thesis project (Figure 2.11).

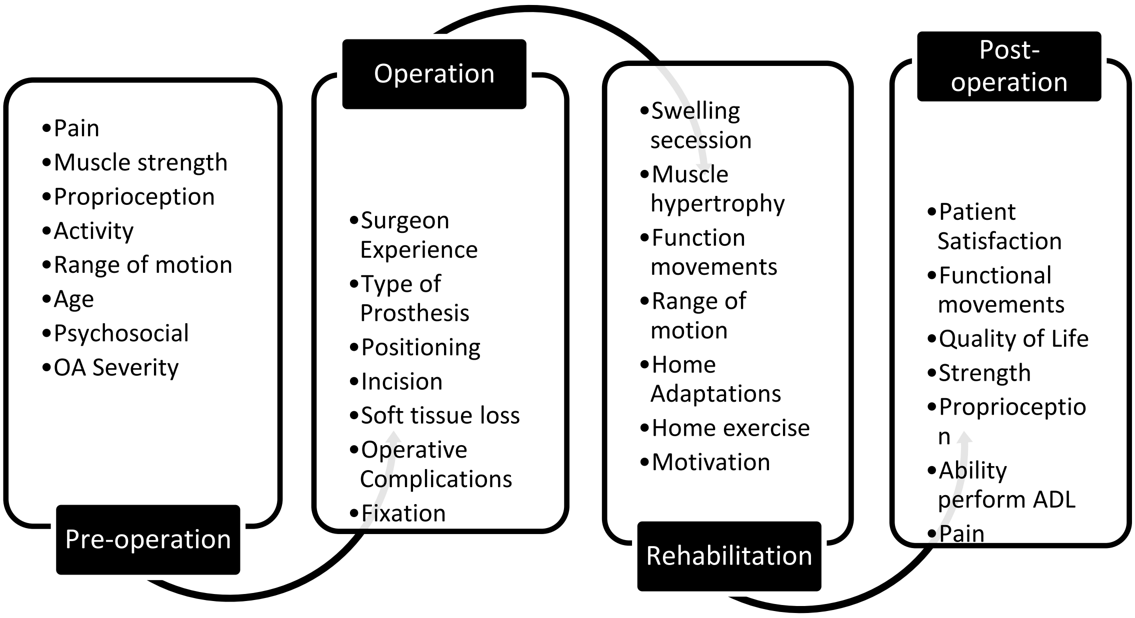


Figure 2.11: (Repeated for the benefit of viewer) Flow chart to show the factors which affect function, all linked to kinematics and kinetics of functional movements.

2.7 Conclusion

Results from the literature show that KA function is a multi-factor entity which includes differing levels of joint disability, changes in perceptions of function, changes in activity patterns, and in some cases retention of pain. It is also apparent that there a number of factors which can affect the outcome of the KA procedure. However, to date there is little evidence to suggest one factor is more prominent than another in the functional gains post-KA. There is a clear need to assess what functional limitations are present in the KA population, and to determine the factors which influence functional recovery the most.

Chapter 3

Subjective Assessment, Clinical Objective Assessment and Motion Capture

3.1 Introduction

It is obvious from the literature (Section 2.4) that there are many factors which could affect post-KA function and there is a need to find assessment tools to analyse function accurately and reliably. Evidence also suggests that assessment tools are not always implemented and analysed to the same standard. When reviews attempt to collate data on factors which affect function, there are very few studies which can be used in meta-analysis due to the varying patient populations and assessment protocols [14, 109]. Methods of assessing function can be broadly classified into two groups; subjective (patient perceived) assessment, and objective (observed) assessment.

3.2 Subjective Assessment

Subjective assessment generally consists of qualitative or quantitative measures of perceived function which can then provide feedback for therapy goals and intervention outcomes. These assessment techniques are commonly used both in research and within health care practice. They are a quick and inexpensive method to collect and analyse patient data. The main tools for subjective assessment are questionnaires, which are generally devised to analyse specific areas of function for a given pathology, although more general quality of life measures are available. There is no current gold standard of measuring KA function using subjective measures; this has led to a number of assessment techniques being used in the literature.

3.2.1 Questionnaires

In a review by Davies it was discovered that there was little consensus in the use of questionnaires in the British orthopaedic community [120]. There are however a few questionnaires which are commonly used in the literature, these are highlighted in the following section.

The ***Oxford Knee Score*** (OKS) was developed by Dawson et al in 1998 at the University of Oxford in the Nuffield Orthopaedic Centre [121]. The OKS consists of twelve questions focussing on knee specific functional ability over a 4 week period are outlined with a tick box answering system. Each item was scored 4-0 from no to most severe symptoms, and combined to produce a single score that ranges from 48-0 (Appendix E). The OKS has been used in large scale patient satisfaction trials [7], being chosen for reliability, validity, and responsiveness [122]. It has been recommended as an appropriate disease-specific tool for assessing outcomes after TKR [120], ideal for large databases on knee arthroplasty in a cross-sectional population [120]. However there is evidence to suggest that this questionnaire does not take into account other comorbidity, and some of the questions can cause confusion for patients [123].

The **Western Ontario and McMaster University Osteoarthritis Index** (WOMAC) is a self-administered health questionnaire specifically designed for patients with osteoarthritis of the hip or knee. It consists of 24 multiple-choice items grouped into 3 categories: pain, stiffness, and physical function (Appendix F). The questions are ranked on a 5-point Likert scale (0 point, best result; 4 points, worst result), and the scores are added up for each category. The WOMAC's reliability and validity were established in the context of knee and hip arthroplasty studies as well as clinical trials of OA subjects [124]. However when factor analysis was performed to assess the construct validity and test-retest reliability of the WOMAC in other languages (French-Canadian) it was shown that validity could not be demonstrated [125].

The ***SF-36*** was judged to be the most widely evaluated generic patient assessed health outcome measure in a bibliographic study of the growth of "quality of life (QoL)" measures published in the British Medical Journal (BMJ) [122]. It comprises 8 dimensions of health status: physical functioning, role physical, bodily pain, general health, vitality, social functioning, role emotional, mental health, and health transition. The SF-36 has been used in nearly 4,000 publications; citations for those published in 1988 through 2000 are documented in a bibliography covering the SF-36 and other instruments in the "SF" family of tools [126]. However, because the SF-36 is a general questionnaire on quality of life its ability to predict postoperative KA improvement on an individual basis has not been shown, so it cannot be used alone to determine KA function [127].

3.2.2 Visual Analog Scale (VAS)

VAS scales have been used for a number of years to measures various functional outcomes in KA patients. When compared to questionnaires looking at multiple pain questions the VAS was seen to be the most reliable and valid [128]. VAS has also shown to provide an accurate method to assess patient satisfaction post TKA [129]. There are many different types of VAS, some are colour coordinated, some have words, and some are just a simple line. Often in a VAS measures there are statements at the start and end of the scale which represent the extremes of the measure. Numbers placed at intervals in the scale can give objective feedback on the position of the patient's outcome on the scale (Figure 3.1).

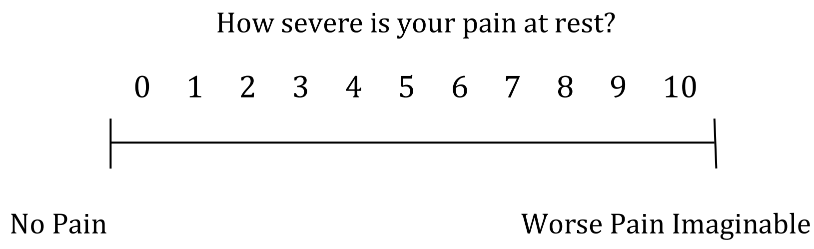


Figure 3.1: VAS scale for the measurement of pain at rest.

3.2.3 Summary of Subjective Measures

When questionnaires have been compared there have been differences in the minimal clinically important differences (MCIDs) [130], differences in the presentation [131], and differences between subjective self-reported measures and objective measurements in the assessment of KA patients [60, 132]. There is also a body of evidence looking into response shift phenomenon (individual's ability to change over time in terms of internal standards, and values as a result of external factors) [133]. This response shift phenomenon has been shown to confound post-KA assessment and has the potential to significantly affect questionnaire based results [133]. It is mainly thought that the response shift arises from the sudden changes in pain symptoms from pre- to post-KA. Further to this questionnaire measures have been shown to be significantly affected by pain [134]. Although many of the questionnaires have some reliability and validity evidence, when further analysis of the measure is conducted results show that construct validation may not be attainable. When questionnaires were used to distinguish between intervention of knee pathology it was shown that they were not sensitive enough to detect differences when objective measures achieved discrimination between groups [135]. Based on current evidence there is no clear advantage of using one questionnaire over another to measure KA function. Other questionnaires are available apart from the ones reviewed in section 3.2.1, but similar limitations can be found.

3.3 Objective Assessment of Musculoskeletal Function

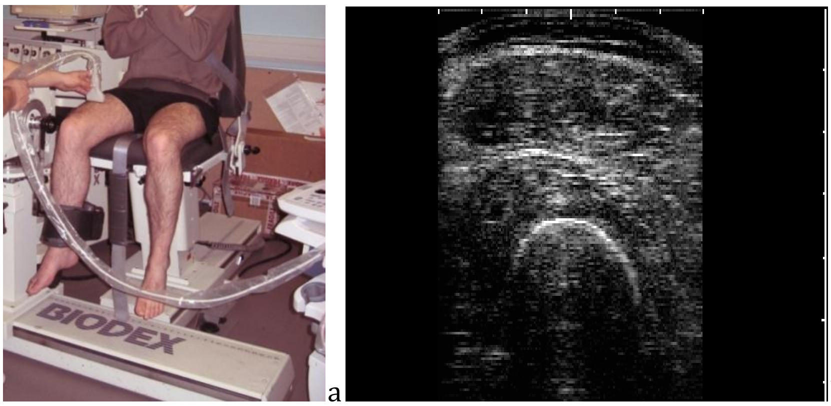
Objective measures are used to provide general and joint/muscle specific measures of disability and function. Unlike questionnaires objective measures are often used with the assistance of a health care professional, and can involve various pieces of equipment. Objective measures tend to differ between the health care setting and that of the research laboratory. Measures in the health care setting usually involve tests that are easy to implement, and require little financial burden. Research in the laboratory tends to use specialist equipment that can focus on specific areas of joint or muscle function. During inpatient rehabilitation active range of motion, strength, gait, and stairs are the main physical functional tests. Standardised tests including the 6 minute walking test (6MWT) [136], and the timed up and go (TUG) [137] are often used clinically. The TUG test measures, in seconds, the time taken by an individual to stand up from a standard arm chair, walk a distance of 3 metres, turn, walk back to the chair and sit down. The subject wears their regular footwear and uses their customary walking aid. The 6MWT has been proven to be responsive in the early stages of TKA rehabilitation [86] and there is a strong correlation between the TUG and gait in orthopaedic patients [138]. Clinical trials have gone further in their objective analysis to include detailed measurements of strength, imaging of muscles size, proprioception tests, and kinematics and kinetics analysis of ADL.

3.3.1 Strength

As highlighted in Section 2.4.5 strength has a direct effect on KA function. Assessment of strength differs significantly between the health care and research laboratory setting. Clinically strength is often measured manually using a isotonic (through range) contraction. Muscle strength is graded according to the Medical Research Council (MRC) scale [139]. Grades of muscle strength range from 0 (‘no contraction’) to 5 (‘Normal power), and are often compared from one limb to the other [140]. Manual muscle techniques (MMT) for assessing strength were found to have poor reliability between therapist, and required repeat training to increase the inter-rater reliability [141]. Various methods have been used to assess strength in the research setting, these include; maximal voluntary contraction (MVC) [142], isometric burst superimposition technique [72, 73], isokinetic testing [143], and hamstrings to quadriceps ratios (H/Q) [71]. Isometric burst superimposition technique estimates quadriceps activation by superimposing a supra-maximal electrical stimulus on a maximum voluntary isometric contraction (MVIC) [144]. Many of these methods use an isokinetic dynamometer (Figure 3.2.1) which has been found to be a reliable and valid measuring tool for measuring torque production about joints [145]. But this method of assessing strength can be both uncomfortable and poses stresses on the knee joint. Pain and limitations in movement can give erroneous results, along with the questionable use of burst superimposition to give a stimulated contraction (eliminating inhibitory factors).

3.3.1.1 Rehabilitative Ultrasound Imaging (RUSI)

Rehabilitative Ultrasound imaging (RUSI) has also been in used in the assessment of normal and weak muscle to measure atrophy [146], and also as an indirect measure of force of contraction [147]. RUSI has been shown to be highly correlated with magnetic resonance imaging (MRI) which is seen as the gold standard for measuring soft tissues [148]. A recent review by Whittaker et al 2007 highlighted the growing body of evidence supporting the use of RUSI in physiotherapy practice [149]. RUSI and EMG have been used in studies looking at several different muscles [149]. They found a good correlation between changes in muscle thickness on RUSI images and changes in EMG signal properties but only at low levels of MVC percentage (up to 30% MVC). Subsequently a study by Delaney et al has used RUSI to assess the relationship between the contractibility of rectus femoris and MVC/EMG outputs (Figure 3.2) [150].



a b

Figure 3.2: (a) Example of an isokinetic dynamometer, with simultaneous ultrasound imaging being performed on quadriceps femoris. (b) ultrasound image of rectus femoris taken at rest in supine position.

Delaney et al were able to show a relationship in changes of muscle dimension and force production for the first 25% of MVC [150]. The authors of this study also managed to establish high inter- and intra-rater reliability in both imaging and interpretation [150]. RUSI has also been used to assess rectus femoris atrophy in KA patients [151]. Results showed KA patients had smaller muscles bilaterally compared to the healthy age and sex matched population. The effected limb did also show increased atrophy compared to the contralateral limb [151].

Clinical and laboratory techniques vary significantly, with subjective MMT techniques used in the health care setting and objective measures of muscle force used in the research literature. The convenience of the MMT techniques provide a quick, cheap, pain free, and relatively easy method of assessing strength. However, the reliability of the measure is questionable. Although the methods to assess muscle strength using assessment of torque production from a given muscle group appear to be reliable there are ethical considerations. For example often a MVC contraction of quadriceps in KA patients can cause pain and discomfort [152]. Ultrasound imaging offers a cheap and relatively fast way of assessing muscle size, with evidence of validation (MRI) and good reliability. Although some evidence suggests that RUSI can be used to predict low force muscle contraction (up to 25% MVC), it is limited in assessing a muscles force producing ability and the effects of potential inhibition.

3.3.2 Proprioception Testing

Proprioceptive tests have varied in protocol, with both joint position sense (JPS) [11] and postural sway (PS) [96] being the main assessment tools. JPS is measured with isokinetic dynamometers that have pre-set knee flexion angles that the participants have to recall whilst blind folded. It has been shown to be reliable, valid, and is seen as gold standard [153]. PS can be measured with the use of force plates, analysed using centre of pressure (COP) changes. Measures of sway included sway area and sway path, which measures the total area and total distance respectively of centre of mass or pressure displacement during 30s data capture period [93]. JPS measured with goniometry has been shown to be less reliable [154], however this could be down to a combination of patient and measurement technique (Section 3.3.3).

3.3.3 Range of Motion Measurement

Accurate measurement of knee range of motion (RoM) is an important tool for assessing success of a KA. As highlighted in section 2.1.5 there are large differences in active and passive RoM, although active (ARoM) is seen as the most clinically representative and it will therefore be the focus of investigation. One of the most commonly used tools for measuring knee RoM in the clinical and research setting is a hand held goniometer (Figure 3.3).

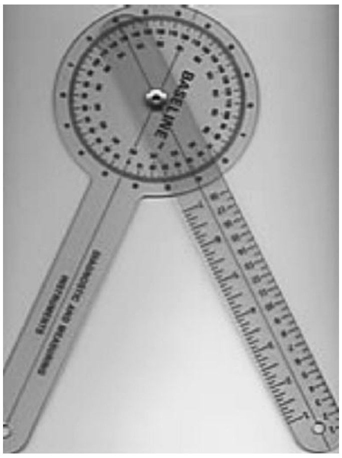


Figure 3.3: Example of a hand held goniometer

Multiple authors have reported on the consistency of measuring knee joint RoM, within-tester and between tester reliability [155]. Visual inspection of sub maximal knee joint RoM using a goniometer has been reported to be very close to the gold standard (radiographic image) [156]. Edwards et al reported that the inter-tester reliability (Inter-class correlation coefficient = 0.91) was high between 3 different testers [157]. However on closer inspection of the data there appears to be a lot more error than initially stated. Ranges of error were -14° to 5 ° more than the true degree of flexion. Twenty two percent of the goniometric measurements were greater than 5 ° different from the gold standard and 84% of these measurements underestimated flexion.

Another commonly used tool to assess joint movement and RoM during ADL is electrogoniometry. Benefits of the use of electrogoniometry include low expense (compared to motion capture), portability, and ease of use [158]. Electrogoniometry has been used to assess KA patients and establish required RoM for performing ADL post-operation [159]. When electrogoniometry was compared to motion capture systems (details of motion capture in Section 3.3.5) it was shown to replicate joint angle predictions with only minor deviations [158]. However it has been shown that electrogoniometry devices are sensitive to placement and abduction adduction angle of the TFJ [160].

Range of motion is a key outcome of KA, and is commonly measured clinically and in the research setting. Current non-invasive techniques using goniometry (hand held and electric) show potential for reasonable accuracy when the tools are used in an standardised method (fixation and placement). However when compared to the gold standard of measurement (radiographic measurement) there appears to be some error. Electrogoniometry offers the user to measure RoM at joints during ADL, however when activities involve greater degrees of flexion reliability appears to drop.

3.3.4 Electromyography (EMG)

The patterns and magnitude of muscle activity have been of interest in the research setting for many years, one of the key methods of measuring this muscle activity is electromyography or EMG. EMG is often measured by electrodes placed on the skin (known as surface EMG) over the muscle belly of interest [161], although there are other invasive techniques [162]. EMG produces a electromyogram which is a representation of the sum of electrical potential generated by motor units during a given muscle contraction. This electrical potential is elicited when there is neurological activation of the muscle creating an action potential for contraction within a motor unit. These electromyograms (Figure 3.4) are therefore represented in mV (milli Volts), with increasing levels of muscle contraction producing higher recordings of voltage (more motor units recruited). As well as magnitude of voltage, muscle firing rate is measured in Hertz (Hz).

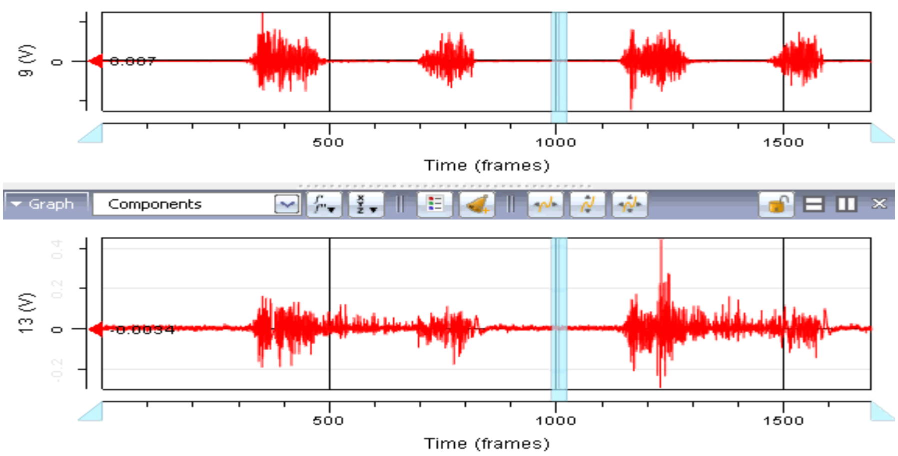


Figure 3.4: Example EMG electromyograms from vastus medialis and medial hamstrings during gait. The bursts of increase in mV amplitude and frequency are resulting from muscle contraction.

Many studies have used surface EMG when assessing knee arthroplasty function over varying times of post-operative rehabilitation [89, 163]. Studies have also looked into the reliability of surface EMG when compared to muscle contraction, with poor results for MVC [164] and fatigue testing [164]. It has been highlighted that if any kind of reliability is to be established, the instrumentation, experimental protocol, and the data processing techniques all need to be standardised [165]. It is also of note that measured electrical activity of a given motor unit doesn't directly relate to mechanical activity, particularly when muscle is fatigued [164]. Current evidence would suggest that there may be a curvilinear relationship between EMG amplitude (mV) and muscle force [166]. Although more stringent testing on multiple age, sex, and pathological subjects is needed before robust relationships can be stated.

EMG provides an indication of muscle activity during function ADL, however current evidence suggests that there is questionable reliability in the outputs and accurate conversion of the EMG signal to force production of the muscle is yet to be established. Studies using EMG in the analysis of KA patients, have been able to identify differences in muscle activation patterns [89], however these studies have been small in size and clinical relevance of the findings were limited. On the basis of the current evidence it appears that testing protocol must be defined and implemented reliably and interpretation of the EMG signal can be assessed for muscle activation timing but little else.

3.3.5 Human Movement Analysis - Stereophotogrammetry

Human movement analysis aims at gathering quantitative information about the mechanics of the musculo-skeletal system during a motor task [167]. Human movement analysis using stereophotogrammetry has progressed over the last 15 years due to major advances in hardware (camera/sensor and computing devices) software (engineering algorithms) [168]. During motion analysis information is measured pertaining to the relative movement of adjacent bones, forces exchanged with environment, and the resultant loads transmitted across body segments. Measurements during the movement analysis can include:

- relative positions of markers placed on the skin
- External forces (usually with a force plate)
- Electromyography (EMG, see section 2.24) [167]

In order to collect position data of markers placed on the skin and motion capture systems commonly use infrared (VICON, Oxford UK) or electromyomagnetic (Codamotion, Charnwood Dynamics Ltd) technology to track these markers from cameras/sensors placed around a certain capture area. The 3-D coordinates of markers are computed based upon 2-D data from two of more cameras, their known location and internal parameters. The cameras are calibrated around a set volume and global origin to capture the required data (Figure 3.5).

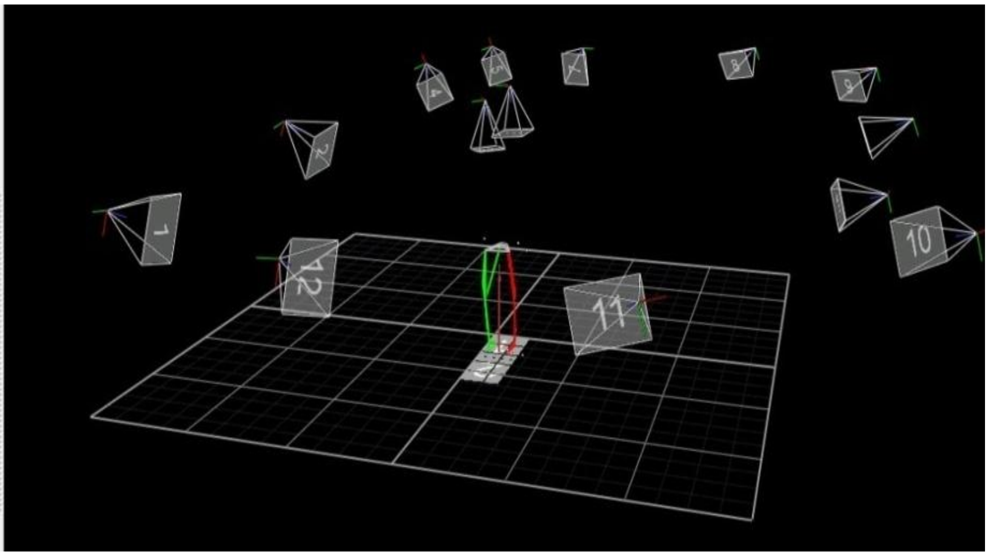


Figure 3.5: Nexus (VICON, Oxford, UK) environment for motion analysis. Cameras are mounted around a given capture are (numbered), other devises such as force plate can be included in the environment (centre).

To assess human movement motion analysis markers are placed on key anatomical landmarks (ALs). The Newington Hospital Helen Hayes model is frequently used as the basis for the marker positions (Appendix G)[169]. These markers are then used in turn to describe segmental kinematics, in order to describe these kinematics the following are needed;

- position vector and orientation matrix of an arbitrary local frame for each body segment, relative to a selected global frame, in each sampled instant of time.
- position vectors of selected particles of the link segments in the relevant local frame.

[170]

External forces are commonly captured using force plates embedded into the laboratory floor. Force plate technology has developed over the years to provide accurate and reliable measures of force and moment feedback during static/dynamic movements. The latest force plate use piezoelectric (Kistler, Zurich Switzerland) or strain gage (AMTI, Advanced Medical Technology Inc) technology to measure a range of forces and moments. Small errors in force plate centre of pressure (COP) measures have been shown in piezoelectric [171] and strain gage designs [172]. It has been highlighted that stringent calibration of force plates is required on a regular basis in order to obtain the most accurate results [173]. When the accuracy of force measures has been tested on calibrated force platforms high levels of accuracy were achieved [174].

3.3.5.1 Error in Human Motion Analysis

Recently a four part review of stereophotogrammetry was published highlighting the theoretical background [167], instrumental errors [170], error and compensation of soft tissue artefact (STA) [175], and finally the anatomical assessment and its impact on kinematic outputs [176]. This four part review highlighted the errors in the technique which has limited the accuracy of findings for many years.

The second of these review papers [170] highlighting the instrumental error in motion analysis made some key points on the estimation of position and orientation of marker data. Firstly that the markers are not rigidly associated with the underlying bones [177], and even under static conditions marker positions are not stationary due to errors intrinsic in the measuring system [170]. Instrumental errors can be described as either systematic, or random [170]. These errors can be minimised with appropriate camera calibration, however there are several methods to calibrate camera systems [178]. Random errors are often compensated for using filtering and smoothing techniques, however careful consideration must be given to the cut-off frequency (frequency where the filter takes affect) in order to retain pertinent details of the marker data [170]. Error in marker estimation also occurs when markers are occluded during a given trial, reconstruction of the missing marker can be performed using a variety of techniques but accuracy could be compromised [170]. Factors influencing the accuracy and precision of a motion capture system include:

- adequacy and quality of system
- number and location of cameras
- size of measurement volume
- size and shape of calibration object

- calibration procedure

[170]

3.3.5.2 Palpation Error in Motion Analysis

Della Croce et al reviewed anatomical landmark (AL) misplacement and its effects on joint kinematics [176]. Three main errors were highlighted for the identification of subcutaneous bony AL's through palpation.

- Palpation of AL's are not points, but surfaces, sometimes large and irregular.
- Soft tissue layer of variable thickness and composition over AL's.
- the identification of AL's depends on palpation protocol.

[176]

Others studies have also looked into palpation identification error. Piazza et al used 10 observers to palpate the medial and lateral epicondyle of the femur and found a 10mm inter-rater difference [179]. Della Croce et al studied the precision of lower limb AL's, its effects on anatomical frame (AF) orientation determination, and the kinematic prediction [176]. Intra- and Inter-examiner AL precision values were determined from subjects with skin markers attached to the pelvis and lower limb by physiotherapist who had lab experience. Intra-examiner precision was higher than inter-examiner, with the greater trochanter variation having the largest error in precision [176]. The study by Della Croce et al showed inter-examiner AL error could account for 10^{o} of knee flexion error [176].

3.3.5.3 Soft-tissue Artefact (STA)

When using optoelectronic stereophotogrammetric systems (OSS), skin deformation and displacement causes marker movement with respect to the underlying bone [175]. This movement represents an artefact, which is commonly known as soft-tissue artefact (STA). Leadini et al [178] and more recently Peters et al [183] have reviewed soft tissue artefact assessment. The studies included in the reviews provide a large quantity of data for describing the amount and the effects of STA at the lower extremities [175, 180]. The discrepancies between the values reported by different authors may be justified by the different techniques used, the large variability in the subjects analysed, the tasks performed, but mainly by the different locations of the skin-mounted markers. However, the following general conclusions were drawn:

- errors introduced by the STA are much larger than stereophotogrammetry systematic errors.
- the pattern of the artefact is task dependent.
- STA is reproducible within, but not among, subjects.
- STA introduces systematic as well as random errors.
- The STA associated with the thigh is greater than any other lower limb segment.

Studies have shown that only gross movements of the body can be estimated accurately and reliably, and that secondary smaller movement patterns cannot be estimated with true accuracy [175]. Magnitudes of STA at certain points has also been analysed at length, with shank STA reaching 11mm and 10^{o}, and thigh markers exceeding 20mm and 12^{o}, for translation and rotations [181, 182]. Both Garling et al (2007) and Manal et al (2000) found that plate mounted (PM) marker sets on the thigh and shank produced less error in terms of measured IE rotation and abduction outputs when compared to skin mounted (SM) markers [181, 182]. Manal et al (2000) also found that location of the marker arrays over the lateral shank was the only factor to statistically influence estimates of tibial rotation when compared to marker fixation techniques [181].

3.3.5.4 Optimisation Methods

When kinematics and kinetics are determined from external marker motion analysis, the markers represent locations relative to segments and joint centres in order to equate position, velocity and acceleration properties. With the known errors in marker data (Section 3.3.5.1-3), there are errors in estimating joint kinematics and kinetics during ADL. Optimisation techniques have been developed over the recent years to combat the problem of marker noise and uncertainty in motion analysis techniques. One of the early methods of optimisation was the segmental optimisation method (SOM), which estimates the segment pose in terms of its transformation matrix by minimising marker array deformation from its reference shape in a least-squares sense [183]. Although SOM improves on directly driving segments with marker data by taking account of skin movement artefacts at the segment level, the method treats body segments separately without imposing joint constraints, which could lead to joint dislocation.

A new approach was stated by Lu and Connor [184]. Here a rigid body multilink system is attached to a marker set. The system has constraints at each joint aimed to estimate the movements which would be available in a normal human. The markers are then used to equate the position of these segments for each time phase of a dynamic trial by minimising the over-all differences between the measured and model-determined marker coordinates in a weighted least squared sense, subject to the constraints of the whole model. This technique was regarded as the global optimisation model (GOM). For each model DoF a marker coordinate vector is chosen to drive movement. However, typical lower limb musculoskeletal models have around 18 DOF, and a standard marker set of 16 markers has 48 potential drivers. This creates an over-determined system i.e. there are more known drivers than degrees of freedom. The method proposed by Lu and Connor therefore has to neglect marker data to solve the determinacy resulting in loss of key information [185]. In order to overcome this error in loss of data Anderson et al proposed a new optimisation technique [186], using principles derived from Lu and Connor [185]. Andersen proposed a method where kinematics were solved using over-determinant system (driving a MS system with more marker data than model DoF) using a 'best fit' analysis [187]. This method resulted in considerable smoothing of velocity and acceleration data from the marker drivers, which has a smoothing effect on the resultant moments about the given joints. However, it is noted that optimisation method proposed by Andersen et al cannot be seen as a direct minimiser of STA. When the method was compared to bone pin equated kinematics there remained significant errors in knee kinematics apart from gross flexion [188].

3.3.5.5 Summary of Human Movement Analysis

Despite developments in human movement analysis in recent years evidence suggest there are still systematic and random errors associated with the technique resulting in errors when estimating joint kinematics and kinetics. Systematic errors can be reduced using accurate and reliable calibration techniques along with appropriate capture volumes for a given number of cameras [170]. One of the most influential errors in stereophotogrammetry is STA, which has been shown to be very variable between subjects being assessed [189]. Optimisation methods have been developed to reduce the error associated with STA. However, to date accuracy of optimised kinematics data derived from motion capture markers is still limited to gross movement patterns [175]. In order to assess the associated error with motion analysis, accuracy and repeatability analysis needs to be conducted on; the motion capture system and forces plates, AL definition during testing, and the effects of AL definition on the estimation of joint kinematics and kinetics (optimised and un-optimised).

3.4 Discussion

The evidence presented in this chapter clearly shows the vast variety of methods that have been utilised to assess KA function. This has led to many small studies looking at specific functional scoring methods, reducing the significance of the results. When subjective and objective functional analysis has been directly compared on the same patient cohort, significant differences were found at multiple assessment times [60]. Subjective assessment techniques have been shown to be repeatable and reliable (Section 3.1), although much of this data has come from the author responsible for the questionnaire design. When more stringent testing is performed the construct validity of the measurement techniques has come under question [125]. The implication of this reduced validity and difference between subjective and objective measures is that questionnaire data alone cannot be relied on for accurate assessment of patient function. In order to evaluate function comprehensively a combination of subjective and objective measures are required [60].

Objective assessment techniques vary significantly between the clinical setting and that of the laboratory. Many different aspects of patients function can be analysed using objective measures, however the reliability and validity of the instrumentation and measurement technique is often questionable. With this in mind, stringent reliability and verification testing was undertaken in order to establish a valid testing protocol (Chapter 6). Even with reliable testing protocols in place, errors in objective measures will be unavoidable, for example, STA during motion analysis. Compensation for these errors must be implemented, and error which remains must be taken into account when analysis of the data is performed. Previous literature surrounding KA functional analysis often used measurement techniques that have been shown to be referenced to be reliable, however important evidence that may contradict this reliability is often not quoted.

Despite the widespread use of questionnaires there is a growing body of evidence suggesting that these measures can be effected by psychological factors [133], pain [190], and often the results from questionnaires do not correlate with performance based measures [60]. Objective measures of function have been considered less valid because they measure physical functioning in an artificial situation, are influenced by the subject's motivation to participate, and may provide little information about how a person copes in his/her own environment [132]. On the other hand, performance-based methods are claimed to be less influenced by psychological factors such as expectations and beliefs, cognitive impairments, culture, language, and education level [132].

3.5 Conclusion

The methods presented in this chapter show techniques that are commonly used in the research setting to assess KA function. It is evident that a number of different techniques have been used to assess perceived and observed disability in the KA population. Many of the assessment techniques have been shown to have some reliability and validity uncertainty. When these techniques are used to assess function there is a need to investigate the reliability and validity of the assessment in order to quantify the potential error in the implementation and evaluation of a given measure.

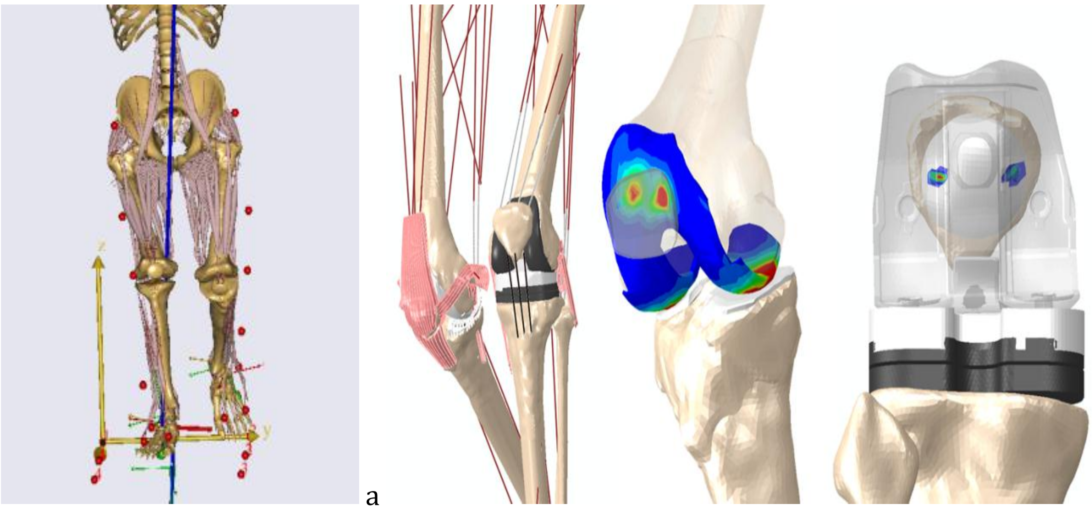
In recent years musculoskeletal modelling has been developed to predict muscle and joint forces during ADL. The potential for this technique to be used as a clinical assessment tool has not fully been explored. The following chapter will review the latest musculoskeletal modelling techniques and its potential in deriving significant clinical findings.

Chapter 4

Musculoskeletal modelling: Inverse Dynamics, Muscle Recruitment, Muscle Modelling and Errors

4.1 Introduction

Musculoskeletal (MS) modelling has progressed over the last 15 years due to major advances in computer performance, methods, accuracy and the application of sophisticated engineering and dynamic modelling procedures [168]. This is reflected in the growing interest in its application as a practical and reliable tool for use in the field of biomechanical and biomedical modelling [168]. Musculoskeletal models can be divided into two groups; forward and inverse dynamic simulations. Static optimisation, an inverse dynamics approach, has been utilised to convert motion analysis to MS models in order to predict joint kinematics and kinetics during functional ADL [191]. Static models are computationally efficient with the scope for adding detail of multiple soft tissue structures (Figure 4.1a).



a b

Figure 4.1: (a) Example of an inverse dynamic musculoskeletal model in AnyBody software application [192].(b) Six Degree of Freedom (DoF) forward dynamic implicit FE knee model. Natural and implanted knees during the step-down activity (left), stress in natural femoral cartilage (centre), contact in TKR patellar component (right) [29].

Forward dynamic optimisation (Figure 4.1b) integrates system dynamics into the solution process, muscle forces and the performance criterion are treated as time dependent state variables who's behaviour is governed by set differential equations [193]. Dynamic optimisation incurs large computational expense [194], resulting in heavily simplified models. Anderson and Pandy (2001) looked at comparing static to dynamic solutions. They used a 23 DOF MS model with 54 Hill type muscles to model the gait cycle in healthy males. They found very similar results when comparing the two types of solutions, but importantly the dynamic solutions took approximately 1000 times longer to compute [194]. Forward dynamic simulation does give the user the ability to model deformable structures and perform analysis of the effects of loading patterns, for example wear in the knee arthroplasty prosthesis.

Inverse, or reverse MS models have been developed since the early 1960's with John Paul creating a seven segment rigid body lower extremity [40]. The data sets created from the model are still widely used in the literature and help form the recommended loading patterns for *in-vitro* studies as set by the ISO. Research groups have used inverse dynamic modelling to predict joint forces in a number of different ADL [24, 25, 28] (Section 1.3). Both commercial and freeware applications are now readily available for researchers to utilise the techniques of creating subject specific models from motion capture data. Each of the applications has its strengths and weaknesses, with all the modelling applications looking to strengthen evidence for reliability and validity. However, significant differences in the anthropometric detail can be observed between MS modelling applications.

4.2 Inverse Dynamics

Inverse dynamics is a major application across the field of biomechanics, which has been used for the assessment of total joint replacements and understanding the functional adaptations specific to a design [22]. It is a method for computing forces and moments of force (torques) based on the kinematics (see Section 3.3.5) of a body and the body's inertial properties (mass and moment of inertia) [23]. Typically it uses link-segment models to represent the mechanical behaviour of interconnected segments, such as the limbs of humans, where given the kinematics of the various parts, inverse dynamics derives the net joint moments, net joint powers, and net joint inter-segmental forces [24]. Inverse dynamics computes these internal moments and forces from measurements of the motion of limbs and external forces such as ground reaction forces, under a special set of assumptions [24]. In order to describe these kinematic and kinetic quantities, there is a set of Newton-Euler equations:

$$\bar{F} = m\bar{a} \qquad (4.1)$$

$$\bar{M} = I\,\bar{\alpha} \qquad (4.2)$$

where F is force, m is mass, a is acceleration, M is moments, I is mass moment of inertia, and α is angular acceleration. These equations can then be used to model the action of a limb within a link-segment model. Traditionally this method uses a bottom-up approach, where solving the equations starts at the foot solving for the ankle joint inter-segmental forces and net ankle moments. Then the Newton–Euler equations for the shank, and lastly the thigh, are solved to compute the net joint moment and joint inter-segmental force at the knee and hip.

Joint contact force is the sum of the joint inter-segmental force, which is estimated directly from the traditional inverse dynamics approach, and the compressive joint force caused by muscle forces surrounding the joint, which is estimated using additional methodology. This additional methodology is structured to decompose the net muscle moments, which are found from the traditional inverse dynamics approach, into individual muscle moments using static optimization. The individual muscle forces are then determined from the moments using a musculoskeletal model of moment arms. The joint compressive forces are then estimated from these muscle forces and information about the lines of action of each force. The addition of force from muscle recruitment has been shown to produce the largest share of overall joint reaction [26], it is therefore essential that a valid and reliable muscle recruitment algorithm is implemented in the modelling process.

4.3 Muscle Recruitment

The solution of the muscle recruitment problem in the inverse dynamics approach is generally formulated as an optimization problem. A global function, stated in terms of muscle forces is minimised with respect to all unknown forces i.e., muscle forces and joint reactions. Constraints are added on the muscle forces, which ensures that muscles can only pull, not push, and the upper bounds limit their capability, i.e., can't work beyond their MVC [192].

There have been many different recruitment criterion developed to solve this optimisation problem, although few have provided sufficient validity. One of the most common objective functions is the polynomial recruitment criterion. Here the sum of the muscles forces are normalised typically by the strength of each muscle. This normalising factor ensures the larger muscles with the greatest capacity to produce force will then work the hardest to produce a given moment. For increasing polynomial power the work between the muscles gets increasing distributed. One problem with this model is that there are no constraints for the muscle to overload (work in excess of its maximal force output). Another commonly used objective function is the soft saturation recruitment criteria. This criterion eliminates the need for additional constraints to prevent overloading the muscles.

Where the polynomial criteria can be interpreted as minimizing the weighted average of the muscle forces, the soft saturation criterion maximizes an average distance from the maximum load. The square root plays the role of insuring that no muscle reaches its maximum force if another, less-loaded, muscle can contribute to carrying the external load. This eliminates the need for the additional constraints necessary in the polynomial case, and ensures that all muscles become simultaneously fully active when the external load reaches the upper physiological limit.

A third option was proposed by Rassmussen et al, called the min/max criterion [195]. This methods distributes muscle forces so that the maximum relative muscle force is a small as possible [192]. This criterion was found to be comparable to the polynomial and soft saturation criterion [196]. Min/Max criteria ensures an even spread of force across muscle groups, rather than a single dominant muscle doing all the work. Finally, Rasmussen et al showed that polynomial and soft saturation converge towards each other and towards Min/Max for increasing power, p [16]. The Min/Max criterion appears to be attractive in the physiological sense as well as the mathematical. Assuming muscle fatigue and activity are proportional, the criteria will postpone fatigue for as long as possible [195].

The method of minimising the global function for muscle recruitment is thought to replicate that of the central nervous system (CNS), however the CNS is an extremely complicated neural system that relies on afferent feedback during movements. This general assumption that muscle force recruitment is minimised surely does not cover the true complexity of motor neurone recruitment in the human body. When studies have looked at this approach to predict muscle coordination, there has been low confidence in the optimisation methods [197] and the inability of most of these methods to predict co-contractions limits its application in KA modelling [198]. Studies have tried to use EMG to drive MS models [199]. However, these studies are limited due to the muscles which are available to surface EMG, and the known limitations of relating EMG to muscle force production (Section 3.3.4).

4.4 Muscle Modelling

With the load distribution completed by the optimisation criterion, muscles in the MS model are required to apply the specific loads. Hill type muscle models are commonly used in MS modelling (Figure 4.2) [200]. Hill component models represent the active and passive properties of the musculo-tendinous unit. Muscle models are defined by numerous parameters, which, for many musculoskeletal models, are taken from literature [201].

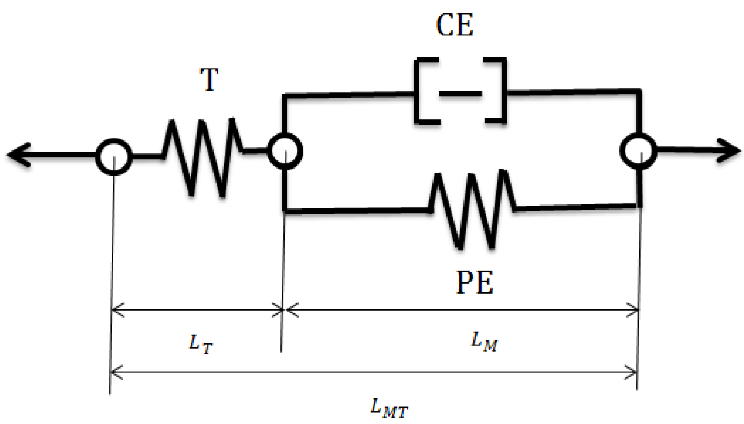


Figure 4.2: Mechanical model of the musculo-tendon actuator. Parallel elastic element (PE), contractile element (CE), and tendon (T). $\boldsymbol{L_t}$ length of the tendon, $\boldsymbol{L_m}$ length of contractile element

The functionality of the muscle elements are described as the following;

- Contractile Element (CE) Hill type contractile element, models the force/length and force/velocity characteristic.
- Series elastic element (SE), models the short-range stiffness. For the rapid and small length changes of the muscle, CE will remain at the same length working isometrically,

while the length changes will be taken up by the SE element. For larger or slow movements the CE element will take up the length changes.

- Parallel elastic element (PE), models the passive properties.
- Elastic tendon (T).

Even though this multi-element muscle model design is seen as a general standard across MS modelling, there are assumptions in the design. For example, all the muscle fibres are parallel and are inserted in the same pennation angle γ on tendon and there is no fatigue mechanism included in the model. The above model (Figure 4.2) has primarily been documented in forward dynamic models, where the models drive the system [202]. When the muscle model is used in inverse dynamic simulations it must be inverted. When sensitivity analysis of Hill Type muscles was assessed in a forward dynamic simulation it was found that optimal muscle fibre length, maximum isometric force, and the width of parabola in the force-length curve, were extremely sensitive to parameter changes [201]. This study highlighted the importance of accurate measurement and optimisation of Hill Type muscle parameters, especially those which are extremely sensitive to changes.

4.5 Errors in Inverse Dynamic Modelling

When Zajac et al reviewed inverse dynamic methods they concluded that 'the clinical applications of these methods are limited by the assumptions generically scaled models use' [23]. The authors also described the high sensitivity to changes in patient specific parameters limits the confidence in the MS model outputs. However, since this review, modelling methods have increased significantly in complexity and optimisation methods have improved motion capture data to drive models more accurately. Although many limitations of converting motion capture data to inverse dynamic modelling have been highlighted;

- highly dependent on the accurate collection and processing of body segmental kinematics [203]
- time-independence of the performance criterion required by static optimization may not permit the objectives of the motor task to be properly characterized [204]
- analyses based on an inverse dynamics approach may not be appropriate for explaining muscle coordination principles [200].

- Simplification of segments, i.e. foot is represented as a single segment.
- Joints are idealised by adding constraints, for example the knee is a hinge joint with only 1 DoF.
- Scaling of the model is generic and therefore does not represent the varying physical properties of specific subject anthropometrics.
- Soft tissues structures are ignored, for example the joint capsule and patella retinaculum in the knee.

4.5.1 Estimating Joint Parameters

Errors in anatomical landmark (AL) definition during motion capture have already been outlined (Section 3.3.5.2). In addition to these errors joint parameters such as the centre of rotation (CoR) and axis of rotation (AoR) also play a fundamental role in kinematic and kinetic analysis within MS modelling applications [23]. In most rigid body modelling systems joint centres are measured by scaling laws or regression equations taken from the pelvis and thigh segments. It has been shown that the accuracy and precision in which the hip joint centre (HJC) locations are estimated is crucial for the error propagation of hip and knee joint kinematics and kinetics [205]. HJC misplacement error of 30mm in the AP direction resulted in a mean flexion/extension error of 22% of its value [206]. However the effects of HJC location on knee kinematics was negligible [206].

4.5.2 Influence of body segment parameter estimation

Body segment parameter (BSP) refers to the estimated segmental masses, centre of mass locations, and moments of inertia. BSP influence on inverse dynamic error has a mixed evidence base. Researchers have reported low importance in BSP uncertainty [207], while others have found that inaccuracy in BSPs can generate significant variation in joint kinetics [208]. Reimer et al conducted a review of BSP and AL factors when applying inverse dynamics to gait assessment [30]. They found the main contributor to uncertainty was inaccuracy in segmental angles caused by AL definition and STA, with this error making up 90% of the uncertainty [30]. However, this study did not use any of the current global optimisation techniques used to reduce marker noise. It has been shown that global optimisation techniques significantly decrease the error between estimated marker trajectories and that measured in the lab [209].

4.5.3 Simplification of Joint DoF

In order to complete the inverse dynamic solutions efficiently, joint constraints are applied to the model to reduce the number of unknowns. This idealisation, although essential to keep the modelling efficient is not anatomically or physiologically correct. For example, the knee is commonly modelled as a hinge joint with a single degree of freedom where flexion to extension occurs [25]. It has been widely established that the knee in fact has 6 degrees of freedom, translating and rotating around all its planes (Section 2.1.7). There is however a strong argument to keep the knee with a single degree of freedom, this is mainly due to the limitations of external marker motion analysis that were previously highlighted (Section 4.4). Here the error in marker placement and STA factors are far larger than the degree of secondary motion seen in the knee joint during functional activities.

4.6 Summary of Musculoskeletal Modelling

The main limitation of the modelling process is the dependence on accurate data collection and the error in data to model conversion. Reimer et al [35] reported that torque magnitude estimates derived by inverse dynamic solutions can have uncertainties of between 6-232% [30]. Limitations in the MS modelling technique could explain some of the discrepancy in predicted joint loading and that measured by telemetrised prostheses (Section 2.2). The difference in predicted loading is likely to result from a combination of the limitations, including:

- Measurement errors in motion capture (force plate and marker trajectory)
- Error in the conversion of motion capture to MS modelling environment
- Simplification of joint DoF
- Anthropometric assumptions
- Simplified muscle models
- Assumption made in the muscle recruitment criteria

4.7 Conclusion

Inverse dynamic modelling of functional movements is still one of the few methods to assess gross kinematics and kinetics non-invasively. To date, musculoskeletal modelling has not been used extensively for assessing KA patients during functional ADL. Despite the limitations with the current MS modelling technique it may have the potential for comparative studies between groups as long as assumptions are constant in the modelling protocol. Further verification and reliability studies would give an insight into the clinical applicability of the technique to assess between healthy and pathological populations.

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Chapter 5

Methodology*: Recruitment, Subjective Assessment, Objective Assessment, Musculoskeletal Modelling and Statistical Analysis*

5.1 Introduction

To date, there have been few studies that have completed multiple functional assessments in order to establish a comprehensive evaluation of KA function. There has also been limited evaluation of factors which affect functional recovery of KA patients (Section 2.6). This study took non-invasive functional assessment techniques with the most reliable and valid analysis methods available from the literature to build a comprehensive evaluation of pre- and post-operation function. The study aimed to compare these data to those of a healthy control group in order to establish the true disparity between KA and healthy age and sex matched individuals function. Gains and losses in function were also to be established from pre- to post-operation and a hierarchy of factors affecting function recovery was built. This chapter will outline the standardised testing protocols used to achieve the aims of the project. Testing included subjective questionnaires, objective measures of muscle size, proprioception, RoM, and kinematics and kinetics of common ADL. This was aimed to establish a comprehensive evaluation of global function (Section 2.4). Close coordination was also in place with surgeons and rehabilitation teams in order to gather as much information about the KA process as possible to derive what factors affected changes in function the most (Section 2.5).

5.2 Study Populations: Recruitment and Characteristics

Before testing started institutional and National Health Service (NHS) ethical approval for the recruitment and testing protocol was sought (Appendix H). Participants were then recruited for the study; both healthy and pre-operative KA patients were needed in order to complete the aims of the project. With the time limitations of the study (3 years), realistic targets were established to fulfil the aims of the project. In order to make comparisons, a control group of healthy age and sex matched participants (to the KA population) were analysed with the standardized protocol. This data set provided a baseline from which comparisons can be made for both the pre- and post-operation KA patients. Twenty healthy individuals were therefore recruited from the local community (Participant demographics in Table 7.1), with the appropriate institutional ethics obtained to collect the necessary data. Participants were eligible if they were between the age of 50-80 years and had no previous lower limb pathology in the last 2 years, had the ability to walk, sit-stand-sit, and descend stairs with relative ease.

The pre- and post-KA patients were recruited from Southampton General Hospital (SGH), the consultant surgeon provided the initial point of contact for patient recruitment and were subsequently followed up by telephone by the principal investigator. Forty patients were recruited for the investigation (Patient demographics in Table 7.1), which consisted of patients who are scheduled for a TKA or UKA. Patients were eligible if they are receiving their first primary joint replacement, and had no other pathology which could bias the results. Patients were seen at 4 weeks pre-operation and then 6 months post-operation. Further follow up was not sought due to the time restrictions of the project. The total number of participants recruited (sixty) was a factor of the time constraints of the project, constraints on laboratory time, ethical limitations (numbers sought in the application), and the time needed for recruitment.

5.3 Subjective Assessment

From the review of the current methods to assess KA function there are many different questionnaires and scores that have been used to date (section 3.2). The questionnaires specific to knee function that have been shown to be reliable and valid are the WOMAC (Appendix F), the 12 item Oxford Knee Score (Appendix E), and the VAS. These were used during this study and all were implemented according to the standardised instructions for each questionnaire. Both the WOMAC and 12 Item OKS provided feedback from the patient for pain, stiffness, and difficulties performing ADL. The VAS scores were used to assess pain at rest and during activity, as well as instability in their operated knee. Participants marked down on a standardised 10cm long scale (Figure 3.1) where they felt there symptoms were applicable. Questions were structured in the following way;

- ‘How much pain do you have during activity in your affected knee? 0 is no pain at all, and 10 is the worst pain imaginable.’
- ‘How stable does your knee feel going up and down stairs. 0 is fully stable, and 10 you can’t manage the stairs due to instability.’

These questions were used for the healthy control, pre-operation, and post-operation participants. In addition to these all of the participants were also asked;

- 'Which leg would you consider to be your dominant side, right or left?'
- 'How much activity do you undertake during an average week? Activity would be defined as working up to the point where you are slightly out of breath.'

However, in addition to this patients who were scheduled for KA were asked a series of questions depending on whether they were attending a pre- or post-operative assessment. Pre-operatively they were asked;

- 'How long have you been suffering from your knee OA, to the nearest year?'.

Post-operatively the patients were asked the following questions;

- 'How many days did you spend as an inpatient?'.
- 'Did you reach your functional goals of 90^{o} knee flexion and a straight leg raise (SLR)?'
- 'How many hours of outpatient physiotherapy did you receive?'
- 'How much activity do you undertake during an average week? Activity would be defined as working up to the point where you are slightly out of breathe.'
- 'If you were to give your knee replacement a mark from 1-10 for your current satisfaction, what would you give it?'

5.4 Objective Assessment

During the objective assessment a comprehensive examination was performed in order to build a data base of all the factors that are known to affect function (section 2.4). The same objective assessments were used for the control, pre-operation, and post-operation examinations.

5.4.1 Anthropometrics

In order to create participant specific models a detailed anthropometric assessment was performed. Each participant was measured for height, weight, leg length (tape measure), knee width, and ankle width (callipers). Body Mass Index (BMI) was then calculated from the height and weight data (Equation 5.1).

$$BMI = \frac{mass\ (kg)}{height(m)^2} \qquad (5.1)$$

5.4.2 Range of Motion (RoM)

RoM in the knee joints of each participant were measured using a hand held long arm goniometer (Figure 3.3). Participants were asked to take both of their knees into full active extension, followed by full active flexion one leg at a time. The goniometer was placed on the lateral joint line, with the arms of the device directly along the line of the femur and fibula.

5.4.3 Rehabilitative Ultrasound Imaging (RUSI)

In order to assess muscle size rehabilitative ultrasound imaging (RUSI) was used. This technique was used for several reasons following the review of muscle strength assessments (Section 2.2.1). RUSI offered a quick and painless assessment of multiple muscles within the thigh, which has been previously validated against gold standard imaging techniques [148]. Although this did not give a direct measure of muscle force production, it did give a measure of muscle size, which is known to be closely correlated with force of quadriceps [210] and hence an indirect measure of force. Muscle size could then be assessed from one limb to another in order to find an estimate of muscle asymmetry (percentage atrophy). It is of note that strength deficit in KA patients is not just a result from muscle atrophy, inhibition is another key factor (Section 2.4.4). Interpretation of the RUSI findings was presented with the known limitation that inhibition was not taken into account in the analysis.

Imaging sites were standardised as follows:

- Rectus Femoris (RF); 50% length of thigh (greater trochanter to lateral joint line)
- Vastus Lateralis (VL); 66% length of thigh (distal to greater trochanter)
- Vastus Medialis (VM); proximal and medial to superior aspect of patella.

A real-time ultrasound scanner (Aquila; Esaote SpA, Genova Italy) with a 6-MHZ linear transducer array (60-mm footprint) was used to take B-mode cross-sectional images of the RF, VL, and VM muscles. Muscle borders were established by the fascia surrounding the muscle and measurements were taken at standardised locations on each image (Figure 5.1). Measurements of the muscle images were interpreted using ImageJ software [211] (available at: http://rsb.info.nih.gov/ij/docs/index.html).

Muscle thickness of RF was measured as the greatest vertical distance between the anterior and posterior borders of RF from their inside edges. Width of RF was measured at 50% of the vertical distance between the anterior and posterior borders of RF, perpendicular to the vertical measure (Figure 5.1). Although not necessarily a measure of maximal width, this method of measurement was chosen because it avoided potential errors from interpretation of the lateral borders, which was problematic in some cases. Cross-sectional area (CSA) of RF was measured by tracing the inside edge of the border of RF using the on- screen cursor.

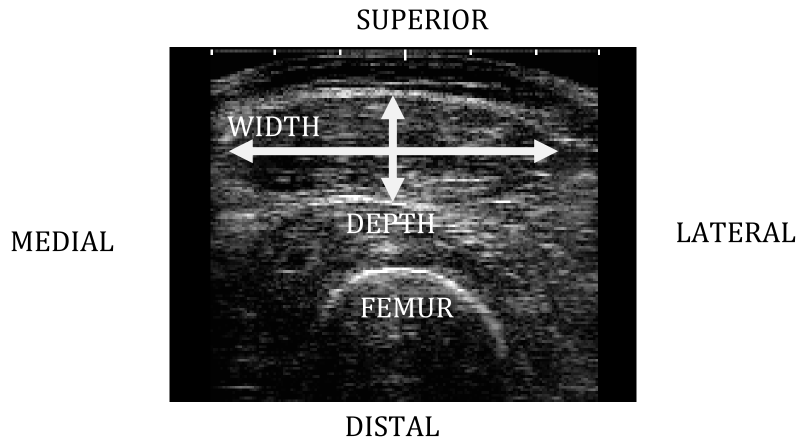

Figure 5.1: Ultrasound of Rectus Femoris taken in supine with knee fully extended. Top of the image is the superior structures of the thigh (skin, subcutaneous tissue), bottom of the image are the distal structures (femur).

Muscle thickness of VM was measured by finding the deep medial border of the muscle which lies adjacent to the medial femoral epicondyle. A line was then traced through the muscle in line with the bone feature of the epicondyle up to the point where the line met the underside of the superficial muscle fascia (Figure 5.2).

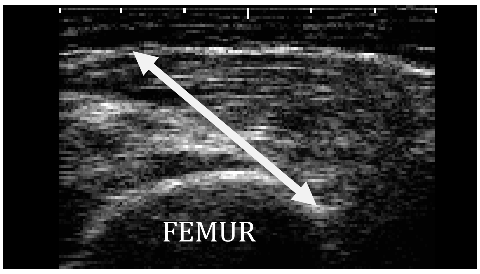

Figure 5.2: Ultrasound of Vastus Medialis taken in supine with knee fully extended. Top of the image is the superior structures of the thigh (skin, subcutaneous tissue), bottom of the image are the distal structures (femur).

Thickness of VL muscle was established by tracing a line from the prominent aspect of the lateral border of the femur, vertically travelling up through the muscle belly to the underside of the superficial muscle border (Figure 5.3).

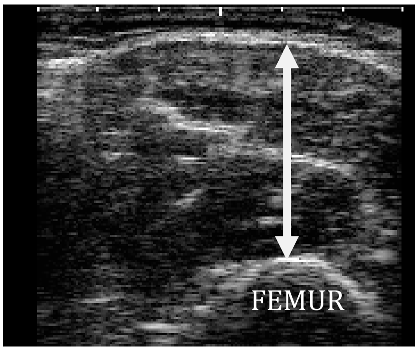

Figure 5.3: Ultrasound of Vastus Lateralis taken in supine with knee fully extended. Top of the image is the superior structures of the thigh (skin, subcutaneous tissue), bottom of the image are the distal structures (femur).

Image interpretations were repeated twice and averaged, followed by an averaging of the two images taken for each muscle of each participant. As the literature highlights the need for stringent reliability checks for both imaging and interpretation, these were performed prior to the main investigation (Section 6.2).

The measurements from the musles of each leg were then compared to assess between limb asymmetry of muscle size. It is hypothesised that the pre- and post-operative KA patients would present with some muscle atrophy of quadriceps in their effected limb

(Section 2.4.5). As a comparions the muscle dimensions of the dominant and non-dominant limb were also compared in te healthy group. Percentage difference in muscle dimensions between the limbs were labelled as '% atrpohy'.

5.4.4 Proprioception

The initial aim for the project was to measure both dynamic proprioception (postural sway) and joint position sense (JPS). However when JPS was assessed using the VICON during the pilot testing, occlusion of the anterior iliac crest markers caused loss of data (impossible to locate hip joint centre). Therefore only postural sway was measured to gather information of dynamic balance. Postural sway was measured in bilateral leg standing and single leg standing for 30 seconds. Subjects were asked to stand on either one or two Kistler force plates (Kistler Instrument AG, Winterthur, Switzerland), where forces, moments, and centre of pressure (CoP) were analysed. Sway coefficient was calculated using the following formulae;

$$\text{Anterior} - \text{Posterior Coefficent} = \sqrt{\left(\text{mean}\left(\frac{F_x}{\text{mean}(F_x)}\right)^2\right)} \qquad (5.2)$$

$$\text{Medial} - \text{Lateral Coefficent} = \sqrt{\left(\text{mean}\left(\frac{F_y}{\text{mean}(F_y)}\right)^2\right)} \qquad (5.3)$$

$$\text{Sway Coefficient} = \left(\text{mean}\left(\sqrt{((F_x/\text{mean}F_x)^2) + \left(F_y/\text{mean}F_y\right)^2}\right)\right) \qquad (5.4)$$

where F_x is force in the medial-lateral direction, and F_y is the force in the anterior-posterior direction.

5.4.5 Motion Capture of Activities of Daily Living

Motion capture techniques were used to assess ADL movements for all of the participants. During the initial part of the healthy control group testing a 6 camera VICON 460 system was used to recreate retroreflective markers placed on the participants. However towards the end of the control group testing the camera system began to suffer from technical difficulties. A new system was therefore installed to finish the control testing and the complete the pre- and post-operative KA assessment. This change in equipment needed to be analysed to check for reliability and validity of results (Appendix I). This comparison was conducted using the final two healthy control subjects. Mean static differences in marker trajectories were below 2.5mm, and under 3.3mm during a dynamic trial. However, during the dynamic trials there were considerable ranges in differences between the systems (up to 28mm at the periphery of the capture area). These measured differences could have resulted from a number of factors, and it is of note that the comparison was conducted with five of the old cameras, and twelve of the new. The largest errors were observed at the periphery of the capture area. These differences in measures between equipment were of obvious concern, however they were unavoidable with the equipment changes and the mean errors were under that of known STA deviations in marker trajectories and AL placement error (Section 2.2.5.2). Given the previously highlighted systematic errors in the motion capture equipment and calibration procedure, stringent testing was performed prior to the testing within the present study (Section 6.3).

Nine millimetre retroreflective markers were placed on key anatomical landmarks using a modified Helen Hayes marker set [205] (Appendix G). These markers were placed in order to represent segment and joint centre locations during dynamic movement. These markers are prone to error (Section 2.251). Therefore the reliability of marker placement was tested in order to ensure repeatability of measures (Section 6.4). Synchronised with the motion capture, analogue data were collected from a number of sources. Two Kistler force plates (Kistler Instrument AG, Winterthur, Switzerland) measured forces, moments, and centre of pressure (COP) of foot reactions from all the activities captured. Electromyography (EMG) was collected from seven muscles on each lower limb; vastus medialis, rectus femoris, vastus lateralis, medial hamstrings, lateral hamstrings, gastrocnemeus, and tibialis anterior. Electrode placement was conducted by researcher PW, and protocol followed the SENIAM guidelines (www.seniam.org) for skin preparation, placement, and processing (band pass filtering). Analogue signals from the NORAXON MyoSystem1400 (NORAXON, Arizona, USA) were imported into the VICON workstation, sampled at 1080Hz through a transceiver unit. The data were band pass filtered using a 20Hz high pass (to remove low frequency noise) and 500Hz low pass filter (normal range for functional contractions is between 10-250Hz).

5.4.6 Activities Assessed

Motion capture techniques give a unique opportunity to assess many different ADL. Activities need to be chosen to represent movement patterns that are commonly performed but also offer a challenge to those who have undergone KA. Studies have looked at what activities are performed most during an average day, with gait, sit-stand-sit, and stairs being some of the most common [21]. These activities have also been shown to challenge patients who have undergone KA, with known adaptations to the movement patterns and joint loading (Section 2.4.8). They were therefore chosen as the ADL to assess for the present study. In addition to these common ADL a static standing trial was also taken. It is of note that step-descent differs from stairs descent. However it is a movement that challenges strength and joint RoM in the lower limb. The step-descent activity was performed off a standardised 18cm step with the force plate mounted into it. The participants performed the step-descent leading with both right and left legs. The sit-stand-sit activity was performed using a standardised 45cm chair, the back of the chair was removed so the iliac crest markers were not occluded. Each activity was performed five times by all participants at a self-selected speed collecting marker, force plate, and EMG data.

5.5 AnyBody Musculoskeletal Modelling

The motion capture data of the three selected ADL were converted in subject specific MS models using AnyBody (Aalborg, Denmark). AnyBody is a MS modelling application which is designed to simulate ADL, predicting muscle and joint forces (Chapter 4). The software uses an anthropometric data set from Klein Horsman et al [212], along with standards from the International Society of Biomechanics (ISB) to provide a user interface to model subject specific motion capture data. MS modelling consisted of a multi-link rigid body system that has a number of constraints (18 DoF in total) at each joint (Table 5.1).

Table 5.1: Details of the joints and their degrees of freedom in the AnyBody Musculoskeletal modelling system.

Joint	No. DOF	Movements
Pelvis	6	Pelvis moves freely within the MS modelling environment
Sacro-lumbar	0	Trunk tracks movement relative to pelvis
Hip	3*2	Flexion-Extension, Abduction-Adduction, Internal/External Rotation.
Knee	1*2	Flexion-Extension
Sub-Talar	1*2	Inversion-Eversion
Talo-calcaneal	1*2	Dorsiflexion-Plantar flexion

This inverse modelling application suffers from many of the limitations highlighted in Section 4.5. In order to derive kinematics and kinetics, assumptions have to be made in order to make the modelling process efficient. The creation of participant specific inverse dynamic models is made up of several stages in model preparation and refinement.

5.5.1 Model setup

The first step was to create a baseline model of the participant who is being modelled using a static trial (participant is standing in a neutral position with arms folded at chest height) taken from the motion capture system. Marker and anthropometric data were transferred to the musculoskeletal modelling software. The environment of the modelling system was matched to that of the motion capture session, with a global centre from which the markers coordinate systems relate. The makers placed on key anatomical landmarks (Section 4.35) were then used to position and scale the musculoskeletal model (Figure 5.4). This data was exported in c3d format, these binary files contain all of the pertinent data related to the motion capture system, markers, and force plate data.

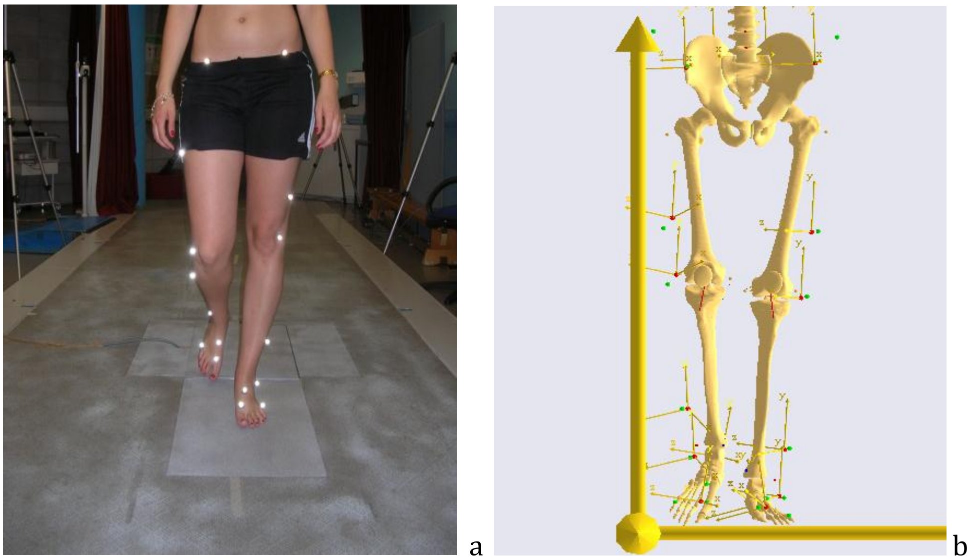

Figure 5.4: (a) Markers captured during motion analysis. (b) AnyBody modelling system, with imported markers and scaled model.

A 12 segment rigid body model is scaled in AnyBody to reflect that of the participant that is being modelled, using both the anthropometric measures, the motion capture data, and the digital camera feedback. The MS modelling interface used generic scaling laws to adjust the anthropometric data set [212]. The model estimated joint centres, masses, inertia points, and muscle attachment sites, and geometries which scaled in accordance with a linear geometry scaling law;

$$s = Sp + t \qquad (5.5)$$

Where s is the scaled point, S is the scaling matrix, p is the original point, and t is the translation. In order to scale both the soft and hard tissue structures a Length-Mass-Fat scaling law was used, where tissues such as fat, muscle, bone and cartilage are scaled as a function of the participant's Body Mass Index (BMI).

When the model had been scaled it was positioned within the three-dimensional (3-D) environment, this was achieved through changing the global position of the model and adjusting the position of the joints (i.e. changing flexion, abduction, rotation angles). The marker coordinates relative to the segments represented the data collected within the motion capture session, marker locations on the musculoskeletal model were estimated. This was achieved through changing the location of nodes in the local coordinates frames of each of the segments (Figure 5.5). This part of modelling, although time consuming, was essential for the accuracy of the model, with markers ultimately driving each of the segments. This process was assisted with visual feedback provided by the Basler digital cameras in the sagittal and transverse planes.

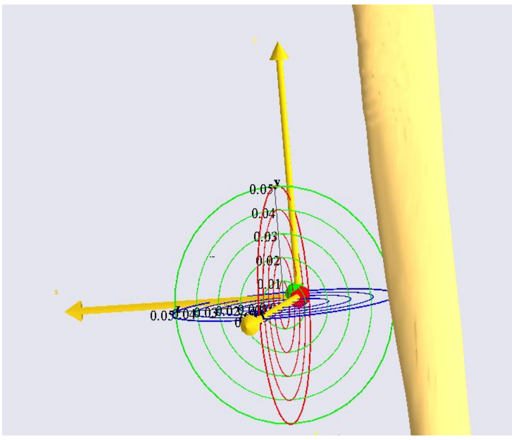

Figure 5.5: Node re-positioning for estimation of marker positions.

After initial scaling was performed these scaling parameters and marker positions were kept for the subsequent kinematic and kinetic analysis of the dynamic trials.

5.5.1.1 Kinematic analysis

During the dynamic trials the model were driven by the marker coordinates derived from the motion capture data. However it is well known that there is error in these marker locations (Section 3.3.5.1), although there are optimisation methods available to minimise the known error (Section 3.3.5.4). The method proposed by Andersen et al was used to estimate position, velocity, and accelerations of the multi-link segment model [187]. This approach for solving position, velocity, and acceleration of an over-determinate system (more maker drivers than DoF) subject to model constraints splits the original equation into two;

$$\Phi(q,t) = 0 \qquad \text{(5.6, the original position analysis equation)}$$

$$\Gamma(q,t) = \begin{pmatrix} \Psi(q,t) \\ \Phi(q,t) \end{pmatrix} \qquad \text{(5.7, Andersen et al equation for position analysis)}$$

where q is the assembled coordinate vector for all of the segments and t, is the elicit time. In the Andersen et al proposed method the original equation of position analysis,$\Phi(q,t)$, has to be solved exactly. The additional equation$\Psi(q,t)$ only has to be solved as well as possible. During the kinematic analysis the experimental data belongs to Ψ and joint constraints and additional driver equations toΦ. In order to solve Ψ a constrained optimisation problem can be solved where a scalar objective function is introduced, G, as a function of the constraint equations that are allowed to be violated [187].

$$\min_{q} \quad G\big(\Psi(q,t)\big) \qquad (5.9)$$

$$s \cdot t \qquad \Phi(q,t) = 0,$$

There have been a few objective functions with respect to solving the marker position analysis previously reported in the literature, including a weighted least-square with a time varying weight matrix [184, 213]. The time-dependency in the weight matrix can be used to vary the weights on the measurements differently along the motion, for example when a measurement can be trusted its weight can be reduced. However, there is very limited evidence suggesting validity of certain markers during a given movement, therefore this weighting matrix is very difficult to deem. When the optimisation problem had been solved in equation 5.9, the system coordinates q were known for each time step of a trial, however velocities and accelerations need to be derived. Andersen et al showed that it was possible to derive exact equations for these using Karush-Kuhn-Tucker (KKT) conditions for optimality [214].

5.5.1.2 Kinetic analysis

From the derived position, velocity, and acceleration analysis of each segment within the model, joint moments about joint DoF were equated. These moments were calculated by multiplying the mass moment of inertia of each segment by the angular acceleration about each joint (Equation 4.2). As discussed in section 4.3, muscle recruitment was optimised about each joint to solve the indeterminacy. There are over 300 Hill Type muscles in the MS model (Figure 5.6), each having its own set of parameters taken from the literature.

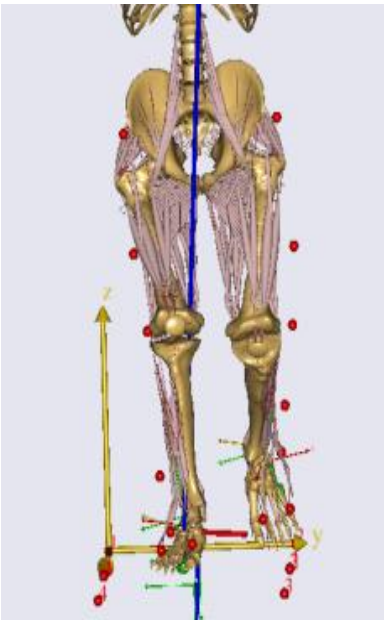

Figure 5.6: Twelve segment AnyBody MS model, with eighteen DoF and over 300 Hill Type muscles.

Muscles were calibrated prior to a dynamic trial; this process runs through the specified movement and computed the variation of the origin-insertion length of the muscle. It subsequently changed the user-defined value of the length of tendon,L_t, such that the length of the contractile element equals the optimum muscle length, L_m, when the origin-insertion length is at its mean value. The rationale behind this method of tendon length calibration is that if you analyze a movement that is representative for what the body is created to do, then the muscles should probably attain their optimum fibre lengths somewhere safely within the interval of movement. Once calibration of muscles was completed the optimisation criterion was implemented. A MinMax recruitment criterion with an upper bound restriction, and a quadratic weighting term were selected. The upper bound restriction provides the limit where any given muscle cannot work beyond its MVC. A weight used to tune the influence of the quadratic term. Muscle recruitment was normalised to muscle physiological CSA which is directly linked to force production of each muscle. This produced a combination of soft onset and offset of muscles together with a clearly defined envelope on which several muscles cooperate evenly to carry the load. Verification of this recruitment solver was performed by comparing the predicted muscle recruitment to the EMG data collected during the motion capture testing (Section 6.6). Final joint reactions were derived from the combination of applied (force plate), known (segment mass), and optimised muscle forces acting about each joint (Figure 5.7).

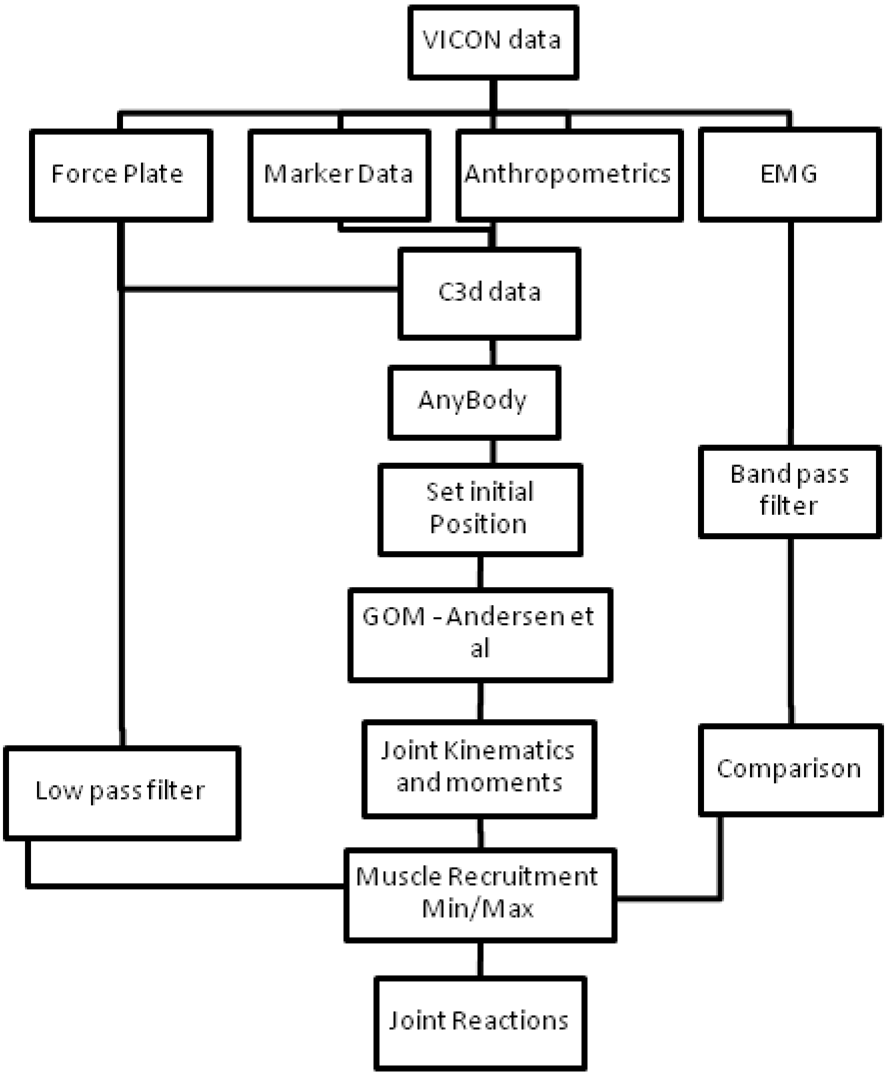

Figure 5.7: Flow chart of motion capture to MS model.

5.6 Details of Surgical Assessment and Procedures, and Rehabilitation

This project worked in close collaboration with the surgical team at Southampton General Hospital (SGH). Prior to surgery each surgeon was given a standardised form to fill out highlighting the details of the surgical approach and prosthesis used (Appendix D). This feedback sheet also detailed surgeon perceived valgus-varus correction, as well as pre- and post-surgical range of motion at the effected knee. Details of the surgeon performing the operation were also noted i.e. whether the surgeon was a consultant or registrar. Details of the rehabilitation comprised patient reported days spent as an inpatient, and the number of hours of outpatient physiotherapy. This is obviously subject to error, if the patient cannot recall their precise amount of therapy.

5.7 Statistical Analysis

Given the comprehensive and complex nature of the evaluation of patient function, one of the key elements is the choice of statistical analysis. Other projects which have tried to combine multiple data sources have used a variety of statistical methods. The MS modelling of gait, sit-stand-sit, and step-descent gives the opportunity to export waveform data of joint kinematics and kinetics, muscle forces, foot reaction data, and centre of mass (COM). With the vast volume of data being collected one of the main statistical aims was for data reduction [215]. There are difficulties associated with the analysis of ADL information, with temporal dependence [216] and variability [38] being two of the most significant factors [215]. During the proposed data collection process there were multiple variable outputs which consisted of discrete and non-discrete data. In order to reduce the number of variables taken into the final analysis, careful consideration of the potential of each variable to discriminate between participants groups (Healthy, OA, KA) was needed. This section discusses statistical methods used in the reduction and analysis of the data.

There were many stages to the statistical analysis in order to complete the given aims of the project. These stages were

1. Normalise data in order to perform comparison analysis
2. Reduce data whilst retaining pertinent details of the original data set.
3. Identify variables that best discriminated between groups
4. Collate data into a statistical format where group classification can be achieved
5. Define changes in pre- to post-operative functional status
6. Create a hierarchy of factors which have contributed to the functional gain/loss.

5.7.1 Data Normalisation

In order to compare data sets normalisation was implemented. There have been various ways to normalise differing data series in the literature and choosing the correct normalisation tool is essential. The literature suggests there are some simplistic techniques, and some are more complex. To process the waveform data from joint kinematics and kinetics interpolation was used to normalise data to percentage activity

(0-100%). This interpolation of the data resulted in a certain amount of loss depending on the number of original data points. Most data collection during ADL is performed between 50-120Hz, with a gait cycle taking a little over a second in most average participants. If you sample at 120Hz, and the gait cycle takes 1.2 seconds, this results in an interpolation loss of ~17% from the original data set. With this in mind, the interpolation of the data can also be seen as a data reduction technique. In addition to this reduction in data points, outputs of forces and moments at joints were normalised to percentage body weight (BW). This is a common method applied to joint kinetics in several previous studies [25, 28, 36]. This takes a large amount of the variance away from the magnitude of the force and moment outputs.

5.7.2 Data Reduction

A severe example of data reduction is also very common in the literature, where just one section of ADL is taken, for example stance phase of gait [217, 218]. This results in reduction of variance by taking out some of the temporal dependence from the activity; however data from the swing phase of gait is completely lost. In the extremes of data reduction single points (usually maximal/minimal values) are taken from the waveform data for analysis [87]. This then makes for much easier analysis, with discrete values representing a given ADL for a participant group. This does however result in the loss of a huge amount of data which might be fundamental in classifying certain groups. This loss of data has led to other statistical techniques being applied to waveform data, in order to reduce data without loss of detail, one of which is principle component analysis (PCA).

5.7.2.1 Data Reduction - Principle Component Analysis (PCA)

Principle Component Analysis (PCA) is a widely used technique which can be found across the scientific spectrum. PCA is a simple, non-parametric method of extracting relevant information from confusing data sets. PCA can reduce a complex data set to a lower dimension to reveal trends, with the main goal of PCA being to compute the most meaningful *basis* to re-express a noisy data set. This allows the user to discern which data are important, redundant, or just noise [219]. An example of PCA is reduction of waveform data which has been performed on gait data which can date back over a decade [220]. However, recent publications have highlighted its potential for quality analysis [41, 42, 91]. PCA has been described as the 'first choice' in data reduction techniques in a review by Chau et al [220].

PCA is an algebraic algorithm that attempts to find a small set of orthogonal new variables or principle components $\{P_j\}$ (PCs) that sufficiently captures the total observed variation in the original variables $\{X_i\}$ (Figure 5.8). The PCs are linear combinations of the original variables, with the jth PC given by,

$$P_j = a_{j\,1}X_1 + a_{j\,2}X_2 + \cdots + a_{j\,n}X_n, where \quad \sum_i a_{ji}^2 = 1. \tag{5.13}$$

The coefficients $a_{ji}, i = 1, \dots, n$ are called the factor loadings. The magnitude of $a_{ji}$is indicative of the amount of variance in variable X that is captured by the PC, P_j. The sign of a_{ji} indicates the correlation between PC and the variable. PCA can be interpreted as an optimisation that finds the minimum squared distance between data points, x_i, and their projection of data points from a space of lower dimensionality $\hat{x}_i$. The object of PCA is to find an n-dimensional space S to minimise.

$$\phi(S) = \sum_i (x_i - \hat{x}_i)^T (x_i - \hat{x}_i), \tag{5.14}$$

where T denotes the transpose. The projections $\hat{x}_i$ are determined by the space S, whose orthogonal axes are defined by the PCs. In order to preserve the variance of the original data, optimisation is performed through eigendecomposition of the correlation matrix of X.

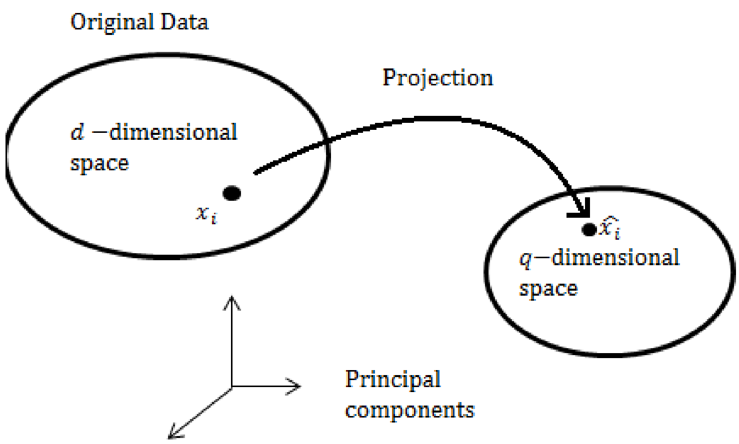

Figure 5.8: Action of PCA [215].

Within the present study PCA of each waveform was performed by:

1. Standardisation of the entire dataset so that each variable (1% of the waveform) has zero mean and unit standard deviation.
2. Eigendecomposition approach; compute correlation matrix $C = XX^T/(n-1)$. Find its eigendecomposition, $C = E\Lambda E^T$, where Λ is the diagonal matrix of eigenvalues sorted from largest to smallest and the columns, and E are the corresponding eigenvectors. The variance of the jth PC is given by λ_j. The first PC has the largest associated variance whilst the last PC has the smallest variance.
3. Calculate the minimum amount of PCs that describe the original data set
4. Assign meaningful labels to the PCs

There are numerous possible methods to determine the number of PCs needed to adequately explain the original data. Kaiser's rule has been used by several authors [42, 90, 221], where any PC with a variance less than one is not retained. This method however has led to <95% of variance explained in retained data which has the potential for misleading interpretation. Another method is to examine the cumulative percentage of total variance each PC explains. The total variance, t_m, accounted for by the first m PCs is given by $t_m = (\frac{100}{p})\sum_{j=1}^{m}\lambda_j$. The number of PCs required to explain q% of the variation is the smallest value of m for which $t_m \geq q$. A commonly used value of q is 95%, where the majority of variance is explained. However for gait analysis data there is often significant noise present, and a lower value maybe selected to cut the number of PCs down. Deluzio et al chose a 90% criterion, however only a low number of PCs met the criteria implying an underlying structure to the variability present in the gait waveforms [42]. When Jones et al used the Kaiser criterion, they also found only 2-3 PCs were included for the post PCA analysis [91] . An example of the knee flexion for the pre-operative patients is shown in Figure 5.9. The figure shows the cumulative mode energy (explanation of variance, q) of the data from all of the patients. It is clear to see that the first three PCs explain 95% of the variance, thus giving the ability to reduce the data set. It is of note that the PCs retained from the analysis can then be turned back into the original data, which represents the variance in the original data set.

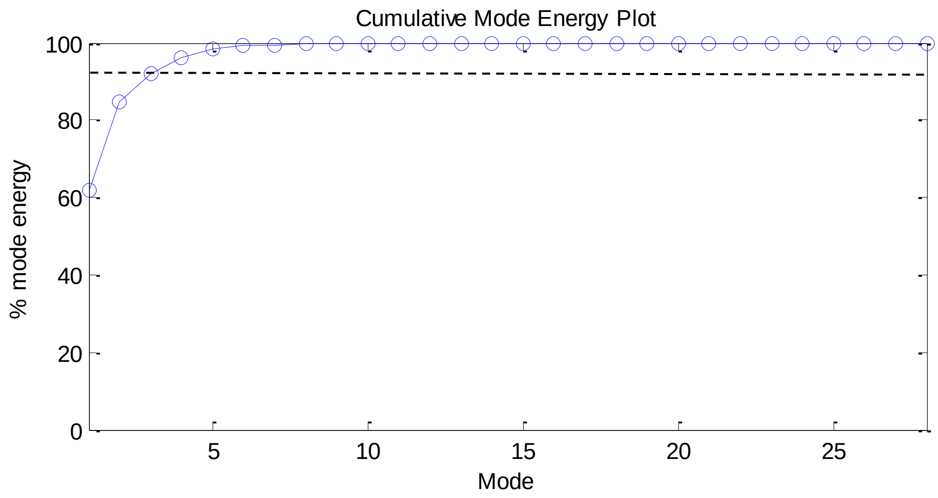

Figure 5.9: Cumulative Mode Energy plot of knee flexion during the gait cycle.

5.7.2.2 Data Classification - Linear Discriminate Analysis (LDA)

Discriminate analysis has been an active area of research for over 70 years since the celebrated paper of Fisher in 1936 [222]. Linear discriminate analysis (LDA) techniques have subsequently been applied in a wide variety of problem domains. This approach has been applied to define differences in gait characteristics between healthy and OA groups [223], and comparing PC scores derived from PCA [42]. LDA is also closely related to PCA in that both look for linear combinations of variables which best explain the data. LDA explicitly attempts to model the difference between the classes of data, whereas PCA does not take into account any difference in class, and factor analysis builds the feature combinations based on differences rather than similarities. LDA constructs linear discriminates between the populations by some measure of maximal separation. LDA gives the user visual feedback on the separation between groups within given data sets. There are several steps in order to measure this maximal separation, an example of the technique is described below.

One form of LDA is Fisher linear discriminate analysis (FLDA), where a transform matrix W is sought, such that the sample x_i can be projected into dimensional space as

$$z_i = W^T x_i, \qquad i = 1,2, \ldots l. \qquad (5.15)$$

The matrix W is computed by simultaneously maximising the overall separation between centres of the m classes, and minimizing the sum of the within class scatter in the transformed space of dimension q. This involves maximising the Rayleigh quotient

$$J(W) = \frac{W^T \sum_b W}{W^T \sum_w W} \qquad (5.16)$$

where $\Sigma_b$and Σ_w denote the between and within class covariant matrices, which are defined as;

$$\sum\nolimits_b = \sum_{i=1}^{m} (\boldsymbol{u}_i - \boldsymbol{u})(\boldsymbol{u}_i - \boldsymbol{u})^T \qquad (5.17)$$

and

$$\sum\nolimits_w = \sum_{i=1}^{m} \sum_{x_j \in S_i} (x_j - \boldsymbol{u}_i)(x_j - \boldsymbol{u}_i)^T \qquad (5.18)$$

where $\boldsymbol{u}$ denotes the global centre of all the samples, and $\boldsymbol{u}_i$ denotes the centre of class i. To maximise the Rayleigh quotient $J(W)$, the transformation matrix $W$is computed by solving the eigenvalue problem

$$\sum\nolimits_b W = \Omega \sum\nolimits_w W, \qquad (5.19)$$

where Ω 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 5.10).

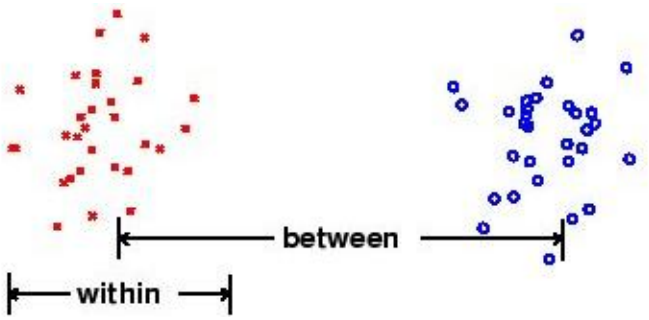

Figure 5.10: Example of within and between class covariance.

The present study used LDA to find variables which offer the highest discrimination between KA and healthy participants. It is of 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.

5.7.2.3 Data Classification - Dempster-Shafer Theory (DST)

With the large number of variables collected during the assessment there is a need to find a method to collate the measures. The Dempster–Shafer theory (DST) is a mathematical theory of evidence. It allows one to combine evidence from different sources and arrive at a degree of belief (represented by a belief function) that takes into account all the available evidence [224, 225]. During the proposed data collection process there are multiple variables being collected about the function of Healthy, pre-, and post-KA individuals. With the relevance of each variable in discriminating between the groups partially described by the LDA, the DST classifiers offered the opportunity to expand the analysis. Some variables may support, not support, or offer no significance in a participants classification. This in turn then provides an element of uncertainty when trying to classify between groups. This uncertainty is difficult to quantify using the LDA and PCA approaches when classifying between groups. The DST provides a way of using mathematical probability to quantify subjective judgements [226]. The DST comprises two main elements: the assignment of belief values to different hypotheses, and the combination of belief values [226]. Jones et al used DST to provide a basis for classification between Healthy and TKA/OA patients [91, 227]. The classification method comprised of a number of stages;

1. ***Conversion of input variables into confidence factors***. Variables (v) are standardised to a confidence factor ($cf(v)$), on a scale of 0-1, and represent a level of confidence in the variable's support of a given hypothesis (x).

2. ***Conversion of confidence factors to Body of Evidence's (BoEs) using DST***, i.e. a set of belief measures established within the context of DST. Belief measures are; belief in the hypothesis ($m(\{x\})$), belief in not the hypothesis ($m(\{-x\})$), and belief in either the hypothesis or not the hypothesis ($m(\{x, -x\})$) i.e. uncertainty. With multiple variables, multiple BOEs were constructed offering positive or negative evidence to support the classification of a participant.
3. ***Combination of individual BOEs.*** This is achieved using Dempster's rule of combination, which assumes that the input variables are independent. With the combination of BOEs a final BOE is constructed, it comprises of the same three focal elements as present in the individual BOEs.
4. ***Visualisation of BOEs using simplex plots.*** In the simplex plot, a point p_v exists within an equilateral triangle such that the least distance from p_v to a given side of the triangle is equal to $\lambda_i h$, where h is the height of the triangle and λ_{1-3} are the three belief values. The simplex plot can be divided up into regions providing boundaries for belief values (Figure 5.11).

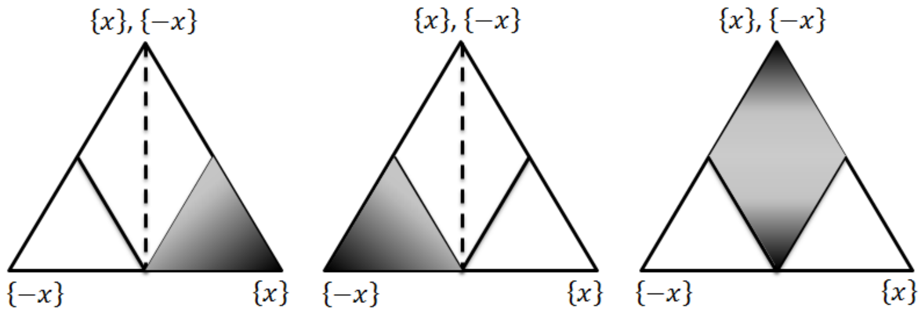

Figure 5.11: The classification method showing the three main areas: (left) shaded area supporting the hypothesis. (middle) shaded area not supporting the hypothesis. (right) shaded area showing uncertainty in the classification. The higher the position in the simplex the greater the uncertainty in the input data. The lower the position in the simplex plot the greater the certainty in the classification.

The classifier has the ability to define gait differences between healthy and OA patients [91]. It also has the ability to track the function progression from pre-operation to post-operative [227]. Given this tracking ability this project used the DST method to first produce a baseline classifier that can discriminate the healthy control group against the pre-operative KA patients. The post-operative data were then added to this classifier and the changes in function were tracked by the migration from one side of the simplex plot (OA classification) to the other (Healthy classification). Verification tests for the DST involved using the leave one out cross validation (LOOCV) where the trained classifiers were tested by data sets that did not originally go into the classification. The classifier was then used to estimate changes in subjective, objective, and combined (objective and subjective measure based classifier) function from pre- to post-KA. These changes in function were then analysed with multivariate linear regression to find out which factors affected the changes in function the most.

5.7.2.4 Multiple Linear Regression

When trying to deem a relationship between one variable and another, regression analysis is often utilised. Linear regression includes any approach to modelling the relationship between a scalar variable y and one or more variables denoted x, such that the model depends linearly on the unknown parameters to be estimated from the data. When there are a number of variables, multiple linear regression can be applied where linear correlations are deemed between two or more independent variables (IVs) and a single dependent variable (DV). However dealing with several IVs simultaneously in a regression analysis is considerably more difficult than dealing with a single independent variable for the following reasons [228]:

1. It is more difficult to choose the best model, since several reasonable candidates may exist
2. It is more difficult to visualise what the fitted mode looks like since it is not possible to plot either the data of the fitted model directly in more than 3 dimensions.
3. It is sometimes more difficult to interpret what the best-fitting model means in real life terms
4. Computations efficiency is slow.

The general form of a regression model for k IVs is given by

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + E \qquad (5.20)$$

where β_0, β_1, β_2,..., β_k are the regression coefficients that need to be estimated. The IVs X_1, X_2, X_3,..., X_k may all be separate basic variables, or some be functions of a few basic variables. This type of linear regression analysis has many limitations [228];

- **Existence**; for each specific combination of values of the IVs (X_3,..., X_k), Y is a random variable with a certain probability distribution having finite mean and variance
- **Independence**; the Y observations are statistically independent of one another.
- **Linearity**; the mean value of Y for each specific combination of IVs is a linear function of the regression coefficients.
- **Homogeneity of variance**; The variance of Y is the same for any fixed combination of IVs.
- **Normality**; For any fixed combination of IVs, the variable Y is normally distributed.

Examples of the application of multiple linear regression can be seen when authors have tried to determine function after TKA [119], and duration of inpatient stay [229]. However in these studies only very weak correlations have been found, with peak values ranging from *r*=0.18-0.41 [39,40]. The previous studies have also shown that only a few IVs meet criteria to be added to a multivariate analysis, with only a small amount of the variation being described by the IVs selected [39]. The very weak correlations provide little or no strength when drawing conclusions. The reliance on self-reported measures may have contributed to the weak findings of these studies.

During the analysis for the present project, both subjective and objective changes in function were assessed using multiple linear regression analysis. The variables that have been highlighted to affect KA function in the literature (Section 2.5) were used as IVs in the analysis.

Outputs from the multiple linear regression included; the R^2 value, or coefficient of determination, which is the proportion of the variation in the dependent variable explained by the regression model, and is a measure of the goodness of fit of the model (Equation 34).

$$R^2 = \frac{\text{explained variation}}{\text{total variation}} = \frac{\sum(\mathrm{Y_{est}} - \bar{\mathrm{Y}})^2}{(\mathrm{Y} - \bar{\mathrm{Y}})^2} \qquad (5.25)$$

where Y are the observed values for the DV, $\bar{\mathrm{Y}}$ is the average of the observed values and $\mathrm{Y_{est}}$ are predicted values of the DV. The F statistic is the ratio of the model mean square to the error mean square. If the significance level for the Fstatistic is small (less than 0.05), then the hypothesis that there is no (linear) relationship can be rejected, and the multiple correlation coefficient can be called statistically significant. The Root Mean Square Error (RMSE, also known as the standard error of the estimate) is the square root of the Residual Mean Square. It is the standard deviation of the data about the regression line, rather than about the sample mean. Finally, the p value was output, this is the probability that you would have found the current result if the coefficient were equal to 0 (null hypothesis). If the p value for one or more coefficients is less than the conventional 0.05, then these coefficients can be called statistically significant, and the corresponding IVs exert independent effects on the DVs. Additionally a vector of regression coefficients for the multiple linear regression of the responses in the DV on the predictors in IVs were output.

5.8 Power Calculation

Many studies consider that a statistically significant result can accept or reject an hypothesis (e.g. pre-operative function is the key determinant to post-operative function). However statistical significance is only one of two criteria, the second is the statistical power, or the probability that statistical significance will be obtained and that probability is determined primarily by the size of the effect that an experiment is likely to produce [230]. Effect size refers to a measure of the difference between groups or the strength of the relationship(s) between its variables [230]. As this project is a pilot study, it is well suited to find the effect size of the KA process and to give guidance for future research in patient numbers required to establish statistically significant results in factors which could affect function. The primary purpose of a power analysis is to estimate three parameters:

a) the number of subjects needed
b) the maximum detectable effect size
c) the available power at the design phase of an experiment based on a fixed number of subjects and effect size.

[230]

Depending on the statistical methods being used sample size and effect size can be used to determine statistical power. For example using a t-test for independent variables, if the researcher hypothesised an effect size of 0.6 and had 45 subjects in each group, the statistical power would be 0.80, or an 80% chance of obtaining statistical significance.

Recommendations for statistical significance are set to $p \leq 0.05$ and the minimum acceptable power level is most often considered to be 0.80 [230]. Within the KA literature there is evidence of statistical power analysis [85], however more frequently there is no mention of power analysis in the methodology or results [231].

5.9 Statistical Summary

Presented in Section 5.7 are examples of statistical approaches to reduce, classify, and identify relationships between functional variables and changes in function. The present study used normalisation similar to that of the current literature using Body Weight to normalise forces and moments acting about the knee and force plates. Further to this the data from the MS modelling of the ADL were normalised to percentage of activity. Data were then collated into three groups; Healthy (H), pre-operation (OA), and post-operation (KA). Waveform data that were selected was further reduced using PCA. PCA was performed on a matrix of waveform data for all participants (ensuring data is projected onto the same subspace). PCs were retained according to Kaisers criteria [232], and the cumulative variance was subsequently checked to ensure the majority of the original data sets variance was retained. All variables from H and OA groups were then analysed with LDA. Variables that showed clear discrimination between groups were selected for the final analysis. When PCs and discrete variables have been selected they were applied to the DST model classifier in order to classify between the H and OA groups. This provided a baseline model for participant classification. After this has been achieved the KA group data was then entered into the same classifier. A measure of the change in function, i.e. the distance travelled from OA to Healthy group classification was then obtained. Multivariate regression analysis was used to find out which factors contribute the most to the changes from pre- to post-operative subjective and objective functional outcomes. A hierarchy of factors was then built in order to make recommendations for future practice and research (Figure 5.12).

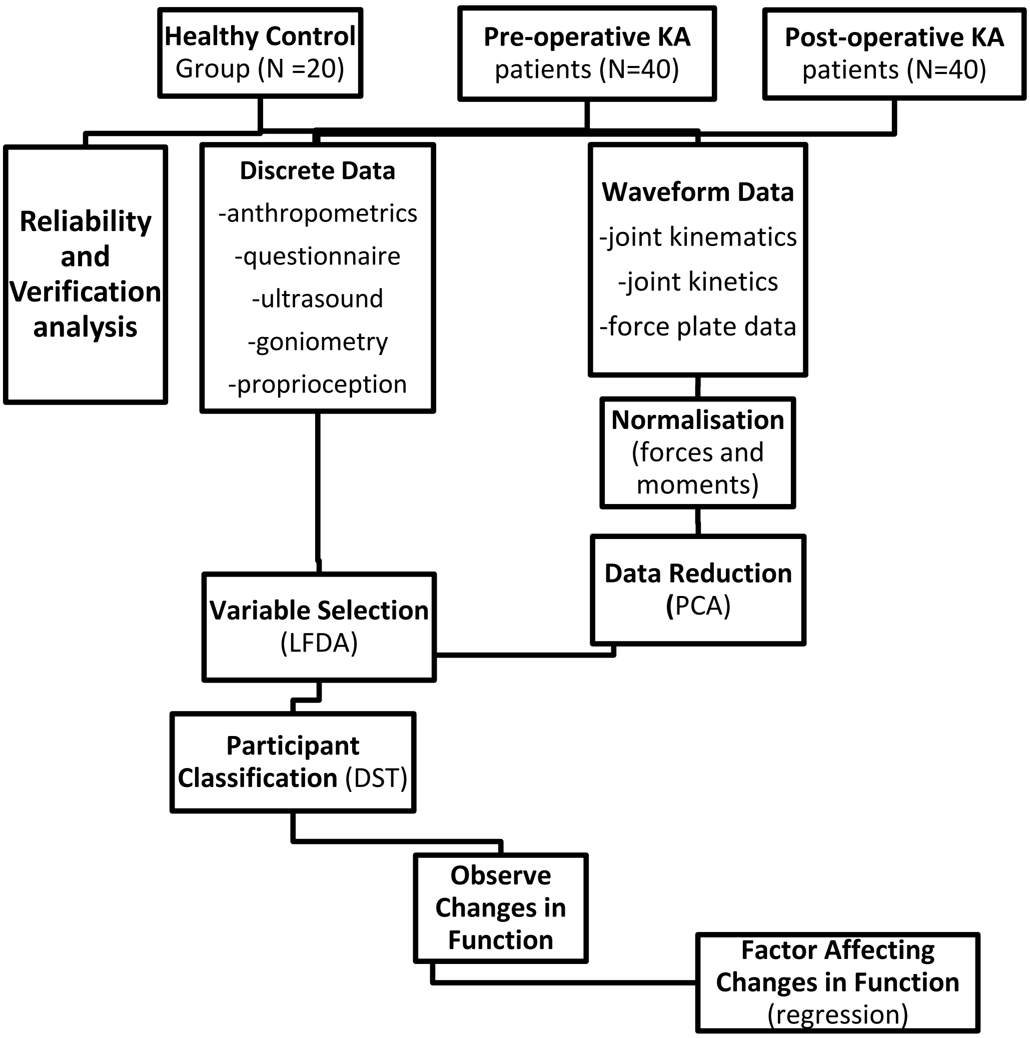

Figure 5.12: Flow diagram of statistical analysis techniques.

5.1 Conclusion

The methodology of the present study was highlighted in this chapter. It was proposed that function was assessed in 20 healthy and 40 pre- and six month post-KA patients. Subjective (perceived) assessment techniques included questionnaires and VAS which are commonly implemented in the previous literature. Objective function assessments also included commonly used techniques for assessing RoM, activity, and proprioception. This study also used more novel techniques such as MS modelling and RUSI. Statistical analysis techniques selected for the present study were aimed to reduce the data whilst retaining the variance observed in the original data set. Optimal variables which discriminate between healthy and pre-operative patients were used to classify participant function, and the subsequent changes in function. Finally multiple linear regression analysis of the changes in function against known factors which could affect function (pre-operative, surgical, and rehabilitative) was completed to accomplish the aims of the present study.

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Chapter 6

Reliability and Verification: *Test re-test analysis, Monte Carlo simulation and comparison to literature*

6.1 Introduction

In order to conduct the analysis of the participants function the testing protocol had to be evaluated for reliability and validity. It has been highlighted in the literature that there are significant difficulties in performing functional assessments reliably and accurately (Chapter 3). Prior to the testing, reliability analysis were therefore performed on a number of the objective assessments. The subjective assessments have already been tested for reliability [122] and validity [124], and the estimated errors found in these studies were taken into account in the final analysis. To minimise the error from the assessment tools, careful calibration was performed on the force plates, motion capture cameras, scales (measuring body weight), and ultrasound imaging equipment.

From the literature review (Chapter 3) the objective measures that have known inter/intra-rater reliability and verification errors are;

- Ultrasound imaging and interpretation
- Motion analysis system accuracy and calibration
- Marker placement during motion capture
- Conversion of motion capture to MS models
- Estimation of muscle coordination in the MS modelling (EMG comparison)
- Verification of model outputs (comparing to current literature base)

The reliability and validity of the findings from these studies were then taken into account in the final statistical analysis. Confidence values in the data can be assigned giving further information of the weighting for each factor which could affect post-operative function in the KA patients. This confidence value is especially pertinent in the DST statistical analysis (Section 4.64). In order to carry out reliability testing repeat day analysis was performed on the control group. As well as this, additional testing was performed on healthy individuals as part of Masters (MSc) projects with the Faculty of Health Sciences at the University of Southampton. To assess between raters, an experienced technician in the particular field was chosen to compare against.

6.2 Ultrasound Imaging reliability *

Prior to the testing thorough analysis of ultrasound imaging reliability was performed [150]. Both inter- and intra-reliability of imaging and interpretation were analysed. Testing was performed during two different pilot studies on a population of young healthy individuals. In the first study protocol for imaging and interpretation of rectus femoris (RF) followed that which was previously outlined (section 5.4.3), although patients were imaged in a seated position with their knee flexed to 90^{o}. The second study assessed vastus medialis oblique (VMO) and vastus lateralis (VL) muscles of females in a relaxed standing position. Protocol of imaging sites and image interpretation also followed the protocol in section 5.4.3.

Test–retest reliability between measurements (by P.W.) on scans taken on 2 days was examined using intra-class correlation coefficient (ICC) analysis. Inter-rater reliability between P.W. and another experienced ultrasound user was examined using ICC, Bland and Altman plots [233], and standard error measurement (SEM). Reliability results for RF showed that the imaging technique was highly reliable (Table 6.1).

Table 6.1: Intra- and inter-rater reliability of ultrasound imaging.

	Depth (ICC)	Width (ICC)	CSA (ICC)	SEM (cm)
Between-scan reliability				
RF Rest	0.99	0.99	0.67	0.16
RF 75% MVC	0.99	0.99	0.99	0.11
VMO Rest	0.99			0.046
VL Rest	0.99			0.015
Inter-rater reliability				
RF Rest	0.8	0.88	0.92	0.16
RF 75% MVC	0.98	0.97	0.93	0.15

The ICCs for between raters were 0.8–0.99 and between-scan measurements were 0.81–0.99, with the exception of 0.67, which was for CSA at rest (P.W.). Bland and Altman plots confirm low mean differences in interpretation and a relatively small spread in between day error (Figure 6.1). Higher ICC values tended to occur for contracted muscle, possibly due to the better definition of boundaries and more regular shape of the muscle. Intra-
r … tation

** Delaney S, Worsley P, Warner M, Taylor M, Stokes M. Assessing contractile ability of the quadriceps muscle using ultrasound imaging Muscle & Nerve 2010; 42: 530–538.*

reliability (ICC>0.9). Results from VM and VL ultrasound imaging reliability analysis (Table 6.1) showed that the technique has little error between days (intra-rater) and within users (inter-rater).

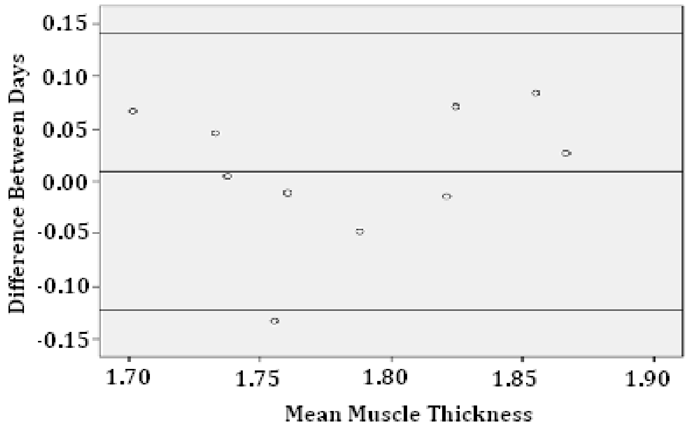

Figure 6.1: Example of Bland and Altman plot of between day reliability of interpreting ultrasound images of Vastus Medialis Oblique thickness.

6.2.1 Conclusion

A high level of reliability was observed for both intra- and inter-rater reliability of imaging and image interpretation. It is of note that this reliability analysis was conducted on young healthy adults and in different postures to that described in the methodology chapter (section 5.4.3). These reliability scores were taken forward and utilised for the end analysis.

6.3 Motion analysis system accuracy and calibration reliability

As highlighted in Section 3.3.5.1 there can be systematic error from the motion capture systems. To assess the inter-rater reliability and validity of the 12 camera Vicon System repeat calibration and measures were compared between two experienced users. Calibration of the system was conducted over an 8*3*2m capture area using a standard 5 marker calibration wand (Figure 6.2). Camera error after the calibration was then calculated in Nexus (Vicon) software over two thousand refinement frames. After each calibration the wand was used to check accuracy of marker reconstruction in both static and dynamic trials. Precise measures of inter-marker distances on the wand were calculated using callipers (Figure 6.2).

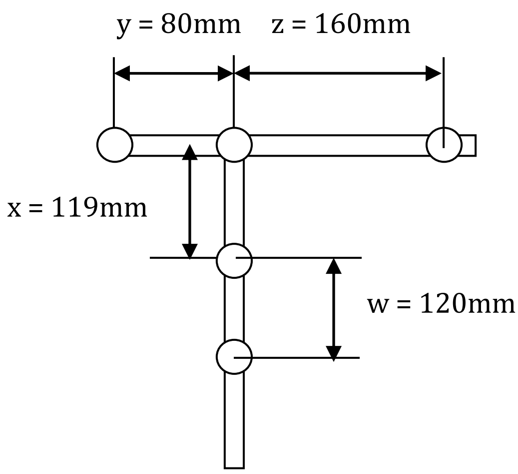

Figure 6.2: Representation of the 5 marker calibration wand used in the systematic error analysis (not to scale).

Five trials were completed for each rater to measure static, and dynamic accuracy of the motion capture system. During the dynamic trials the wand was taken along the walk way at three different height levels (foot, pelvic, and head height), and then a swinging trial was completed where the wand was rotated and varied along the entire capture area. Mean and standard deviation of the error in marker reproduction (w, x, y, z distances) were calculated across each trial and compared between rater.

Results from the calibration showed that accuracy in all cameras was high, with an average error of 0.26 (range 0.16-0.36) and 0.22mm (range 0.14-0.38mm) for each rater. Results from recreating the wand markers show low error for all of the trials, with a mean error of 0.33mm (range 0.02-0.67mm) and 0.29mm (range 0.02-0.44mm) for each rater respectively. The highest error was seen in the head height and swing trial where the wand was taken into the furthest periphery of the capture volume. It is of note, that although there was low mean error in the marker reconstruction there was higher error in the extremities of the capture volume.

Table 6.2: Mean error of wand reconstruction (distances w, x, y, z, Figure **6.2**) during static and dynamic trials (foot, pelvis, and head height). SD = standard deviation in error.

	Rater 1 mean error (mm)				**Rater 2 mean error (mm)**			
Height	w	x	y	z	w	x	y	z
Static	0.02	0.38	0.33	0.21	0.02	0.38	0.38	0.38
SD	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.03)
Foot	0.12	0.41	0.47	0.1	0.19	0.37	0.21	0.14
SD	(0.11)	(0.21)	(0.28)	(0.11)	(0.16)	(0.2)	(0.13)	(0.08)
Pelvic	0.22	0.67	0.32	0.24	0.24	0.39	0.33	0.3
SD	(0.19)	(0.59)	(0.3)	(0.12)	(0.2)	(0.28)	(0.19)	(0.21)
Head	0.54	0.42	0.45	0.26	0.13	0.43	0.4	0.32
SD	(0.49)	(0.22)	(0.27)	(0.18)	(0.09)	(0.35)	(0.31)	(0.28)
Swing	0.16	0.35	0.41	0.49	0.14	0.27	0.44	0.37
SD	(0.17)	(0.26)	(0.34)	(0.25)	(0.18)	(0.19)	(0.42)	(0.29)

6.3.1 Conclusion

The results from this study show that there is low systematic error in the motion capture system. Calibration of the motion capture system showed that only small errors were shown for both raters. There were also little differences between-raters in the reconstruction error of the marker trajectories in the wand, with all mean errors below 1mm.

6.4 Anatomical Landmark Definition during Motion Capture

During the motion capture process retroreflective markers are placed on key anatomical landmarks (AL) to define anatomical points on the body. Error in this definition of AL has been previously established (Section 3.3.5.2). This reliability of AL definition will also have an impact on the conversion of the motion capture data to MS models. In order to assess the intra-rater reliability of AL definition between day analyses were conducted on 10 participants of the healthy control group. Static standing trials of participants were taken on separate days using the VICON motion capture system. ALs were defined by the modified Helen Hayes approach (Appendix G). This static trial data from each day was imported into the MS modelling software where AL's and scaling factors were defined according to the protocol previously set out in Section 4.41. The AL definition and scaling of the MS models were blinded between days, and data was imported into Matlab (The MathWorks, Inc., USA) for analysis. Between day differences of marker coordinates and scaling factors were calculated for each participant (Table 6.3). ICC analysis of the between day reliability was also conducted.

Table 6.3: Mean and standard deviation (SD) of the difference in marker position estimation (mm) from the ten static trials on two separate days.

Marker	X coordinate			Y coordinate			z coordinate		
	mean	**SD**	**ICC**	**mean**	**SD**	**ICC**	**mean**	**SD**	**ICC**
RTHI	5.57	6.47	**0.28**	2.11	1.52	**0.99**	4.41	5.13	**0.99**
RKNE	6.06	5.73	**0.52**	6.67	8.09	**0.64**	3.98	3.18	**0.99**
LKNE	6.55	6.97	**0.82**	2.86	1.84	**0.95**	3.31	3.46	**0.98**
LPSI	4.64	5.35	**0.97**	2.40	1.95	**0.99**	5.42	2.42	**0.99**
RASI	7.71	9.14	**0.92**	5.98	4.98	**0.95**	5.09	4.07	**0.75**
RTIB	3.61	5.47	**0.91**	3.98	2.94	**0.99**	8.30	6.35	**0.95**
RANK	8.34	9.03	**0.63**	4.93	4.03	**0.83**	5.25	5.70	**0.84**
RTOE	10.67	9.60	**0.2**	8.85	11.20	**0.54**	8.54	9.50	**0.64**
LTIB	3.94	2.30	**0.78**	1.19	1.10	**0.99**	7.96	6.50	**0.85**
LANK	4.03	3.20	**0.9**	4.52	2.55	**0.93**	5.01	3.22	**0.84**
RHEE	4.42	4.07	**0.92**	4.54	3.37	**0.91**	3.80	3.27	**0.64**
LHEE	1.82	2.42	**0.96**	4.85	4.49	**0.86**	5.80	3.49	**0.85**
RPSI	3.73	6.69	**0.97**	4.47	3.64	**0.96**	2.94	3.50	**0.99**
LTOE	12.57	9.94	**0.3**	8.05	5.05	**0.54**	9.51	6.77	**0.17**
LASI	6.97	6.65	**0.98**	4.53	4.55	**0.99**	6.40	5.97	**0.91**
LTHI	7.88	5.89	**0.94**	4.39	5.11	**0.93**	4.70	2.56	**0.98**

Segment	Scaling factor	SD	ICC
Pelvis	0.005	0.004	**0.92**
Thigh	0.005	0.005	**0.99**
Shank	0.004	0.003	**0.99**
Foot	0.008	0.008	**0.92**

These between day values show a mean error of 4.6mm, however between day differences ranged from 0-28.4mm. Scaling factors showed low intra-rater error with a mean of 0.005 scaling factor deviance which equates to approximately 8.15mm in segment length. ICC analysis on the reliability of the marker positions and scaling analysis shows poor to excellent results for the markers coordinate estimations and was dependent on the marker and the dimension (Table 6.4). ICC analysis shows reliability results ranging from 0.17-0.99, however the majority of marker locations have ICCs above 0.9 (58%). Markers with the poorest reliability are at the foot (toe), where marker location is effected by pose variations in the initial position estimation and scaling factors. Marker estimates in the X (sagittal) direction show the poorest reliability (mean ICC = 0.75), and the Y direction (transverse) was the most reliable (mean ICC = 0.87). This poor reliability in the sagittal plane could have been due to variances in the pose estimation of each joint.

It is of note that this study looked at the between day difference in marker position estimation, the precise location of the markers was still unknown. This could result in marker estimation error from both days. Authors have used invasive techniques to check the precise location of markers relative to AL [28], however as this project aimed to use non-invasive techniques and this option was not applicable. When comparing the intra-rater difference results to the literature, similar ranges in error were observed (6-21mm) [234]. It is of note that the inter-rater error has been shown to be higher than the intra-rater [234], however as all of the motion capture and MS modelling will be performed by the principle investigator PW only intra-rater reliability was assessed. It is of note that the error in AL definition is much larger in general than that of the motion capture system change (Section 5.4.5). It is therefore assumed that the differences in the motion capture system would have a negligible impact on the outputs of the MS models compared to the known AL and STA error.

6.4.1 Conclusion

The results of this reliability study of AL conversion from motion capture to MS model show that errors can range significantly. For the majority of markers high ICC between day reliability was achieved, although there were markers which showed very poor reliability (foot). There was a need to find out of the effects of this poor reliability on the outputs of the MS models.

6.5 Monte Carlo Study of MS Modelling Reliability *

In order to quantify the effects of the between day error in AL definition and scaling factors on the MS modelling outputs a parameter study was performed [235]. Here the known variance in markers position estimation and scaling factors were imposed on the MS model. A Monte Carlo technique of marker variance distribution was applied to the MS

** Worsley, Peter, Stokes, M. and Taylor, M. (2010) Robustness of optimised motion capture and musculoskeletal modelling of Gait. At CMBBE 2010, Valencia, ES* models over 1000 simulations. A standard model was selected for the variance study in order to find how much affect AL landmark definition error had on the model outputs. Pose variations on AL definition and scaling were applied during the model setup (Section 4.41) using a custom Matlab script. The 1000 simulations were then completed using the standardised method for calculating kinematics (Section 4.2) and kinetics (Section 4.3) at each joint.

Out of the 1000 simulations, 1.2% failed due to model error and a further 6.4% showed erroneous constraint reactions. From the remaining models (92.4%), standard error in kinematics from 0-100% of the gait cycle in the hip, knee, and ankle ranged from ± 6.3 degrees (SD range 0.075-0.504). The lowest deviations being in knee flexion and the highest in hip internal/external rotation (Figure 6.3).

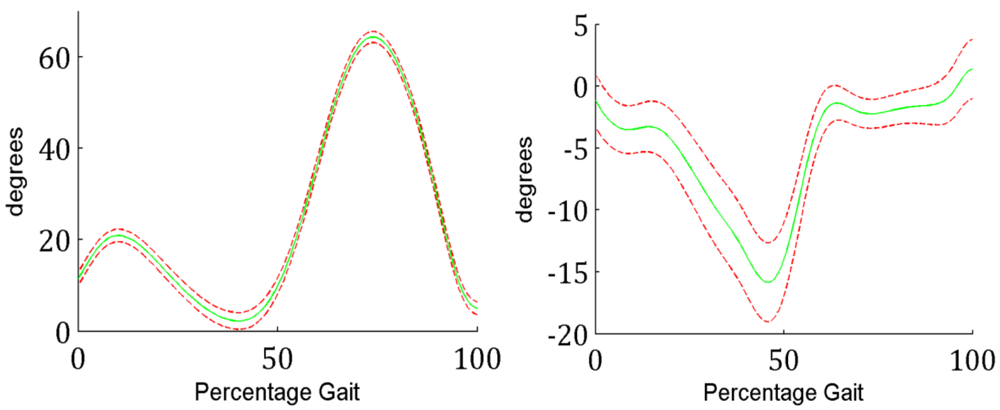

Figure 6.3: Knee flexion (Left) and hip internal/external rotation (Right) during gait after Monte Carlo simulation. Mean in green. Two times standard deviation in red.

Maximal deviations in knee joint reactions was 0.54*BW (24% of peak mean) found in D-P TFJ reaction (Figure 6.4). The maximal deviations for anterior-posterior (A-P) and medial-lateral (M-L) reactions were 0.26*BW (24% of peak mean) and 0.04*BW (28% of peak mean) respectively. Moments about the knee showed the smallest deviance from the mean, with a maximal deviation from the mean of 0.1*BWm for valgus-varus (V-V) moment. The variance in moment outputs did show deviation in respect to the mean magnitude of the data. V-V standard deviation represented 15% of the magnitude of the peak, and internal-external (I-E) moment standard deviation was 12% of the peak.

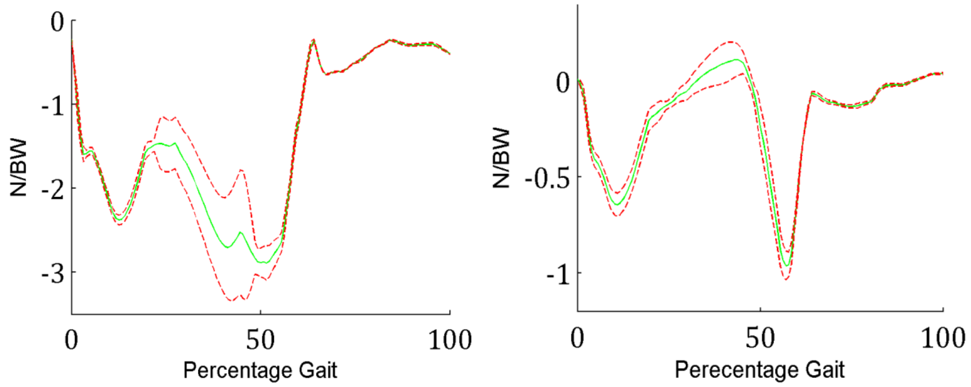

Figure 6.4: Axial (Left) and A-P reaction (Right) during gait after Monte Carlo simulation. Mean in green. Two times standard deviation in red.

6.5.1 Conclusion

The results from this study show how variance of marker positions and scaling in MS modelling can produce deviations in output. However, this investigation shows that inverse MS modelling with optimized kinematic inputs is relatively robust when assessing kinematics and kinetics at the knee, and error ranges and standard deviations are lower than previously reported (4-203%) [30].

6.6 MS modelling Muscle Recruitment vs. EMG *

There have been few examples in the literature of MS model muscle recruitment verification, with one of the only examples being a mandibular joint study [236]. Some models have used EMG to drive their MS simulations [26, 199], however there are questions over this approach due to the inaccessibility of deep muscles when using surface EMG data collection. There is an evident need to compare the EMG contraction timings to that of the MS model recruitment criteria, as it has been established that muscle coordination may not be modelled properly by the current optimisation recruitment algorithms (Section 3.2). For this study 20 pre-operative participants were chosen for the analysis. Data were extracted for EMG and MS models using the pre-defined protocol (Section 4.35&4.4). In order to make comparisons from EMG to MS model a number of stages was required to normalise the EMG data.

** Worsley, Peter, Stokes, M. and Taylor, M. (2010) Ultrasound Imaging to Scale Strength in Patient Specific Musculoskeletal Models. ESB, Edinburgh, Scotland.*

1. EMG high pass filtered (20Hz) - remove low frequency noise
2. Rectified
3. Normalised to % MVC - MVC taken during a static isometric contraction
4. Low pass filter (Butterworth 6Hz)
5. Normalise to % gait
6. Re-sampled at 120Hz

When the EMG data was normalised, the data were compared to that of the %MVC contraction from the respective MS model muscle output (Figure 6.5). For statistical comparison correlation coefficients were calculated.

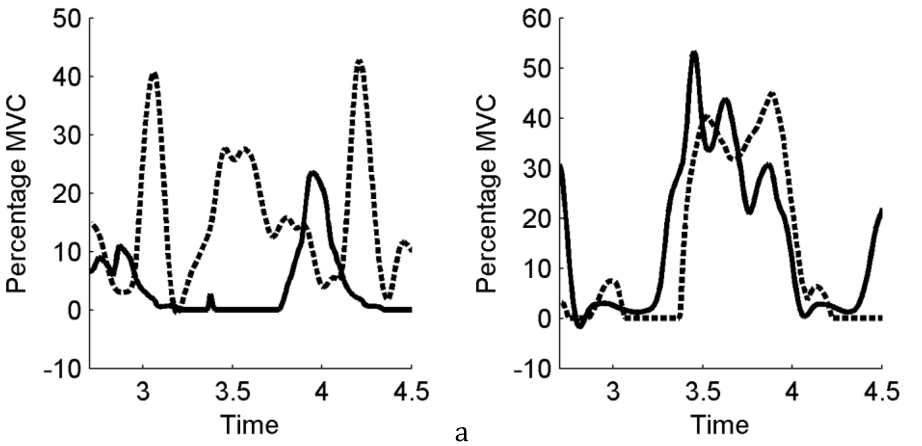

Figure 6.5: Comparison of EMG and MS model: (a) rectus femoris muscle output during the gait cycle(b) vastus lateralis muscle outputs during the gait cycle. EMG recording in solid line, MS model prediction in dashed line.

The results from this verification study show only weak correlations between EMG and the MS models muscle activity predictions. Two muscles showed no correlation (RF and TA), while all of the other muscles studied showed a weak to moderate correlation. Correlations ranged significantly between subjects, with the effected (OA) lower limb recording slightly lower correlations on average (Table 6.4). The muscle with the highest correlation was vastus lateralis (mean correlation coefficient 0.61 on contralateral limb), and the lowest was rectus femoris (mean correlation coefficient -0.3 on affected limb). Vastus lateralis, gastrocnemeus, and the hamstrings also showed some correlation (>0,5), although standard deviation between the participants correlations was high (>0.2).

Table 6.4: Mean and standard deviation (SD) of correlations between EMG and MS model predicted muscle activity from 20 pre-operative patients.

	Effected Limb		Contra-lateral Limb	
Muscle	Mean correlation coefficient	SD correlation coefficient	Mean correlation coefficient	SD correlation coefficient
Rectus Femoris	-0.30	0.12	-0.18	0.25
Vastus Medialis	0.55	0.14	0.61	0.17
Vastus Lateralis	0.56	0.18	0.62	0.19
Tibialis Anterior	0.27	0.22	0.27	0.26
Gastrocnemeus	0.51	0.29	0.56	0.31
Medial Hamstrings	0.52	0.25	0.54	0.22
Lateral Hamstrings	0.53	0.25	0.52	0.20

6.6.1 Conclusion

Poor to moderate correlations were observed between the EMG and predicted MS modelling muscle recruitment in the pre-operative KA patients during gait. There were, however, limitations with this comparison study. Processing of the EMG removes some detail in the contractions, and the normalising can also mask some peaks in the data. Also no direct comparison of force production can be deemed from the EMG, so comparing MVC levels may not be valid i.e. that MVC scales could be completely different from EMG to MS model. A reason for the poor result seen in RF could be that this muscle has low activity levels during gait and high susceptibility to noise. It could also be the fact that this muscle is a bi-articular muscle (knee extensor and hip flexor), and it is known that these muscles are poorly modelled during dynamic movement (Section 4.4).

There was also a common delay in onset of the MS model muscle activation compared to the EMG, again showing some weakness in the MS models ability to predict stabilising muscle contractions, for example during heal strike. The muscle forces contribute significantly to the total loading at the joint (~66% of total loading during stance phase of gait), so this poor correlation result is concerning for the verification of the modelling. However, although correlation coefficients of the EMG comparison were low, there were definite trends for the majority of muscles activation patterns. The statistical analysis of comparing EMG and MS model predicated muscle contractions provides a large challenge.

With the significant differences in the signal properties this verification study should be interpreted given the limitations caused by signal processing and the statistical methods.

6.7 MS modelling Predicted Loading vs. Literature

The final verification study involved the analysis of the MS modelling kinematic and kinetic prediction of the healthy control group. The MS modelling technique has been directly compared to *in-vivo* telemetrised KA data, in the recent 'Grand Challenge' at the American Society Of Mechanical Engineers (ASME) summer conference in 2010 [51]. Here predicted loading using the MS modelling technique showed an over-prediction in estimated loading compared to the telemetrised prosthesis when modelling a squat movement (Figure 6.6). Possible reasons for this over-prediction were highlighted as;

1. the knee joint was modelled as a hinge (heavily simplified)
2. model properties were scaled from a single healthy anthropometric data set
3. surface interaction of the tibia and femur were not taken into account

It is of note however that even though the absolute values of the knee loading were poorly predicted, the similarity of measured and simulated trends indicates that correct internal forces might be obtained if the model had been set-up in a more thorough methodology. For example, the exact bone geometry and soft tissue structures were not modelled in this verification study.

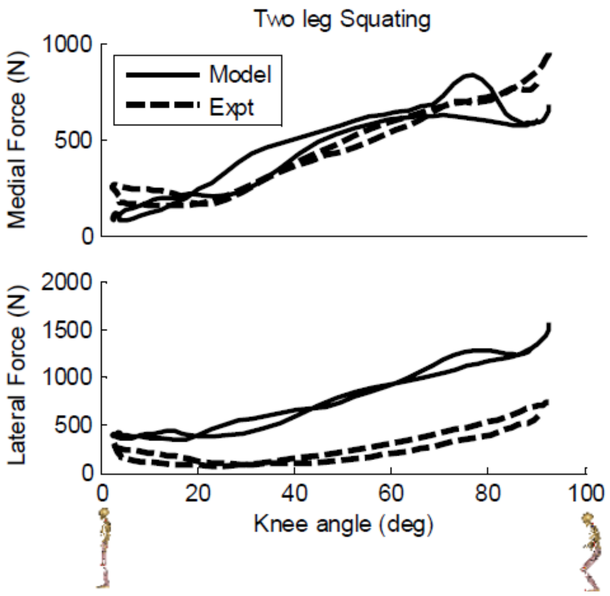

Figure 6.6: Comparison between AnyBody MS modelling knee loading prediction vs. telemetrised data during a squat trial [51].

One of the few other ways to conduct this loading prediction verification in this study was compared the outputs to that of the literature base for known loading at the knee. For this the control group data for knee kinematics and kinetics were used [237]. These comparisons are limited due to the data available in the literature and the difference in methodology from each study. When comparing the kinematics at the knee few studies have looked at a similar age group of participants. One such study was conducted by Marin et al, where knee flexion was observed in the aging population [38]. The findings from the present study are very similar to the Marin et al results in both magnitude and standard deviation across the groups studied (Figure 6.7).

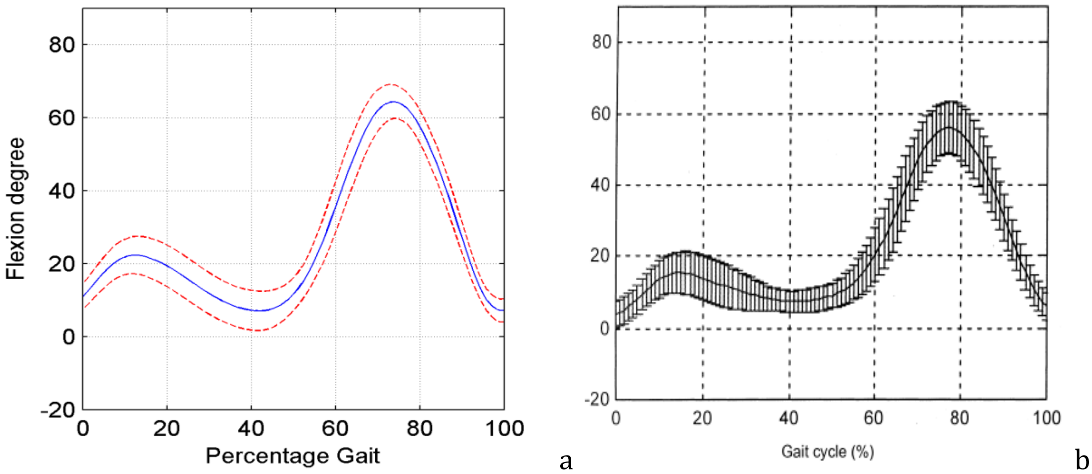

Figure 6.7: (a) Mean of Healthy control group knee flexion angle during 100% of the gait cycle. Mean in blue, standard deviation red dashed. (b) Flexion-extension curves of the older population during gait cycle [38].

When comparing the control group knee kinetics during ADL the obvious literature is from that of Costigan et al, where 35 young healthy individuals were assessed [28]. Although the telemetrised data is seen as a gold standard the data comes from five TKA patients, and a direct comparison would not be valid. The comparison between the control data and that of Costigan et al has its limitations, with different participant age groups, motion capture systems, marker configurations, and MS modelling techniques. Despite these limitations loading data at the knee was similar in magnitude and variance between the two studies (Table 6.5). Worsley et al [238] showed a reduced axial loading, although a slightly increased A-P shear reaction compared to Costigan et al [35]. Both predictive MS modelling studies (Costigan et al, Worsley et al) showed higher loading predictions than that measured by the telemetrised data (Table 6.5).

Table 6.5: Mean peak knee loading during the gait cycle from Costigan et al [35], Kutzner et al [40]. and Worsley et al [238]. Standard deviation following ± sign.

Author	n	D-P N/BW	P-A N/BW	M-L N/BW	Flex Nm/BW	V-V Nm/BW	I-E Nm/BW
Costigan et al	35	3.7 ± 1.07	0.51 ± 0.16	0.15 ± 0.05	0.06 ± 0.01	0.05 ± 0.02	0.008 ± 0.007
Worsley et al	20	3.06 ± 0.89	0.70 ± 0.31	0.14 ± 0.08	0.04 ± 0.03	0.07 ± 0.03	0.013 ± 0.004
Kutzner et al	5	2.47± 0.65	0.24 ± 0.14	0.07 ± 0.19	0.01 ± 0.01	0.02 ± 0.02	0.004± 0.006

The largest difference in loading prediction compared to the telemetrised data is the A-P M-L, and all moment predictions, with peak magnitudes of loading being over double in the predicted models. Patterns in TFJ waveforms showed similar trends for D-P and I-E outputs. Other knee outputs showed a much poorer relation to the telemetrised data sets, examples of which are A-P reaction and flexion moment. In these cases variance can be observed in both magnitude and shape of the waveform measures.

6.7.1 Conclusion

The data produced by the MS models of the healthy participants gait showed that TFJ kinematics and kinetics are similar to previous predictive modelling studies. However, TFJ kinetics appear to be over-predicted using current inverse dynamic MS modelling when compared to *in-vivo* telemetrised data taken from TKA patients. When MS modelling was directly compared to the telemetrised data TKA data over-estimation of TFJ forces were in excess of a whole body weight at times. There were, however, clear trends in the waveform patterns of the outputs, suggesting that although magnitude of MS modelling results maybe too high the trend in loading is accurate.

6.8 Discussion

Results from the reliability and verification testing show that the ultrasound imaging and interpretation, and motion capture system have good reliability in both intra- and inter-rater testing. The study of systematic errors associated with the motion capture showed high levels of marker reconstruction accuracy in two experienced users. Average errors of under one millimetre were observed for both researchers post-camera calibration. When the AL definition during motion capture was tested between days for reliability similar magnitudes of error were observed to that of the literature. Between day difference ranged from 0-28.4mm, with a mean difference of 7.52mm. This result agrees with the current literature suggesting that systematic errors are much less than those of random errors [68].

These errors were then shown to influence the MS model prediction for kinetics at the TFJ. However, knee kinematics were shown to be reliable. Forces at the TFJ did vary with the deviation in marker and scaling inputs, however this deviation was much lower than that previously shown in the literature by an non-optimised model [7]. Further analysis of the MS model verification showed that predicted muscle recruitments only moderately correlated with EMG. However the comparison was limited to activation pattern alone and force outputs from the muscles could not be compared. Finally, the MS model was directly compared to telemetrised knee data in a study by Schwartz et al [51]. The results showed that there was an over prediction in knee forces in the MS models, however total forces matched the telemetrised data in waveform shape. When the knee force and moment data collected from the present study were compared to other inverse modelling data, the magnitudes and deviations in force prediction were similar.

Although there were some reliability errors associated with the objective measures, these have now been quantified and can be taken into account when interpreting data. The MS modelling has been shown to be robust under variance in inputs (markers and scaling), with modest deviations in TFJ outputs. There is, however, still a lack of verification on the muscle recruitment which the model estimates with relatively low correlations found in an EMG comparison. During the project the same MS modelling techniques were used, resulting in the same assumptions for all participants. Despite the over-prediction in the modelling process compared to the *in-vivo* data set the MS models still could have the ability to determine differences in loading patterns between participants. It is therefore deemed that the magnitudes of forces and moments predicted should be interpreted with the known limitations, however if clear differences in the trends of the MS model predications are observed between groups, this data could still hold value in the final analysis.

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Chapter 7

Data Analysis: *Normalisation, Variable Selection, Principal Component Analysis, Data Reduction and Labelling.*

7.1 Introduction

The protocol set out in Chapter five was completed for 20 healthy individuals (H), 39 pre-operative KA (OA), and 33 post-operative KA patients (KA). The data collected during this process was then collated and summarised. Although final pre- and post-operative numbers are lower than estimated, this group of patients data will provide the basis for analysis. Anthropometric details of the participants show that the mean age of the healthy group was slightly lower than that of the KA patients. However, there were large standard deviations within the KA group, with the youngest participants being just 39 years old. Both the weight and body mass index (BMI) of the KA participants was higher than that of the healthy group, however there are large ranges in all groups (Table 7.1). In all three groups there were slightly more females than males participating, and this agrees with the national average for KA patients [239].

Table 7.1: Anthropometric measurements of 20 healthy, 39 pre-operative, and 33 post-operative individuals.

Variable	**Age (years)**			**Weight (BW)**			**BMI**			**Gender %female**		
Group	H	OA	KA	H	OA	KA	H	OA	KA	H	OA	KA
Mean	62.4	64.3	65.2	77.8	84.9	86	28.1	30.8	30.5	55	54	52
SD	5.9	9.5	9.3	13.2	17.7	17.2	3.9	5.9	5.1			
Max	79	81	82	96	127	123	34.9	42.2	40.2			
Min	55	39	40	53	54	60	20.2	19.1	22.6			

The control group were seen on two occasions in order to complete the protocol set out in Chapter five, and to perform reliability studies (Chapter 6). Patients undergoing KA were seen on average 5 weeks pre-operation (range 2-13 weeks), and the follow up assessment was undertaken on average 5.2 months post-operation (range 3-8 months). Patients who attended the pre-operative assessment and could not attend the post-operation appointment were not removed from the study, as this data provided additional information to produce an initial classification of function.

7.2 Clinical Data

The results from the clinical data showed that the control group had high objective and subjective function along with no pain or stability problems in their lower limbs. However the pre- and post-operative KA patients exhibited reduced objective and subjective function from the clinical measures. The most pertinent functional limitation pre-operation was pain, which in most cases had improved post-operation (Table 7.2).

Table 7.2: Clinical measurements of 20 healthy, 39 pre-operative, and 34 post-operative individuals.

	Healthy			**Pre-op**			**Post-op**		
Clinical Measure	mean	SD	Range	mean	SD	Range	mean	SD	Range
WOMAC	1.4	2.6	0-9	45.6	14.9	8-68	16.7	13.4	0-42
12 Item Oxford	47.3	1.7	41-48	23.7	8.5	4-40	38.5	7.6	22-48
Pain (VAS) 0-10	0	0	0	6.4	1.9	2-9	1.8	1.5	0-8
Instability (VAS) 0-10	0	0	0	3.6	2.3	0-9	1.4	1.4	0-8
Active flexion (deg.)	141.6	9.2	120-160	113.2	17.7	70-140	110.5	13.6	75-130
Active extension (deg.)	0	0.5	-3-2	2.1	4.1	-5-20	1.7	3.7	0-15
Active ROM (deg.)	142.3	8.3	125-160	111.1	20.2	64-140	108.8	15.3	65-130
Activity (hrs. per week)	7.1	5.2	3-20	6.7	4.9	0-20	13.2	10.1	2-20
Pathology (years)	0	0	0	5.1	5.7	1-18	10.3	9.2	3-30
RF atrophy (% diff.)	1.3	2.5	-3-7	19.9	16.9	1.9-52	16.9	8.7	-4-39
VM atrophy (% diff.)	1.4	1.7	-1-4	6.1	11.2	3.4 -26	8.4	6.0	-1-23
VL atrophy (% diff.)	1.9	3	-4-8	4.2	7.4	-2-23	6.6	6.7	-2-28

The clinical scores from the pre-operative patients highlighted the range of function in pre- and post-KA patients. RoM was on average heavily impaired both pre- and post-operation compared to the healthy group. Muscle atrophy (Section 5.4.3) was particularly prominent in rectus femoris muscle, however both vastus medialis and lateralis were also atrophied both pre- and post-operation. The activity measure (subjective question) showed a difference in healthy and pre-operative groups, however the post-operative patients reported on average much higher activity than that of the healthy group. Post-operative satisfaction measures with a VAS at the six month follow up showed that patients scored the KA procedure to be 8.3 out of 10. There was however a considerable range (3 to 10/10), with one patient scoring satisfaction of just three out of ten.

There were some differences between the patients scheduled for TKA and those scheduled for a UKA (Table 7.3). The pre-operative clinical and anthropometric data shows that TKA patients were older, had higher BMI, higher percentage of female population, and lower perceived function pre-operation. They had also been suffering from pathology for nearly double of the time of the UKA group on average. However those who had undergone TKA were on average more satisfied with the procedure at the six month follow up assessment.

Table 7.3: Key clinical and anthropometric measurements of 20 healthy, 16 pre-operative UKA patients, and 23 TKA post-operative individuals.

Parameter	Healthy mean (±S.D.)	UKA mean (±S.D.)	TKA mean (±S.D.)
Age (years)	62.4 (±5.9)	60.9 (±10.1)	67.2 (±8.1)
Weight (kg)	77.8 (±13.2)	80.3 (±16.9)	87.1 (±17.8)
BMI	28.1 (±3.9)	28.5 (±5.8)	32 (±5.3)
WOMAC	1.4 (±2.6)	33.9 (±14.7)	54 (±7.9)
OKS	47.3 (±1.7)	30.8 (±6.1)	18.4 (±6.3)
Years with Pathology	0 (±0)	5.1 (±5.7)	10.3 (±9.2)
Satisfaction (0-10)	NA	8.1 (±2.2)	8.4 (±1.2)
Gender			
Male	45%	57%	40%
Female	55%	43%	60%

It is of note that some of the measures originally included in the protocol could not be implemented in practice. Measures of proprioception were not obtained, this was because pre-operative patients felt that balancing on one leg was too demanding and painful on their effected limb. For ethics reasons the test was not enforced and therefore removed from the subsequent protocol.

7.3 Surgical Results

Feedback from the surgical procedure of all KA patients was collected from the standardised form (Appendix D). Twenty nine out of the thirty three patients (88%) were operated by their consultant, with 12% being operated by a registrar with the consultant overseeing the operation. The medial parapatellar approach was used in all cases bar one, where a lateral UKA was inserted with a lateral parapatellar approach. There were three different UKA, and four different TKA designs used in the thirty three patients assessed, with all TKAs sacrificing the PCL. In addition to the UKA and TKA procedures there was also one patient who received a bi-UKA (unicompartmental prosthesis on medial and lateral compartment, retained ACL and PCL), and one patient with a tri-UKA (unicompartmental prosthesis on medial, lateral compartment, and PFJ, retained ACL and PCL). All surgeons used cement to achieve fixation of the prosthesis, although there were six different types of cement being used. Two of the patients underwent TKA using a CAS technique (Section 2.5.2).

7.4 Rehabilitation

Patients spent on average 6.7 days as inpatients after their KA, although this ranged from 3-31 days. Post-operative time was extended when patients had other medical issues other than their KA, which is reflected in the wide spread of data. During their inpatient therapy 12% of patients were given continuous passive motion (CPM, where the knee is flexed and extended by a robotic device). On discharge 90% of patients had met their functional goals of 90^{o} flexion and a straight leg raise (SLR). On average patients received four hours of outpatient therapy through either the NHS or a private health care provider. This outpatient therapy varied between patients (0-18 hours), with some receiving no therapy (21%). Those who did receive post-operative physiotherapy generally only had a few sessions, with 74% of patients receiving four of less appointments. Post-operative activity ranged considerably post-operation (2-20 hours per week), however there were clear increases from pre- to post-operation.

7.5 ADL Data

Some activities performed by the participants at times had to be omitted from the analysis. The main obstacles with the motion analysis assessment were decreased stride length in gait and marker occlusion during the sit-to-stand-to-sit activity. Decreased stride length was particularly prevalent in the pre-operative patients. In order to complete the gait analysis, the study required two clean stance phases on each force plate. If a participant had a short stride length they would often heel strike with both feet on a single force plate (60cm in length). This resulted in only 20 healthy, 34/39 pre-operative, and 31/33 post-operative participant gait cycles captures. The second issue of anterior superior iliac crest marker occlusion was prevalent in all of the groups. This generally occurred when the participant flexed at the trunk, with the belly covering the marker. Markers on the lateral iliac crest were implemented so the data could be reconstructed. However, even with marker pattern filtering some data sets were un-usable. This resulted in 20 healthy, 34 pre-operative (17 TKA, 15 UKA, 2 bi-UKA) and 31 post-operative (15 TKA, 14 UKA, 2 bi-UKA) sit-to-stand-to-sit participant data sets.

Resultant TFJ kinematics and kinetics along with force plate data from one to three trials (depending on data available) were averaged and collated for all participants (Appendices J-M). The forces and moments produced from the musculoskeletal modelling and force plate were normalised to body weight (BW). Each activity was normalised to 0-100% of the activity giving 101 values in each waveform. Additional information for the gait activity was added which included velocity, cadence, double support time, and stride length. Analysis of forces from the knee and force plate data were analysed for just stance phase in both level gait and step-descent activities. A list of the variables collected and their notations was then gathered (Table 7.4). With the large number of measures taken there is a need to reduce the data, in order to make statistical analysis more practical. With eighteen waveform measures from each activity and ten discrete clinical measures were collected during the project. With an eighty two (20 healthy, 31 pre-operation, 31 post-operation) one participants ADL data there were fewer participants than variables. There is a need to reduce this data set in order to perform accurate analysis, selecting key values from the waveforms, and clinical measures need to be performed logically and standardised across the entire data set.

Table 7.4: List of variables for analysis.

Input measures					
Waveform			**Discrete measure**		
Notation	**Description**	**Units**	**Notation**	**Description**	**Units**
$AF_{activity}$	Ankle plantar flexion	deg	d_1	WOMAC	1-54
$KF_{activity}$	Knee flexion	deg	d_2	12 Item Oxford	1-48
$HF_{activity}$	Hip flexion	deg	d_3	Knee AROM	deg
$HA_{activity}$	Hip abduction	deg	d_4	Pain (VAS)	1-10
$HER_{activity}$	Hip external rotation	deg	d_5	Stability (VAS)	1-10
$DP_{activity}$	D-P knee reaction	N/BW	d_6	BMI	Kg/m^2
$AP_{activity}$	A-P knee reaction	N/BW	d_7	Activity	Hrs/week
$ML_{activity}$	M-L knee reaction	N/BW	d_8	RF atrophy	%diff
$VV_{activity}$	V-V knee moment	Nm/BW	d_9	VM atrophy	%diff
$IE_{activity}$	I-E knee moment	Nm/BW	d_{10}	VL atrophy	%diff
$mom_{activity}$	Knee flexion moment	Nm/BW	g_1	Gait Velocity	m/sec
$FPfx_{activity}$	force plate A-P reaction	N/BW	g_2	Gait Cadence	Step/min
$FPfy_{activity}$	force plate M-L reaction	N/BW	g_3	Gait Stride length	m
$FPfz_{activity}$	force plate D-P reaction	N/BW	g_4	Gait Double Support	sec
$FPmx_{activity}$	force plate sagittal moment	Nm/BW			
$FPmy_{activity}$	force plate frontal moment	Nm/BW			
$FPmz_{activity}$	force plate longitudinal moment	Nm/BW			

Deg = degrees. N/BW = Newton/Body Weight. Nm/BW = Newton metres/Body Weight.

7.6 Principal Component Analysis (PCA)

PCA was performed on each waveform for each activity in a number of stages according to the protocol previous highlighted in section 5.7.2.1. The PCs were retained according to Kaisers criteria [232], where any PC with a variance less than one was discarded because it contains less information than the original data [232]. Cumulative total variance explained within the retained PCs was analysed in order to check that the original data was adequately explained by the retained PCs [240]. Each retained PC was assigned a label by examining the matrix of component loadings, L, which is a weighted relationship between PCs and the original variables. The matrix was calculated using the expression $L = E\Lambda^{1/2}$ [241], where Λ is the diagonal matrix of eigenvalues sorted from largest to smallest and the columns, and E are the corresponding eigenvectors. In order to assign labels to the PCs a threshold value of 0.71 was used [242] to retain PCs and ensure each variable can only load against one component (ensures each PC has a different interpretation). Any PC which shows a factor loading which is greater than Comrey's threshold can be interpreted as the dominant PC for the given stage of the gait cycle. Finally PC scores were calculated for each individual in the sample using the expression $\Omega = ZE$, where Z is the matrix containing the standardised variables (z_j).

Following the application of Kaiser's criteria between 3 and 10 PCs were retained for each waveform in each activity. The waveforms with a higher variance resulted in retention of the most PCs. When the cumulative variance was examined within these retained PCs, it was shown that in each waveform over 90% of the cumulative variance was explained (Table 7.4). During labelling of the PCs a number of were discarded because they did not meet the 0.71 threshold required to assign a meaningful label. After the PCs were labelled the final number of retained PCs were 51 PCs for gait (average three per waveform), 31 PCs for sit-to-stand, 28 PCs for stand-to-sit, and 39 PCs for step-descent (Table 7.5). Cumulative variance analysis shows on average that 74%, 78%, 77%, and 79% of variance was capture in the retained PCs for gait, sit-to-stand, stand-to-sit, and step-descent respectively. This reduction in captured cumulative variance could result in PCs being lost that contained pertinent data, however meaningful labels are required for each PC in order to interpret differences between activity data for the healthy, pre-, and post-operation groups. It is worth noting that even though a PC may contain a high loading factor for a certain part of the waveform, it will be one of a number of PCs which interact in the PCA projection of the original data. Other PCs would therefore have the potential to include pertinent data about a particular feature, however in order to reduce the data set the PCs with the highest factor loadings were kept.

Despite this reduction in the number of PC's, a large STV ratio still existed. This resultant STV ratio 144 data points (PCs and discrete clinical measures) to just 51 healthy and pre-KA participants. Further reduction of the number of data points is needed to amend this ratio, in order to reduce the number of variables their discrimination between groups must be analysed. If a variable shows little or no discrimination between the healthy and pre-operative group it will not provide any basis for analysing the change in function for pre- to post-KA. In order to analyse the discriminative power of the retained PCs and the clinical scores LDA was performed (Section 5.7.2.2). This analysis produced a ratio (Rayleigh Quotient) of the *between*- and *within-class* covariance. It also described how much separation there is between the healthy and pre-operative groups.

Table 7.5: PCs retained and the percentage of cumulative variance explained from PCA analysis of the waveform data from gait, sit-stand-sit, and step-descent. PCs retained before Comrey's labelling criteria and their percentage cumulative variance explained in brackets.

	Activity							
Variable	Gait		Sit to Stand		Stand to Sit		Step-descent	
	PCs	Cumulative Variance %	PCs	Cumulative Variance	PCs	Cumulative Variance	PCs	Cumulative Variance
DP	3 (7)	72 (94)	2 (7)	68 (98)	2 (7)	76 (98)	4 (6)	92 (97)
AP	2 (5)	73 (94)	1 (5)	40 (95)	1 (5)	37 (95)	3 (6)	92 (98)
ML	3 (6)	88 (97)	2 (7)	77 (99)	2 (6)	84 (99)	2 (6)	79 (98)
VV	1 (7)	59 (97)	1 (6)	70 (99)	2 (6)	80 (99)	3 (6)	92 (98)
IE	4 (5)	91 (93)	2 (5)	84 (98)	2 (5)	82 (98)	1 (6)	74 (99)
Mom	2 (6)	77 (97)	2 (6)	80 (98)	2 (6)	75 (98)	3 (7)	95 (99)
KF	2 (6)	71 (98)	2 (4)	87 (99)	2 (5)	85 (99)	3 (7)	82 (99)
HF	1 (5)	71 (99)	1 (4)	79 (99)	1 (4)	74 (99)	1 (6)	76 (99)
HA	3 (6)	92 (98)	2 (4)	93 (99)	2 (4)	94 (99)	1 (6)	54 (98)
HER	1 (6)	71 (99)	1 (4)	85 (99)	1 (4)	85 (99)	1(5)	78 (98)
AF	2 (7)	75 (99)	2 (4)	92 (99)	2 (4)	93 (99)	1 (6)	67 (98)
FPfx	2 (7)	63 (94)	2 (9)	61 (96)	2 (9)	60 (96)	3 (8)	80 (97)
FPfy	2 (7)	62 (95)	3 (5)	94 (98)	1 (5)	80 (97)	3 (10)	69 (97)
FPfz	2 (6)	57 (94)	2 (7)	72 (98)	2 (6)	76 (96)	2 (6)	78 (98)
FPmx	3 (7)	77 (96)	3 (5)	94 (98)	2 (6)	84 (97)	4 (8)	84 (97)
FPmy	1 (5)	70 (95)	1 (5)	73 (98)	1 (6)	68 (98)	2 (6)	79 (98)
FPmz	2 (5)	81 (96)	2 (6)	82 (99)	1 (5)	70 (98)	2 (6)	78 (98)
Mean	2 (6)	74 (96)	2 (6)	78 (98)	2 (5)	77 (98)	2 (7)	79 (98)
Std Dev.	1 (1)	10 (2)	1 (1)	14 (1)	1 (1)	13 (1)	1 (2)	10 (1)

7.7 Variable Ranking - Linear Discriminate Analysis (LDA)

LDA was performed on the retained PCs and clinical measures in order to build a hierarchy of variables which discriminate between healthy and pre-operative patients. LDA was performed using the protocol highlighted in Section 5.7.2.2 where a Rayleigh Quotient ($J(W)$) of the ratio between the *between-* and *within-class* covariance of the variable is calculated. Visual feedback on the separation between groups was given by the histograms of the LDA analysis.

Joliffe has previously highlighted limitations with running LDA on PCs. A common assumption in discriminant analysis is that the covariance matrix is the same for all groups, and the PCA may therefore be done on an estimate of this common *within-group* covariance matrix. This assumption is limited for two reasons

1. the *within-group* covariance maybe matrix maybe different for two groups.
2. there is no guarantee that the separation between groups will be in the direction of the high-variance PCs.[219]

To overcome these limitations a stepwise discrimination procedure was used to find the optimal number of PC scores to provide the best discrimination between the OA and healthy individuals [42]. All of the PC scores that were retained following the Kaiser's criteria (over 90% cumulative variance for all waveform measures) were included in this analysis. By conducting this stepwise analysis of all the PC scores retained an optimal set was found which could include both high and low variance PCs. The accuracy of these optimal PC scores to discriminate between groups will then be tested by observing the misclassification of participants when a linear discriminative reference point was observed [42].

7.7.1 LDA of Clinical Data

LDA analysis revealed that the most discriminatory variables were the pain, WOMAC, and 12 item OKS. The subjective clinical assessments (questionnaires and VAS) show high discrimination between groups, with the pre-KA patients showing large perceived functional deficits (Table 7.2). Other clinical measures show less discrimination, however there are still differences in RoM and muscle atrophy. LDA analysis between the healthy and pre-operative groups of these clinical measures reveals high Rayleigh Quotient scores (Table 7.6).

Table 7.6: Ranking of the pre-operative clinical measures after LDA analysis

Clinical Measures			
Ranking	**Measure**	**Rayleigh Quotient**	**Description**
1	Pain (VAS)	0.121	Pain was much higher pre-operation
2	WOMAC	0.102	Pre-operation group had lower perceived function
3	Oxford	0.087	Pre-operation group had lower perceived function
4	Instability (VAS)	0.033	Pre-operative patients had higher perceived knee instability
5	Flexion ROM	0.025	Pre-operative patients had less knee flexion
6	Total ROM	0.024	Pre-operative patients had reduce knee range of motion
7	RF atrophy	0.0179	Pre-operative patients had more RF muscle atrophy
8	VM atrophy	0.016	Pre-operative patients had more VM muscle atrophy
9	VL atrophy	0.005	Pre-operative patients slightly more VL muscle atrophy
10	BMI	0.001	Pre-operative patients had marginally higher BMI

As pain is the predominant reason for a patient to undergo KA it is not surprising that it is the highest ranking variables in the LDA comparison between the healthy and pre-operative groups. It is of note that none of the healthy group had any pain (pain was part of the exclusion criteria) and therefore the group had no deviation in scores which could have affected the LDA analysis. This very small distribution in the data was also seen in the stability and questionnaire analysis. However the KA group was very different in the spread of the data, with large standard deviations for all of the clinical measures (Table 7.2). Despite these *within-class* covariance's separation between groups was achieved for most of the clinical measures, showing their potential to discriminate between groups.

7.7.2 LDA of Gait

The stepwise discrimination process for the PC scores retained in the gait data showed that six PCs provided an optimal linear discrimination with just 3% misclassification (Figure 7.1).

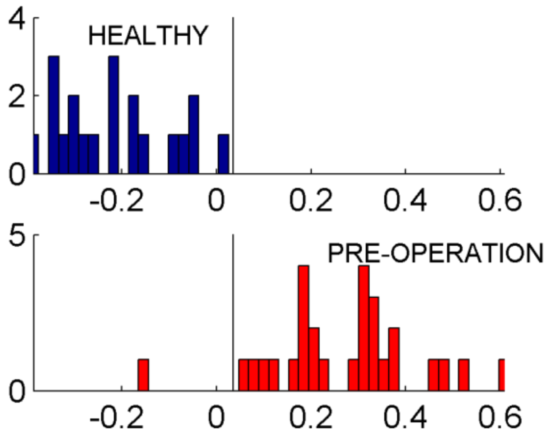


Figure 7.1: Histogram of the LDA subspace projection for the six highest discriminating PC scores of the gait cycle (Rayleigh Quotient = 0.11).

A summary of the top ranking discriminatory variables from the PCA analysis of the gait waveform and discrete outputs between the healthy and pre-operative group was collated (Table 7.7).

Table 7.7: Ranking of the gait measures after PCA and LDA analysis. Rayleigh Quotient of between group differences and percent of the variance explained within the retained PC.

	Gait		
Ranking	**Measure**	**Rayleigh Quotient**	**% Variance Explained**
1	mom_{gait} (PC1)	0.035	20.9
2	ML_{gait} (PC1)	0.028	20.2
3	$FPfz_{gait}$ (PC1)	0.025	18.3
4	g_4 (double support)	0.023	NA
5	KF_{gait} (PC1)	0.02	38.4

Results from the LDA analysis of the gait variables show that flexion moment during stance is the most discriminatory variable between that healthy group and pre-operative patients. Other variables with a lower Rayleigh Quotient have significant overlap between groups, showing limited discriminatory power. Discrete gait parameters show that there is a difference in all variables, with the pre-KA patients having slower gait velocity (mean H = 1.15m/sec, mean OA = 0.96m/sec), longer double support time (mean H = 0.24sec, mean OA = 0.32sec), decreased stride length (mean H = 1.27m, mean OA = 1.11m), and reduced cadence (mean H = 108 steps/min, mean OA = 98 steps/min) compared to the Healthy group. There was however considerable variance in the discrete gait measures resulting in fairly low LDA scores for all of the variables apart from double support time (Table 7.6).

7.7.2.1 Retained Gait Parameters

The loading factors of these retained gait PCs were then assessed to assign labels to the determine the variable (Appendix N). The top five gait cycle parameters included knee flexion moment, M-L reaction, vertical force plate reaction, knee flexion PCs. The top ranking PC from gait was knee flexion moment, the raw data shows some clear mean differences between the healthy and pre-operation patients (Figure 7.2a). Factor loading analysis (Figure 7.2b) reveals that the PC that showed the highest discrimination in the LDA analysis has high loading during the early stages of gait (5-22% of stance phase of gait), and peak extension moment during stance (50-70% of stance phase of gait). This variable can be labelled 'flexion moment during weight acceptance and mid phase of stance during gait'.

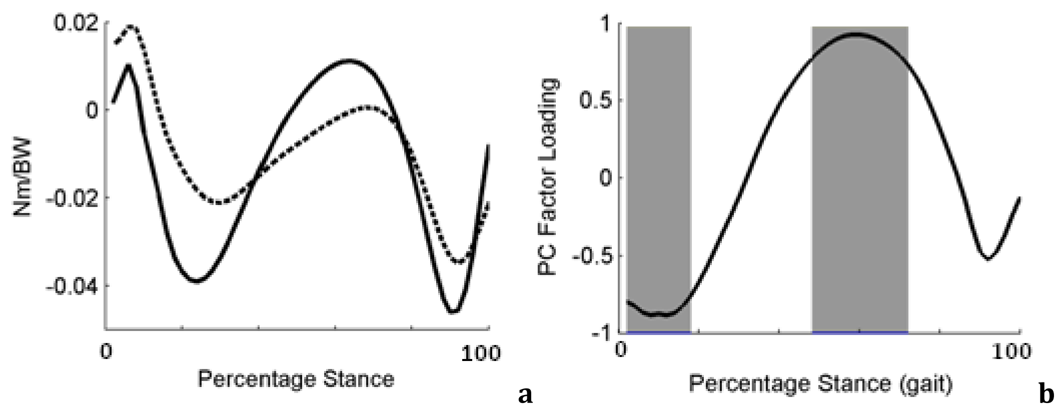


Figure 7.2: (a) Mean Knee flexion moment during stance phase of the gait cycle. Healthy in solid line, pre-operation patients dashed. (b). Component loading of the second PC retained from knee flexion moment PCA during stance phase of gait (black line), area of Comrey's threshold highlighted in grey.

The second most discriminatory factor in gait was M-L loading during stance phase. Factor loading analysis reveals that the first PC shows a difference between 10-20%, and 55-70% of stance phase of gait (Figure 7.3a). Although this has the smallest mean difference it is the section of the waveform with the least *within-class* variance. This variable can be labelled 'M-L reaction during weight acceptance and mid phase of stance during gait'. Analysis of the PC retained for vertical force plate data show that the loading occurs in similar areas to M-L. Vertical force plate reaction has two clear areas of factor loading during weight acceptation and end stance phase of gait which coincides with peaks in reaction (Figure 7.3d). It is labelled according 'Peak Vertical force plate reaction during stance phase of gait'.

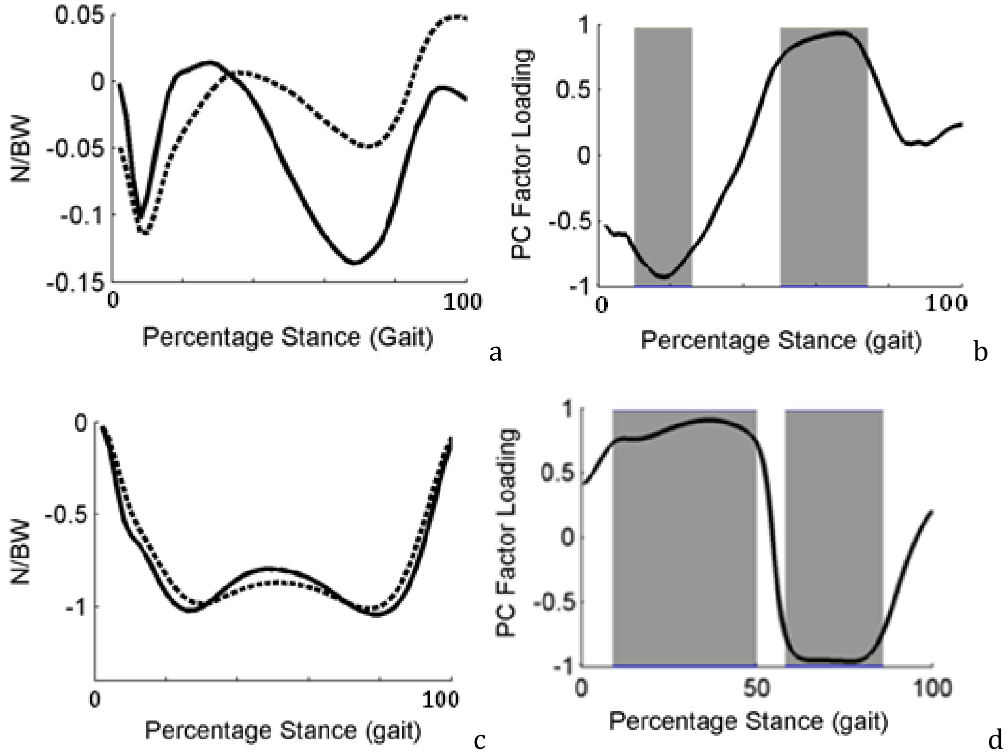


Figure 7.3: (a). Mean M-L tibiofemoral (TFJ) reaction during stance phase of the gait cycle. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from M-L TFJ reaction during stance phase of the gait cycle. (c). Mean vertical force plate reaction during stance phase of the gait cycle. Healthy in solid line, pre-operation patients dashed. (d) Component loading of the first PC retained from vertical force plate reaction during stance phase of the gait cycle.

The final variable selected is knee flexion during the gait cycle. Factor analysis shows that loading of the second retained PC occurs during 35-40% and 60-75% of gait (Figure 7.4b). This coincides with the peak knee flexion and extension angle during stance and swing phase of gait and there are clear mean differences in the original data set (Figure 7.4a). However there was considerable *within-class* covariance resulting in a relatively low LDA score. This retained variable can be labelled 'Knee range of motion during gait'.

Factor analysis of the retained PCs highlighted that there was a clear link to the factor weighting of the PCs and mean differences in the original gait data set. The LDA analysis however highlights that although there are *between-class* difference between the healthy and pre-operation participants, there is considerable *within-class* covariance in the data.

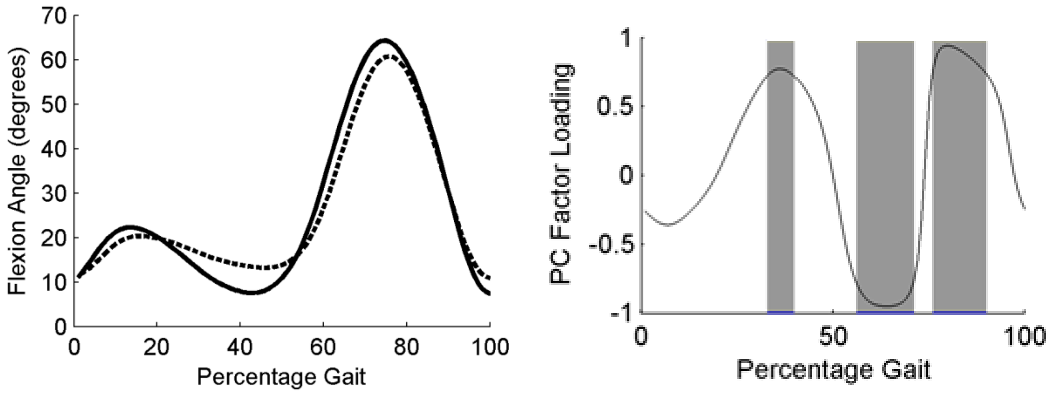


Figure 7.4: (a). Mean Knee flexion during the gait cycle. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from Knee flexion during the gait cycle.

7.7.3 LDA of Sit-Stand-Sit

Ten PC scores were shown to provide the optimal discriminatory power of the sit-stand activity (Appendix K). This linear discrimination model of sit-stand PC scores had a misclassification rate of 9%. The stand-sit analysis revealed that twelve PC scores provided the most powerful discrimination (Appendix L), with a misclassification rate of 11% (Figure 7.5).

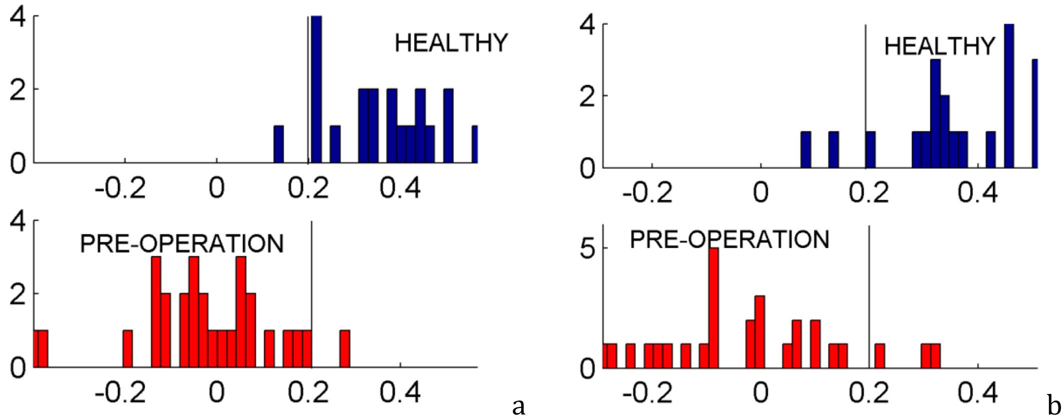


Figure 7.5: (a) Histogram of the LDA subspace projection for the ten highest discriminating PC scores of the sit-stand cycle (Rayleigh Quotient = 0.065). (b) Histogram of the LDA subspace projection for the twelve highest discriminating PC scores of the stand-sit cycle (Rayleigh Quotient = 0.043).

During Sit-to-stand and stand-to-sit activities the top two variables that discriminated between healthy and OA groups were force plate sagittal moment and vertical reaction. Discrimination was lower than that of gait for many of the variables, reflecting relatively limited scope for deviations in the kinematics and kinetics during the activities (Table 7.8).

Table 7.8: Ranking of the sit-stand-sit measures after PCA and LDA analysis

		Sit-Stand Measures	
Ranking	**Measure**	**Rayleigh Quotient**	**% Variance Explained**
1	$FPmy_{sit-stand}$ (PC1)	0.027	50.5
2	$FPfz_{sit-stand}$ (PC1)	0.019	48
3	$DP_{sit-stand}$ (PC1)	0.014	43.4
4	$FPmx_{sit-stand}$ (PC1)	0.009	63
5	$FPfy_{sit-stand}$ (PC2)	0.008	28.6

		Stand-Sit Measures	
Ranking	**Measure**	**Rayleigh Quotient**	**% Variance Explained**
1	$FPmy_{stand-sit}$ (PC1)	0.016	40.8
2	$FPfz_{stand-sitd}$ (PC1)	0.013	44.6
3	$mom_{stand-sit}$ (PC1)	0.011	40.8
4	$FPmx_{stand-sit}$ (PC1)	0.008	55
5	$KF_{stand-sit}$ (PC2)	0.007	27.9

Poor discrimination was also a factor of the variance in both the healthy and OA groups, with large covariance's in the data for both the healthy and pre-operative patients. Although there were mean differences in the force plate loading data between the healthy and OA groups, the variance confounded any discrimination in the post-PCA data. This is apparent when the raw data is observed, with one times the standard deviation overlapping heavily between groups (Figure 7.6).

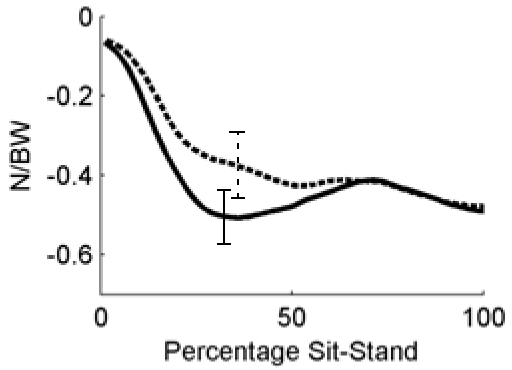


Figure 7.6: Mean force plate vertical reaction during the sit-stand cycle. Healthy in solid line, pre-operation patients dashed. One times the standard deviation represented by bars at 30% (healthy) and 35% (OA) of activity.

7.7.3.1 Retained Sit-Stand-Sit Parameters

During the sit-stand-sit activities the most discriminating measures were dominated by force plate data. Three out of the top five discriminating PCs were provided by force plate forces and moments with sagittal plane moment being the most discriminatory in both sit-stand and stand-sit. The raw data clearly shows that the control group have a much larger peak in sagittal moment during the early-mid (10-70%) stages of the activity, with a peak mean difference of 0.044Nm/BW (37.6Nm) during sit-stand (Figure 7.7a). The most discriminatory PC of the sagittal force plate moment was the first PC which described 50.5% of the variance in the original data set. Factor loading of this PC clearly shows high significance during 20-50% and 70-100% of the activity which coincides with the peak mean difference in the raw data (Figure 7.7), it is therefore labelled 'sagittal force plate moment during sit-stand'.

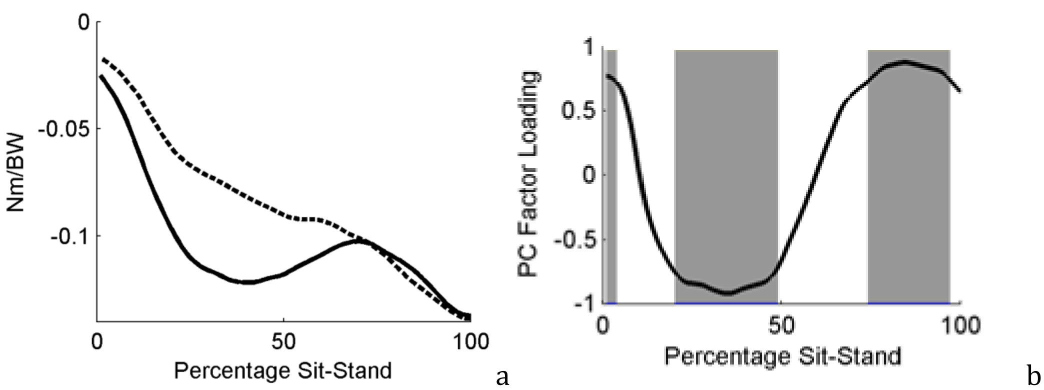


Figure 7.7:(a) Mean sagittal force plate moment during sit-stand. Healthy in solid line, pre-operation patients dashed. (b). Component loading of the first PC retained from force plate sagittal moment during sit-stand.

The second most discriminatory PC during sit-stand-sit was the first PC for vertical force plate reaction (48% of variance explained). As with the sagittal moment there is a clear reduction in the peak magnitude of vertical force (peak mean difference of 0.14N/BW, ~119N) in the OA group compared to the healthy controls (Figure 7.8a). A similar factor loading pattern is observed in this PC during sit-stand with significant labelling areas during 20-40% and 65-90% of the activity (Figure7.8b). This PC score was labelled 'vertical force plate reaction during early and late sit-stand'.

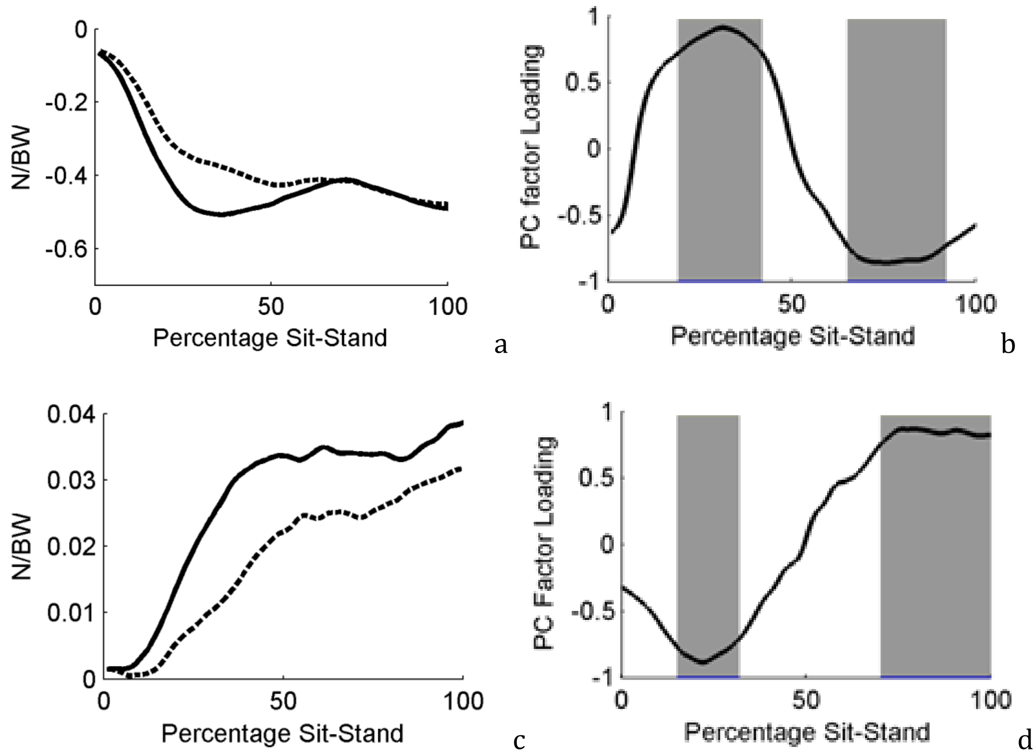


Figure 7.8: (a). Mean vertical force plate reaction during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from vertical force plate reaction during sit-stand. (c). Mean M-L force plate reaction during sit-stand. Healthy in solid line, pre-operation patients dashed. (d) Component loading of the first PC retained from M-L force plate reaction during sit-stand.

This reduction in vertical force plate loading resulted in significant reduction in distal-proximal (D-P) loading at the knee joint in the OA group. D-P knee reaction was the third most discriminatory PC during sit-stand. The raw data shows that a large mean peak difference is seen between 20-60% of the activity (mean peak difference of 0.65N/BW, ~555N). Factor loading is similar to that of the vertical force plate reaction (Appendix O) and the PC was labelled 'D-P TFJ reaction during early and late sit-stand'. The final two high ranking PC scores were coronal force plate moment, and M-L force plate reaction.

Similar loading of the PCs were observed to the previous factors (Appendix O), labelling was consequently given as 'Coronal force plate moment during early and late sit-stand' and 'M-L force plate reaction during early and late sit-stand'.

As with sit-stand data force plate PC scores dominated the highest discriminating factors during stand-sit. There were however lower peak mean differences in the data which is reflected in lower Rayleigh Quotient outputs. Loading of the retained force plate PCs shows that the labelling threshold is met at the early and late stages of the activity (Figure 7.9). Each PC was subsequently labelled according to these areas of labelling threshold.

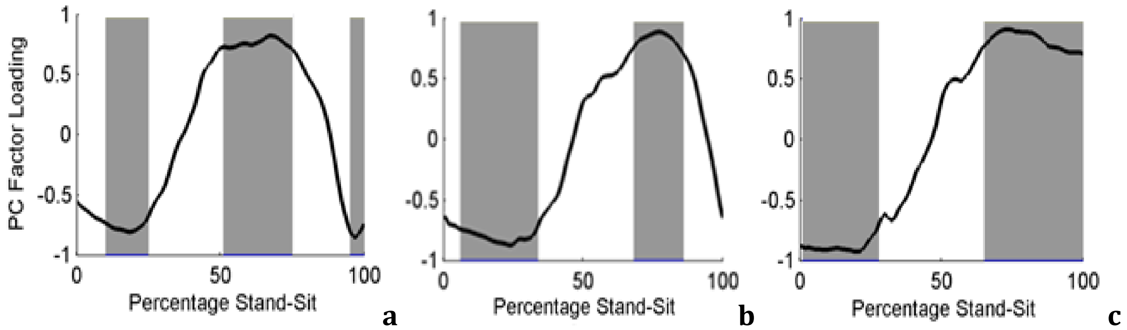


Figure 7.9:(a) Component loading of the first PC retained from sagittal force plate moment during stand-sit. (b) Component loading of the first PC retained from vertical force plate reaction during stand-sit. (c) Component loading of the first PC retained from coronal force plate moment during stand-sit.

D-P knee reaction was not one of the most discriminating factors during stand-sit, instead knee flexion moment showed large between group differences (Figure 7.9). The raw data clearly shows that between 60-80% of the activity there are large difference in the mean data from each group (peak mean difference of 0.016Nm/BW, ~13.7Nm). The factor loading at this PC clearly shows high loading between 70-90% of activity, corresponding with high mean differences in the raw data (Figure 7.10). This PC score was accordingly labelled 'peak flexion moment during stand-sit'.

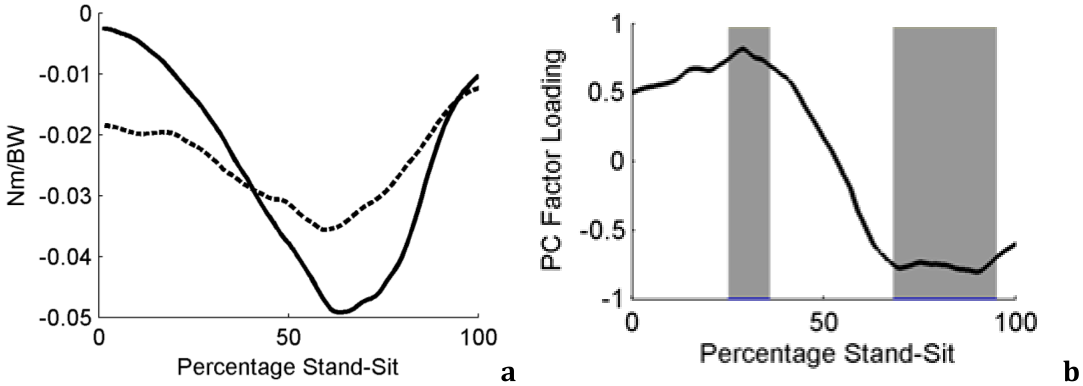


Figure 7.10:(a) Mean knee flexion moment during sit-stand. Healthy in solid line, pre-operation patients dashed. (b). Component loading of the first PC retained from knee flexion moment during sit-stand.

When the five most discriminatory PCs were collated for the sit-stand-sit activity it is clear that the sagittal moment and vertical forces recorded by the force plate were the most discriminatory factors (Table 7.7). The only kinematic finding which made the top five factors was knee flexion during stand-sit, however the low Rayleigh Quotient ($J(W)$ = 0.007) indicates a small *between-class* difference with high *within-class* covariance. Factor loading for the PC retained from knee flexion shows the labelling threshold was met at the beginning and ending of the activity and it was hence labelled 'Knee flexion range during stand-sit'.

7.7.4 LDA of Step-Descent

Finally the step-descent activity analysis showed that twelve PC scores were optimal in the linear classification (Appendix M), however misclassification was the highest in this activity at 18% (Figure 7.11). Step-descent provided the least discrimination between groups, this was mainly due to the variance in the healthy and OA groups data. All other results produced a Rayleigh Quotient below 0.004 (Table 7.9). This variance in knee reactions and moments was also seen in the telemetrised data (Section 2.2.7). As with the other activities force plate vertical reaction, TFJ flexion moment, and knee flexion all were prominent in the highest discriminating PC scores.

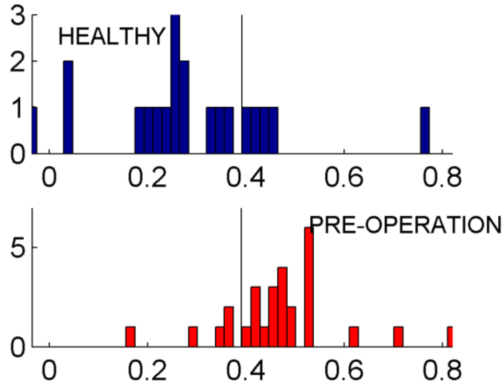


Figure 7.11: Histogram of the LDA subspace projection for the twelve highest discriminating PC scores of the step-descent cycle (Rayleigh Quotient = 0.017).

Table 7.9: Ranking of the step-descent measures after PCA and LDA analysis

	Step-descent		
Ranking	**Measure**	**Rayleigh Quotient**	**% Variance Explained**
1	$FPfz_{step-down}$ (PC1)	0.004	58
2	$mom_{step-down}$ (PC3)	0.003	58
3	$FPfx_{step-down}$ (PC1)	0.003	49.6
4	$HA_{step-down}$ (PC2)	0.003	41.2
5	$KF_{step-down}$ (PC1)	0.003	38.2

Step-descent was the least discriminating activity, however the standardisation of the activity to percentage stance and full cycle was challenging. The process of standardisation could have resulted in more variance within the data resulting in poor LDA outcomes.

7.7.4.1 Retained Step-Descent Parameters

One of the few discriminating variables was vertical force plate reaction during stance phase of the activity. The mean of the raw data clearly shows a difference in the peak reaction at the knee (Figure 7.12a). Factor loading shows that the retained vertical ground reaction force PC had a high component loading during the majority of the activity, it is simply labelled 'Vertical force plate reaction during stance phase of step-descent'.

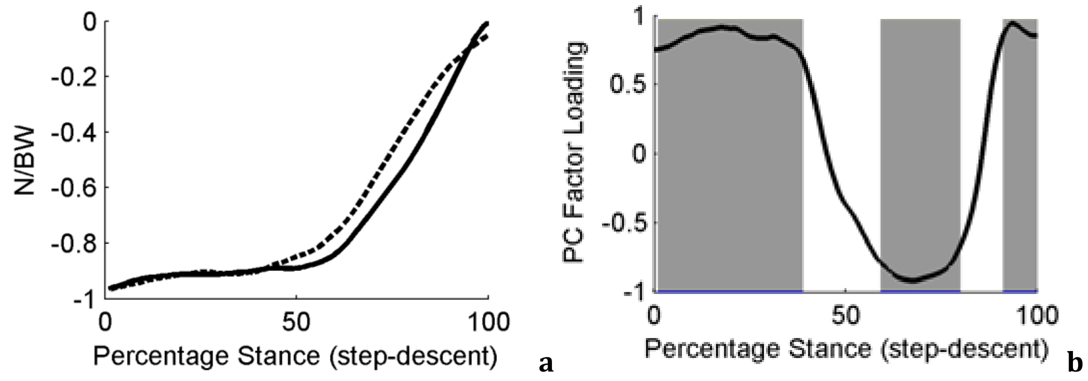


Figure 7.12: (a) Mean vertical force plate reaction during the step-descent (stance) cycle. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from vertical force plate reaction during the step-descent (stance) cycle.

LDA analysis of this PC shows that there is a large amount of *within-class* covariance and this results in a low Rayleigh Quotient(Figure 7.13). This large variance was a common theme in the activity. The rest of the top five ranking variables for the step-descent activity were knee flexion moment (third PC), A-P force plate reaction (first PC), hip abduction (second PC), and knee flexion (first PC).

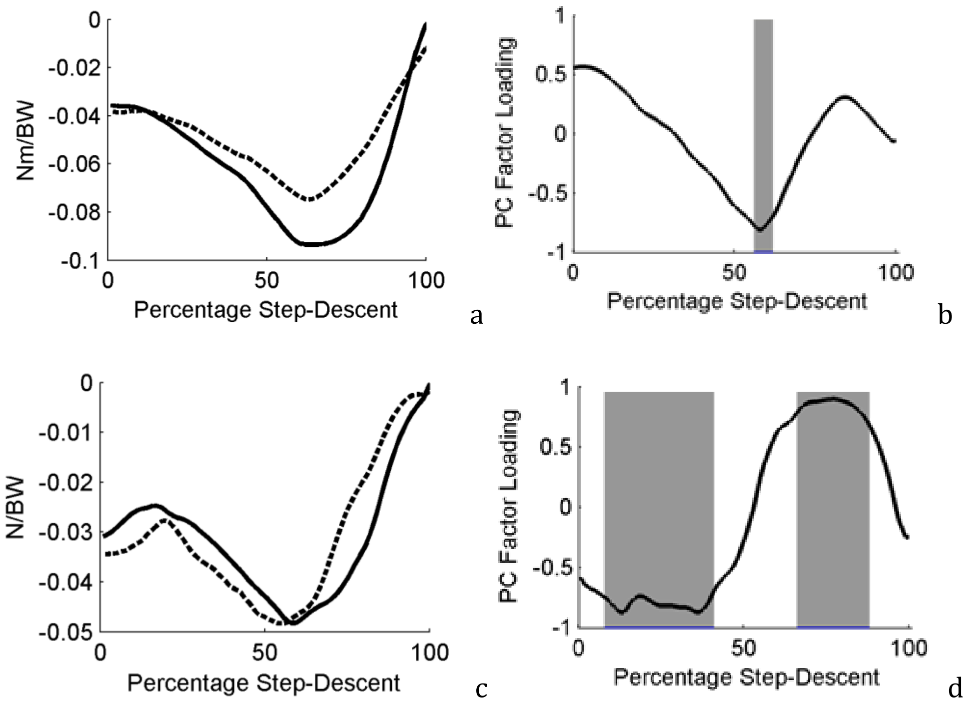


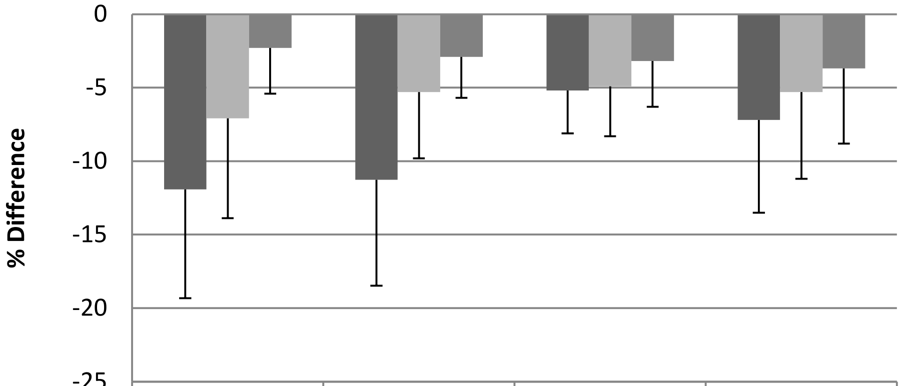
Figure 7.13: Mean tibiofemoral joint (TFJ) flexion moment during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the third PC retained from TFJ flexion moment during step-descent. (c). Mean A-P force plate reaction during step-descent. Healthy in solid line, pre-operation patients dashed. (d) Component loading of the first PC retained from A-P force plate reaction during step-descent.

Factor loading analysis of the retained PCs for these variables enables them to be labelled (Figure 7.13, Appendix Q), however the low discriminatory power of these PCs has to be taken into account. Factor loading of the third PC of knee flexion moment during the stance phase of step-descent shows this PC loads during 58-62% of the activity (Figure 7.13b), which coincides with the peak in raw data, its labelled 'Peak knee flexion moment during stance phase of step-descent'. Factor loading of the A-P force plate reaction only occurs during the early stages of the activity (Figure 7.13d) and hence was labelled 'Early A-P force plate reaction during stance phase of step-descent'. The second PC score of hip abduction shows a threshold factor loading at the beginning and mid stages of the step-descent (Appendix Q), it was labelled 'Hip abduction at the beginning and mid stages of step-descent'. Finally the retained knee flexion PC shows labelling threshold at the mid and late stages of the activity (Appendix Q) and was labelled accordingly 'Knee flexion during mid and late stages of step-descent'.

7.8 The Effects of Changes in Movement Patterns

The data presented in Section 7.7 clearly shows that there were kinematic and kinetic changes in the effecting limb of the pre-operative patients compared to the healthy population. Often these changes were a reduction of force and moments about the TFJ during the activities. In order for patients to reduce the loading on the effected TFJ adaptations in movement patterns were adopted. The effects of these changes on the contralateral limb were assessed. It is hypothesised that a reduction in effected TFJ loading during ADL would result in an increase in load on the contralateral limb.

The total Peak TFJ joint forces (Distal-Proximal, Anterior-Posterior, and Medial-Lateral) in the right and left limbs were assessed to calculate the percentage differences in joint loading. Clear reductions in limb loading were shown in the OA individuals' affected limb during all activities The extent of the asymmetry is shown in Figure 7.14, with the scheduled TKA group having on average 11.9% (226N, ±137N) addition force through the contralateral TFJ during sit-stand-sit, which was significantly higher than the healthy group (46N, ±124N. t-test, $p<0.05$). The magnitude of this asymmetry was much less in the patients scheduled for the UKA with an average peak difference of 7.1% (115N, ±95N). There was also evidence loading asymmetry during gait, and to a lesser extent step-descent activities (Figure 7.14). However due to the variance in the data significant differences between groups were not observed.



	sit-stand	stand sit	gait	step-descent
TKA	-11.93	-11.27	-5.2	-7.2
UKA	-7.09	-5.31	-4.9	-5.3
Healthy	-2.3	-2.9	-3.2	-3.7

Figure 7.14: From left to right; Mean stand-sit, sit-stand, gait, and step-descent TFJ percentage loading difference from KA patients affected and the contralateral limb.

Despite there not being a significant loading asymmetry during the step-descent activity, there were some evident changes in loading patterns that could have an effect on the contralateral limb. When the patients were lowering themselves down the step with the effect limb the control of the movement was poor. The result of this change in movement pattern was a heavy impact on the bottom step with the contralateral limb. Force plate data taken from the bottom step clearly shows a sharp peak in vertical forces through the contralateral limb (Figure 7.15).

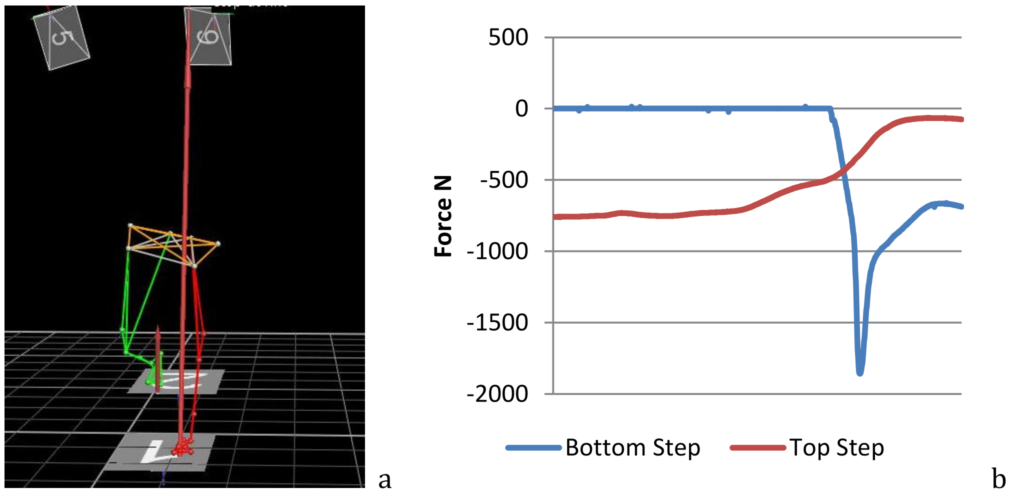


Figure 7.15: (a) Snapshot of VICON Nexus software, with participant performing step-descent activity. Force plate reactions represented by red arrows. (b) Raw vertical force plate data from the same step-descent activity.

When the vertical force plate reactions were compared from the effected limb being lowered to the contralateral limb an average decrease of 242N (±195N) was observed. However this difference ranged considerably (-27N to 785N). The observed differences in impact loading on the bottom step could be due to a number of reasons. The first of which could be the loss of strength in eccentric quadriceps on the effected limb, if a patient was unable to support the full weight of their body this could result in poor control of movement. The patient may also have been putting less weight onto their effected limb when lowering with the contralateral limb in order to protect the TFJ and reduce the risk of pain in the joint.

7.9 Discussion

Analysis of the collated data shows that there are clear differences between the healthy, pre-, and post-operative participants in the present study. With the variables reduced and labelled they can be selected for further analysis. The data collected from the subjective clinical scores reveal that patients have improvements in perceived pain, stability, and function from pre- to post-operation. However, there is still an evident difference between the patients and healthy control group. The objective clinical measures show a clear difference in findings with patients retaining decreases in RoM and muscle size from pre- to post-KA. Feedback from the surgeon shows that the consultant performed the operation in most cases, with a variety of different prosthesis types. All surgeons did however use a similar surgical approach and fixation method. Rehabilitation feedback showed that on average patients remained in hospital for 6.7 days, although outpatient rehabilitation varied significantly between patients.

Analysis of the ADL data shows that PC scores retained from gait waveforms showed the highest discriminatory power. With just six PC scores creating a LDA model that could classify between healthy and pre-operative patients with an accuracy of 97%. This accuracy of classification is similar to that previously reported for gait [42, 91]. The high ranking PC scores correlated with data that has previously been reported. PCs such as peak knee flexion [42], stance phase flexion moment [42], and peak vertical ground reaction [42, 91] were all observed to show differences in the literature.

This study shows that force plate data provides the best discrimination between healthy and OA individuals during sit-stand-sit. These findings are different to that previously reported for gait [243], and stair ascent [84], where joint kinematics and kinetics were found to be the most discriminatory factors after PCA analysis. This difference in outcome was probably due to the nature of the activity, with gait and stairs being a reciprocal activity compared to the closed chain (feet fixed to floor) movement pattern of sit-stand-sit. This closed chain nature of the activity reduces the potential for kinematic differences between groups of patients/healthy individuals. When comparing the accuracy of the stepwise classification process the sit-stand-sit data (9-11% misclassification) showed slightly higher misclassification than gait (8%) [42], and stairs (5%) [244]. The differences in force measures must have come from sources other than kinematic changes. Previous research has highlighted that sit-stand-sit activity can be effected by changes in centre of mass (CoM) about the person performing the activity [47], and changes in posture has been shown to be prevalent in knee replacement patients with shifts in posture to reduce weight bearing (WB) through the operated lower limb during sit-stand [48]. With this in mind the data produced from this study clearly shows that OA patients are reducing weight bearing through the effected knee in order to protect the joint.

A study has previously used PCA to assess differences in stair ascent in older and younger individuals [244]. Reid et al showed twenty five PCs were retained by a 90% variance criterion, however only nine were statistically different and four PCs were retained for the final analysis. PC scores that were the most discriminatory were P-A force PC1, M-L force PC1, V-V moment PC1, and flexion moment PC2 [244]. These PCs correspond do not with the results shown by the present study. The use of a step-descent rather than stair ascent, and the difference in the populations being studied could be the probable reason for these differences. (Table 7.8).

There were limitations with the assessment techniques used within the data reduction. Joliffe has previously highlighted limitations with running LDA on PCs [219]. Although the data did show differences in the *within-group* covariance, this we feel is an important factor to include in analysis. It is known there is large variance in both healthy and OA individuals during ADL [245]. The large *within-group* covariance found in the OA group highlights the range of patients who are about to undergo knee arthroplasty, with some functioning much higher than others. This pre-operative variation may have a significant impact in post-operative outcomes. It was also reassuring to find that factor analysis that the PCs which showed discrimination had high loading during the point in the activity where there were differences in the raw data.

Despite data from gait providing the best discrimination in terms of kinematic and kinetic changes in the affected limb, a novel finding in the present study was that the resultant changes in movement patterns have the greatest effect on the contralateral limb during sit-stand-sit. Patients had increased TFJ reactions during gait, sit-stand-sit, and step-descent on the contralateral TFJ, with those scheduled for a TKA having higher asymmetry in loading compared to UKA and the healthy cohort. This may be more clinically relevant in terms of long term risk of pathology.

7.10 Conclusion

The data presented in this chapter has shown that KA patients have reduced perceived functional scores pre-operation compared to the healthy population. The large difference between healthy and pre-operative patients is highlighted by the high discriminatory power of the measures (Table 7.6). There were improvements in these scores post-operation (Table 7.2), although differences to the healthy population were still observed. Clinical objective measures of RoM and muscle atrophy showed KA patients had reduced joint function pre-operation, and this reduction generally did not improve post-KA (Table 7.2). PCA and LDA analysis of the ADL data derived from MS modelling showed that gait was the most discriminatory activity, and TFJ flexion moment was reduced for all activities assessed. Analysis of between limb loading showed that the changes in movement pattern resulted in an increased load on the contralateral limb, especially during the sit-stand activity.

The next stage of the analysis was designed to see if a classification of participant groups can be built using the selected variables.

Chapter 8
Participant Classification: *Dempster-Shafer Theory*

8.1 Introduction

Chapter seven has focussed on condensing the data set into variables which discriminate between healthy and pre-operative KA patients. These data provided the basis for classifying between the healthy (H) and pre-operative (OA) participants in the study. LDA analysis showed that there were differences in the data between the H and OA groups, with the subjective clinical scores offering the most discrimination. ADL data provided less discrimination due to the variance in the data collected. In order to classify whether a participant is healthy or has OA there is a need to collate data together in order to make the classification of function a holistic process (in accordance with ICF recommendations). To collate data collected during the present study the Dempster-Shafer Theory (DST) classifier (Section 5.6.5) was used in collaboration with Cardiff University. DTS classifiers were then used to predict the change in functional status from pre- to post-KA. The classifiers also gave feedback on the post-operative function of the KA patients compared to the H group (i.e. what functional deficit if any still existed post-operation).

These changes in function estimated by the DST analysis then provided the basis to answer the following questions;

- What are the functional limitations of KA patients pre-operation?
- What are the changes in function from pre- to post-KA?
- What is the six month post-KA functional status of the patients included in the present study?

8.2 Dempster Shafer Theory (DST)

As discussed in Section 5.6.5 the DST combines evidence from different sources to arrive at a degree of belief (represented by a belief function) that takes into account all the available evidence [224, 225]. In the case of the data collected for the present project the evidence consisted of PC scores from MS modelling derived joint kinematic and kinetic data, discrete gait measures, clinical measures of RoM and muscle atrophy, and subjective measures of pain, stability, and function (WOMAC and OKS). The classification process comprised of a number of stages: (1) conversion of input variables into confidence factors, (2) conversion of confidence factors to bodies of evidence (BoEs) using DST, (3) combination of individual BoEs and (4) visualisation of BoEs using simplex plots [227]. The BoE comprised of three focal beliefs;

- the person is healthy (H); $m(\{x\})$
- the person has OA; $m(\{-x\})$
- the person is either healthy or has OA (uncertainty); $m(\{x, -x\})$

Each BoE consisted of three values, the sum of which is one. If a patient is classified to be healthy the bias of these three values will be with the $m(\{x\})$ classification, for example $m(\{x\}) = 0.75, m(\{-x\}) = 0.15, m(\{x, -x\}) = 0.1$.

The conversion of each input variable into a confidence factor and finally into a BoE is dependent on four control variables, k, θ, A, and B. k describes the steepness of the curve when calculating the confidence factor, $cf(v)$ (Section 5.6.5, Figure 5.6.5), and θ describes the value of the input variable which produces a confidence value equal to 0.5. Control variables A and B refer to the dependence of $m(\{x\})$ on the confidence factor and the maximal support assigned to $m(\{x\})$ or $m(\{-x\})$ repectively. Values for these control variables have been described by Jones et al [246]. k was recommended to reflect the standard deviation in the data, σ, so the expression $k = \pm 1/\sigma$, where the sign depends on the positive or negative association. To avoid bias θ was assigned as the mean value of the variable. Values for A and B depict the dependence of $m(\{x\})$ on the confidence factor and the maximal support assigned to $m(\{x\})$ or $m(\{-x\})$ respectively. These control variables were dependent on the upper and lower bounds of certainty within the variables which were included in the BOE. These were set at between 1 and 0.8 for the objective based measures and 1 and 0.6 of the subjective measures. These bounds of certainty controlled the relative position of the final BOE on the simplex plot (amount of uncertainty in the classification).

In order to establish a baseline classification the H and OA groups data were initially used to form the classifier's parameters. In order to create the most robust classification with DST analysis the best parameters for classification were established. In order to do this several classifiers were built using the following data:

1. subjective measures (questionnaires, VAS, perceived activity)
2. objective measures (PCs from ADL, discrete gait measures, RoM, muscle atrophy)
3. combined measures (top ranking subjective and objective measures)

These classifiers consisted of no more than ten variables in order maintain the STV ratio of 5:1. This STV ratio was chosen in order to provide validity to the analysis whilst taking into account the low numbers of participants in the final analysis. Robustness of participant classification was tested using the LOOCV test, and the ability for the body of evidence (BoE) to classify between H and OA will be assessed. The DST also provides a ranking of each variable in the classification process. This ranking will be compared to the findings in the LDA analysis (Section 7.7).

8.3 Classification of Subjective Measures

Subjective measures during the data collection process were used to derive the first DST classifier. These measures included WOMAC, OKS, VAS, and perceived number of hours exercise performed each week. Although the subjective measures had produced high LDA results it was observed that there was considerable variance in pre-operative data (Table 7.2). However there was very little deviation in the healthy group, with all participants reporting high function and no pain. This resulted in the data being heavily bunched together in the bottom left corner of the DST simplex plot for the healthy group (Figure 8.1). There was much more of a spread in the DST classification of the KA group, with the UKA showing a wide spread in data from each end of the OA and H spectrum. The TKA group showed much less variance in classification with all of the TKA patients being classified on the OA side pre-operatively (Figure 8.1).

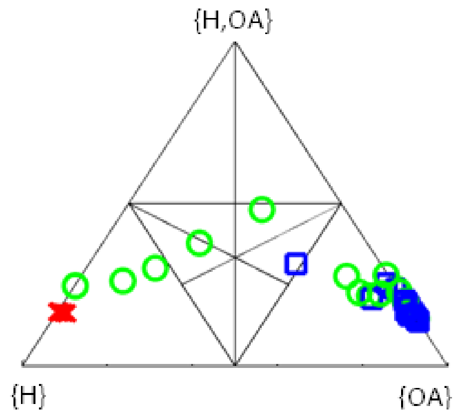


Figure 8.1: Dempster-Shafer Theory (DST) simplex plot of the subjective data collected from the healthy and pre-operative (OA) groups. H = red cross, Unicompartmental Knee Arthroplasty (UKA) group = green circle, Total Knee Arthroplasty (TKA) group = blue square.

When the classifier was assessed using the leave one out test it had a classification accuracy of 90.5%. On inspection of the BoE the WOMAC (d_1), pain (d_4), and OKS (d_2) provided the best confidence of classification (>88%). Perceived pre-operative activity (d_7)was the least discriminatory factor (Table 8.1).

Table 8.1: Table of the subjective DST classifier variables.

	WOMAC (d_1)	OKS (d_2)	Pain (d_4)	Stability (d_5)	Activity (d_7)
Standard deviation (k)	0.87	-0.86	0.90	0.67	-0.15
Mean (θ)	27.6	33.5	4.0	2.2	7
Dependence factor (A)	0.5	0.5	0.5	0.5	0.5
Dependence factor B	0.4	0.4	0.4	0.4	0.4
Confidence factor (v)	90.6	88.7	88.7	79.2	43.4

These ranking scores are similar to those of the LDA (Table 7.5), although the VAS pain measure was seen to be the most discriminatory. The subjective DST plot shows that for five of the UKA subjects they were classified to be healthy. On inspection of these patients they were all high functioning compared to the TKA group. However the increasing height in the DST plot of the five UKA patients highlighted the uncertainty in the classification.

8.4 Classification of Objective Measures

Objective measures included PC scores from the ADL, gait cycle parameters, and clinical measures such as RoM, BMI, age, and muscle atrophy. This, however, posed a problem, with the number of potential variables outnumbering the number of participants in the study. The first stage of the analysis was to compare between the ADL activities for their classification accuracy. The DST analysis of the retained gait variables showed that there was a classification accuracy of 88.2%, with relatively high uncertainty in (Figure 8.2).

Sit-stand had a leave one out accuracy of 75.9%, with a large spread in data for all three groups (Figure 8.2). The same classification accuracy was achieved for stand-sit variables, which also showed considerable variance in the data for all groups. As predicted by the LFDA the step-descent variables provided the least discrimination with a leave one out accuracy of just 58.4%. These classification results are lower than that described by the

LFDA (Section 7.7.2-4). However the DST analysis incorporates bounds of error in the input variables and uncertainty in the classification process (LFDA provides an optimal separation between groups).

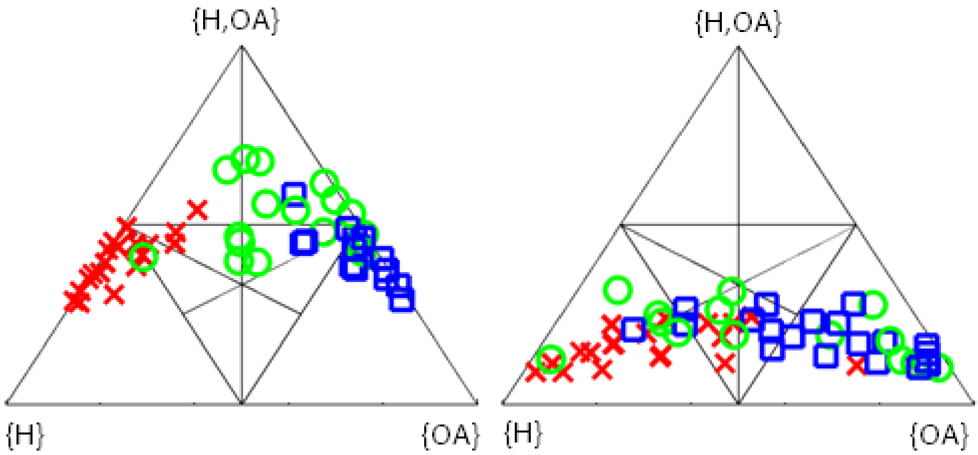


Figure 8.2: DST simplex plot of the retained gait (left) and sit-stand (right) variables collected from the healthy and pre-operative (OA) groups. H = red cross, UKA = green circle, TKA = blue square.

The highest classification accuracy was achieved by combining the clinical objective measures of RoM and muscle atrophy with the top ranking PC scores of each activity. This classifier has an accuracy of 89.9%. In order to lower the number of variables included in the DST classification it was decided that only three retained PC scores from each activity would be kept, along with the clinical measures resulting in sixteen variables. A DST classifier was then built with these variables, and further reduction in the variables was achieved by selecting the top ten ranking variables from this initial DST classifier. The final DST classifier has these top ten variables driving the classification process which resulted in a leave one out accuracy of 94% (Figure 8.3). The objective data showed higher levels of uncertainty (higher up the simplex plot) compared to the subjective based classifier. There was also a much a larger spread in the healthy data set, although they were all classified on the correct side of the simplex plot. As with the subjective data, the pre-operative UKA patients provided the largest spread in classification with three of the patients being classified as healthy, although they had considerable uncertainty. It is of note that these three pre-operation patients coincided with the five patients who were classified as healthy in the subjective DST model.

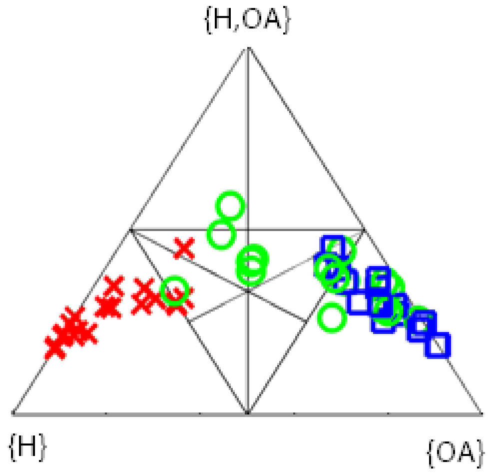


Figure 8.3: DST simplex plot of the objective data collected from the healthy and pre-operative (OA) groups. H = red cross, UKA = green circle, TKA = blue square.

The increase in uncertainty is a factor of the increased variance in the data from the healthy and pre-operative groups. The variables within the objective BoE show that gait PCs and parameters show the highest confidence factor (v) for discrimination (Table 8.2).

Table 8.2: Table of the objective DST classifier variables.

Variable	Standard deviation (k)	Mean (θ)	Dependence factor (A)	Dependence factor B	Confidence factor (v)
mom_{gait}	0.79	-0.09	0.5	0.2	96.1
ML_{gait}	0.74	-0.71	0.5	0.2	86.3
$FPfz_{gait}$	0.65	0.50	0.5	0.2	70.3
$FPmy_{st-sd}$	0.59	-0.26	0.5	0.2	74.5
$FPmy_{sd-st}$	0.54	0.49	0.5	0.2	74.5
$FPfz_{st-sd}$	0.61	-0.61	0.5	0.2	72.5
DP_{st-sd}	0.49	0.02	0.5	0.2	72.5
Gait double support (g_4)	0.48	0.29	0.5	0.2	74.5
ROM (d_3)	15.67	123	0.5	0.2	78.4
RF Atrophy (d_8)	16.9	10.9	0.5	0.2	83.7

This ranking confirms the LFDA findings that gait is the highest ranking in discriminating between H and OA groups. Sit-stand-sit and step-descent PC scores could be a potential source of the increased uncertainty within the classifier. Combining data from multiple subjective and objective measures was then explored to see if this would increase classification accuracy.

8.5 Classification of Combined Subjective and Objective Measures

In order to incorporate both objective and subjective variables in the classification process a combined DST model was built. This used the top ranking subjective and objective measures to classify the patients function. By combining both types of measures it was hoped that a holistic interpretation of function could be achieved. By combining the measures the classifier increased in accuracy with the leave one out test showing a 96% successful classification (Figure 8.4).

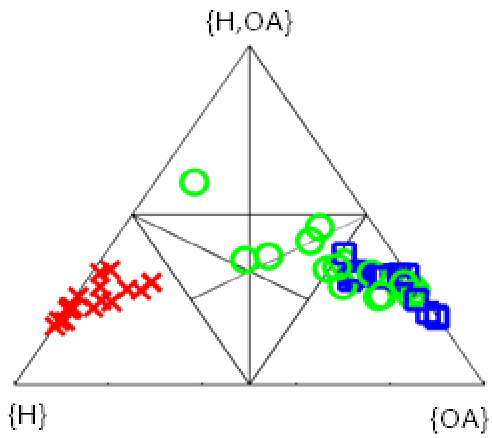


Figure 8.4: DST simplex plot of the combined subjective and objective data collected from the healthy and pre-operative (OA) groups. H = red cross, UKA = green circle, TKA = blue square.

Figure 8.4 shows that the classifier is accurate at classifying between the healthy and pre-operative patients all apart from two UKA patients. On inspection of the raw data these patients were both young (under 65 years of age), had high perceived pre-operative function (WOMAC = 8 and 12 respectively), and had only been suffering from symptoms for one year. These factors suggest that the patients were highly functioning and confirm their position on the DST simplex plot. As with the objective and subjective based classifiers, the UKA patients had a large spread on the simplex plot, with the TKA group bunched towards the OA classification. The healthy group were all positioned in the bottom corner of the healthy classification with a relatively small spread in placement. It is of note that the classifier has an element of uncertainty with the positions of the simplex plot markers all positioned a distance off the bottom of the plot (the more uncertainty the higher the markers). The final ranking of the chosen ten variables for the classification between H and OA groups are shown in Table 8.3. Analysis of the combined BoE showed that pain (d_4), WOMAC (d_1), and gait measures provided the highest confidence values of discrimination. Seven out of the ten selected variables had a confidence value above 75%, contributing to the accuracy of the classifier and keeping uncertainty in classification down.

Table 8.3: Table of the combined DST classifier variables.

	Standard deviation (k)	Mean (θ)	Dependence factor (A)	Dependence factor B	Confidence factor (v)
mom_{gait}	0.79	-0.09	0.5	0.2	96.1
ML_{gait}	0.74	-0.71	0.5	0.2	86.3
$FPfz_{gait}$	0.65	0.50	0.5	0.2	70.3
$FPmy_{st-sd}$	0.59	-0.26	0.5	0.2	74.5
$FPmy_{sd-st}$	0.54	0.49	0.5	0.2	74.5
Pain (d_4)	0.9	4.0	0.5	0.4	88.7
WOMAC (d_2)	0.87	33.5	0.5	0.4	88.7
RF Atrophy (d_8)	16.9	10.9	0.5	0.2	83.7
ROM (d_3)	15.67	123	0.5	0.2	78.4
Stability (d_7)	0.67	2.2	0.5	0.2	79.2

In order to lower the classifier uncertainty, the variance in functional scores was reduced. In order to achieve this UKA and TKA groups were split into two. The subsequent classifiers then achieved 99.9% classification in the leave one out test (Figure 8.5). These classifiers also show less uncertainty with the simplex plots placing patients and healthy participants further down the graphical representation. This subdividing of patients does however limit the subject numbers entering the classifier, with just 17 TKA (2 of which were bi-UKA) and 14 UKA patients. This limitation in numbers creates a SVT ratio which is below that which was stated in the protocol (Section 8.2). Although subdividing the data provides a better classification it was decided to keep all of the data together for analysis so that as many variables as possible could be included.

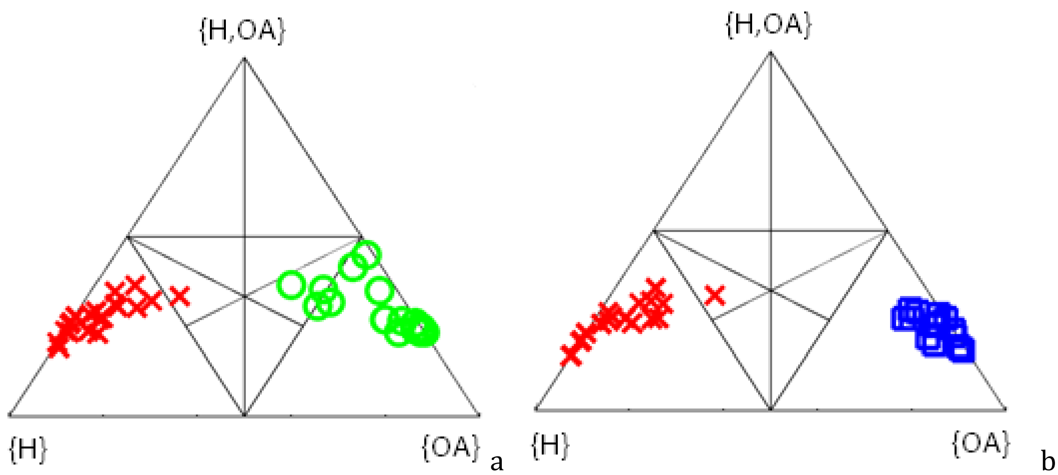


Figure 8.5: (a) DST simplex plot of the combined subjective and objective data collected from the healthy and UKA pre-operative patients. (b) DST simplex plot of the combined subjective and objective data collected from the healthy and TKA pre-operative patients. H = red cross, UKA = green circle, TKA = blue square.

8.6 Changes in Function

When the classification of patient function was achieved, the next stage in the analysis was to plot the changes in function from pre- to post-KA. To achieve this three classifiers were used;

1. Classifier based on subjective measures (WOMAC, OKS, Pain, Stability, Activity)
2. Classifier based on objective measures (PC scores of joint kinematics and kinetics, gait parameters, RoM, muscle atrophy).
3. Classifier based on combined subjective and objective measures (WOMAC, Pain, PC scores of joint kinematics and kinetics, RoM, muscle atrophy).

The classifier parameters obtained from the H and OA group classification process were kept, and the exact same data for the post-operative patients was input into the classifier. Changes in the BoE that identifies the position on the simplex plot where then observed. The changes in the BoE which was a function of the evidence supporting each of the three hypotheses was then used to estimate a change in function.

8.6.1 Changes in Subjective Function

When the classifier of the subjective measures was used to predict changes in function it showed that for some patients their post-operative classification of function was similar to that of the healthy group (Figure 8.6). With patients reporting no pain, increased function (Questionnaire based data), and more perceived activity levels. For all patients bar one there was an increase in BoE towards the healthy classification. The mean increase in healthy belief within the BoE for each participant was 0.53 (range -0.004 to 0.86). This increase in healthy belief was mirrored by a decrease in OA belief (mean change = -0.52, range 0.004 to -0.81). However, there was a slight increase in uncertainty (mean = 0.01, range -0.31 to 0.25).

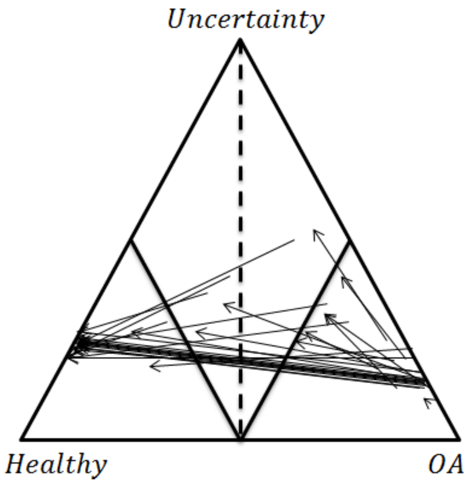


Figure 8.6: DST simplex plot of the change in subjective BoE of the KA participants collected from the pre- and post-operation assessments.

The changes in subjective function indicate a large variance in gains in perceived function and even a loss in function for one of the participants. This is reflected in the raw data with the changes in WOMAC scores ranging from 2 to 68. The large functional gains seen in the DST classifier were attributed to improvements in pain scores (mean improvement 4.6/10), stability (mean improvement 2.2/10), and perceived function scores (mean WOMAC improvement 28.9, mean OKS improvement -14.8). If the subjective measures alone were used to classify post-KA function 74% of the patients (23 out of 31) would be classified in the healthy region of the simplex plot. This was observed despite the post-operative KA patients presenting with retained perceived limitations in function and in some cases pain (Table 7.2). The six month post-operation subjective classification does not seem be an accurate reflection of function, and the known limitations of questionnaire based measures (Section 3.2.3) could have affected results. In addition to this the large pre-operative difference in functional scores (compared to healthy) and the small standard deviation in the healthy participant's subjective classification could have biased the post-operative changes within the BoE. The following sections illustrate that objective and combined simplex plots provided additional feedback on patient function.

8.6.2 Changes in Objective Function

The classifier of the objective measures was slightly more accurate at classifying the patients than that of the subjective measures. However, with the known error and variance in the data there was considerable uncertainty in the simplex plots (Figure 8.3). When the post-operative variables were input into the baseline classifier there were much more modest gains in function compared to the subjective results. Mean changes in the BoE towards healthy classification were just 0.1, with a large range in results (-0.31 to 0.46). There was also a small change away from the OA classification (mean = -0.081, range -0.21 to 0.45). However, as with the classification of subjective measures there was an increase in uncertainty (mean = 0.02, range -0.22 to 0.2). The final classification of the post-operative objective function revealed that only 23% of the patients (7 out of 31) were classified as healthy, two of which were classified as healthy pre-operation. When directly comparing the classifiers of subjective and objective measures it is clear to see the differences in observed changes in the BoE (Figure 8.7).

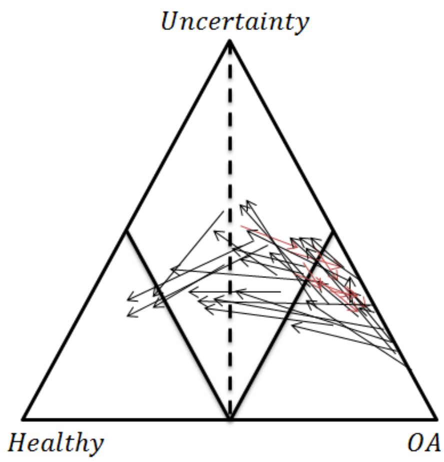


Figure 8.7: DST simplex plot of the change in objective BoE of the KA participants collected from the pre- and post-operation assessments. Black = positive healthy change, Red = negative healthy change

Changes in objective function were limited in the raw data (Table 7.2), which reflects the small changes seen within the objective measure based DST classifier. Measures of RoM and muscle atrophy both showed limited or negative gains from pre- to post-KA, with a mean change of -2.3° and 3% (RF atrophy) respectively. The improvements that were observed were mainly driven by the ADL waveform data, with the discrete gait measures showing some mean improvements in all measures (Table 8.4).

Table 8.4: Discrete measures of the gait cycle from the healthy, pre-operation, and post-operation knee arthroplasty patients.

Discrete Gait Measure	**Mean Healthy**	**Mean Pre-Operation**	**Mean Post-Operation**
Velocity (m/sec)	1.15 (0.13)	0.96 (0.14)	1.03 (0.23)
Double Support Time (Seconds)	0.24 (0.03)	0.32 (0.07)	0.28 (0.06)
Stride Length (m)	1.27 (0.14)	1.11 (0.08)	1.19 (0.17)
Cadence (steps/min)	108 (7.9)	98 (10.6)	103 (13.7)

These changes in discrete measures were combined with changes to the waveform measures at the TFJ. Here increases in knee flexion moment and knee RoM during the gait cycle were observed (Figure 8.8).

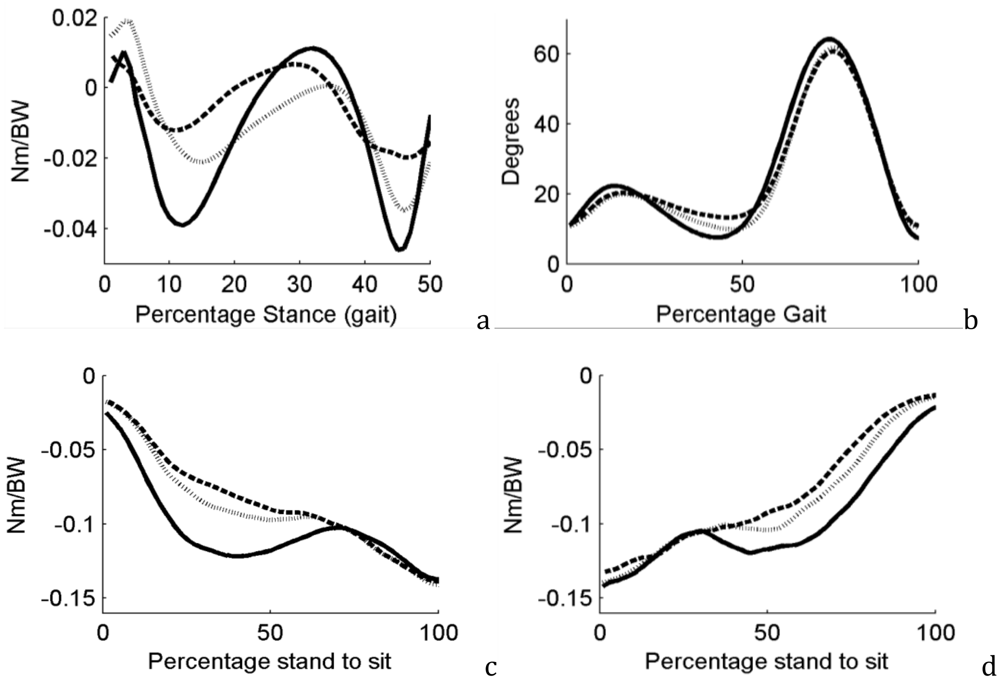


Figure 8.8: (a) Graph of knee flexion moment during stance phase of gait. (b) Graph of knee flexion angle during the gait cycle. (c) Sagittal force plate moment during sit to stand. (d) Sagittal force plate moment during stand to sit. Health in solid black line, pre-operation KA patients in dashed black line, post-operation KA patients in dashed grey line.

There were also changes to the sit-stand-sit waveform measures from pre- to post-KA, with increases in force plate and TFJ moments (Figure 8.8c-d) and reactions during the activity (Appendices K-L). On the evidence of the objective classifier it seems function has not improved significantly in a number of patients, and the subjective changes appear to over-predict what is seen objectively. A limitation of the objective measures could have been a decreased ability to detect changes in pre- and post-KA function due to the known reliability error in the data collection process (Section 6.2-7). There was also larger variance and uncertainty in the baseline classifier (Figure 8.3).

8.6.3 Changes in Combined Function

In order to establish the change in holistic patient function the combined classifier was used. As with the subjective and objective analysis, the post-operative data was input into the baseline combined classifier. Using this approach the optimal subjective and objective measures which classified healthy and pre-operative patients the best were used (Figure 8.9).

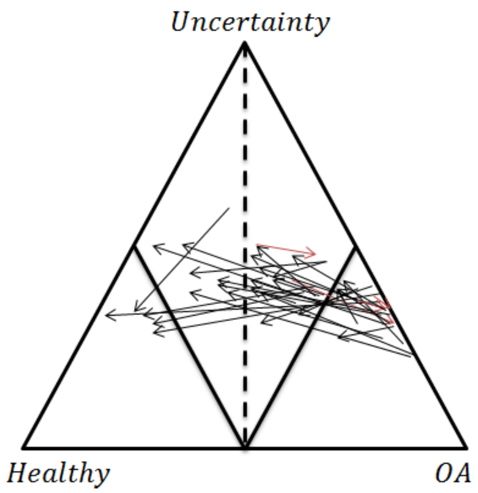


Figure 8.9: DST simplex plot of the change in combined BoE of the KA participants collected from the pre- and post-operation assessments. Black = positive healthy change, Red = negative healthy change

The changes in the BoE with the combined classifier were mainly attributed to the large changes in the subjective measures of pain and perceived function (WOMAC). This was mainly due to large changes in the raw data from pre- to post-KA and the high discriminatory influence of the measures. Mean changes from pre- to post-KA in the belief value that the patients were healthy was 0.22 (range -0.21 to 0.58), with all bar four patients improving in combined function. From pre- to post-KA there was a small increase in the uncertainty in classification (mean = 0.02), although there was considerable range in uncertainty (-0.17 to 0.31). The belief that the patient had OA dropped by 0.2, showing the general trend from OA to H classification. On inspection of the final BoE classification, 42% (17 out of 31) of the post-operative patients were classified in the healthy side of the simplex plot. The combined classifier appears to give a representation of both subjective and objective measured outcomes for the patients

The combined classifier shows that the combination of subjective and objective measures results in positive functional changes for the majority of the patients. However, less than half of the patient's 6 month post-KA classification falls within the healthy side of the simplex plot. There were also large variations in the change of belief values, and the final BoE which depicts the functional status of the patient.

8.7 Summary of Changes in Function

The DST classification process has shown that healthy and pre-operative KA patients were classified with a strong degree of accuracy for subjective, objective, and combined measures. These baseline classifications were then used to track the changes in function from pre- to six months post-operation function. These changes in function have been measured by the changes in the BoE, and in particular the belief values which are within the BoE. For all types of measures the majority of patients increased the belief value that they were healthy from pre- to post-KA, although for all measures there were increases in the uncertainty of the classification. There was also difference in the TKA and UKA population for both changes in function and the final post-operative BoE (Table 8.5-6). The results in Table 8.5 were calculated by deducting the pre-operative belief values away from that of the post-operative beliefs for each classifier. The results showed that the largest change in belief was away from OA classification for all three types of classifiers.

The results show that changes in the BoE were greater in the TKA patients compared to the UKA for subjective and combined classifiers. Subjectively the TKA group had a significant shift towards the healthy belief with a relatively low standard deviation, with all of the patients reporting improved subjective function. However the UKA subjective changes were much lower on average with a larger standard deviation, with one patient reporting a decrease in subjective pain and function.

Table 8.5: Changes in the Body of Evidence (BoE) for the objective, subjective, and combined classifiers. Patients have been split up into TKA and UKA groups.

Classifier	Prosthesis Type	Change in BoE					
		Healthy		**OA**		**uncertainty**	
		mean	SD	mean	SD	mean	SD
Subjective	**TKA**	0.65	0.22	-0.69	0.21	-0.04	0.05
	UKA	0.39	0.3	-0.37	0.29	-0.01	0.14
Objective	**TKA**	0.09	0.15	-0.15	0.22	0.06	0.11
	UKA	0.09	0.17	-0.08	0.2	0.01	0.09
Combined	**TKA**	0.23	0.19	-0.29	0.19	-0.06	0.07
	UKA	0.2	0.17	-0.17	0.18	0.03	0.1

The same change towards a healthy belief was observed in the objective classifier. However, these results had much lower mean changes in the belief values with considerable variance between patients. It is also of note that for the objective changes in BoE there was a mean increase in the uncertainty of the classification. The combined classifier shows that on average the TKA patients had higher functional gains towards the healthy belief, although the standard deviation across the patients was high for both TKA and UKA. One of the main reasons for the difference in the changes in BoE are because of the pre-operative function. The UKA patients generally had a much higher pre-operative function, and therefore had less scope for functional gains.

On inspection of the objective changes in function for each individual patient, 73% of the TKA patients exhibited an increase in the healthy belief within the BoE, although gains were relatively small (mean change = 0.14). Only 57% of the UKA patients improved their objective healthy belief within the BoE. However, those that did improve in function had a larger shift towards healthy belief (mean change = 0.22) than the TKA patients. The TKA patients who had negative changes in healthy belief within the objective classifier only exhibited small shifts in belief (mean = -0.07, range 0.02 to 0.12). However, the UKA patients with a negative shift showed a slightly larger peak in healthy belief reductions (mean = -0.08, range 0.02 to 0.21). This shows that for objective function, when the KA procedure is successful there is large scope for functional gains, however if the KA process is poor marked objective functional losses can been evident. The TKA procedure appears to be much more robust in objective functional gains, although smaller in magnitude.

Interestingly the two patients who received a bi-unicompartmental and tri-unicompartmental procedure show negative changes in function. These negative changes were seen in the subjective, objective, and combined classifiers (Figure 8.10).

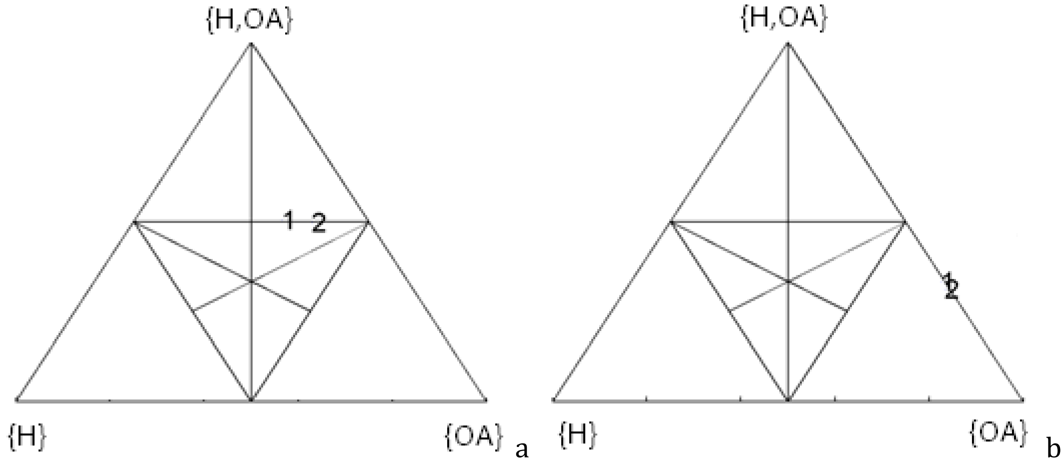


Figure 8.10: (a) DST simplex plot of the combined subjective and objective data of a030 (tri-unicompartmental patient) collected from the pre- and post-operation. (b) DST simplex plot of the combined subjective and objective data of a040 (bi-unicompartmental patient) collected from the pre- and post-operation. Pre-operation = 1, Post-operation =2.

It appears that both the bi- and tri-unicompartmental procedures were not very successful in these two cases for improving patient function. As the bi- and tri-unicompartmental patients are neither a UKA or TKA patient they will be excluded in the subsequent analysis. However further discussion of these two patients functional outcomes will be discussed in Chapters ten and eleven.

8.8 Summary of Final Functional Classification

The change in function is only one part of the analysis. The final outcome in function is perhaps the most pertinent measure to consider. The results in Section 8.7 show that the majority of patients improved in function. However, if they had poor pre-operative function and their improvement was small, the patients may still be suffering from several functional limitations. The final BoE gave the indication of remaining functional limitations and identified the patients that recovered towards the healthy population. A summary of the final BoE is given below (Table 8.6). Final classification was determined by the placement of a particular patient within the DST simplex plot with the horizontal axis of the plot (Figure 5.11) acting as the discrimination point between OA and healthy classification.

Table 8.6: Post-operative Body of Evidence (BoE) for the objective, subjective, and combined classifiers. Patients have been split up into TKA and UKA groups. Final classification is given as percentage healthy (according to simplex plot position).

Classifier	Prosthesis Type	Post-operative BoE						Final Classification % Healthy
		Healthy		OA		uncertainty		
		mean	SD	mean	SD	mean	SD	
Subjective	**TKA**	0.67	0.22	0.1	0.19	0.23	0.05	80
	UKA	0.64	0.3	0.13	0.27	0.23	0.09	79
Objective	**TKA**	0.14	0.13	0.48	0.17	0.38	0.08	20
	UKA	0.25	0.19	0.38	0.19	0.38	0.05	36
Combined	**TKA**	0.28	0.18	0.31	0.17	0.41	0.05	27
	UKA	0.32	0.18	0.31	0.2	0.38	0.04	57

Analysis of the post-operative classification revealed that subjectively the TKA group had a slightly higher belief that they were healthy compared to the UKA patients. However, the objective classifier contradicted this with strong belief values for OA classification in both the TKA and UKA groups. The objective classifier also showed that the UKA had a stronger healthy belief compared to the TKA group, although there was a large amount of uncertainty for both groups. The final combined classifier showed that on average there was double the amount of UKA patients classified as healthy (57%) compared to TKA (27%). Belief values however revealed a strong retention of OA belief, along with a large amount of uncertainty. There were also considerable standard deviations for all of the measures within the BoE of each classifier.

When the subjective, objective, and combined classifications were compared for each patient only five TKA patients (33%) had the same classification for each type of input. However, eight (57%) of the UKA patients had the same classification for all three types of input. It was evident that for the majority of cases, reduced subjective function is reflected in reduced objective function within the UKA group. For the TKA patients, the majority had healthy post-operative perceived function (80%). However, in 77% (10 out of 13) of these cases the objective classifier had a BoE suggesting they were in the OA classification.

There is a clear increase in disparity between objective and subjective measures within the TKA group, although this was less of a factor in the UKA patients.

8.9 Discussion

The classification process of patient function revealed that when subjective assessment techniques were used there was the lowest leave one out accuracy, with the UKA patients having a wide spread in pre-operative subjective measures. Classification of the optimal objective measures had a slightly higher accuracy, although the uncertainty belief in the classification was much higher. When the two measurement types were combined, the highest accuracy was achieved with reasonable amount of uncertainty (Figure 8.4). Variables that showed the highest confidence value (v) to classify within the DST also corresponded with the results from the LDA analysis (Chapter 7). Despite this increase in accuracy in the combined classifier, some of the UKA patients were still classified as healthy, showing the variance in the data. Comparing the classification results to the LDA analysis (Section 7.7.2-4) and previous literature, similar out-of-sample accuracy was achieved to Jones et al 90-97.6%, and Astephen and Deluzio 94% [91, 223, 227]. The present project, however, has expanded on the analysis of gait which was previously relied on, and now clinical measures, questionnaire data, and multiple ADL PC scores have been used to classify patient function. When the patients were subdivided (Figure 8.5) a classification accuracy of 99.9% was achieved in the leave one out test. This level of accuracy has not been shown previously in the literature and it showed the combination of objective and subjective measures along with patient subdivision could provide an accurate classification.

On closer inspection of the final BoE within the classifiers based on objective measures the five patients with the highest healthy belief value were all UKA patients (Table 8.7). This suggests that the highest functioning post-operative patients tend to be those who have undergone UKA. Despite this fact, a UKA and bi-UKA patient were also in the group of patients with the poorest functional outcomes in both the subjective and objective post-operative classifications (Table 8.7).

Table 8.7: Post-operative objective classifier highest and lowest healthy belief values for the post-operative KA group. Satisfaction (Satis.), prosthesis type, rehabilitation, and post-operative activity also highlighted.

Highest Healthy Belief							
Pt ID	Post-op H belief	Pre-op H belief	Satis.	Prosthesis	Days inpatient	Outpatient therapy (hrs)	Activity (hrs)
A026	0.57	0.21	9	UKA	5	3	20
A014	0.51	0.31	8	UKA	3	0	20
A036	0.51	0.24	10	UKA	4	4	20
A028	0.45	0.21	9	UKA	5	3	20
A021	0.41	0.25	10	UKA	3	3	15

Lowest Healthy Belief							
Pt ID	Post-op H belief	Pre-op H belief	Satis.	Prosthesis	Days inpatient	Outpatient therapy (hrs)	Activity (hrs)
A040	0.01	0.12	5	Bi-UKA	3	1	3
A013	0.02	0.02	3	UKA	9	3	5
A024	0.02	0.04	7	TKA	7	0	2
A045	0.02	0.08	9	TKA	3	1	4
A023	0.04	0	7	TKA	12	10	3

The results in Table 8.7 also show that there are clear trends in patients who perform well post-operatively and those who did not. The data showed that patients with a high post-operative objective healthy belief had higher pre-operative healthy belief, higher satisfaction, and reported higher levels of activity post-operation. To highlight the disparity between good and poor post-operative outcomes, the five patients with the highest healthy belief had on average affected knee RoM of 124° (range 120-130 °) and perceived activity of 19 hours (range 15-20 hours), compared to 106 ° (range 92-114 °) and 3.5 hours (range 2-5 hours) respectively for the lowest post-operative healthy belief patients. It is clear the pre-operative healthy belief had an impact on the post-operative outcomes. The worst functioning patients had low pre-operative objective healthy belief (mean of 0.05, compared to 0.24) and low post-operative satisfaction (mean 6.2, compared to 9.2) scores.

Section 8.7 showed that patients who received a bi- and tri-unicompartmental KA had very poor functional outcomes. This may well be to do with the learning curve of the surgeon performing the operation. Few bi and tri- unicompartmental procedures had been performed by the consultant surgeon, and it had been shown that volume of procedures and surgical learning curve is significant in patient outcomes [247]. It is also of note that for one of the patients (A013, UKA), previous injuries had resulted in the loss of ACL and damage to LCL ligaments. Previous studies have found unacceptable revision rates in UKA patients with deficient ACL due to joint laxity, and it was defined as a contraindication [248]. Another recent body of evidence has shown that patients with a higher BMI are more at risk of having revision and poorer UKA outcomes [249]. With this in mind the BMI was taken from the worst functioning UKA/TKA patients. Results showed that their pre- and post-operative BMI averaged 35.8 and 34.6 (range 31.4-39.2) respectively. Berend et al showed that patients with a BMI above 32 had a statistically higher risk of revision [249]. This clearly puts the worse functioning UKA patients into that category. The patients who had higher post-operative function had a mean BMI below 30 (range 24-33). In the present study BMI did not provide high discrimination between the healthy and KA population (Section 7.7.1). However it could contribute to potential gains in function which will be discussed in Chapter Nine.

The differences between subjective and objective outcomes between TKA and UKA patients were very apparent (Figure 8.11). Subjectively more TKA patients were classified as healthy post-operation than UKA patients (Table 8.6). This is in stark contrast to the objective findings, where UKA patients had a higher healthy belief than TKA (Table 8.6).

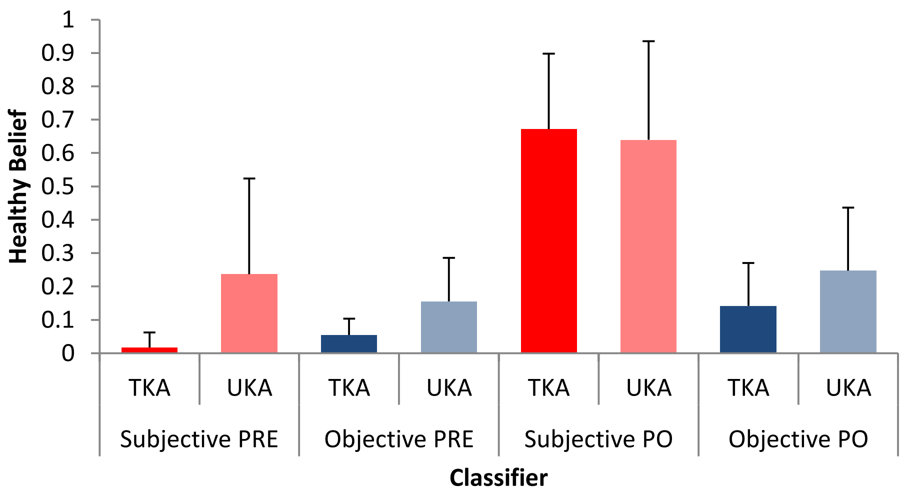


Figure 8.11: Bar chart to show the healthy belief for subjective (red) and objective (blue)classifiers at the pre-(PRE) and post-operation (PO) assessments. One times standard deviation shown in error bars.

This lack of correlation between objective and subjective outcomes has been shown in the previous literature [60]. This difference could be down to the factors previously highlighted in Section 3.4, where psychological [133] and pain [250] factors have been shown to effect questionnaire based measures.

8.10 Conclusion

This chapter has shown that patient perceived (subjective) and observed (objective) function can be classified using a combination of clinical data and MS model outputs. Classifiers of healthy and pre-operative function have shown accuracy that is comparative to the literature and show trends between different patient populations (UKA vs. TKA). These classifiers have been used to quantify changes in functional beliefs post-operation. One of the outstand results of which is the stark contrast in relative belief changes between subjective and objective measure based classifiers. The results show that patient perceived (subjective) function changes significantly six months post-operation with large improvements for the majority of patients. However objectively little improvement in healthy classification was seen.

The next stage of the analysis was to determine what factors affected the observed changes in functional beliefs within the classifiers.

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Chapter 9

Regression Analysis: *Analysis of Factors Affecting Changes in Classification*

9.1 Introduction

Chapter Eight highlighted the changes in belief values within the DST classifiers for pre- and post-operative function. Quantification of post-operative objective, subjective, and combined functional beliefs were also established based on the DST analysis. The next stage of analysis was to find which factors affected the changes in the belief values from pre- to post-operation. This was designed to complete the penultimate aim of the PhD thesis. Multiple linear regression analysis (Section 5.7.2.4) of the changes in belief values within the BoE, and the final BoE (dependent variables (DV)) was performed using the known factors which could affect function highlighted in the literature (Section 2.5). These included; pre-operative factors, surgical factors, and rehabilitation factors.

Pre-operative independent variables (IVs) included;

- Age
- Sex
- BMI
- years with pathology
- pre-operative perceived activity
- RoM
- muscle atrophy
- Pre-operative healthy belief in baseline objective classifier (Section 8.2.2, Table 8.2) - composite function of; ADL PCs, gait parameter, RoM, and muscle atrophy.
- subjective function (Healthy pre-operative belief in baseline subjective classifier, Section 8.2.1, Table 8.1) - composite function of; pain, stability, WOMAC, and OKS scores

Surgical IVs included;

- type of prosthesis (UKA or TKA)
- Surgeon (consultant or registrar)
- CAS vs. conventional

Rehabilitation IVs included;

- days as inpatient
- whether or not the patient met their inpatient goals
- post-operative therapy (hours)
- post-operative activity

In addition to the regression analysis of these factors, further analysis was performed with patient satisfaction. A final regression analysis with the top IVs from pre-operation, surgery, and rehabilitation was then performed in order to gather a weighted representation of how each factor affects the changes in function and the final post-operative functional classification. Key outputs in the regression analysis were the IV regression coefficients, R^2 values, and p values (Section 5.7.2.4).

9.2 Analysis of Changes in Subjective Function

The first classifier to be assessed was that containing the subjective variables. This was the classifier which showed the largest changes in function (Table 8.5). Multiple linear regression analysis was performed using the changes in BoE belief values within the subjective measure based classifier. Independent variable of each stage of the KA process (pre-operation, surgery, rehabilitation) were used to find relationships between the changes in BoE, and the coefficients of each factor within a stage of the KA process were highlighted. A summary of the regression analysis of the changes in subjective classifier are given below (Table 9.1-2).

Regression coefficients of the pre-operative variables show that there is little or no relationship within the discrete measures (sex, age, activity, BMI, RoM, atrophy) of pre-operative function (coefficients <0.01) and changes in subjective healthy belief (Table 9.1). There were, however, high regression coefficients in the pre-operative healthy belief values from the subjective and objective measure based classifiers. This shows that although single measures of function do not relate to changes in perceived function, when they were combined in the classifiers to form pre-operative belief values, high regression coefficients were achieved (>0.7). The combined pre-operative beliefs from objective and subjective based measures did differ in their relationship between changes in subjective function. The results showed that those with a higher pre-operative subjective healthy belief had smaller gains in subjective healthy belief post-operation (correlation coefficient = -0.7), perhaps due to a limited scope for improvement. However, those with higher pre-operative objective healthy belief showed large gains in post-operative subjective healthy belief (correlation coefficient = 1.29).

Table 9.1: Regression Analysis of changes in the Subjective Belief values from pre- to post-KA with the pre-operative known factors which could affect function.

Pre-operative Factors						
	Belief					
Independent Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
Sex	-0.076		0.038		0.037	
Age	0.007		-0.008		0	
Pre-operative Activity	0.002		-0.003		0	
BMI	0		-0.005		0.005	
RoM	-0.004		0.004		0	
RF % atrophy	-0.004		0.003		0.001	
Pre-operative Subjective Classifier H belief	-0.7		0.872		-0.17	
Pre-operative Objective Classifier H belief	1.288		-0.985		-0.303	
	R^2	p value	R^2	p value	R^2	p value
Combined pre-operative Regression Analysis	0.474	0.044*	0.6	0.004*	0.386	0.147

The result of the multiple linear regression when using all of the pre-operative variables showed that there were significant relationships between pre-operative function and changes in healthy (H) and pathological (OA) belief ($p<0.05$). The largest amount of variance explained in the BoE were found between changes in OA belief and pre-operative variables (R^2 =0.6).

Relationships between surgical factors and changes in subjective belief values were limited (Table 9.2). The highest regression coefficient was found between the type of prosthesis (UKA vs. TKA), with those having a TKA showing larger gains in post-operative subjective healthy belief. This could be due to the fact that the TKA patients had a lower pre-operative subjective healthy belief score compared to UKA (Figure 8.1), which was previously shown to relate with changes in subjective function (Table 9.1). Multiple linear regression analysis showed that there was a significant relationship between changes in pre-operative subjective OA belief and combined surgical factors (p=0.02), although these IVs only explained a small amount of the variance in the data (R^2 =0.31).

There were no significant relationship between rehabilitative factors and changes in subjective healthy belief (Table 9.2).

Table 9.2 : Regression Analysis of changes in the Subjective Belief values from pre- to post-KA with the surgical and rehabilitative known factors which could affect function.

Surgical Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
UKA vs. TKA	0.251		-0.302		0.051	
Surgeon	-0.049		0.026		0.023	
CAS vs. conventional	0.156		-0.144		-0.013	
	R^2	***p* value**	R^2	***p* value**	R^2	***p* value**
Combined Regression Surgical Analysis	0.228	0.067	0.308	0.018*	0.07	0.598

Rehabilitation Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
Days as inpatient	-0.003		0.011		-0.008	
Inpatient Goals	-0.001		0.001		0.001	
Post-operation therapy	-0.021		0.028		-0.007	
Post-operation activity	0.006		-0.005		0	
	R^2	***p* value**	R^2	***p* value**	R^2	***p* value**
Combined Regression Rehab Analysis	0.025	0.874	0.061	0.63	0.17	0.16

The IVs with the highest correlation coefficients were combined for a final multiple linear regression model. These included pre-operative subjective H belief, pre-operative objective H belief, TKA vs. UKA, and outpatient therapy hours. This refined regression model produced a R^2 value of 0.49, which was significant p<0.002. Looking at the regression coefficients from the IVs it was clear the pre-operative objective healthy belief had the greatest relation to changes in pre- to post-operative belief.

1. pre-operative objective function (Healthy Belief) - regression coefficient 1.3

2. pre-operative subjective function (Healthy Belief) - regression coefficient -0.5
3. TKA vs. UKA - regression coefficient 0.3
4. outpatient therapy - regression coefficient -0.01

9.3 Analysis of Changes in Objective Function

There were smaller changes in the belief values of the objective classifier from pre- to post-operation (Table 8.5). However, pertinent details of ADL activities and clinical measures were included within this analysis. As with the subjective classifier the same pre-operative, surgical, and rehabilitation factors were used with multiple linear regression to find relationships between changes in BoE beliefs. A summary of the regression analysis of the objective classifier are given below (Table 9.3-4).

Table 9.3: Regression Analysis of changes in the Objective Belief values from pre- to post-KA with the known pre-operative factors which could affect function.

Pre-operative Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
Sex	0.111		-0.182		0.071	
Age	0.003		-0.003		0	
Pre-operative Activity	0.007		-0.007		0	
BMI	-0.004		0.012		-0.009	
RoM	0.001		-0.002		0	
RF % atrophy	-0.002		0.001		0	
Pre-operative Subjective Classifier H belief	0.022		0.109		-0.13	
Pre-operative Objective Classifier H belief	-0.23		0.845		-0.61	
	R^2	***p* value**	R^2	***p* value**	R^2	***p* value**
Combined Regression pre-operative Analysis	0.383	0.15	0.579	0.006*	0.518	0.021*

The independent variables of pre-operative function (sex, age, activity, BMI, RoM, atrophy) had small regression coefficients with changes in objective healthy belief (Table 9.3). Sex of patients did show higher correlation coefficients (>0.1), with males performing slightly better than females. As with the changes in subjective belief, the factor with the largest regression coefficient was the objective healthy belief score taken from the pre-operative DST classifiers. Here a regression coefficient of 0.85 was seen when comparing the changes in OA objective belief. This shows that the patients with a higher pre-operative objective healthy belief had less improvement away from the OA belief post-operation, potentially due to the decreased scope for improvement.

Table 9.4: Regression Analysis of changes in the Objective Belief values from pre- to post-KA with the known surgical and rehabilitative factors which could affect function.

Surgical Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
UKA vs. TKA	0.015		-0.065		0.063	
Surgeon	0.041		-0.105		0.064	
CAS vs. conventional	0.038		-0.051		0.013	
	R^2	***p* value**	R^2	***p* value**	R^2	***p* value**
Combined Regression surgical Analysis	0.01	0.96	0.072	0.564	0.168	0.168

Rehabilitation Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
Days as inpatient	0.001		-0.007		0.004	
Inpatient Goals	0.001		-0.001		0.001	
Post-operation therapy	0.003		-0.007		0.004	
Post-operation activity	0.19		-0.22		0.002	
	R^2	***p* value**	R^2	***p* value**	R^2	***p* value**
Combined Regression rehab Analysis	0.553	0.001*	0.398	0.003*	0.067	0.593

The multiple linear regression analysis showed that there was a significant relationship between pre-operative variables and changes in the objective OA and H, OA belief. This relationship was mainly driven by the pre-operative objective healthy belief. However, changes in objective function compared to the surgical factors showed no correlations (Table 9.4). All IVs were below 0.11, and R^2 and p values reflected the poor correlation.

A significant relationship was found between rehabilitative factor and changes in objective healthy (H) and pathological (OA) belief (p<0.01). The independent variable which was most pertinent in this relationship was post-operative activity levels (Figure 9.1).

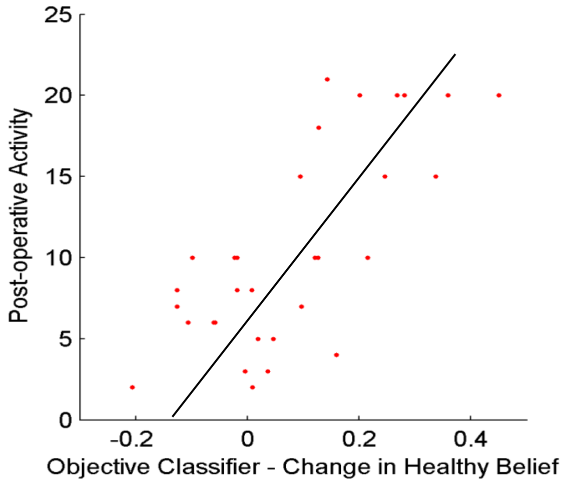

Figure 9.1: Plot of the changes in healthy belief value within the objective classifier over the post-operative activity levels (Spearman correlation coefficient = 0.65, $\boldsymbol{p}$<0.02).

The data clearly showed a significant relationship, with those who were more active post-operation having larger gains in objective function. This was the only significant variables within the rehabilitative factors, with all other measures producing correlation coefficients below 0.005.

The IVs with the highest correlation coefficients were combined for a final multiple linear regression model. These included; sex, pre-operative subjective H belief, pre-operative objective H belief, surgeon, and post-operative activity. This refined regression model produced a R^2 value of 0.69, which was significant p<0.001. Analysis of the coefficients within the refined regression model show that the highest coefficient estimate for the multiple linear regression was pre-operative objective function.

1. pre-operative objective function (Healthy Belief) - regression coefficient -0.48
2. pre-operative subjective function (Healthy Belief) - regression coefficient 0.087
3. post-operative activity 0.082
4. Sex (male vs female) 0.023
5. Surgeon -0.02

9.4 Analysis of Changes in Combined Function

The same regression analysis was applied to the changes in combined function. Again, the pre-operative, surgical, and rehabilitation factors were included in the multiple linear regression analysis (Table 9.5-6).

Table 9.5: Regression Analysis of changes in the combined classifier belief values from pre- to post-KA with the known pre-operative factors which could affect function.

Pre-operative Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
Sex	-0.024		0.039		-0.016	
Age	0.008		-0.09		0.001	
Pre-operative Activity	0.15		-0.14		-0.001	
BMI	0.003		0.001		-0.004	
RoM	0		0		0	
RF % atrophy	-0.004		0.005		0	
Pre-operative Subjective Classifier H belief	-0.036		0.13		-0.095	
Pre-operative Objective Classifier H belief	0.93		-0.65		-0.284	
	R^2	***p* value**	R^2	***p* value**	R^2	***p* value**
Combined pre-operative Analysis	0.607	0.003*	0.608	0.003*	0.273	0.442

The results from this regression analysis follow a similar trend to that of the objective and subjective changes in belief, where the pre-operative objective healthy belief had the highest coefficient estimate. Here the trend was the same of that in the subjective regression analysis (Section 9.2) where the higher the pre-operative objective healthy belief resulted in larger gains of combined healthy belief. The multiple linear regression showed that significant relationships were observed (p>0.005) for changes in healthy and pathological (OA) beliefs with that of the pre-operative variables, with R^2 values above 0.6.

Not surprisingly there was no relationship between surgical factors and the changes in combined function (Table 9.6). Low coefficient estimates were found for all variables within the surgical factors, and multiple linear regression results showed no significant relationship (p>0.05). There were significant relationships between the changes in combined healthy and pathology (OA) belief and rehabilitative factors (Table 9.6). Once again the factor with the highest coefficient estimate was post-operative activity. Here the patients with the highest activity had the largest gain in combined classifier healthy belief. The strongest relationship was with changes in combined healthy belief with an R^2 value of 0.54, which was significant p<0.001.

Table 9.6: Regression Analysis of changes in the combined belief values from pre- to post-KA with the known surgical and rehabilitative factors which could affect function.

Surgical Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
UKA vs. TKA	0.066		-0.148		0.082	
Surgeon	-0.04		0.006		0.034	
CAS vs. conventional	-0.004		-0.008		0.011	
	R^2	**p value**	R^2	**p value**	R^2	**p value**
Combined surgical Analysis	0.033	0.823	0.142	0.241	0.245	0.13

Rehabilitation Factors						
	Belief					
Variable	**H coefficient**		**OA coefficient**		**H,OA coefficient**	
Days as inpatient	0.004		-0.004		0	
Inpatient Goals	0.001		0		-0.001	
Post-operation therapy	0		-0.003		0.004	
Post-operation activity	0.023		-0.02		-0.0025	
	R^2	**p value**	R^2	**p value**	R^2	**p value**
Combined rehab Analysis	0.541	0.001*	0.365	0.006*	0.07	0.597

A final regression analysis on the changes in combined function was performed using the pre-operative objective and subjective function, TKA vs. UKA, and post-operative activity IVs. This produced an R^2 value of 0.68 which was significant (p<0.001). The regression coefficients for each IV were as follows;

1. pre-operative objective function (Healthy belief); regression coefficient = 0.37
2. post-operative activity; regression coefficient = 0.13

3. pre-operative subjective function (Healthy belief); regression coefficient = -0.11
4. TKA vs. UKA; regression coefficient = 0.03

These results show that the higher the patient's pre-operative objective belief and the more activity the patient does post-operation, the greater the gain in combined healthy belief.

Table 8.6 highlighted the final classification of the patients varied between types of classifier, and between patient groups. Analysis was performed to find which factors affected the six month post-operative classification for each of the three classifiers (objective, subjective, and combined). Independent variables including; pre-operative, surgical, and rehabilitative factors were used in the analysis.

9.5 Factors Affecting Post-operative Classification

Multiple linear regression analysis was performed to find correlations between the six month post-operative healthy beliefs of the three classifiers and the known factors which could affect function (Table 9.7). The results from this analysis showed that a significant relationship (p<0.05) between pre-operative and rehabilitative factors was present. The strongest relationship was found between the post-operative combined healthy belief and the known pre-operative factors (R^2=0.63). As with the previous regression analysis (section 8.6.1-3) the pre-operative objective classifier healthy belief produced the highest coefficient estimate. The simple interpretation of this is that those patients with a higher pre-operative objective function had higher post-operative combined classifier healthy belief. When the values are combined to form the beliefs within the pre-operative classifiers the regression coefficients are increased and significant findings are achieved. This highlights the need to combine data so patients function can be a factor of multiple measures, this in turn offers a more powerful tool for correlating changes in function.

Rehabilitative factors also showed a significant relationship with post-operative objective and combined classifier healthy belief (Table 9.7). Post-operative activity was once again the predominant factor in this relationship.

Table 9.7: Regression Analysis of post-operative healthy belief from objective, subjective, and combined classifiers, and the known factors which could affect knee arthroplasty function.

Pre-operative Factors						
	Classifier					
	Subjective		Objective		Combined	
Variable	**coefficient**		**coefficient**		**coefficient**	
Sex	-0.08		0.111		-0.006	
Age	0.007		0.003		0.008	
Pre-operative Activity	0.002		0.007		0.013	
BMI	0		-0.004		0.001	
RoM	-0.004		0.001		0	
RF % atrophy	-0.004		-0.002		-0.003	
Pre-operative Subjective Classifier H belief	0.3		0.022		0.111	
Pre-operative Objective Classifier H belief	1.29		0.766		1.154	
	R^2	**p value**	R^2	**p value**	R^2	**p value**
Combined pre-operative Analysis	0.349	0.224	0.426	0.04*	0.632	0.002*
Surgical Factors						
UKA vs. TKA	0.073		-0.09		-0.008	
Surgeon	-0.109		0.038		-0.03	
CAS vs. conventional	0.125		0.026		0.043	
	R^2	**p value**	R^2	**p value**	R^2	**p value**
Combined surgical Analysis	0.057	0.659	0.068	0.585	0.008	0.976
Rehabilitation Factors						
Days as inpatient	-0.002		-0.007		0.004	
Inpatient Goals	0		0		0	
Post-operation therapy	-0.003		0.007		-0.002	
Post-operation activity	0.016		-0.018		0.023	
	R^2	**p value**	R^2	**p value**	R^2	**p value**
Combined rehab Analysis	0.146	0.228	0.527	0.001*	0.592	0.001*

9.6 Post-operative Satisfaction

Post-operative satisfaction was high for the majority of patients at the six month assessment (mean 8.3/10), however there were patients who reported low satisfaction (range 3 to 10/10). Previous studies have shown significant relations between patient satisfaction and questionnaire based measures [7]. In order to find the relationship between satisfaction and the changes in functional healthy belief values, regression analysis was once again used. The change in healthy belief, and the final post-operative healthy belief was used for all three types of classifier. It was predicted that those who had larger changes in healthy belief, and a higher final healthy belief would be the most satisfied patients. A summary of the regression analysis is given below (Table 9.8).

Table 9.8: Regression Analysis of the patient satisfaction compared to the change in, and final, healthy belief value of the objective, subjective, and combined classifiers.

	Change in H Belief		Six month Post-Operative H Belief	
Classifier	R^2	***p* value**	R^2	***p* value**
Subjective	0.35	0.001*	0.745	0.001*
Objective	0.007	0.16	0.17	0.02*
Combined	0.193	0.02*	0.198	0.01*

Results from the satisfaction regression analysis showed the highest relating factor was post-operative subjective healthy belief (R^2 value = 0.745, p value <0.001). This finding confirms previous reports which have linked satisfaction with perceived pain and function scores post-KA [7]. Other changes in healthy belief values within the objective and subjective classifiers show very poor R^2 values, however there are some significant p values in the post-operative outcomes. When the post-operative subjective healthy belief is plotted against satisfaction it is clear to see that those with the higher healthy belief were more satisfied with the outcome of their KA (Figure 9.2).

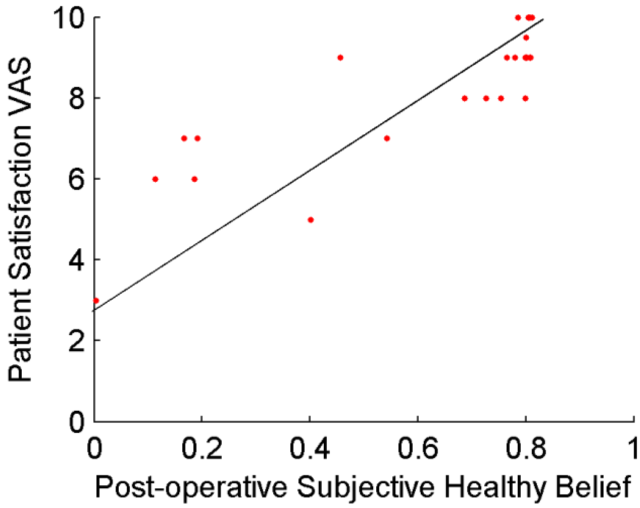

Figure 9.2: Plot of final subjective healthy belief over the post-operative satisfaction ($\boldsymbol{R^2}$ value = 0.74, $\boldsymbol{p}$ value <0.001).

Those patients who had a subjective healthy belief below 0.5, all had post-operative satisfaction of below seven out of ten. The patient who had the lowest post-operative subjective and objective healthy belief reported the lowest satisfaction of just 3/10. The simple interpretation of these results is that those who had high functioning scores in the WOMAC and OKS, along with low pain scores, not surprisingly had better satisfaction. The results do suggest that objective function (RoM, muscle atrophy, ADL movement patterns) is much less of a factor in post-operative satisfaction.

9.7 Summary of Regression Analysis.

Changes and the final belief of the DST classifiers (Chapter Eight) were analysed using multiple linear regression with the known factors which could affect changes in function (Section 2.5). Changes in subjective belief values were seen to be related to pre-operative subjective function, with those who had the lowest pre-operative function showing the largest belief gains. However, changes in the objective and combined classifiers were related to pre-operative objective classification, and post-operative activity levels. These three IVs were all then factors in the regression analysis of post-operative healthy belief values. When these IVs were compared the following factors affecting post-operative healthy belief was observed;

1. Pre-operative objective function (Healthy belief)

2. Post-operative activity
3. Pre-operative subjective function
4. TKA vs. UKA
5. Males vs. Females

Results from the regression analysis showed that single independent variables did not correlate significantly with changes in the DST based belief values. However when the composite function of multiple variables were used (pre-operative healthy belief values from the DST analysis) much higher regression coefficients were found. The results from the present study suggest that by collating evidence together provided a much more significant relationships between changes in function could be achieved. Finally patient satisfaction was assessed against the changes in healthy belief values for the three types of classifiers. Poor relationships were found between the changes in objective belief and patient satisfaction. The six month subjective healthy belief value explained a large percentage of the variation in patient satisfaction with a R^2 value = 0.74, p value <0.001. This shows that the main factor which affects post-operative satisfaction was subjective measures, with those who had higher subjective function reporting higher post-operative satisfaction.

9.8 Discussion

This study has shown that KA patients who have lower pre-operative subjective function are more likely to show larger changes in objective scores six months post-operation. On the other hand the patients with higher objective function pre-operation were more likely to have greater increases in objective function post-operation. Higher pre-operative objective function also correlated the highest when the combined classifier was used to assess changes in function. When pre-operative function was broken down into individual variables (Table 9.5), there were low regression coefficients. However, when subjective variables were combined to form the BoE within the DST analysis there were significant findings. Along with pre-operative function, post-operative activity was shown to relate to changes in objective healthy belief, with those who were more active having larger gains in function. There is limited evidence about this in the literature. However, one paper has shown that patients who perform leg exercises more regularly have greater functional gains post-operation [251].

Six month post-operative belief was significantly related to pre-operative subjective and objective function, as well as post-operative perceived activity levels. These findings agree with the current evidence base which suggests that pre-op function is the biggest predictor of post-operative outcomes [92, 252]. There is also a small body of evidence in support of post-operative leg exercises showing increases in post-KA function [251]. In the previous studies which used multiple regression analysis R^2 values between 0.2 and 0.36 for WOMAC and SF-36 physical function were achieved when comparing six month post-operative outcomes [118, 119], showing only a small amount of the variance explained. The present study has shown that regression analysis of post-operative objective and combined belief outcomes has significant relationship with pre-operative and rehabilitation factors (R^2 values between 0.45-0.6, p<0.05). These regression values are much greater than those previously reported, however the changes in belief values are different to changes in the raw data. When the pre-operative WOMAC was used in regression analysis with post-operative WOMAC scores an R^2 value of 0.01 with no statistical significance (p<0.05) was found. The results from this suggest collating pre-operative data together can provide a more powerful tool to predict post-operative outcome. This is however a novel approach in the assessment of function and it has not been previously used in the literature when being applied to regression analysis. Further testing is required to assess the validity of using the composite scores within the BoE as the dependent variable instead of the traditional clinical scores.

Clinical outcome measures have been shown to correlate with patient satisfaction [61, 253]. The results from the present study agree with these findings with a strong correlation between post-operative subjective outcome and satisfaction. In one of the most comprehensive studies of post-KA satisfaction by Robertsson et al they found nonparametric correlation coefficients of between 0.63-0.68 for WOMAC and OKS scores [254]. When the same analysis was performed on the satisfaction data collected for the present study correlation coefficients of 0.72 and 0.74 for WOMAC and OKS were found. However, this relationship between satisfaction and perceived outcomes in the KA patients could also be a factor in the response shift phenomenon (Section 8.9).

9.9 Conclusion

Results from the regression analysis of the changes in DST based belief values showed that pre-operative objective and subjective function, and post-operative activity levels are significantly related to changes in function, and the final six month post-operative function. The most significant factor was pre-operative objective function (RoM, muscle size, PC scores derived from joint kinematics and kinetics of MS models during ADL) with the patients with the highest pre-operative function, performing the best post-operatively. Satisfaction was highly correlated with perceived function and pain scores post-operation. The amount of variance explained in the regression analysis from the belief values of the DST classifiers were double that previously reported using single questionnaire measures, highlighting the need to collate function scores.

Chapter 10

Discussion

This PhD thesis aimed to identify factors which affect KA function. In order to achieve this aim a literature review of the current evidence base surrounding KA function, and assessment techniques was undertaken. From the literature it was clear that despite developments in prosthetic design and surgical approaches there is still significant functional limitations and in some cases low satisfaction in the KA population. What was clear from the literature was that function was a product of many different factors and there was a wide range of levels of function within the KA patients. Factors which could affect function were also varied, however key processes were identified;

- Pre-operative factors
- Surgical factors
- Rehabilitation factors

Data were subsequently collected in order to provide a holistic evaluation of function. Measures included both patient reported (subjective) and observed (objective) data. Data collection was aimed to meet the World Health Organisations (WHO) International Classification of Functioning, Disability, and Health (ICF) [117] where possible. This was performed in order to establish all functional limitations within the patients. These data from healthy, pre-operative, and post-operative KA patients were then reduced and the data which optimally separated between healthy and pre-operative patients were established (Chapter 7). Results from the optimal variables to separate healthy and pre-operative KA patients showed that perceived measures of pain and function were the most discriminatory (Section 7.7.1). Pre-operation the KA patients reported high levels of pain and several limitations when performing ADL (from questionnaire based measures). Clinical objective measures (RoM and muscle atrophy) provided less discrimination with high *within-class* covariance in each healthy and pre-operative patient groups (Section 7.7.1). Data derived from PCA analysis of waveform measures showed that gait was the most discriminatory activity, follow by sit to stand to sit, and step-descent. Knee flexion moment was one of the highest discriminatory factors for all of the activities, with the pre-operative patients showing a reduction in flexion and extension moment (Figure 8.6).

Three classifiers were created using the optimal subjective (perceived), objective (measured), and combined (objective and subjective) measures of differing aspects of function (Chapter 8). These classifiers were able to classify participant function with an accuracy of above 90%, which is comparable to the current literature [42, 91] (Section 8.10). The classifiers also showed differences in function between TKA and UKA patients, although the variance in results was high.

A combined classifier was built with the top ten discriminating variables from the data collection. A hierarchy of the power of each of these variables to classify between healthy and pre-operative KA patients is given below;

1. WOMAC
2. Pain
3. Gait knee flexion moment
4. RF atrophy
5. Sit-stand sagittal force plate moment
6. Gait knee M-L reaction
7. Sit-stand vertical force plate reaction
8. Stand-sit sagittal force plate moment
9. Knee RoM
10. Perceived activity

These three DST classifiers were used to assess the changes in function from pre- to post-KA. Using the subjective measure based classifier, 74% of the post-operative patients were classified as healthy from an original 13% at the pre-operative assessment. This resulted from patient-reported (subjective) measures improving for all patients at the six month follow up appointment, pain was seen to drop from 6.4 to 1.8 out of 10 when performing light exercise. This dramatic improvement was not seen in the objective measures, with patients retaining decreases in RoM, muscle atrophy, and altered ADL kinematics and kinetics. The objective classifier showed that only 65% of patients improved in function and only 23% of the patients (7 out of 31, 3 of which were classified as healthy pre-operation) were classified as healthy post-operation. This finding adds to the growing body of evidence suggesting a disparity between objective and subjective measures in KA assessment (Section 8.9) [60, 250]. In a recent study by Mizner et al they found that perceived function increased beyond observed function at one and 12 month assessments compared to pre-operative scores [60]. The authors also found that observed measures of strength, RoM, 6MWT, and TUG were reduced at one month post-operation. However, at 12 months these observed measured improved compared to pre-operative levels [60]. The current study assessed function at 6 months which falls within the middle of the assessments by Mizner et al. The present study assessed the KA patients and six months post-operation, the results suggests similar trends to those by Mizner et al.

Results from the present study show that patients were on the whole satisfied with their KA, and improved in function from pre- to post-operation. Changes in function from pre- to post-operation were assessed using the DST results along with multiple linear regression (Chapter 9). From the regression analysis the key factors affecting changes in subjective and objective classification were found, although subjective and objective changes were seen to differ significantly. Key determinates in the changes in function were subjective and objective pre-operative function, and post-operative perceived activity. These findings are in agreement with the current literature [118, 119]. However, the magnitude of the variance explained in the regression analysis was much higher in the present study (R^2 values between 0.45-0.6, p<0.05) compared to previous literature (R^2 values between 0.2-0.3, p<0.05) [118, 119]. The combination of data within a BoE has provided a much stronger platform for analysis of changes in function. It is strongly recommended that functional assessment in the future should be based around the known functional limitation of patients in relation to the ICF classification. Assessments should include aspects of joint function, activity, body function, and quality of life. Discussion of these findings will be presented in the following sections.

10.1 Pre-Operative Function

This study has shown that pre-operative function is the most significantly related factor with changes in function, and six month functional outcomes compared to surgical and rehabilitative factors (Section 9.8). This is in agreement with much of the current literature which has assessed factors which affect function [61, 92]. It is then clear that in order to maximise the outcomes of KA there is a need to get pre-operative function to the highest possible levels. One such way would be to encourage early intervention; here patients would be operated on before knee degeneration and pain reduced holistic function substantially. Procedures such as high tibial osteotomy (HTO), and UKA could be options for the early intervention approach. These interventions generally occur when patients objective and subjective function has not dramatically depreciated (Figure 8.3) and they allow for ligament and bone stock retention. There is also a body of evidence to suggest that UKA is a more cost effective procedure than TKA [255]. The problem with these less invasive implants is that the evidence suggests that there are increases in long term complication rates compared to TKA [256], and the present study has indicated that poor patient selection could result in poor functional outcomes and satisfaction (Section 8.9). The TKA procedure could also be implemented earlier in order to raise baseline function. However, after this procedure significant bone stock and ligament loss is common, and revision can be limited. With this in mind, the argument to delay TKA is understandable, but this study has agreed with previous literature [118] highlighting that if pre-operative function is significantly lost post-operative function could be compromised. It is also of note that the polyethylene insert in the current TKA/UKA designs can wear, and if severe will need revision. There is a need to increase the durability of the implants so that surgeons can feel confident in the longevity of the procedure.

Another way in which pre-operative function could be increased is to have pre-operative physiotherapy and exercise regimes. It has been shown that physiotherapy interventions can increase strength [257], proprioception [258], and ADL function in elderly and OA patients [259]. Current evidence looking into pre-operative rehabilitation has shown no significant results [114], however study designs have been poor with limited functional assessment and low patient numbers (Section 2.5.3). Coudeyre et al conducted a systematic review of pre-operative rehabilitation for elective arthroplasty as part of the French clinical practice guidelines [260]. The systematic review found little evidence of the long term impact of pre-operative physiotherapy and the cost effectiveness of increase therapy input. The review found just three papers focussing on pre-operative KA rehabilitation, with participant numbers ranging from 30-133 and all the studies had limited length of follow up [260]. The review also highlighted the disparity between physicians and orthopaedic surgeons. More than 50% of the physicians prescribed physiotherapy, whereas less than 15% of orthopaedic surgeons did so [260]. There is a definite need to perform a thorough investigation of the potential benefits of pre-operative rehabilitation. In addition to this there is the potential for more education and therapy input to lower the risk of elderly persons reducing their baseline function. If OA patients can be encouraged to exercise and maintain active lifestyles there is the potential to retain muscle strength, joint RoM, and cardiovascular fitness, which could put them in a better position for potential KA outcomes.

10.2 Post-Operative Activity

Studies assessing post-operative activity levels have been more concerned with the effects of wear on the prosthesis than the beneficial effects of activity on the patients well being [261]. There is still considerable debate about the long-term effects of high physical activity on prosthetic wear, loosening and revision rates [261]. The present study has shown that post-operative perceived activity is one of the predominant factors that effects changes in function and six month post-operative outcomes. Correlations with activity have been shown to be greater than those previously reported [251]. In addition to this regular exercise is associated with an increased cardiac reserve and lowering of systemic blood pressure [262]. Increased physical activity also helps to maintain a good bone stock and high quality mineralised bone surrounding any cemented prosthesis can have important clinical implications [263]. Encouragement of activity should be given to all KA patients, as it has been shown to correlate with increased changes in function within this present study (Section 9.7). Moderate levels of activity could also have a positive impact on lowering BMI both pre- and post-operation, with BMI having been shown to affect post-operative function in the previous literature [264].

The importance of activity being a prominent factor in KA function has to be put into the context of the accuracy of the measure used within the present study, as activity was assessed using a standardised question;

'How much activity do you undertake during an average week? Activity would be defined as working up to the point where you are slightly out of breath.'

This question is obviously open to different interpretation from both the patients and the healthy control group. In order to validate this finding there is a need to assess activity more accurately. Other reporting measures such as the University of California at Los Angeles (UCLA) activity rating scale [265] and the High-Activity Arthroplasty Score [266] are available. Previous studies have used objective measures such as pedometers [267] and the Step-Watch Activity Monitor (SAM). Previous estimates of walking activity in patients with hip and knee prosthesis using electronic pedometers have sampled walking activity for between 4 days and 4 weeks [268]. Although it would be logical to assume that a longer activity sample would produce a more reliable assessment of walking activity, practical considerations, including subject compliance, limit the length of a valid sampling. Careful selection and validation of the activity monitor are needed as there have been differences observed between devices [268]. If patient perceptions of activity levels could be validated against objective measures using pedometers then this would be the easiest evaluation to use. However, if the measure was not found to be valid the use of pedometers would be necessary in order to assess activity levels accurately.

10.3 Objective vs. Subjective Function

If a patient reports reduced pain, increased stability, an increased perception of their ability to perform ADL, and high satisfaction with the KA the operation should surely be branded as successful. However the findings of this project show that although the perceived function in the patients has increased, for the majority there are still objective physical functional limitations compared to the healthy age matched population. These limitations include decreased RoM, muscle atrophy, and changes to ADL kinematics and kinetics. The question is; 'do these objective limitations matter if the patients perceive a high level of function and satisfaction?' Decreasing pain with increasing function is the end goal of the KA procedure, so if perceptions are reporting this increase surely the operation can be hailed a success? However the objective functional limitation cannot be ignored. Even if the patient's perceived function is high, objective limitations could have an impact on social and health related issues.

Perhaps the first point of discussion should be the validity of the questionnaire based measures with known influence of psychological factors [133]. It has also been shown that pain was the principal determinant in the WOMAC physical function subscale scores [134]. The disparity between increases in perceived function compared to that objectively measured strength, range of motion, 6MWT, and TUG for TKA patients was shown by Mizner et al [60]. Their study found these changes at both one and twelve months post-operation, with the largest difference at the one month assessment. They highlighted the need for performance-based measures to capture true functional disability [60]. Given that the patient demographic is changing and many of the younger patients may need to return to work, there is an obvious need for patients to have an objective function high enough to perform his/her work duties. As well as work, domestic and family needs may also require a certain amount of physical function. There is also a potential for an increase in health related problems if objective function remains low. Assessment of function should be tailored to the individual being assessed. If the patient demographic is changing and the functional requirements post-KA are altered, there needs to be a re-evaluation of the way in which function is assessed.

Many of the patients presented with joint loading asymmetry in ADL tasks, with the majority of patients putting additional loading on the contralateral limb in order to protect the KA side (Section 7.8). These additional forces and moments through the joints on the contralateral side could increase the risk of joint degeneration. In a study by McMahon et al they found that 37.2% of patients who had undergone primary TKA would have a replacement on the contralateral side within 10 years [269], with this finding being subsequently reiterated by Sayeed et al [270]. With over 70,000 replacements performed every year in the England and Wales this would account for a large number of replacements (26,600) and a considerable expense to the NHS. The studies also showed that those who had more severe OA were much more likely to need a contralateral replacement [269, 270]. The present study has shown that patients scheduled for a TKA had significantly higher asymmetry in loading during sit-stand-sit compared to UKA and healthy patients (Section 7.8). This could potentially increase the risk of contralateral replacement in TKA patients. It is of note that patients who have a primary KA could also present with OA in the contralateral limb, and that forces may not be a direct cause of increased risk of OA progression. However, the result of retained inter-limb loading asymmetry is worthy of future investigation.

The WHO classification of function and disability (ICF) was described at the start of this thesis (Chapter 1, Section 1.1). Here function was described into subsections of body functions, body structures, activities and participation, and environmental factors. Given this classification it is clear that KA patients still have significant functional limitations at six months post-operation. Results from this study have shown decreased joint RoM, muscle atrophy, and retention of perceived and observed difficulties during ADL (Table 7.2, Figure 8.8). There was also a proportion of patients who reported pain, instability, and decreased satisfaction with the KA process (Table 7.2). With this in mind there is clear evidence to suggest KA patients retained decreased function six months post-operation. Previous studies looking into function and factors affecting function have not taken into account the multiple patient specific contributors to the ICF definition of function. Until function is measured accurately taking into account all of the subsections within the ICF there is limited scope to define a study as 'assessing function'. Research is designed in principle to impact on practice and real life patient outcomes. For those studies which aim to assess function there is a need to perform assessments which incorporate the different subsections of the ICF classification [117].

10.4 Clinical Implications

The clinical implications of this work can be described for both future clinical research and in practice. Previous research surrounding KA function has been biased towards prostheses design and surgical technique (Section 2.5). The present study has highlighted that there are many other factors which could affect function, some of which have been given very little consideration in the present literature base. There is a need for clinical studies to investigate the effects of pre-operative function on post-operative outcomes in KA patients. If pre-operative function could be improved, perhaps post-operative functional gains would be greater, and this could increase satisfaction post-operation. There is also a need to investigate the effects of encouraging activity post-operation, as the present study had shown strong correlations with activity and functional gains. Activities which limit heavy impact at joints could, perhaps, be the best option for an exercise program. Activities such as swimming and cycling would have a strong effect on fitness, muscle strength, and could increase ADL function. The present study has also shown that assessing function in a holistic fashion has yielded strong results relating to functional gains, and there is a need to assess function subject to a gold standard definition (ICF). The present study has also shown that future work should also take into account differences in subjective and objective measures. The hierarchy of functional measures could also be used for guidance on future research. Measures which can discriminate between healthy and KA patients have been shown to classify patient function with a high level of accuracy (Section 9.4). Future research should also take into account the known error in some of the measurement techniques and thorough reliability and verification analysis (Section 6.2-7) will add strength to findings.

In practice the present study has shown that the patients who were seen earlier in the knee degeneration (UKA) had on average better objective functional outcomes post-operation. This could imply that there is a need to operative on patients sooner in order to retain baseline function, and in cases where possible retain soft and hard tissue structures. It is also of note that many of the patients felt that their KA had not met their full expectations. Clinically this could have been down to a lack of patient education. There may be a need to increase education of the potential post-operative functional limitations and the risk of post-operative ADL difficulties. The present study has also shown that changes in movement patterns during ADL currently can cause increased loading on contralateral joints. This could have implications for pathology of these contralateral joints and additional loss of function for the patient and costs to the health service. Rehabilitation which incorporates education and training to return symmetry to movement patterns could have the potential to decrease the risk of contralateral joint pathology, and this in turn could have a large socioeconomic impact.

Another potential application for the multivariate assessment techniques used within this study could be a screening tool for patients. With the development of the functional classifiers, recommendations to perform UKA or TKA could be given. If pre-operative function could be classified using the techniques within the present study a reflection of the potential post-operative gains could be advised to patients. This screening tool would obviously require further research and clinical testing for reliability and verification. One of the strengths of the classifying technique used within this study is the visual feedback to the patients.

10.5 Limitations

As with most studies there were some limitations with this PhD thesis. One of the main limitation was the low number of participants (51 in total who could complete the study), with this low number significantly effecting the number of variables that could be used in the analysis. Even though this study performed one of the most comprehensive assessments of function and ADL (68 waveforms and 14 discrete measures of function for each participant), many of these variables had to be omitted in the final analysis in order to meet the STV ratio recommendations (five subjects to one variable). Perhaps time would have been better spent recruiting more patients and recording less variables, thus increasing the power of the statistical analysis. More thorough analysis of the statistical approaches prior to the investigation would have given a better indication of the number of participants required to perform the study to the degree of detail that I originally set out to do. Measuring function holistically was a goal, however due to recruitment limitations the number of functional measures included in the analysis was limited. It is also of note that from the original 39 patients recruited, eight could not be used in the analysis because they could not complete a full assessment (Section 7.5). These patients tended to be the lowest functioning patients, therefore the methodology set out in this project was only suitable for patients with a higher relative function. This could have resulted in missing data which could have been pertinent in the final analysis.

With this in mind, techniques such as the MS modelling may not have been the best use of time, with the PCA and LDA analysis reducing the data down to just 12 variables that were used in the end analysis. With the MS modelling being a time consuming exercise, other methods to assess objective ADL function may have been more appropriate. Clinical test such as the TUG and 6MWT previously stated (Section 3.3), may have served as a more time efficient method to assess ADL. The MS modelling also remains limited in its validation, and the number of assumptions in the process may limit its reliability to assess joint kinematics and kinetics between persons. Although there are limitations in the MS modelling it did, however, produce some interesting results regarding joint kinematics and kinetics and its potential as a useful clinical tool increases with each step forward in the application.

Another significant limitation with the study was the follow up time for the KA patients (six months). This only allowed a short amount of time for the patients to rehabilitate and in order to enhance the findings of this project a longitudinal assessment would be required. It has been shown that functional gains can occur in patients up to 3 years post-operation [256], although most of the functional gains will be made in the first year. There is a good possibility that when the patients were assessed they were still on the upward slope of functional recovery, the extent of the potential additional functional gains needs to be assessed. Although there were many factors which could affect function included in the regression analysis, there still remained several that were omitted. One of the most limited representations was given to the surgical factors. Section 2.5 highlighted that there are many factors such as type of prosthesis, placement of implant, experience of surgeon that could not be assessed in this project. This was mainly due to the fact that patient numbers were low in the study and these intrinsic surgical factors would have only been seen in small subgroups. In order to fully assess surgical factors detailed feedback from the operation along with precise analysis of implant positioning would give a greater insight into the surgical factors which could affect function. Large patient numbers would be required to perform this analysis of surgical variability.

10.6 Novelty

Previous research assessing KA function has focused on single measures of joint function or perceived disability. This has led to studies having a limited assessment of function relative to the ICF recommendations. The result of this poor assessment has been limited results and recommendations on factors which can affect KA function. The novelty in the present project has been the combination of several assessment techniques to form a body of evidence which can estimate the functional status of a participant. Using statistical methods to provide a number of variables which discriminate between healthy and pre-operative KA patients, has provided an accurate method to classify patients and healthy individuals. From this, the estimated relative changes in function from pre- to post-operation have been formulated on the basis of a combined BoE. This approach we feel is a more accurate method to assess function relative to the ICF classification.

The novelty of this work is not the assessment techniques that have been used (although ultrasound imaging and MS modelling are not frequently used), but the combination of multiple measures using statistical methods. By using these BoE for both objective and subjective measures of function it has given an insight into the functional gains and in some cases losses in the KA cohort assessed. The most comparable study was performed by Jones et al, here multiple liner regression analysis of factor affecting six month post-operative KA function was performed on 276 TKA patients [119]. Jones et al used dependent variables for the regression analysis including the WOMAC and SF-36 questionnaires (Section 3.2.1). They also used independent variables of; (1) demographic variables (age/sex), (2) baseline variables (diagnosis, BMI, previous arthroplasty, pre-operative WOMAC/SF-36, pre-operative RoM, pre-operative ambulatory status, and (3) perioperative variables (the number of in-hospital complications, implant fixation, waiting time, length of stay). Rehabilitation received was not documented and this could have affected the results. The main outcome of this study was that pre-operative measures were related to post-operative SF-36 scores (R^2 value 0.27, p<0.05) [119]. But this result highlights that the pre-operative scores only account for 27% of the variance in the post-operative perceived quality of life. The major limitation of this study was that no objective measures of function were used as dependent variables.

The present study has shown a large disparity in objective and subjective outcomes post-KA, and there is a need to assess both patient perceived and observed measures of KA function in order to fully assess function. Multiple linear regression analysis performed in the present study showed that independent variables of pre-operative function could account for up to 63% of the variance in the post-operative DST based functional belief. Rehabilitative factors could account for up to 59% of the variance in six month post-KA combined DST based healthy belief (Section 9.5). This study is also novel in the analysis of measured changes of function as well as a final post-operative score. Independent variables of pre-operative factors that can affect function accounted for 58 to 61% of the variance in changes of function (measured using DST classifiers based on objective, subjective, and combined function). In addition to these findings the present study also found strong relationship between satisfaction and changes in patient perceptions of pain and function (Section 9.6).

Chapter 11

Conclusions, Future Work

11.1 Conclusions

This study has been one of the few to provide a comprehensive evaluation of patient function, using statistical methods to incorporate a holistic assessment approach. The study has then taken evidence based factors which could affect KA function in an assessment of pre- to six months post-operative function. The findings of the present study have shown that pre-operative perceived and measured function is significantly related to post-operative outcomes, explaining over 60% of the variance in KA function. This is in agreement with previous literature, although greater variance was explained in the current study. In addition to this post-operative activity levels have also been shown to correlate with functional gains; this has only been highlighted in one previous study. The importance of post-operative activity is worthy of further investigation. This study has also shown the disparity between subjective and objective measures. Most patients had significant functional gains in perceived pain and ADL ability, however objective measure show that on average little improvement is made six months post-operation. On average TKA patients were more satisfied and made modest but consistent improvements. However UKA patients have been shown to be much more variable in functional gains, and the efficacy of this procedure could be questionable given poor patient selection.

This novel study has shown the need to assess patients in a holistic manner, accounting for both patient perceived and measured outcomes. Early post-operative outcomes have been related to pre-operative function and post-operative activity levels. The present study has shown the potential for a larger study of KA function to be performed using the assessment and statistical methods which would enable more detailed analysis of long term KA function.

11.2 Future Work

This study showed that collating data together from perceived and observed outcome measures provided a powerful tool to assess changes in function in KA patients. Although this pilot study answered a few questions it created many more. Three future studies were highlighted; they were chosen on the back of this PhD thesis and are thought to be potentially the most clinically relevant for future practice.

1. **Factors affecting Knee Arthroplasty Function**

This title is a mirror of that of the PhD thesis, however the pilot study has shown that there is a need for expansion. If the study was going to be expanded additional information regarding patient expectations, psychological factors, proprioception assessment, and clinical assessment of ADL would be added. Further analysis of surgical factors and rehabilitation protocol would also be included in the analysis to give a better statistical evaluation of factors which could affect function. Other functional factors highlighted in the ICF guidelines could also be included in the analysis such as a patient's ability to return to work or driving. With the addition of these factors increases in patient and healthy individual recruitment would be needed. If 40 variables were used to produce DST based patient classification participant numbers would need to be 200 (healthy and KA combined). With this number of participants regression analysis could include 20 variables. As well as additional numbers the study would also need to be longitudinal, where the patients would be followed up at regular interval post-operation (up to five years).

In order to achieve this number of subjects and longitudinal follow up there would be a need to collaborate with several University and Healthy care institutions. With a standardised assessment protocol there would be a potential to collate data and find significant results from the subsequent study.

2. **The Effects of Pre-operative Rehabilitation on Post-operative Function**

This and other studies have shown that pre-operative function is one of the key determinants in post-operative function. There is a need to investigate the effect of pre-operative rehabilitation on the post-operative outcomes of KA patients. A study with a large number of participants would be needed in order to find statistically significant differences. Pre-operative rehabilitation could be focused on increased activity, education, and controlling pain. Function could be measured with a similar approach to that which was proposed in this PhD study.

3. The Effects of ADL Asymmetry in Knee Arthroplasty Patients

As highlighted in Section 10.3 there is the potential for ADL changes to increase loading on the contralateral limb. With the increasing number of KA being performed each year there is a need to prevent further orthopaedic procedures. Evidence suggests that there is a large number of primary TKA patient who require an operation on the contralateral limb. There is a need to investigate if there is a relationship between predicted increases in contralateral loading and secondary joint replacement (hips, knee, ankles, ect). If there is a significant increase due to increase loading on the contralateral side, then there is a need to rehabilitate patients to educate them from over-loading the contralateral limb. This in turn could have the potential to increase post-operative function and reduce the demands on the Health Service.

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Appendix A

Papers and Conference Abstracts

Papers:

Delaney S, Worsley P, Warner M, Taylor M, Stokes M. Assessing contractile ability of the quadriceps muscle using ultrasound imaging *Muscle & Nerve* 2010; 42: 530–538. doi: 10.1002/mus.21725

Worsley, P., M. Stokes, and M. Taylor, Predicted Knee Kinematics and Kinetics during Functional Activities using Optimised Motion Capture and Musculoskeletal Modelling in Healthy Older People. Gait and Posture, *corrected in press*

Worsley , P., Galloway, F., Nair, P., Stokes, M., Taylor, M. Changes in Movement Patterns during Activities of Daily living in Individuals suffering from Osteoarthritis. Gait and Posture, *under review*

Peter Worsley., Gemma Whatling., Cathy Holt., Maria Stokes., Mark Taylor,. Assessing Changes in Perceived and Observed Function from pre- to post-Knee Arthroplasty using Multivariate Statistical Methods. Arthritis and Rheumatism, *written awaiting to submit*

Conference Abstracts - Podium Presentation

Worsley, Peter, Stokes, M. and Taylor, M. (2010) B-15 comparison of osteoarthritic knee kinematics and kinetics with age matched healthy individuals. At *International Conference on Orthopaedic Biomechanics, Clinical Applications and Surgery, UK.* Journal of Biomechanics, 2010. 43: p. S29-S29.

Worsley, Peter, Stokes, M. and Taylor, M. (2010) Ultrasound Imaging to Scale Strength in Patient Specific Musculoskeletal Models. ESB, Edinburgh, Scotland.

Worsley, Peter, Stokes, Maria and Taylor, Mark (2010) Assessment of knee kinematics and kinetics during gait in healthy older people using optimised motion capture and musculoskeletal modelling. CMBBE*, Valencia, ES.*

Conference Abstracts - Poster

Worsley, Peter, Stokes, M. and Taylor, M. (2010) Robustness of optimised motion capture and musculoskeletal modelling of Gait. At *CMBBE 2010, Valencia, ES* ,

Worsley, Peter, Stokes, Maria, Taylor, Mark and BioEngineering (2010) Assessment of muscle atrophy in knee arthroplasty patients using dynamic ultrasound imaging. *ORS, USA.*

Worsley, Peter, Warner, Martin, Delaney, Sinead, Stokes, Maria and Taylor, Mark (2009) The application of ultrasound imaging in the musculoskeletal modeling process. ORS, USA.

Delaney, S., Worsley, P., Warner, M., Stokes, M. (200) Relationship between changes in force and linear dimensions of rectus femoris muscle in man using ultrasound imaging. in Physoc. 2009. Dublin, Ireland.

Gallaway, F., Seim, H., Kahnt, M., Nair, P., Worsley P., Taylor, M. (2010) A large scale finite element study of an osseointegrated cementless tibial tray. In ISTA, Dubai.

Fitzpatrick, C., Shelburne, K., Clary, C., Worsley, P., Taylor, M., Rullkoetter, P., (2011) Muscle loaded finite element framework for simulation of dynamic activities. In ORS, USA.

Appendix B

Anatomical Planes, axis, and Movement Descriptions

When describing the human body it can be divided up into three orthogonal planes. These planes are defined as the sagittal (travels vertically from the top to the bottom of the body, dividing it into left and right portions) ,transverse (divides the body into superior and inferior parts), and frontal (vertical plane that divides the body into anterior and posterior sections) reference frames (Figure 0.1).

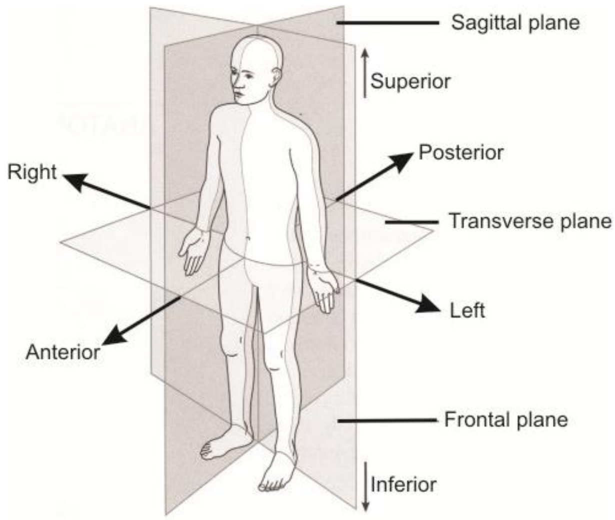


Figure 0.1: Reference frames of the human body. Reproduced [271] with permission

The planes cut through the body to segment areas of description, they can also form the basis for describing movement. Movement translations and rotations within the human body also have specific terminology, these terms often describe the relative position of body parts and not absolute position. There are relative translation and rotations about each anatomical plane (Table.1).

Table.1: Common terminology for anatomical rotations and translations

Translations	**Description**
Distal	Further away from the centre of the body
Proximal	Closer to the centre of the body
Anterior	'Forwards' towards front of body
Posterior	'Backwards' toward back of body
Medial	Towards the middle of body 'inner'
Lateral	Away from the middle of body 'outer'
Rotations	**Description**
Internal	Rotate inwards
External	Rotate outwards
Varus	Inward angulation in sagittal plane 'bow leg'
Valgus	Outward angulation in sagittal plane 'knock knees'
Flexion	Rotation to decrease joint angle
Extension	Rotation to increase joint angle

Appendix C

Southampton General Hospital Rehabilitation Protocol

Following Knee surgery

These exercises are to assist you in your recovery after knee surgery and are helpful in restoring flexibility and strength. As a rule, these exercises should be carried out little and often. It is important not to push through pain in the early stages, but equally important that you try some in order to aid your recovery. If the exercises give you pain, stop and try them again later, reducing the amount you do and then build them up again gradually. The physiotherapist can advise you what is the right level of exercise for you.

Post-operative exercises

On the day after your surgery please do the following exercises, which will improve your circulation to your leg and also start to use the muscles you will need to regain strength in your leg.

Ankle exercises

Pull foot up and then point toes x 20 each foot.

Static Quads exercises

Pull foot up, brace thigh muscle, which pushes the knee into the bed and slightly raises heel off bed (x10 each leg)

Gluteal exercises

Squeeze your bottom cheeks together (x 10 each leg)

To progress these exercises you will be given a sliding board or sheet of plastic and a rolled up bandage which will be placed under your heel and shown the following exercises:

Knee Flexion/ Extension

Slide your heel towards your bottom and hold for a few seconds, slide heel away from bottom until knee is straight. Push your knee into the board and hold for 5 secs. Repeat 10 times

Straight leg raises

Pull your foot up towards you, brace knee down (static quad) and then lift leg straight up from the bed, approx 6 inches high. Hold for 5 secs and lower slowly. repeat 10 times.

Inner Range quads

Place a rolled up towel underneath knee to bend it slightly. Pull foot up and lift heel up off the bed and straighten knee. Hold for 5 secs and repeat 10 times.

In Chair

Pull foot up and raise foot up from floor until your knee is straight. Hold for 5 secodns and relax and repeat x 20.

Sitting to Standing

Place feet together, lean forward and raise bottom off chair

Standing holding on a firm support

Standing Knee flexion

Keep back straight

Take your knee towards chest

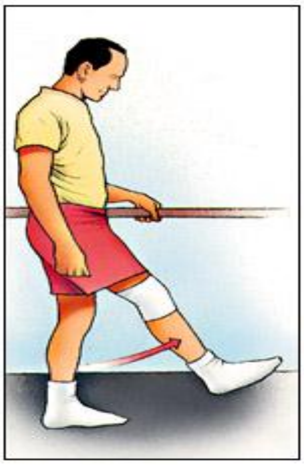
Keep tummy forward

Try not to lean back

Return leg to floor.

Rpt x10

Standing quads exercise



Keep back straight

Pull toe on operated leg up

Keep knee as straight as possible

move leg forward, hold for 5 secs and return to standing position

Rpt x 10

Squats in standing

Keep back straight

Feet level with each other

lower bottom towards floor and bend knees together.

Rpt x 10.

Your recovery after knee surgery

Day 0 (the day of surgery)

Your surgery is likely to take 1-2 hours. You will spend some time in the recovery ward in theatre. A short while later you will return to the ward and the nursing staff will make sure you are comfortable and continue to do regular observations on you. You will be fairly sleepy for a few hours afterwards. Your pain may be managed with an epidural, a special pump or orally with tablets or liquid. You may also have a drain coming from your wound and a drip into your arm to build up your fluid levels. You will also have oxygen via a mask or nose specs. Some patients need to have a catheter if they are having difficulty passing urine, or until they are mobile.

Day 1 post-op (the day after surgery)

Your physiotherapist will introduce themselves and explain the rehabilitation process. It is expected that you will start a gentle exercise program to aid the circulation and early activity of your new knee joint. If all goes well you will be encouraged to get out of bed and sit in your chair for a while. You will be shown how to get in/out of bed and how to use elbow crutches or a zimmer frame depending on the level of your mobility. It is important that you start to exercise and mobilise to prevent further complications.

Day 2 Post-op

You will be encouraged to get out of bed again and start to practice walking with the use of your walking aid. You will be encouraged to walk as far as you can, thus allowing you to walk to the washroom and toilet. This is all dependant on your level of mobility prior to your admission.

You will also be encouraged to continue your exercises by yourself during the day in order to gain more flexibility in your knee. The physio will check through the exercises with you, until you are confident to try them on your own.

Day 3 post-op/Day 4 post op

By now you should be able to walk well with your walking aid. Your physio can observe your walking pattern and give you pointers on how to improve your walking pattern and progress you as able. By now you should be able to walk independently on the ward and manage to get dressed either independently or with minimal help. If you need help getting on and off the bed still, then you will be shown how to manage this at home.

Your exercises will be checked and given some new exercises in standing. You will be shown how to manage a flight of stairs or a step if necessary.

Once you are managing you will be able to go home. Before going home you will be given advice on how to manage your knee in the future and when to wean off your walking aids. You may need some outpatient physio to provide help with this. Your physio will discuss this with you prior to discharge.

Appendix D

Surgical Feedback

Patient code, e.g. A-001, A-002, etc	
Surgeon	
Date of surgery	
Age	
Left/right limb?	
Ethnicity	
Brief patient history	
Femoral model, size and type Eg, PFC Sigma, Size 6, PCL sacrificing	
Tibial model, size and type	
Valgus/Varus correction	
AP tilt (tibial component)	
Patella model, size and type	
Pre-implant passive flexion Post-implant passive flexion	
Comments	

Appendix E

Oxford Knee Score

PROBLEMS WITH YOUR KNEE

During the past 4 weeks..

✓tick one box for every question

1 ***During the past 4 weeks........***

How would you describe the pain you usually have from your knee?

None	Very mild	Mild	Moderate	Severe
❑	❑	❑	❑	❑

2 ***During the past 4 weeks........***

Have you had any trouble with washing and drying yourself (all over) because of your knee?

No trouble at all	Very little trouble	Moderate trouble	Extreme difficulty	Impossible to do
❑	❑	❑	❑	❑

3 ***During the past 4 weeks........***

Have you had any trouble getting in and out of a car or using public transport because of your knee? (whichever you would tend to use)

No trouble at all	Very little trouble	Moderate trouble	Extreme difficulty	Impossible to do
❑	❑	❑	❑	❑

4 ***During the past 4 weeks........***

For how long have you been able to walk before pain from your knee becomes **severe**? (*with or without a stick)*

No pain/ More than 30 minutes	16 to 30 minutes	5 to 15 minutes	Around the house only	Not at all - pain severe when walking
❑	❑	❑	❑	❑

5 ***During the past 4 weeks........***

After a meal (sat at a table), how painful has it been for you to stand up from a chair because of your knee?

Not at all painful	Slightly painful	Moderately painful	Very painful	Unbearable
❑	❑	❑	❑	❑

6 ***During the past 4 weeks......***

Have you been limping when walking, because of your knee?

Rarely/ never	Sometimes, or just at first	Often, not just at first	Most of the time	All of the time
❑	❑	❑	❑	❑

During the past 4 weeks...

✓tick one box for every question

7 *During the past 4 weeks.......*

Could you kneel down and get up again afterwards?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
❑	❑	❑	❑	❑

8 *During the past 4 weeks.......*

Have you been troubled by pain from your knee in bed at night?

No nights	Only 1 or 2 nights	Some nights	Most nights	Every night
❑	❑	❑	❑	❑

9 *During the past 4 weeks.......*

How much has pain from your knee interfered with your usual work *(including housework)*?

Not at all	A little bit	Moderately	Greatly	Totally
❑	❑	❑	❑	❑

10 *During the past 4 weeks.......*

Have you felt that your knee might suddenly 'give way' or let you down?

Rarely/ never	Sometimes, or just at first	Often, not just at first	Most of the time	All of the time
❑	❑	❑	❑	❑

11 *During the past 4 weeks.......*

Could you do the household shopping on your own?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
❑	❑	❑	❑	❑

12 *During the past 4 weeks.......*

Could you walk down one flight of stairs?

Yes, Easily	With little difficulty	With moderate difficulty	With extreme difficulty	No, Impossible
❑	❑	❑	❑	❑

Appendix F

Western Ontario and McMaster University Osteoarthritis Index

WOMAC Osteoarthritis Index LK3.1

INSTRUCTIONS TO PATIENTS

In Sections A, B and C, questions will be asked in the following format. You should give your answers by putting an " ✗ " in one of the boxes.

EXAMPLES:

1. If you put your " ✗ " in the left-hand box, i.e.

None	Mild	Moderate	Severe	Extreme
☒	☐	☐	☐	☐

Then you are indicating that you have **no** pain.

2. If you put your " ✗ " in the right-hand box, i.e.

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☒

Then you are indicating that your pain is **extreme.**

3. Please note:
   a) that the further to the right you place your " ✗ " the **more** pain you are experiencing.
   b) that the further to the left you place your " ✗ " the **less** pain you are experiencing.
   c) **please do not** place your " ✗ " **outside the box**.

You will be asked to indicate on this type of scale the amount of pain, stiffness or disability you have experienced in the last 48 hours.

Think about your _______________ (study joint) when answering the questionnaire. Indicate the severity of your pain, stiffness and physical disability that you feel is caused by arthritis in your _______________ (study joint).

Your study joint has been identified for you by your health care professional. If you are unsure which joint is your study joint, please ask before completing the questionnaire.

V3-United Kingdom

WOMAC Osteoarthritis Index LK3.1

Section A

PAIN

Think about the pain you felt in your ________________ (study joint) due to your arthritis during the <u>last 48 hours</u>.

(Please mark your answers with an " ✗ ".)

QUESTION: **How much pain do you have?**

Question	None	Mild	Moderate	Severe	Extreme	Study Coordinator Use Only
1. Walking on a flat surface.	❑	❑	❑	❑	❑	PAIN1 _____
2. Going up or down stairs.	❑	❑	❑	❑	❑	PAIN2 _____
3. At night while in bed i.e. pain that disturbs your sleep.	❑	❑	❑	❑	❑	PAIN3 _____
4. Sitting or lying.	❑	❑	❑	❑	❑	PAIN4 _____
5. Standing upright.	❑	❑	❑	❑	❑	PAIN5 _____

V3-United Kingdom

WOMAC Osteoarthritis Index LK3.1

Section B

STIFFNESS

Think about the stiffness (not pain) you felt in your_____________ (study joint) due to your arthritis during the last 48 hours.

Stiffness is a sensation of **decreased** ease in moving your joint.

(Please mark your answers with an " ✗ ".)

6. How **severe** is your stiffness **after first awakening** in the morning?

None	Mild	Moderate	Severe	Extreme
❑	❑	❑	❑	❑

7. How **severe** is your stiffness after sitting, lying or resting **later in the day**?

None	Mild	Moderate	Severe	Extreme
❑	❑	❑	❑	❑

Study Coordinator Use Only

STIFF6 _____

STIFF7 _____

V3-United Kingdom

WOMAC Osteoarthritis Index LK3.1

Section C

DIFFICULTY PERFORMING DAILY ACTIVITIES

Think about the difficulty you had in doing the following daily physical activities due to arthritis in your _______________ (study joint) during the last 48 hours. By this we mean **your ability to move around and to look after yourself**.

(Please mark your answers with an " ✗ ".)

QUESTION: **What degree of difficulty do you have?**

Question	None	Mild	Moderate	Severe	Extreme	Study Coordinator Use Only
8. Descending stairs.	❑	❑	❑	❑	❑	PFTN8 _____
9. Ascending stairs.	❑	❑	❑	❑	❑	PFTN9 _____
10. Rising from sitting.	❑	❑	❑	❑	❑	PFTN10 _____
11. Standing.	❑	❑	❑	❑	❑	PFTN11 _____
12. Bending to the floor.	❑	❑	❑	❑	❑	PFTN12 _____
13. Walking on a flat surface.	❑	❑	❑	❑	❑	PFTN13 _____

V3-United Kingdom

WOMAC Osteoarthritis Index LK3.1

Section C

DIFFICULTY PERFORMING DAILY ACTIVITIES

Think about the difficulty you had in doing the following daily physical activities due to arthritis in your _______________ (study joint) during the last 48 hours. By this we mean **your ability to move around and to look after yourself**.

(Please mark your answers with an " ✗ ".)

QUESTION: **What degree of difficulty do you have?**

Study Coordinator Use Only

14. Getting in or out of a car, or getting on or off a bus.

None	Mild	Moderate	Severe	Extreme	
❑	❑	❑	❑	❑	PFTN14 ____

15. Going shopping.

None	Mild	Moderate	Severe	Extreme	
❑	❑	❑	❑	❑	PFTN15 ____

16. Putting on your socks or tights.

None	Mild	Moderate	Severe	Extreme	
❑	❑	❑	❑	❑	PFTN16 ____

17. Rising from bed.

None	Mild	Moderate	Severe	Extreme	
❑	❑	❑	❑	❑	PFTN17 ____

18. Taking off your socks or tights.

None	Mild	Moderate	Severe	Extreme	
❑	❑	❑	❑	❑	PFTN18 ____

19. Lying in bed.

None	Mild	Moderate	Severe	Extreme	
❑	❑	❑	❑	❑	PFTN19 ____

V3-United Kingdom

WOMAC Osteoarthritis Index LK3.1

Section C

DIFFICULTY PERFORMING DAILY ACTIVITIES

Think about the difficulty you had in doing the following daily physical activities due to arthritis in your _______________ (study joint) during the last 48 hours. By this we mean **your ability to move around and to look after yourself**.

(Please mark your answers with an " ✗ ".)

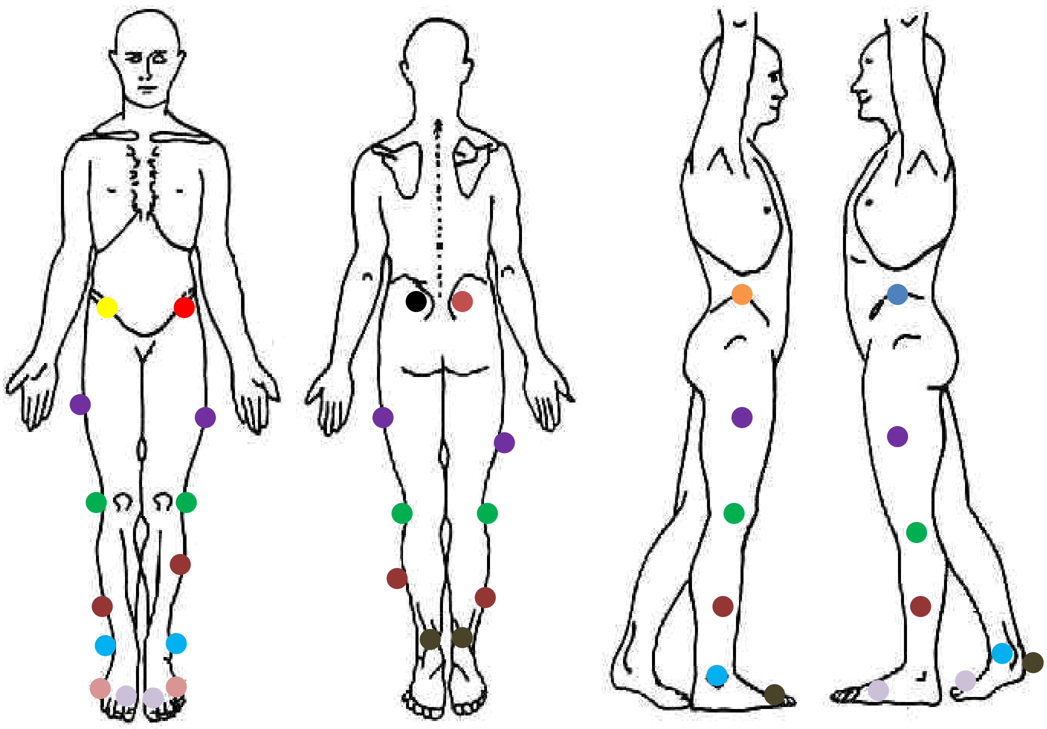
QUESTION: **What degree of difficulty do you have?**

	None	Mild	Moderate	Severe	Extreme	Study Coordinator Use Only
20. Getting in or out of the bath.	❑	❑	❑	❑	❑	PFTN20 ____
21. Sitting.	❑	❑	❑	❑	❑	PFTN21 ____
22. Getting on or off the toilet.	❑	❑	❑	❑	❑	PFTN22 ____
23. Performing heavy domestic duties.	❑	❑	❑	❑	❑	PFTN23 ____
24. Performing light domestic duties.	❑	❑	❑	❑	❑	PFTN24 ____

V3-United Kingdom

Appendix G

Modified Helen Hayes motion capture marker set



Lower Body

Pelvis

LASI	●	Left ASIS	Placed directly over the left anterior superior iliac spine
RASI	●	Right ASIS	Placed directly over the right anterior superior iliac spine
RILC	●	Right Iliac crest	Placed over the midline of the most superior aspect of the right iliac crest
LILC	●	Left Iliac crest	Placed over the midline of the most superior aspect of the left iliac crest
LPSI	●	Left PSIS	Placed directly over the left posterior superior iliac spine
RPSI	●	Right PSIS	Placed directly over the right posterior superior iliac spine

The above markers may need to be placed medially to the ASIS to get the marker to the correct position due to the curvature of the abdomen. In some patients, especially those who are obese, the markers either can't be placed exactly anterior to the ASIS, or are invisible in this position to cameras. In these cases, move each marker laterally by an equal amount, along the ASIS-ASIS axis. The true inter-ASIS Distance must then be recorded and entered on the subject parameters form. These markers, together with the sacral marker or LPSI and RPSI markers, define the pelvic axes.

LPSI and RPSI markers are placed on the slight bony prominences that can be felt immediately below the dimples (sacro-iliac joints), at the point where the spine joins the pelvis.

Leg Markers

KNE ●	knee	Placed on the lateral epicondyle of the knee

To locate the "precise" point for the knee marker placement, passively flex and extend the knee a little while watching the skin surface on the lateral aspect of the knee joint. Identify where knee joint axis passes through the lateral side of the knee by finding the lateral skin surface that comes closest to remaining fixed in the thigh. This landmark should also be the point about which the lower leg appears to rotate. Mark this point with a pen. With an adult patient standing, this pen mark should be about 1.5 cm above the joint line, mid-way between the front and back of the joint. Attach the marker at this point.

THI ●	thigh	Place the marker over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical.

The thigh markers are used to calculate the knee flexion axis location and orientation. Place the marker over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical. The antero-posterior placement of the marker is critical for correct alignment of the knee flexion axis. Try to keep the thigh marker off the belly of the muscle, but place the thigh marker at least two marker diameters proximal of the knee marker. Adjust the position of the marker so that it is aligned in the plane that contains the hip and knee joint centres and the knee flexion/extension axis. There is also another method that uses a mirror to align this marker, allowing the operator to better judge the positioning.

ANK ●	ankle	Placed on the lateral maleolus along an imaginary line that passes through the transmalleolar axis
TIB ●	tibial marker	Similar to the thigh markers, these are placed over the lower 1/3 of the shank to determine the alignment of the ankle flexion axis

The tibial marker should lie in the plane that contains the knee and ankle joint centres and the ankle flexion/extension axis. In a normal subject the ankle joint axis, between the medial and lateral malleoli, is externally rotated by between 5 and 15 degrees with respect to the knee flexion axis. The placements of the shank markers should reflect this.

Foot Markers

TOE ●	toe	Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
HEE ●	heel	Placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker

Appendix H

Ethical Approval Letters

NHS
National Research Ethics Service

SOUTHAMPTON & SOUTH WEST HAMPSHIRE
RESEARCH ETHICS COMMITTEE (B)
1ST Floor, Regents Park Surgery
Park Street, Shirley
Southampton
Hampshire
SO16 4RJ

Tel: 023 8036 2466
023 8036 3462
Fax: 023 8036 4110

Email: scsha.SWHRECB@nhs.net

PW/sta

04 November 2008

Prof David Barrett
Consultant Orthopaedic Surgeon,
Professor of Engineering Sciences
Southampton General Hospital
Tremona Road
Southampton
SO16 6UY

RECEIVED 06 NOV 2008

Dear Prof Barrett

Study title: **Assesment of the effect of Knee prosthesis placement on Kinematics and Gait. Verification of computative predictive data**
REC reference: **08/H0504/69**
Amendment number: **1**
Amendment date: **29 September 2008**

The above amendment was reviewed at the meeting of the Sub-Committee of the REC held on 29 October 2008.

Ethical opinion

The members of the Committee present gave a favourable ethical opinion of the amendment on the basis described in the notice of amendment form and supporting documentation.

Approved documents

The documents reviewed and approved at the meeting were:

Document	Version	Date
Protocol	1.1	29 September 2008
Participant Information Sheet	1.2	29 September 2008
NRES Application Form		
Summary of Changes		08 August 2008
Notice of Substantial Amendment (non-CTIMPs)	1	29 September 2008
Covering Letter		08 August 2008

Membership of the Committee

The members of the Committee who were present at the meeting are listed on the attached sheet.

R&D approval

All investigators and research collaborators in the NHS should notify the R&D office for the relevant NHS care organisation of this amendment and check whether it affects R&D approval of the research.

UNIVERSITY OF Southampton

Mr Peter Worsley
School of Health Sciences
University of Southampton
University Road
Highfield
Southampton
SO17 1BJ

RGO REF - 6006
School Ethics Ref - 08-025

17 September 2008

Dear Mr Worsley

Professional Indemnity and Clinical Trials Insurance

Project Title Reliability and Validity of motion Analysis/EMG

Participant Type:	No Of Participants:	Participant Age Group:	Notes:
Healthy volunteers	25	Adults	

Thank you for forwarding the completed questionnaire and attached papers.

Having taken note of the information provided, I can confirm that this project will be covered under the terms and conditions of the above policy, subject to written consent being obtained from the participating volunteers.

I would also advise that it is a condition of the University's insurance that any incidents that could eventually result in a claim are reported immediately. Adverse events, suspected unexpected serious adverse reactions and similar fall into this category and should also be reported to me at the same time as they are reported under the Protocol. Failure to do this could invalidate the insurance.

If there are any changes to the above details, please advise us as failure to do so may invalidate the insurance.

Yours sincerely

Ruth McFadyen

Mrs Ruth McFadyen
Insurance Services Manager

Tel: 023 8059 2417
email: hrm@soton.ac.uk

cc: File

Finance Department, University of Southampton, Highfield Campus, Southampton SO17 1BJ United Kingdom
Tel: +44 (0) 23 8059 5000 Fax: +44 (0) 23 8059 2195 www.southampton.ac.uk

UNIVERSITY OF Southampton
School of Health Sciences

E04/Oct 2008/ v1.0

Peter Worsley
School of Engineering
Building 27, Room 4055
University of Southampton

6 May 2009

Dear Peter

Ethics Submission No: SoHS-ETHICS-09-003
Title: Assessing vastus medialis/lateralis with ultrasound imaging

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

You are required to complete a University Insurance and Research Governance Application Form (IRGA) in order to receive insurance clearance before you begin data collection. The blank form can be found at http://www.soton.ac.uk/corporateservices/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 SoHS Risk Assessment form, **signed**
- Copy of your information sheet and consent form
- Copy of this SoHS Ethical approval letter

Continued overleaf

Building 67
School of Health Sciences, University of Southampton, Highfield Campus, Southampton SO17 1BJ United Kingdom
Tel: +44 (0)23 8059 7979 Fax: +44 (0)23 8059 7900 www.southampton.ac.uk/healthsciences

Appendix I

Comparison of Motion Capture Systems

A comparison study between the new and old VICON system was performed using 2 of the control group subjects. The old system consisted of a five camera Vicon 460 system, with the new system having twelve Vicon Tseries cameras. Calibration of each camera system was performed at the same time using a standardised 5 marker wand and a global centre was defined for both camera systems. Synchronisation was achieved by using a clicker system which provided a small voltage which was recorded for both systems at the start of a trial. Both camera systems were set to record data at 120Hz.

During their assessment both system were running in synchronisation, with key markers then checked for system differences. Four key markers were selected (RASI, RKNE, RHEE, RTOE), in both static and dynamic conditions. In order to standardise the reconstruction parameters of the markers, VICON NEXUS software package was used for all C3D data (Table J1).

Static conditions	Mean difference (mm)	Range (mm)	Standard deviation
X trajectories	0.58	0.11-2.45	1.52
Y trajectories	0.31	0.52-2.34	1.88
Z trajectories	2.43	1.03-4.28	1.43

Dynamic conditions	Mean difference (mm)	Range (mm)	Standard deviation
X trajectories	3.32	(-28.03 - 18.28)	5.48
Y trajectories	2.23	(-10.2 - 5.71)	2.51
Z trajectories	2.97	(-11.47 - 17.01)	3.93

Table J1. Table of marker trajectory differences between the VICON 460 and VICON T series system for both a static and dynamic trial marker data in the X, Y, and Z pl

Appendix J

Gait Data

Healthy | Pre-operation | Post-operation

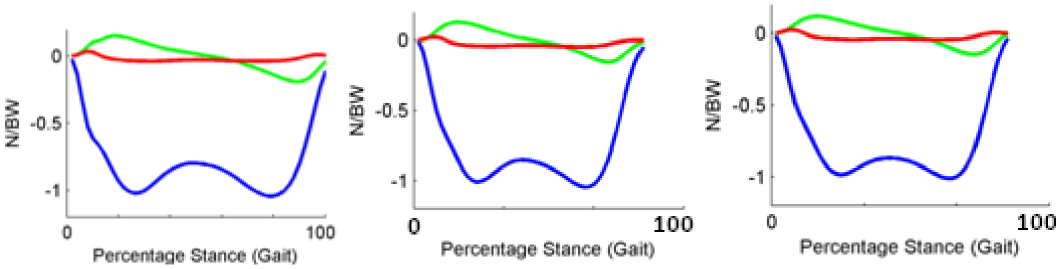


Figure 1: Mean Vertical (blue), A-P (red), and M-L (green) force plate data during stance phase of gait.

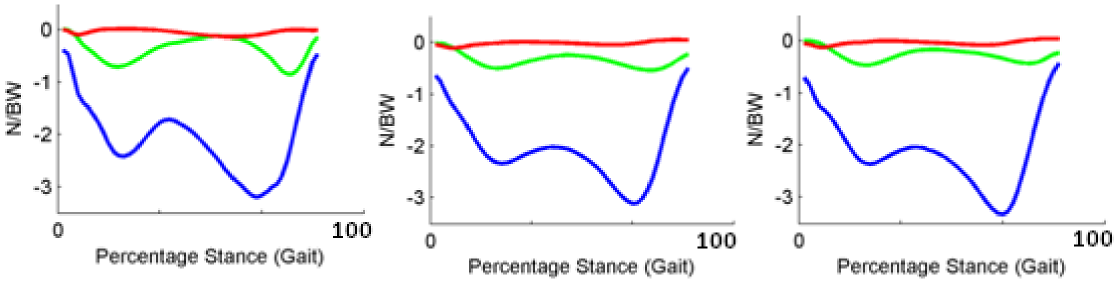


Figure 2: Mean D-P (blue), M-L (red), and P-A (green) TFJ reaction during stance phase of gait.

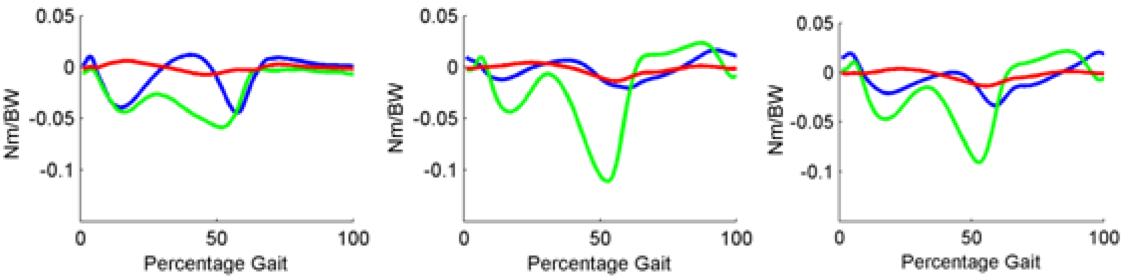


Figure 3: Mean flexion (blue), I-E (red), and V-V (green) TFJ moment during stance phase of gait.

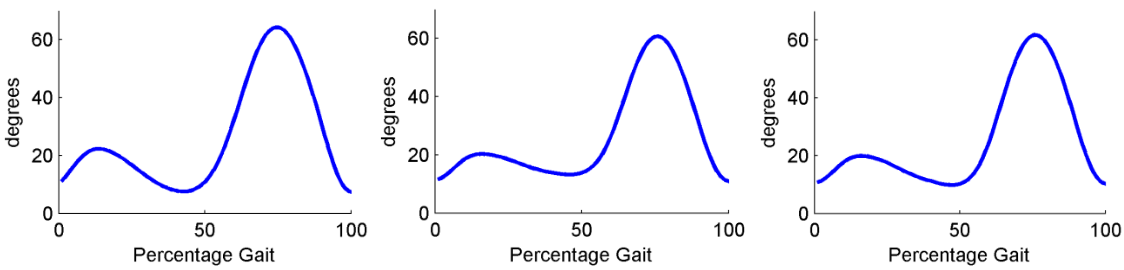


Figure 4: Mean Knee flexion during the gait cycle.

Appendix K

Sit-Stand Data

Healthy | Pre-operation | Post-operation

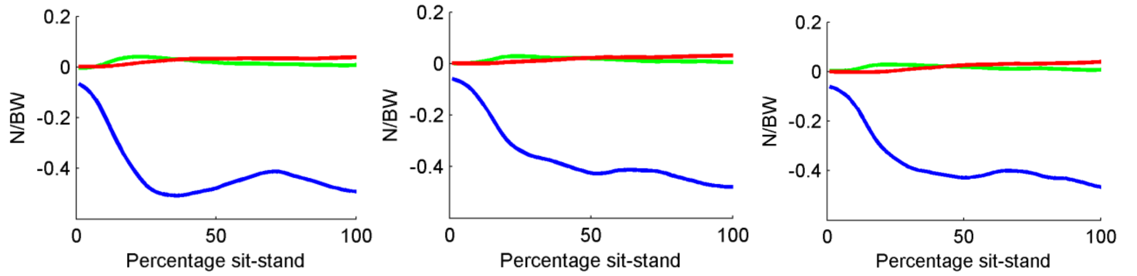


Figure 1: Mean Vertical (blue), A-P (red), and M-L (green) force plate data during sit-stand.

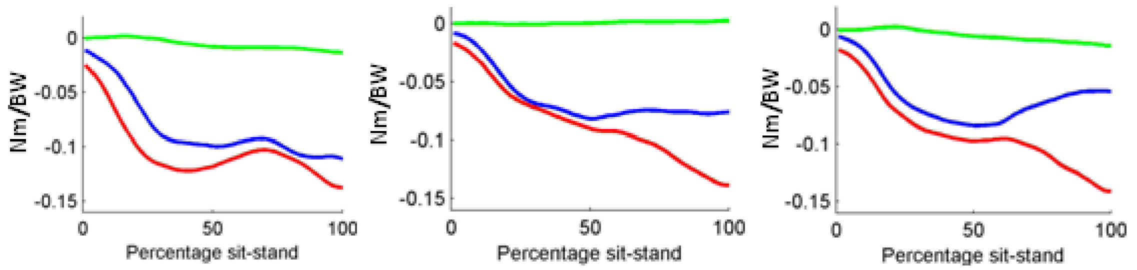


Figure 2: Mean sagittal (blue), coronal (red), transverse M-L (green) force plate data during sit-stand.

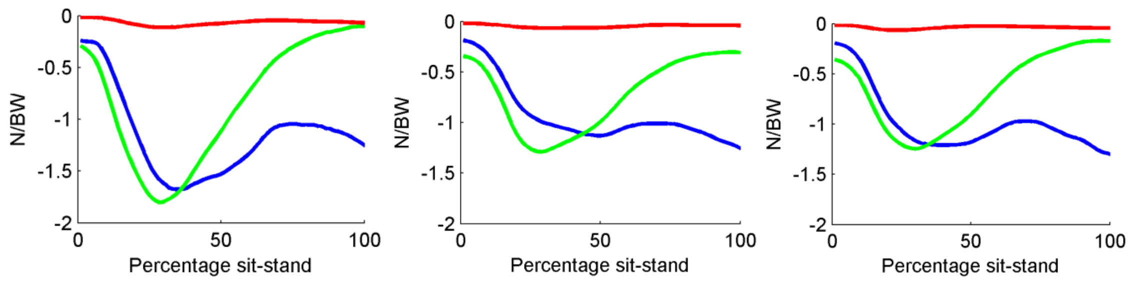


Figure 3: Mean D-P (blue), M-L (red), and P-A (green) TFJ reaction during sit-stand.

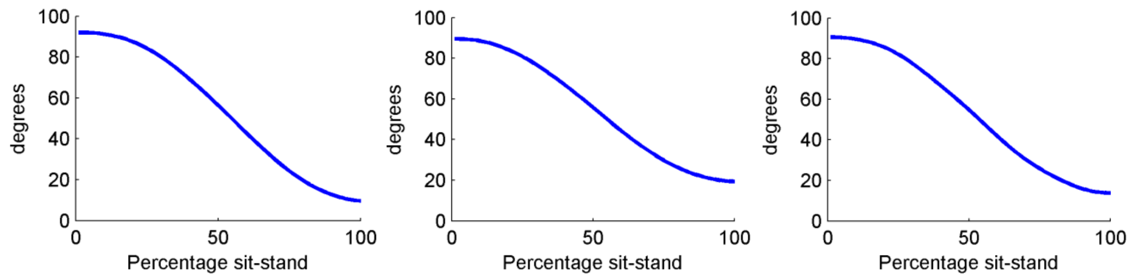


Figure 4: Mean Knee flexion during the sit-stand cycle.

Appendix L

Stand-Sit Data

Healthy | Pre-operation | Post-operation

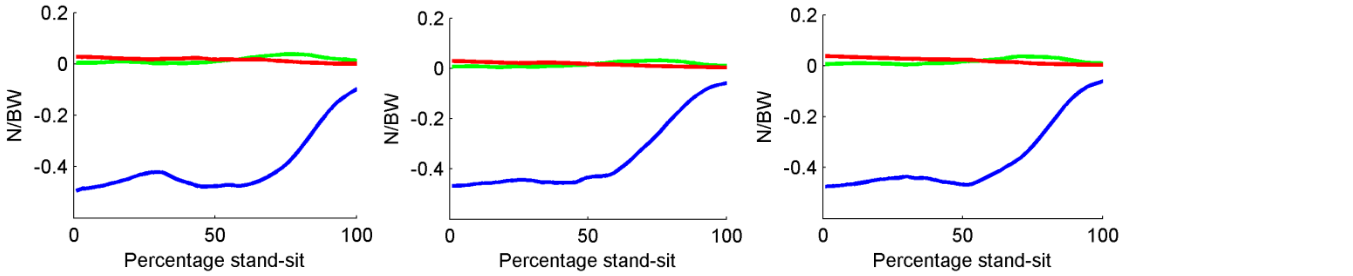


Figure 1: Mean Vertical (blue), A-P (red), and M-L (green) force plate data during stand-sit.

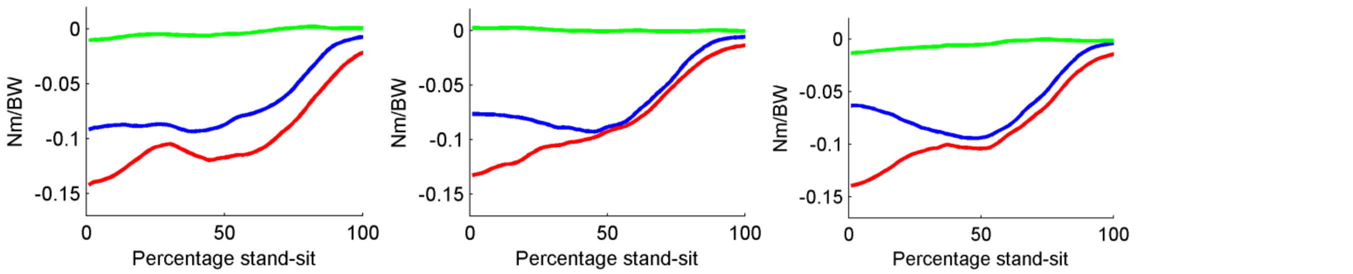


Figure 2: Mean sagittal (blue), coronal (red), transverse M-L (green) force plate data during stand-sit.

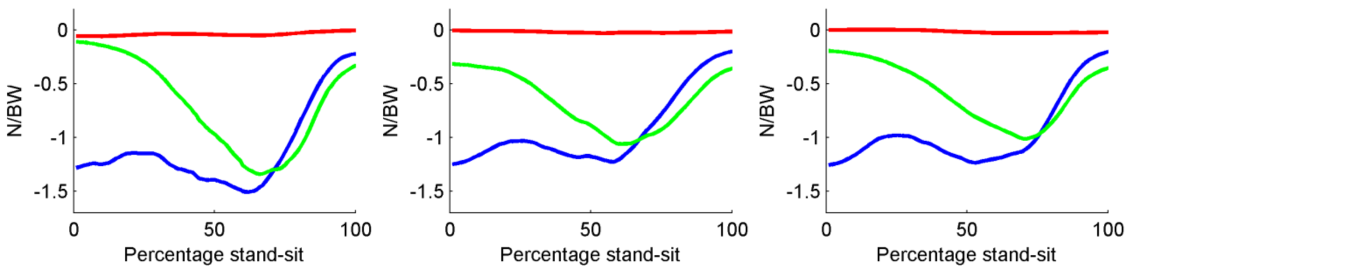


Figure 3: Mean D-P (blue), M-L (red), and P-A (green) TFJ reaction during stand-sit.

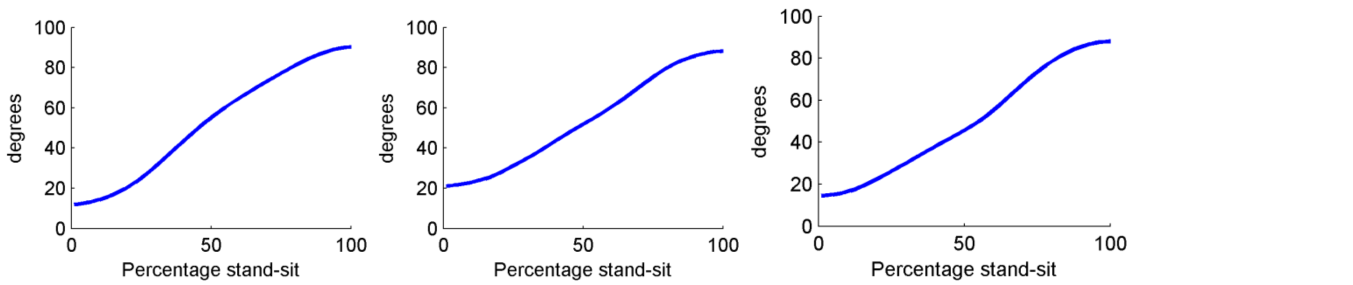


Figure 4: Mean Knee flexion during the stand-sit. cycle.

Appendix M

Step-Descent Data

Healthy Pre-operation Post-operation

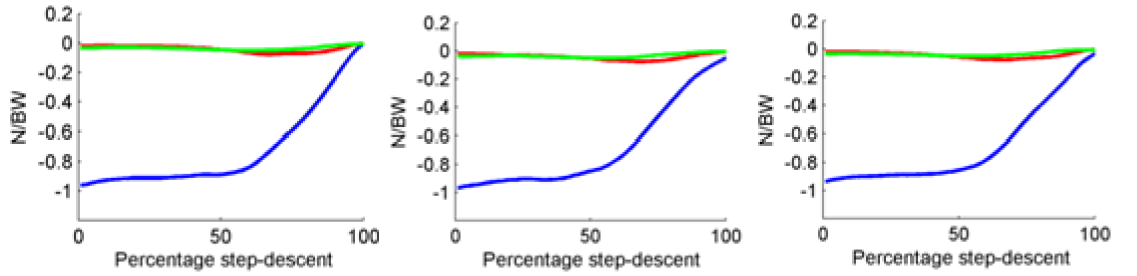


Figure 1: Mean Vertical (blue), A-P (red), and M-L (green) force plate data during step-descent.

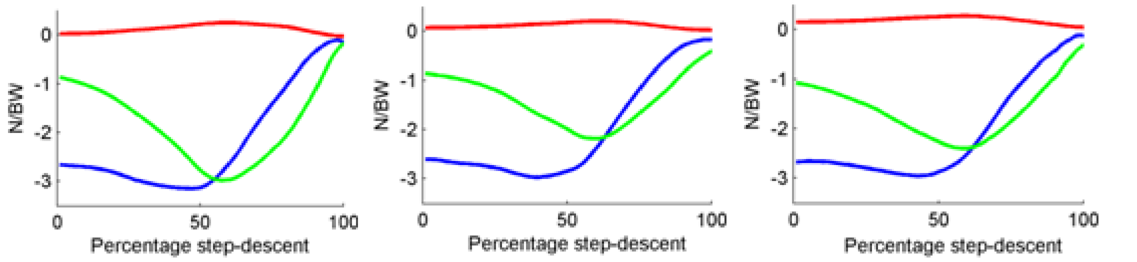


Figure 2: Mean D-P (blue), A-P (red), and M-L (green) TFJ reaction during step-descent.

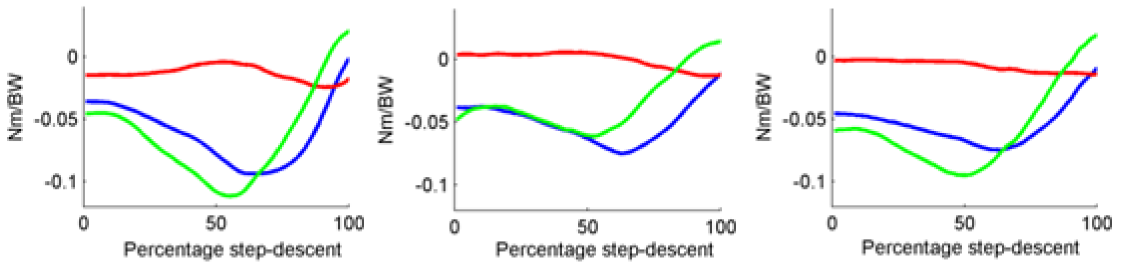


Figure 3: Mean flexion (blue), I-E (red), and V-V (green) TFJ moment during step-descent.

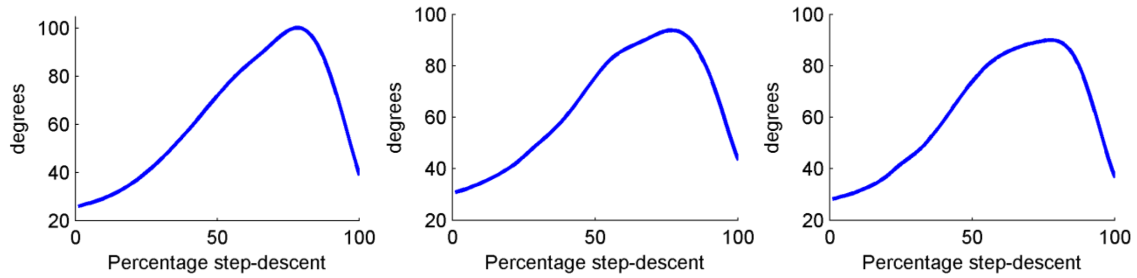


Figure 4: Mean Knee flexion during the step-descent cycle.

Appendix N

Discriminating Gait Waveforms

Gait Principle Components which discriminate between healthy and OA participants

Gait				
Rank	**Measure**	**Rayleigh Quotient**	**% Variance Explained**	**Description**
1	mom_{gait} (PC1)	0.035	20.9	'Peak extension moment during stance phase of gait'
2	ML_{gait} (PC1)	0.028	20.2	'M-L reaction during weight acceptance and mid phase of stance during gait'
3	$FPfz_{gait}$ (PC1)	0.025	18.3	'Peak Vertical force plate reaction during stance phase of gait'
4	KF_{gait} (PC1)	0.02	38.4	'knee range of motion during gait'
5	HF_{gait} (PC1)	0.011	59	'Hip flexion during gait'
6	VV_{gait} (PC2)	0.009	14.2	'Peak adduction moment during stance phase of gait'

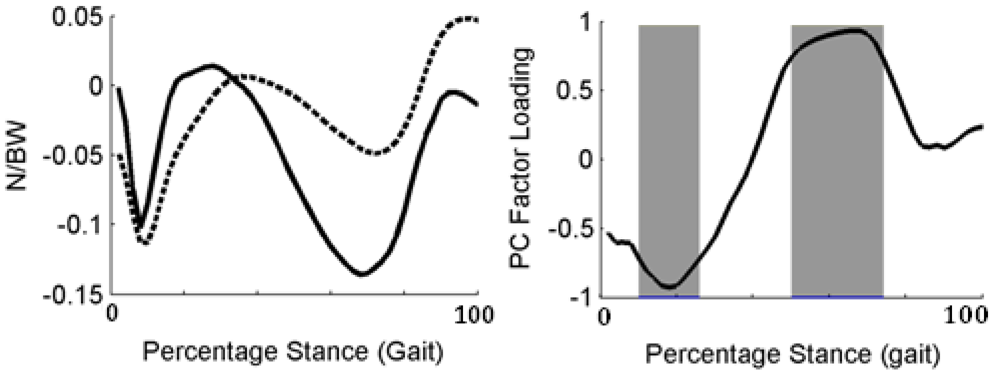


Figure 1:(a). Mean M-L tibiofemoral (TFJ) reaction during stance phase of the gait cycle. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from M-L TFJ reaction during stance phase of the gait cycle.

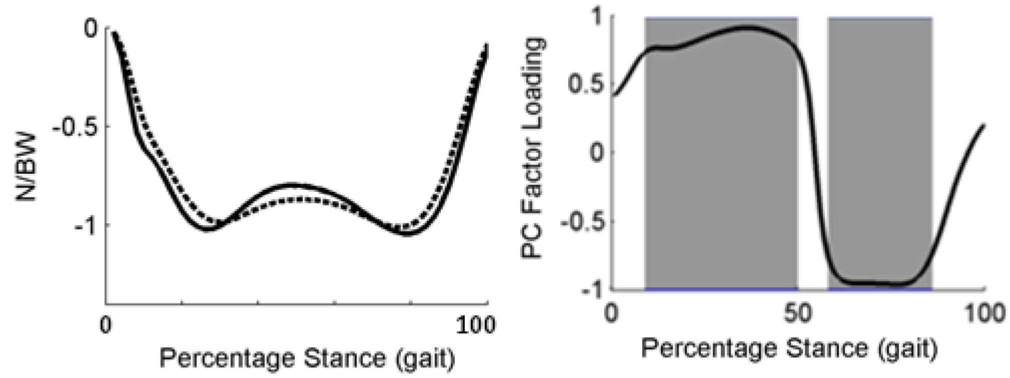


Figure 2:(a). Mean vertical force plate reaction during stance phase of the gait cycle. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from vertical force plate reaction during stance phase of the gait cycle.

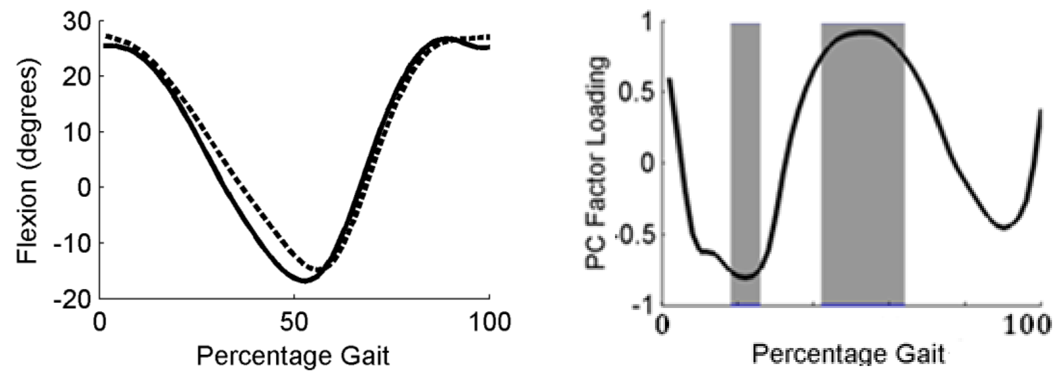


Figure 3:(a). Mean Hip flexion angle during the gait cycle. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from Hip flexion angle during the gait cycle.

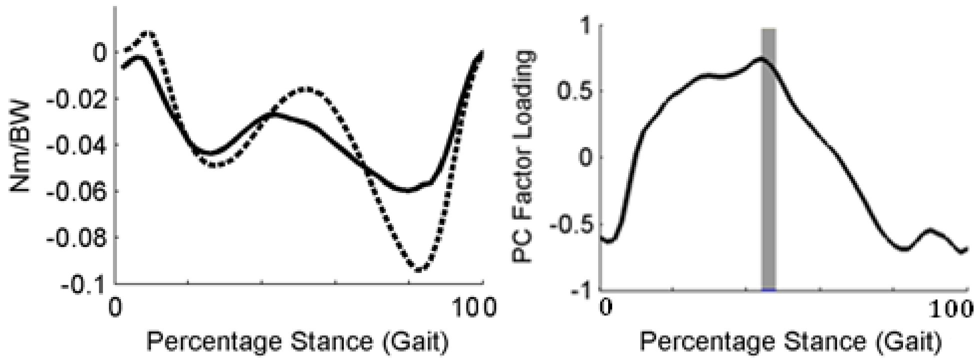


Figure 4:(a). Mean V-V TFJ moment during stance phase of the gait cycle. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from V-V TFJ moment during stance phase of the gait cycle.

Appendix O

Discriminating Sit-Stand Waveforms

Sit-Stand Principle Components which discriminate between healthy and OA participants

Sit-Stand Measures				
Rank	**Measure**	**Rayleigh Quotient**	**% Variance Explained**	**Description**
1	$FPmy_{sit-stand}$ (PC1)	0.027	50.5	'Peak mid and late sagittal force plate moment during sit-stand'
2	$FPfz_{sit-stand}$ (PC1)	0.019	48	'Peak mid and late vertical ground reaction during sit-stand'
3	$DP_{sit-stand}$ (PC1)	0.014	43.4	'Peak mid and late D-P knee reaction during sit-stand'
4	$FPmx_{sit-stand}$ (PC1)	0.009	63	'End coronal force plate moment during sit-stand'
5	$FPfy_{sit-stand}$ (PC1)	0.0057	44.6	'End lateral force plate reaction during sit-stand'
6	$mom_{sit-stand}$ (PC1)	0.0051	44.4	'Peak knee extension moment during sit-stand'
7	$HF_{sit-stand}$ (PC2)	0.0037	61	'Peak hip flexion during sit-stand'
8	$PA_{sit-stand}$ (PC1)	0.003	42	'Range of P-A knee reaction during sit-stand'
9	$KF_{sit-stand}$ (PC1)	0.0024	68	'Range of knee flexion during sit-stand'
10	$VV_{sit-stand}$ (PC1)	0.0014	38	'Range of V-V knee moment during sit-stand'

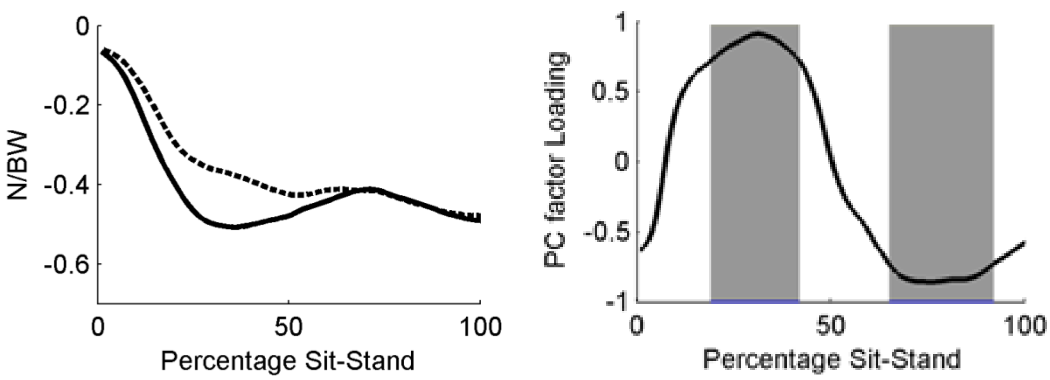


Figure 1:(a). Mean vertical force plate reaction during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from vertical force plate reaction during sit-stand.

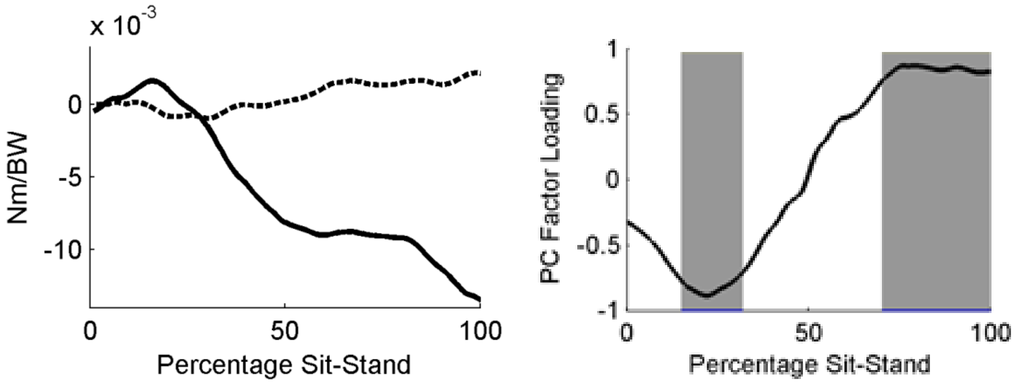


Figure 2:(a). Mean coronal force plate moment during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from coronal force plate moment during sit-stand.

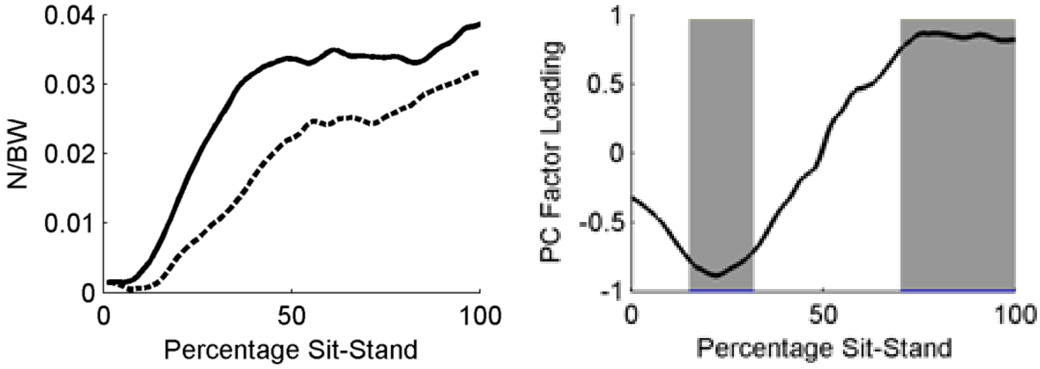


Figure 3:(a). Mean M-L force plate reaction during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from M-L force plate reaction during sit-stand.

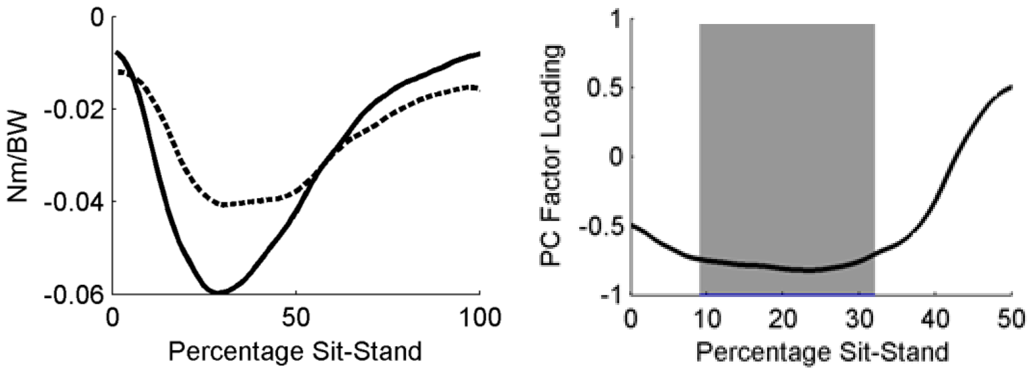


Figure 4:(a). Mean tibiofemoral joint (TFJ) flexion moment during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from TFJ flexion moment during sit-stand.

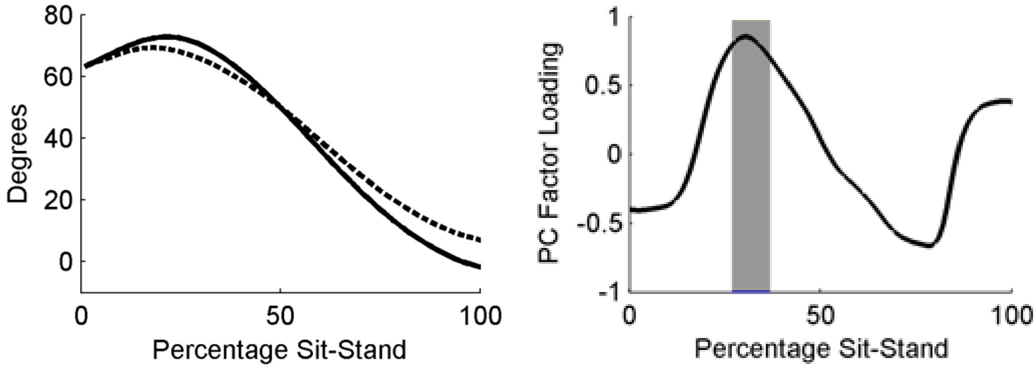


Figure 5:(a). Mean hip flexion during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the second PC retained from hip flexion during sit-stand.

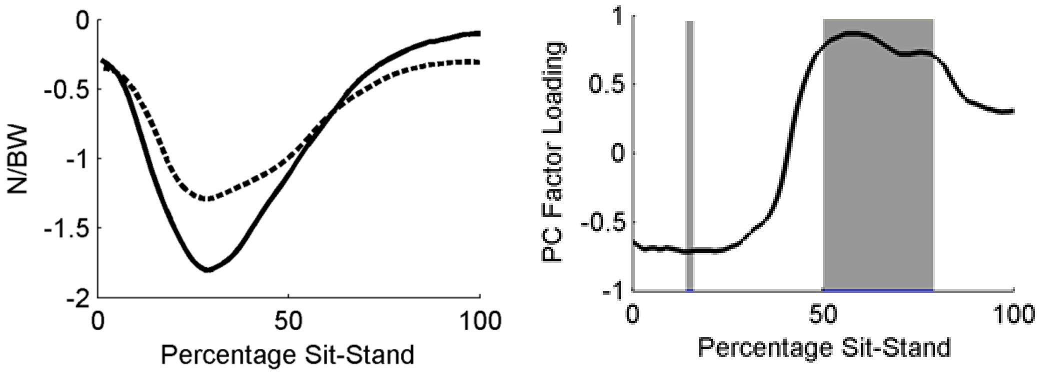


Figure 6:(a). Mean TFJ P-A reaction during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from TFJ P-A reaction during sit-stand.

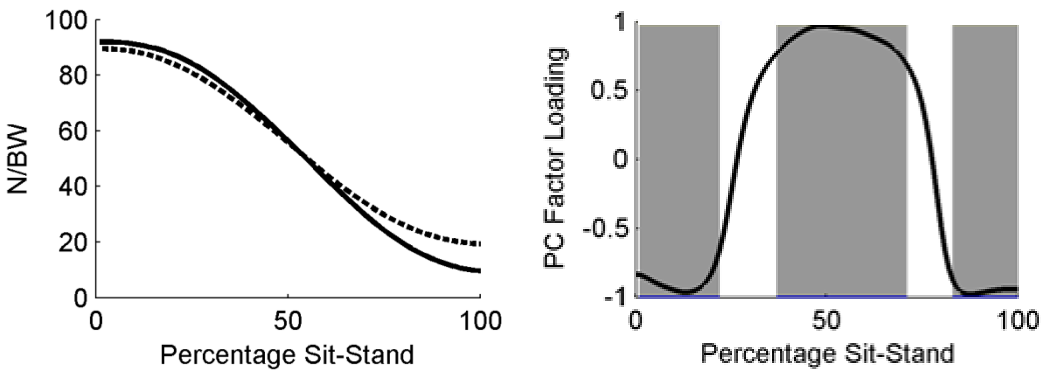


Figure 7:(a). Mean knee flexion during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from knee flexion during sit-stand.

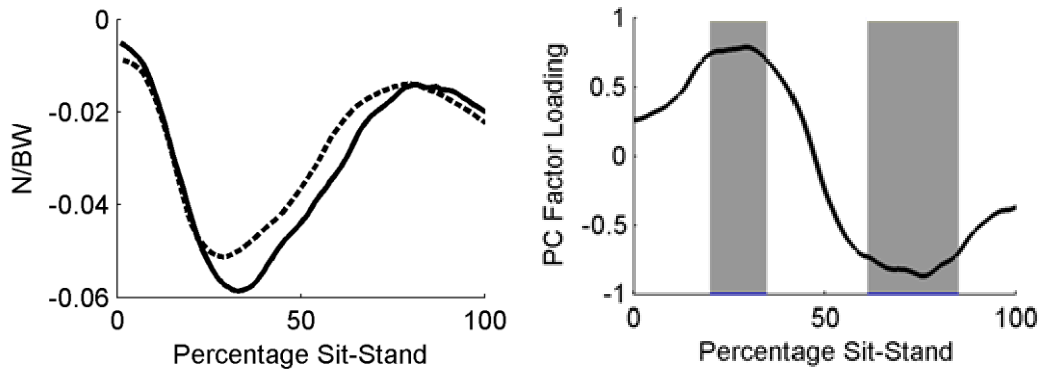


Figure 8:(a). Mean TFJ V-V moment during sit-stand. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from TFJ V-V moment during sit-stand.

Appendix P

Discriminating Stand-Sit Waveforms

Stand-Sit Principle Components which discriminate between healthy and OA participants

Stand-Sit Measures				
Rank	**Measure**	**Rayleigh Quotient**	**% Variance Explained**	**Description**
1	$FPmy_{stand-sit}$ (PC1)	0.016	40.8	'Peak early and mid-sagittal force plate moment during stand-sit'
2	$FPfz_{stand-sitd}$ (PC1)	0.013	44.6	'Peak early and late vertical force plate reaction during stand-sit'
3	$mom_{stand-sit}$ (PC1)	0.011	40.8	'Peak knee flexion moment during stand-sit'
4	$FPmx_{stand-sit}$ (PC1)	0.008	55	'Early and late coronal force plate moment during stand-sit'
5	$KF_{stand-sit}$ (PC2)	0.007	27.9	'Range of knee flexion angle during stand-sit'
6	$IE_{stand-sit}$ (PC3)	0.0065	14.1	'Peak internal rotation moment during stand-sit'
7	$ML_{stand-sit}$ (PC3)	0.0049	20.2	'M-L knee reaction during the start of stand-sit'
8	$DP_{stand-sit}$(PC1)	0.0041	37.3	'Peak D-P reaction during stand-sit'
9	$HF_{stand-sit}$ (PC3)	0.0034	8.3	'Hip flexion during early stand-sit'
10	$PA_{stand-sit}$ (PC1)	0.003	46.1	'PA knee reaction during early and late stand-sit'
11	$HA_{stand-sit}$ (PC2)	0.0013	26.3	'Hip abduction during mid stand-sit'
12	$VV_{stand-sit}$ (PC1)	0.001	43.8	'V-V knee moment during early and late stand-sit'

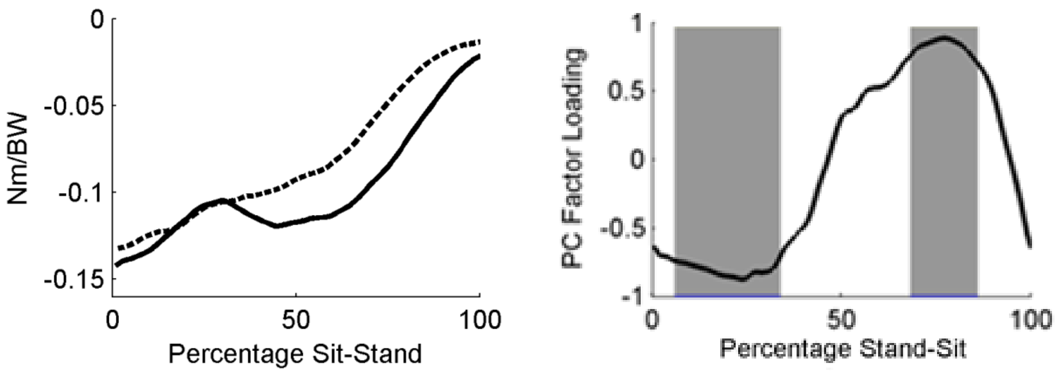


Figure 1:(a). Mean sagittal force plate moment during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from sagittal force plate moment during stand-sit.

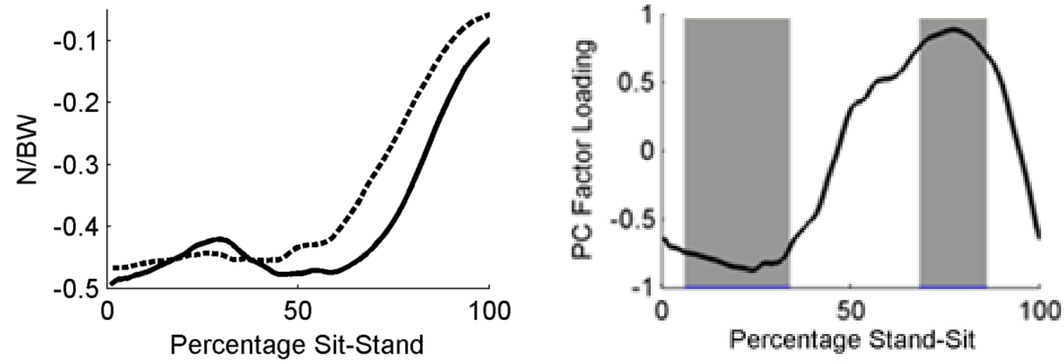


Figure 2:(a). Mean vertical force plate reaction during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from vertical force plate reaction during stand-sit.

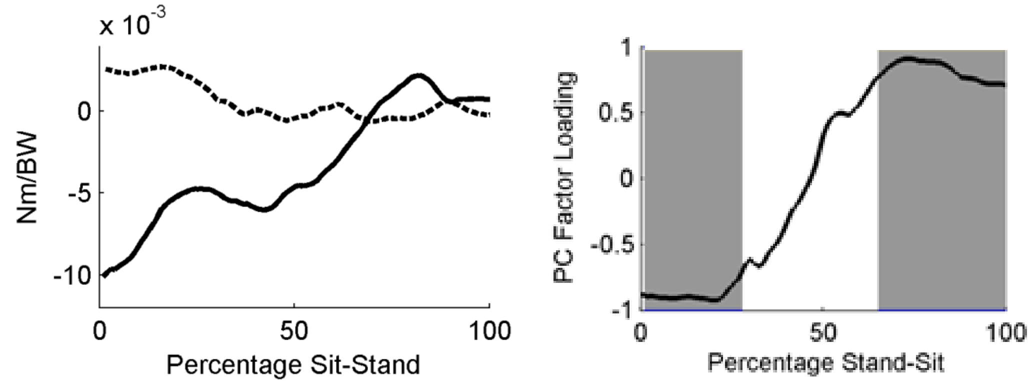


Figure 3:(a). Mean coronal force plate moment during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from coronal force plate moment during stand-sit.

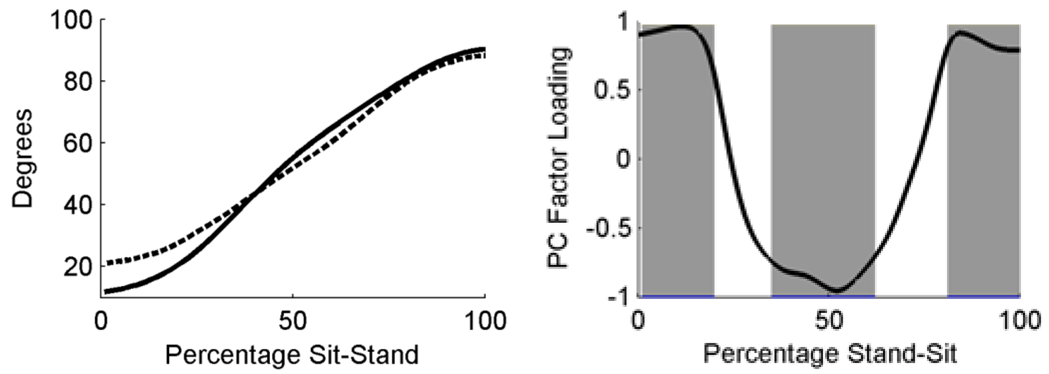


Figure 4:(a). Mean knee flexion angle during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the second PC retained from knee flexion angle during stand-sit.

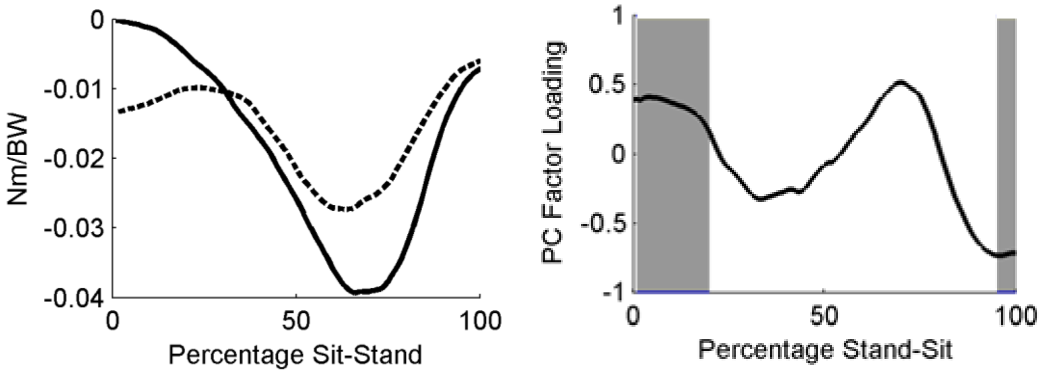


Figure 5:(a). Mean tibiofemoral joint (TFJ) I-E moment during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the third PC retained from TFJ I-E moment during stand-sit.

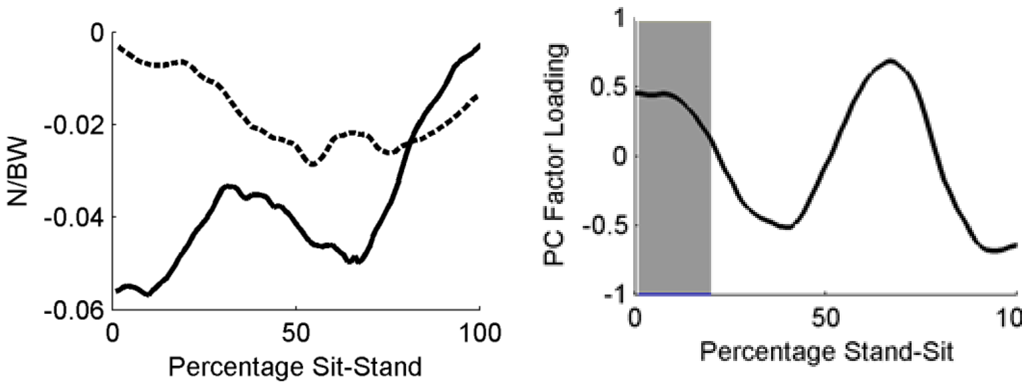


Figure 6:(a). Mean TFJ M-L reaction during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the third PC retained from TFJ M-L reaction during stand-sit.

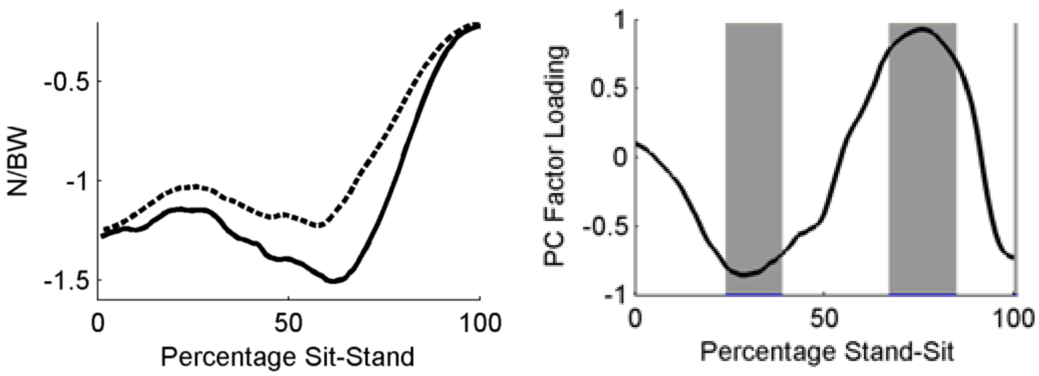


Figure 7:(a). Mean TFJ D-P reaction during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the third PC retained from TFJ D-P reaction during stand-sit.

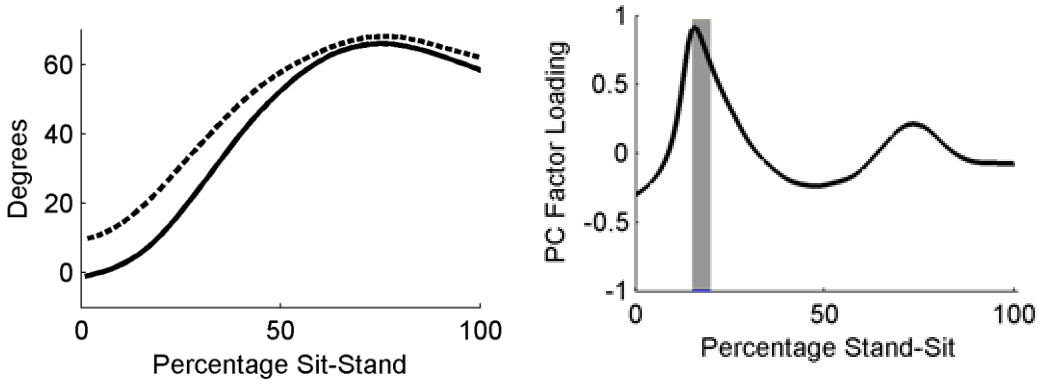


Figure 8:(a). Mean hip flexion angle during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the third PC retained from hip flexion angle during stand-sit.

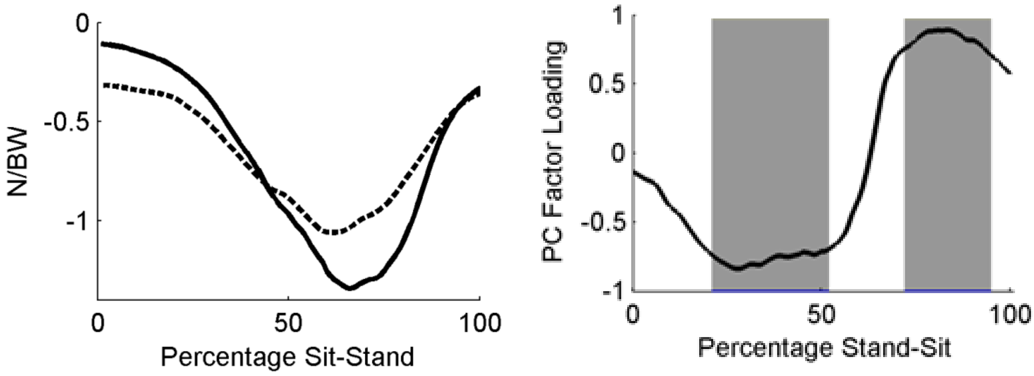


Figure 9:(a). Mean TFJ P-A reaction during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from TFJ P-A reaction during stand-sit.

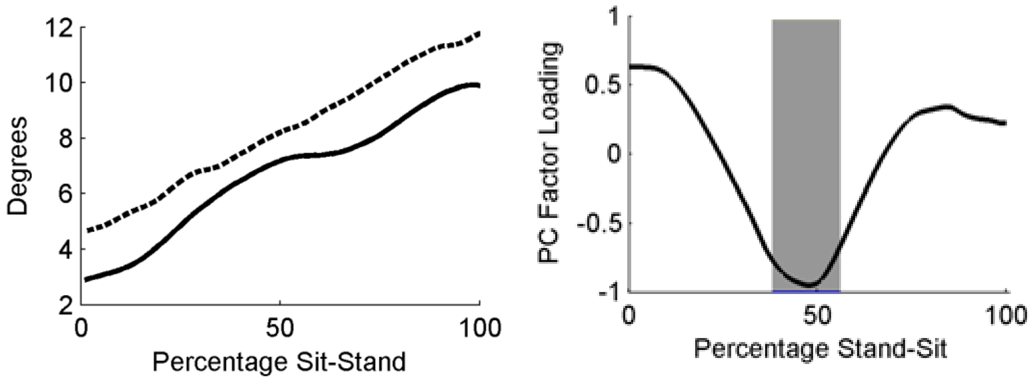


Figure 10:(a). Mean hip abduction angle during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the second PC retained from hip abduction angle during stand-sit.

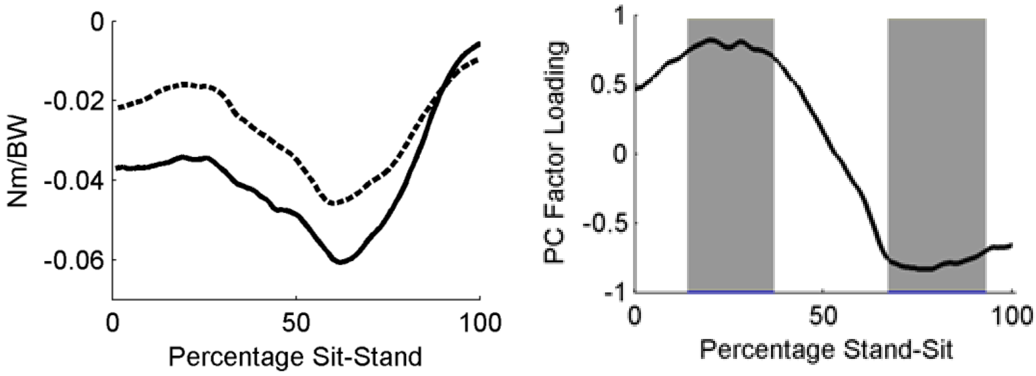


Figure 9:(a). Mean TFJ V-V moment during stand-sit. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from TFJ V-V moment during stand-sit.

Appendix Q

Discriminating Step-Descent Waveforms

Step-descent Principle Components which discriminate between healthy and OA participants.

Step-Descent				
Rank	**Measure**	**Rayleigh Quotient**	**% Variance Explained**	**Description**
1	$FPfz_{step-down}$ (PC1)	0.004	58	'Vertical force plate reaction during stance phase of step-descent'
2	$mom_{step-down}$ (PC3)	0.0032	58	'Peak knee flexion moment during stance phase of step-descent'
3	$FPfx_{step-down}$ (PC1)	0.0031	49.6	'Early and late A-P force plate reaction during stance phase of step-descent'
4	$HA_{step-down}$ (PC2)	0.0027	41.2	'Peak hip abduction during step-descent'
5	$KF_{step-down}$ (PC1)	0.0025	38.2	'Knee flexion during mid and late stages of step-descent'
6	$DP_{step-down}$ (PC3)	0.0025	7.6	Peak D-P reaction during step-descent'
7	$IE_{step-down}$ (PC1)	0.0023	47.1	'Early and late I-E knee moment during step-descent'
8	$VV_{step-down}$ (PC2)	0.0022	29.8	'Peak varus moment during step-descent'
9	$HER_{step-down}$ (PC1)	0.0021	59.6	'Early and late hip external rotation during step-descent'
10	$FPfy_{step-down}$ (PC1)	0.002	33.9	'Early and late M-L force plate reaction during step-descent'
11	$FPmx_{step-down}$ (PC2)	0.0018	19.7	Peak sagittal force plate moment during step-descent'
12	$HF_{step-down}$ (PC2)	0.0016	30	'Early and late hip flexion during step-descent'

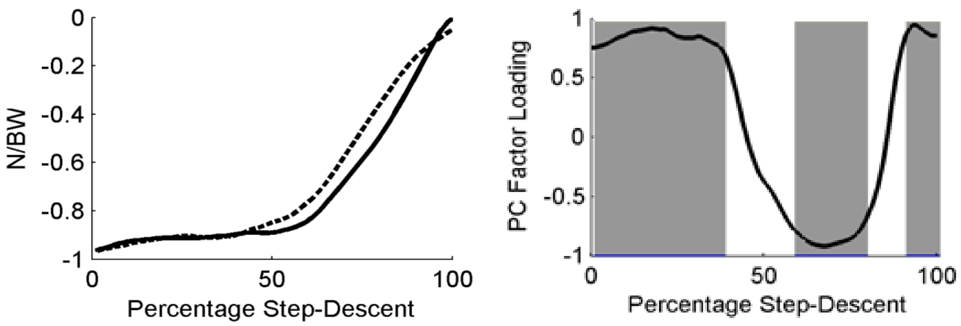


Figure 1:(a). Mean vertical force plate reaction during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from vertical force plate reaction during step-descent.

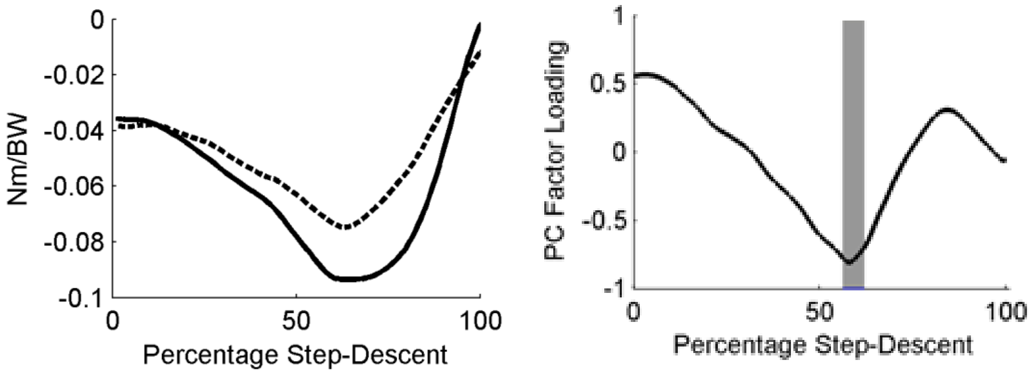


Figure 2:(a). Mean tibiofemoral joint (TFJ) flexion moment during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the third PC retained from TFJ flexion moment during step-descent.

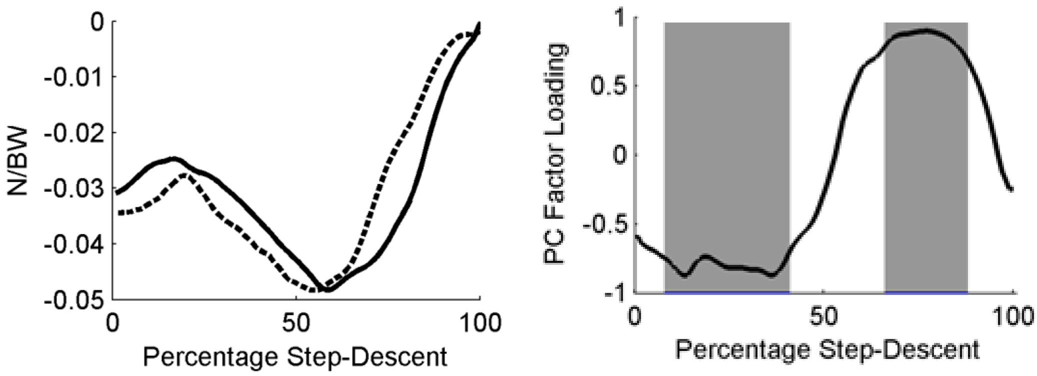


Figure 3:(a). Mean A-P force plate reaction during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from A-P force plate reaction during step-descent.

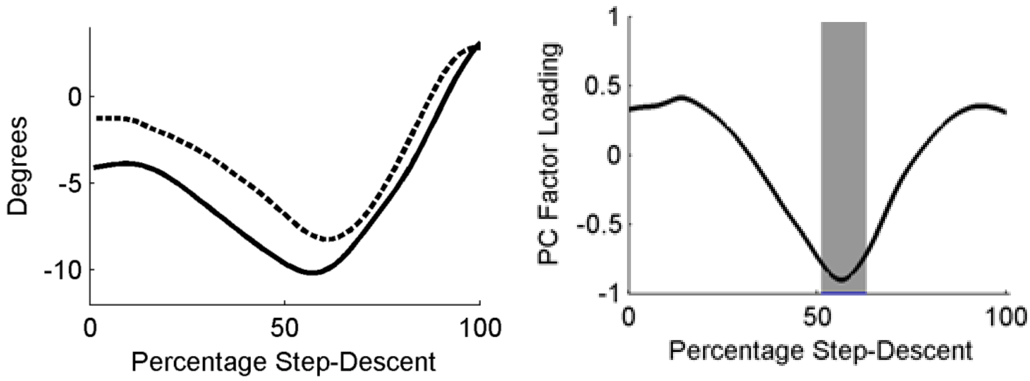


Figure 4:(a). Mean hip abduction during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the second PC retained from hip abduction during step-descent.

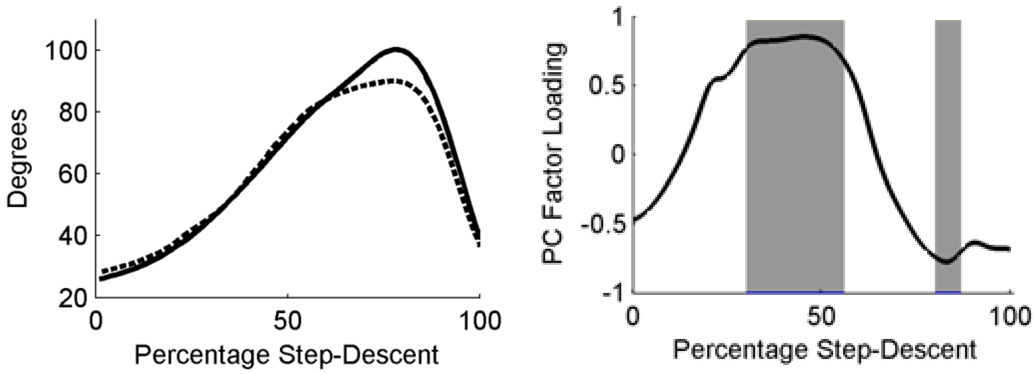


Figure 5:(a). Mean knee flexion during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from knee flexion during step-descent.

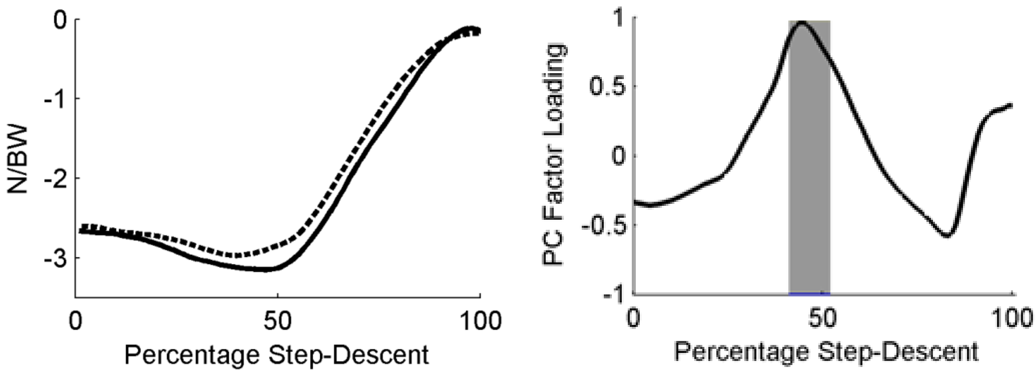


Figure 6:(a). Mean TFJ D-P reaction during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the third PC retained from TFJ D-P reaction during step-descent.

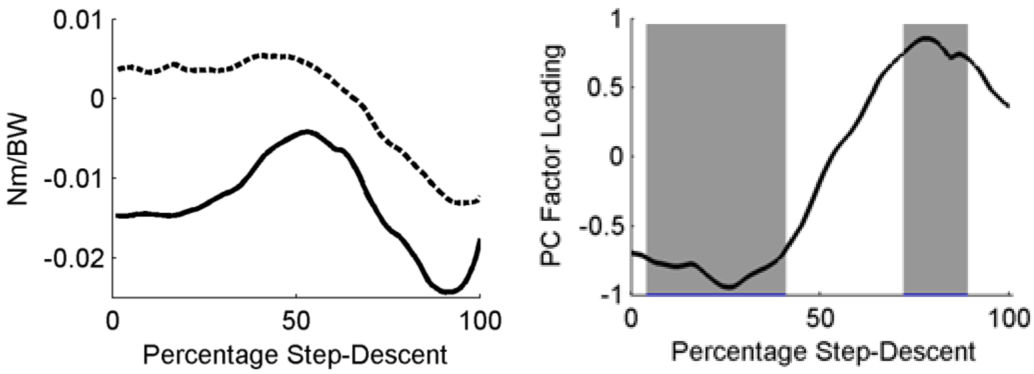


Figure 7:(a). Mean TFJ I-E moment during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from TFJ I-E moment during step-descent.

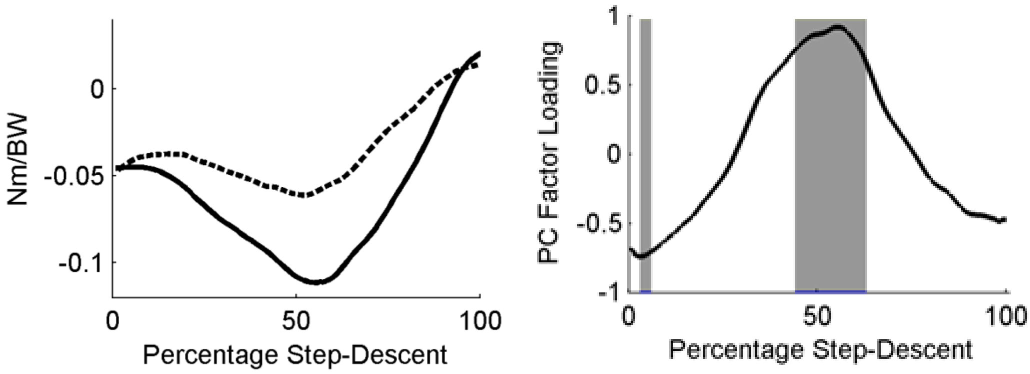


Figure 8:(a). Mean TFJ V-V moment during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the second PC retained from TFJ V-V moment during step-descent.

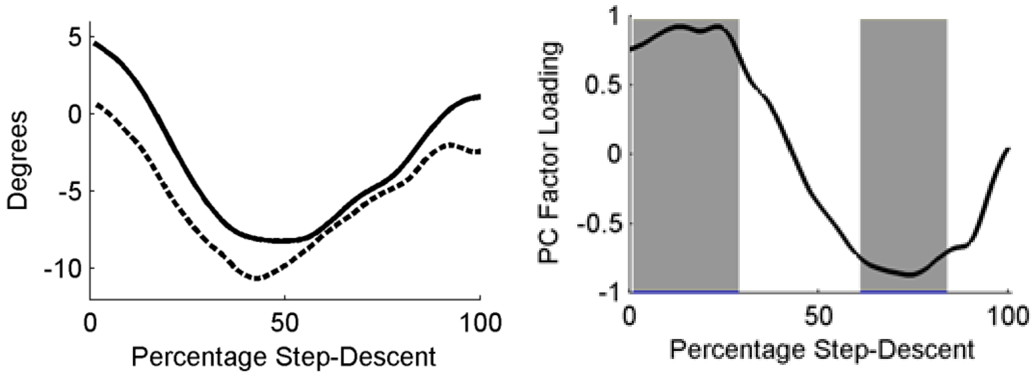


Figure 9:(a). Mean hip external rotation during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from hip external rotation during step-descent.

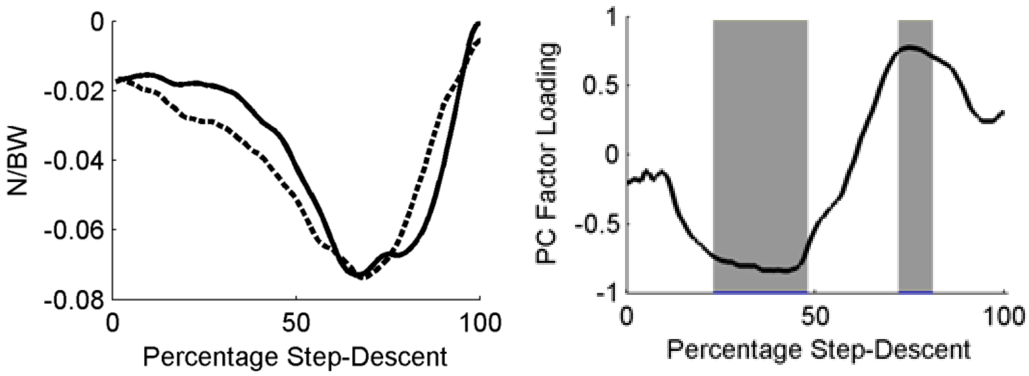


Figure 3:(a). Mean M-L force plate reaction during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the first PC retained from M-L force plate reaction during step-descent.

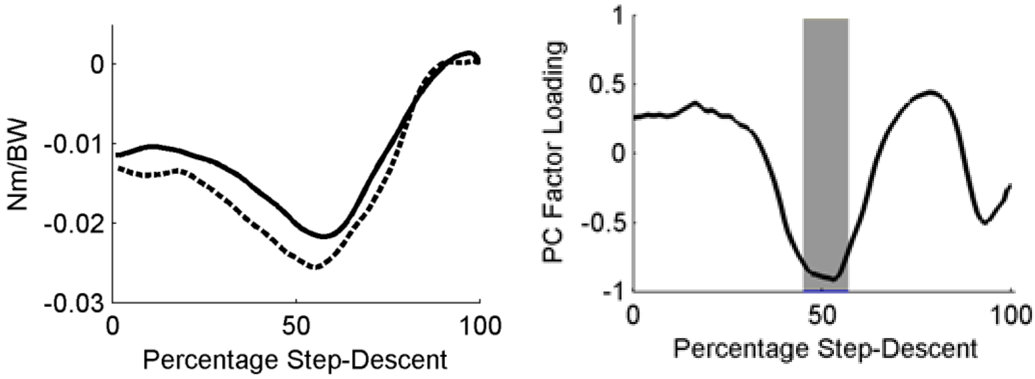


Figure 3:(a). Mean sagittal force plate moment during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the second PC retained from sagittal force plate moment during step-descent.

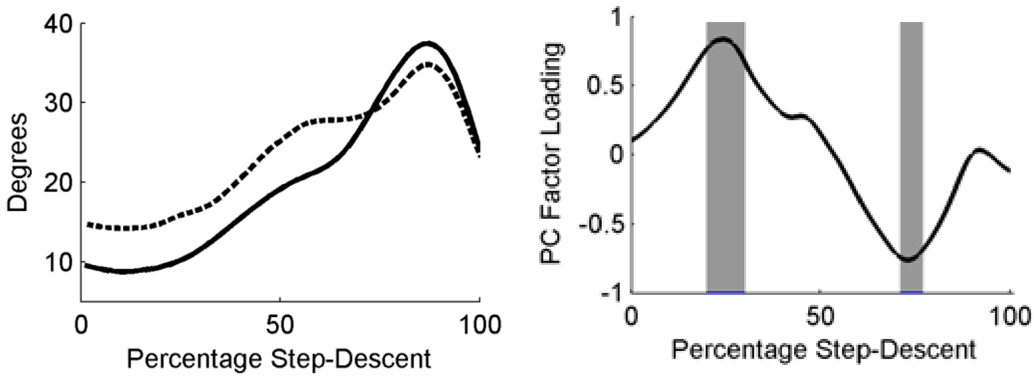


Figure 9:(a). Mean hip flexion during step-descent. Healthy in solid line, pre-operation patients dashed. (b) Component loading of the second PC retained from hip flexion during step-descent.

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