UNIVERSITY OF SOUTHAMPTON

FACULTY OF HEALTH SCIENCES

The reliability and responsiveness of components of breathing pattern

by

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ABSTRACT

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THE RELIABILITY AND RESPONSIVENESS OF COMPONENTS OF BREATHING PATTERN

Fatimah Jaffer AL-ALShaikh

Breathing pattern (BP) may have the potential to be used to monitor respiratory health and be used as an outcome measure for specific interventions designed to improve respiratory health. However, little published research has examined the reliability and responsiveness of BP. This research examines the reliability and responsiveness of specific components of BP in healthy adults and patients with asthma. It comprises three separate studies: The **first study** examines the test re-test reliability of BP at rest in both sitting and supine in 50 healthy individuals measured using Respiratory Inductive Plethysmography (RIP). The **second study** examines the responsiveness of BP before and during recovery from a 10-minute moderate physical exercise stimulus in 43 healthy individuals recorded using Structured Light Plethysmography (SLP). The **third study** recorded BP in 5 participants with asthma using SLP before and after a breathing retraining intervention. Results were: 1) the BP components under examination demonstrated good relative reliability and no systematic bias with Bland-Altman analysis in both the sitting and supine positions. A slightly higher level of test re-test reliability was found for all components in the sitting position in comparison to the supine data. 2) thoracoabdominal motion (TAM) was not significantly changed post exercise in comparison to quiet breathing. Also, TAM responsiveness was not affected by gender. Moreover, there was low relationship between thoracoabdominal motion and timing components. 3) Breath-by-breath analysis did not find any consistency in changes in timing components or TAM following breathing retraining in all participants. Conclusion: This research has produced evidence that the studied components of BP are reliable in healthy adults. Regarding responsiveness, changes in TAM within individuals were observed, but the changes were not found to be significant and did not demonstrate any clear pattern in direction of change. However, the third study involved a small sample size. So, although the BP components were found to remain stable, it is too early to draw firm conclusions regarding the responsiveness.

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DECLARATION OF AUTHORSHIP

I, Fatimah Jaffer Al- ALshaikah, declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

The reliability and responsiveness of components of breathing pattern

I confirm that:

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Definitions and Abbreviations

Abbreviations	Definitions
T_i	Inspiration time
T_e	Expiration time
Bf	Breathing frequency
$\%RC_{exp}$	Rib cage relative expired contribution
$\%AB_{exp}$	Abdominal relative expired contribution
PNT	Pneumotachograph
V_{min}	Minute ventilation
V_T	Tidal volume
V_T/T_i	Mean inspiratory flow
Df	Degrees of freedom
QDC	Qualitative Diagnostic Calibration
SD	Standard Deviation
ANOVA	Analysis of Variance Analysis
ICC	Intra class correlation coefficient
WSSD	Within subjects' standard deviation
SRD	Smallest real difference
LA	Limit of agreement

RIP	Respiratory Inductive Plethysmography
SLP	Structured Light Plethysmography
$ETCO_2$	End Tidal Carbon Dioxide
FEV_1	Forced Expiratory Volume in one second
FVC	Forced Vital Capacity
FEV_1/FVC	Ratio between forced expiratory volume in one second and forced vital capacity
PEF	Peak Expiratory Flow
OEP	Opto-Electronic Plethysmography
EIT	Electrical-Impedance Tomography
CoV	Coefficient of Variation
BMI	Body Mass Index
NHS	National Health Services
WHO	World Health Organisation
VC	Vital Capacity
COPD	Chronic Obstructive Pulmonary Disease
NQ	Nijmegen questionnaire (NQ)
QOL	Quality Of Life

Chapter 1 Introduction

1.1 Clinical usefulness of breathing pattern as an outcome measure

Respiratory physiotherapy is widely used within clinical practice in the management of respiratory health. There are a number of clinical outcome measures currently used within respiratory physiotherapy; however, there is a lack of reliable, valid and responsive outcome measures, specifically related to respiratory physiotherapy meaning that it is difficult to assess whether a lack of change is due to poor intervention or an inappropriate outcome measure (Marques et al. 2006). CliftonSmith and Rowley (2011) emphasise the increasing importance being assigned to breathing pattern as a potential clinically useful outcome measure. The observation and monitoring of breathing pattern can provide a reflection of a number of systems, including biomechanics, biochemistry/physiology and psychology (Yuan et al. 2013). In addition, it can provide useful information regarding respiratory function, particularly regarding the differentiation between normal individuals and those in diseased states (Tobin et al. 1983a; Ragnarsdóttir & Kristinsdóttir 2006; Adamczyk et al. 2008; Parreira et al. 2010). Moreover, changes in breathing pattern are important in diagnostic decisions and disturbance of respiratory function can be potentially life threatening (Wilhelm et al. 2003b).

Regarding the clinical importance of the thoracoabdominal motion components specifically, White (2012) asserts that the observation of chest movements can be used to determine breathing pattern in an objective, non-invasive manner requiring minimal collaboration from the patient. Primary chest wall disease can affect chest wall motion, which can be associated with severe airflow obstruction and neuromuscular disease

(Papastamelos et al. 1996; Laghi & Tobin 2003). While thoracoabdominal asynchrony is indicative of diaphragmatic dysfunction with imminent diaphragmatic fatigue (Roussos 1979) and can denote imminent onset of dyspnoea (Celli et al. 1986). More specifically, useful information relating to the mechanical resistive and elastic load of the respiratory system can be obtained through measuring thoracoabdominal asynchrony and it can be used to identify the prospect of susceptibility to respiratory muscle fatigue (Miranda et al. 2011). Therefore, it might be suggested that the measurement of breathing pattern has the potential to be a clinically useful indicator as it can signify a number of respiratory problems. However, there is a need to establish the reliability and responsiveness of breathing pattern components in order to establish it potential usefulness as an outcome measure.

1.2 Rationale for research

As a physiotherapist practitioner, the researcher has an interest in understanding the usefulness of breathing pattern to be used as an outcome measure, since various rehabilitation programmes frequently involve the evaluation and monitoring of breathing pattern to determine a patient's progress through physiotherapy interventions (Finch 2002). Moreover, in a wider context, detecting changes in breathing pattern before respiratory diseases develop, may reduce hospitalisation and improve quality of life (Levy 2015; Mukherjee 2016).

For an outcome measure to be useful, it needs to be reliable and responsive (Guyatt et al. 1987), and yet within the literature there is a lack of validated and reliable outcome measures specifically related to respiratory physiotherapy interventions (Marques et al. 2015). The lack of reliable outcome measures is a barrier to the further development of an evidence base within the field of respiratory physiotherapy. Hence, this

study aims to establish the reliability and responsiveness of breathing pattern in order to determine its usefulness as an outcome measure.

The first study in this research focuses on establishing the test re-test reliability of breathing pattern components and relates to the extent to which the measured value of a given variable remains consistent at different time points. The second and third studies examine the responsiveness of breathing pattern components to a physical exercise stimulus in healthy participants and to a therapeutic physiotherapy breathing retraining intervention in individuals with asthma. A limited number of studies have focused on examining the test re-test reliability of timing and thoracoabdominal motion components of breathing pattern and very few have examined the responsiveness of thoracoabdominal motion components following physical exercise or breathing pattern following breathing retraining.

Consequently, this research sets out to address the existing gap in the literature in order to contribute meaningful information regarding the potential usefulness of breathing pattern as a reliable and responsive outcome measure.

1.3 Thesis overview

This thesis comprises a detailed review of the literature, which has been divided into three further chapters; firstly, Chapter 2 presents the literature regarding normal and asthma breathing pattern and the factors that can affect breathing pattern, followed by a discussion of the reliability and responsiveness of breathing pattern components. Chapter 3 includes an overview regarding the concepts of reliability and responsiveness, followed by details of the current outcome measures available for monitoring respiratory health. Chapter 4 presents an overview of the instruments used to record breathing pattern, both invasive and non-

invasive devices, including the rationale for the choice of methods in this study. The subsequent three chapters (5, 6 & 7) present each individual study's methods and results. Chapter 8 discusses the findings and their implications, while Chapter 9 presents the conclusions derived from the findings and Chapter 10 outlines recommendations for future research.

1.4 Research aims

First study

1. To examine whether any significant measurable change occurs in specific breathing pattern components timing [T_i (sec), T_e (sec) and Bf (breaths/min)] and thoracoabdominal motion [rib cage relative expired contribution (%RC_{exp}), and abdomen relative expired contribution (%AB_{exp})] in sitting and supine positions at rest ***within one 15 minute session***, ***between two separate sessions*** and ***between two separate days***, in order to determine the test re-test (relative and absolute) reliability of breathing pattern components in healthy adults.

2. To make comparisons between the data collected in the sitting and supine position to examine the impact of position on the relative and absolute reliability of breathing pattern components in healthy adults.

Second study

1. To examine the extent of significant measurable change that occurs in the *thoracoabdominal motion* component of breathing pattern during recovery from a moderate physical exercise stimulus (of 10

minutes incremental cycling on static cycle ergometer) in healthy adults.

2. To examine the effect of gender on the responsiveness of thoracoabdominal motion in healthy adults.

3. To examine the relationship between cohort mean thoracoabdominal motion and cohort mean timing components at rest and during recovery from physical exercise in healthy adults.

Third study

1. To examine whether breathing pattern components timing [T_i (sec), T_e (sec) and Bf (breaths/min)] and thoracoabdominal motion (%RC_{exp} and %AB_{exp} changed following breathing retraining programme in patients with asthma.

Chapter 2 Breathing pattern

2.1 Breathing pattern components under examination

Although the term 'breathing pattern' is often used by respiratory clinicians, there is no consensus regarding its definition and the

characteristics of 'normal' breathing pattern are not well defined (Bruton 2015). For the purposes of this study breathing pattern involves the combined function of three components: lung volume components, timing components and thoracoabdominal motion (Braun 1990; Wilhelm et al. 2003a). Lung volume or tidal volume is the volume of air displaced during inspiration and expiration during quiet breathing at rest. Large variability of 'normal' ranges have been documented in the literature (see table 2-1). In addition, age (Tobin et al. 1983a; Mendes et al. 2015) gender (Parreira et al. 2010; Romei et al. 2010) and position (Verschakelen & Demedts 1995; Takashima et al. 2017) are known to impact resting V_T. Tidal volume is quantified from the average of a collection of breaths obtained over various time periods (Tobin et al. 1983a; Tobin 1992; Parreira et al. 2010) using invasive devices, which may affect breathing pattern (see section 4.2.1), consequently it is not examined in this research. Therefore, this section provides an overview of timing and thoracoabdominal motion components of breathing pattern.

2.1.1 Timing components in healthy adults

Resting breathing is automatic, quiet and effortless (Dougherty & Lister 2011), in healthy adults breathing pattern comprises two phases: active inspiration and passive expiration (Richardson 2006). During the inspiration (or expansion) phase, a contraction of inspiratory muscles, including the diaphragm, occurs to move the air into the lung, this is followed by a passive relaxation phase, which allows the lungs to return passively to their resting volume due to the elastic recoil of the lung and the chest wall (Roberts et al. 2000). The accessory muscles of inspiration and expiration (e.g the scalene muscles and sternocleidomastoid) are not normally used during quiet breathing in normal healthy individuals, but they may contribute to ventilation in a situation of increased ventilatory demand (Aliverti & Pedotti 2014).

The term timing components, used within this research, refers specifically to inspiratory time (T_i), expiratory time (T_e) and breathing frequency (Bf). Bf is often the first observation to indicate a problem within a clinical setting and is a widely used sensitive marker of a deteriorating patient (Braun 1990). Furthermore, T_i and T_e are often monitored within intensive care settings when weaning from mechanical ventilation (Alía & Esteban 2000; Parthasarathy et al. 2000) and during laboratory based studies (Loveridge et al. 1986; Tobin 1992; Bruce 1996). Table 2-1 provides a summary of the research within the literature that includes normal values for T_i (sec), T_e (sec) and Bf (bpm). As can be seen in table 2-1, timing components can vary widely in healthy individuals (Hess et al. 2011) and can be affected by several factors e.g the nature of the device used to record breathing pattern (invasive, non-invasive) and awareness (discussed in more detail in section 2.2).

Table 2-1: Summary for the studies that include normal value of tidal volume, inspiratory, expiratory time and breathing frequency in healthy adults at rest using invasive and non-invasive devices

Study	Recording device	n (age)	V_T (ml)	Ti (sec)	Te (sec)	Bf (bpm)
Sorli et al. (1978)	PNT	9(19-33yrs)	840±12	1.7± 0.3	NR	15.2± 1.9
Savoy et al. (1981)	PNT	7(40-72)	710	1.88	NR	11
Adamczyk et al. (2008)	PNT	30(18-28)	NR	1.76	2.12	17.23
Askanazi et al (1980)	Canopy	28(22-36yrs)	362±8	NR	NR	18.8
Shea et al. (1987)	RIP	41(19-32yrs)	382 to 399	1.69	2.58	15.62

Study	Recording device	n (age)	VT (ml)	Ti (sec)	Te (sec)	Bf (bpm)
Tobin et al. (1983a)	RIP	47(18-60yrs) 18(60-81yrs)	383±85 382±109	1.60±0.30 1.67±0.35	NR	16.7±2.7 16.6±2.8
Shea et al. (1990)	RIP	18(19-54yrs)	390	1.55	2.82	14.62
Han et al. (1997)	RIP-'not aware' RIP-'aware' PNT	74(21-63yrs)	541.2±238.0 575.1±260.0 696.1±373.4	1.9±0.6 2.1±0.8 2.2±1.2	2.6±0.8 2.8±1.0 2.9±1.4	NR
Parreira et al. (2010)	RIP	48(29-39yrs) M F 18(40-59yrs) M F 39(60-80yrs) M F	 441±114 325±127 325±115 309±111 383±124 283±85	NR	NR	 15±2 13±4 14±2 16±3 15±2 15±3

(PNT) pneumotachograph, (RIP) Respiratory Inductive Plethysmography, (RMMI)Respiratory movement measuring instrument, (Ti) Inspiratory time, (Te) expiratory time, (Bf) breathing frequency, (sec) second, (bpm) breath per minutes, (NR) not reported, M=male, F=female.

2.1.2 Thoracoabdominal motion in healthy adults

Thoracoabdominal motion refers to the expansion and retraction of the thorax ribcage and abdomen during inspiration and expiration respectively (Sackner et al. 1984). The relationship between ribcage and abdomen during respiration is inevitably linked and reciprocal in nature (Upton et al. 2012). During normal tidal breathing in healthy individuals, excursions of the ribcage and abdomen occur in near simultaneous synchrony (Hammer & Newth 2009b). The expansion of the rib cage during inspiration is caused by intercostal muscle contraction, diaphragmatic apposition and increased intra-abdominal pressure caused by diaphragmatic contraction, while abdominal expansion during inspiration is caused by the contraction of the diaphragm (Wilhelm et al. 2003a).

The rib cage and abdomen motion can be derived from measurements obtained by any device that detects and measures movement that occurs

in the trunk, including: Opto-Electronic Plethysmography, Thoracic Impedance Pneumography , Structured Light Plethysmography and Respiratory Inductive Plethysmography devices, amongst others (these are discussed in more detail in Chapter 4). Measurements reflecting thoracoabdominal motion are expressed as the percentage of the total movement, which would always total 100%. Hence, rib cage contribution would be x% and abdominal contribution would be y%; so, x% + y% = 100%.

As shown in table 2-2, there have been attempts within the literature to establish normal values; however, it is clear that there can be variation within these values, which may be bought about due to a number of factors, including posture, gender and age. These discrepancies within the literature appear to highlight the complexity associated with interpreting resting breathing patterns in healthy individuals. Given the clinical importance of breathing pattern components to enable differentiation between healthy and unhealthy individuals, it seems necessary to establish its reliability and responsiveness in order to determine its potential usefulness as an outcome measure, which is the aim of this study.

Table 2-2: Summary for the studies that include normal value of thoracoabdominal motion.

Studies	**n**	**Gender (age-years)**	**%RC**	**%AB**	**Measurements device**	**Position**
Parreira et al. (2010)	104	M (20-39) F (20-39) M (60-80) F (60-80)	39±10 46±15 37±14 45±18	-	RIP	Supine
Shea et al. (1987)	41	M&F (19-32)	-	58±3	RIP	Supine
Tobin et al. (1983)	65	M&F (18-60) M&F (60-81)	42± 3 46±14	-	RIP	Sitting

Studies	n	Gender (age-years)	%RC	%AB	Measurements device	Position
LoMauro et al. (2012)	26	M&F (mean 22.4)		71.6±3.6	OEP	Supine

RIP= respiratory inductive plethysmography, OEP= Opto-Electronic Plethysmography, %RC= rib cage contribution percentages, %AB= abdominal contribution percentages.

2.2 Factors affecting breathing pattern

Breathing is a naturally occurring, periodic phenomenon (Rogers 2010). It is primarily an involuntary action that is controlled by the brain; in particular, the medulla (Brown et al. 2006). The medulla can alter breathing rhythmicity in response to a number of mechanisms, including nervous control, chemical control, body temperature, sleep, pain and emotions. However, unlike many other automatic systems (such as cardiovascular and neurological systems), the respiratory system can also be inhibited and facilitated by the individual (Chakrabarty & Chakrabarty 2006). This means that breathing pattern may exhibit complex variability (Goldberger et al. 2002) as a result of interactions between several respiratory pattern generating neuronal networks within central nervous system (Smith et al. 2007) or by mechanical and chemical afferent feedback modulations (Sammon 1994; Van den Aardweg & Karemaker 2002).

Healthy breathing pattern, therefore, is expected to exhibit some degree of random variability within individuals and this is a measure of complexity that accompanies any healthy systems, which enables them to display greater adaptability and functionality (Papaioannou et al. 2013). Loss of this variability is likely to be indicative of the onset of disease or dysfunction (Bokov et al. 2016). This section explores some of the factors that are known to affect breathing pattern components variability.

2.2.1 Posture

Within the literature, posture is reported to affect chest wall motion since changes from sitting to supine positions have been associated with progressive decreases in rib cage compliance and an increase in abdominal compliance (Sharp et al. 1975; Vellody et al. 1978; Ward et al. 1992; Verschakelen & Demedts 1995; Romei et al. 2010). In a study by Verschakelen & Demedts (1995), the breathing pattern of 120 healthy adults (m=60, f=60, aged between 10-60 years) was simultaneously monitored using both RIP and pneumotachograph PNT devices for 1.5 minutes of quiet breathing and during vital capacity manoeuvres in three different positions: standing, sitting and supine. Rib cage motion was found to be predominant over abdominal motion in all participants in two of the three positions, with the exception being for quiet breathing in supine position; this is a similar finding to Parreira et al. (2010), Tobin at el. (1983a) and Romei et al. (2010). However, simultaneous measurements of the breathing pattern were taken using an invasive PNT device (involving a nose-clip and mouth-piece) while the non-invasive RIP device was recording thoracoabdominal motion components, which may have had an impact on the findings (Gilbert et al. 1972; Askanazi et al. 1980; Perez & Tobin 1985). Nevertheless, the findings do suggest that thoracoabdominal motion is influenced by posture during quiet breathing, but a clear relationship was not established in this study.

Recently, Takashima et al. (2017) assessed the influence of posture in thoracoabdominal motion in three different positions: supine, right lateral, and sitting positions using OEP for 2 minutes in each position. The study involved 15 healthy males (mean age of 27.5 ± 4.6 years). The result derived from one way ANOVA showed that ribcage contribution was greater in sitting position than supine and abdominal contribution was greater in supine than sitting, indicating the significant effect of posture

on thoracoabdominal motion. However, the study included only male participants making it difficult to generalize the results in females.

Regardless of the type of device used to record thoracoabdominal motion, all the previous studies (Verschakelen &Demedts 1995; Romei et al. 2010; Takashima et al. 2017) have derived consistent findings regarding the effect of posture on chest wall motion.

2.2.2 Age/gender

Another factor that may affect breathing pattern relates to age. Tobin et al. (1983a) reported that older participants demonstrated more variability in breathing pattern than younger participants. Also, there were age related differences in rib cage contribution percentages of 42 ± 3 (%) in young healthy participants (20-50 years); and 46 ± 14 (%) in older healthy participants (60-81 years). Although they do not mention how statistically significantly these figures differ, it is apparent from the high standard deviation (SD) values that greater variability was found in the older participants. However, there is a lack of any pre-defined criteria within the literature as what constitutes 'normal' range of variability of breathing pattern in healthy individuals. Nevertheless, Kaneko and Horie (2012) suggest that age related changes in breathing mechanism, particularly regarding weaker diaphragmatic muscles, may result in a breathing pattern dominated by ribcage displacement. This would explain the higher percentages in rib cage contribution in the older age group in the Tobin et al. (1983a) study. Hence, age may be an influencing factor on thoracoabdominal motion.

Recently, Mendes et al. (2015) examined the effects of age, gender and posture on breathing pattern in 83 healthy participants (m=31, f= 52, mean aged 42±22 years). The breathing pattern was recorded using OEP in

the sitting, supine and supine with trunk inclination of 45˚. The results derived from multi linar regression analysis revealed that age, gender and posture did not significantly affect Bf, although age was found to have a significant effect on thoracoabdominal motion, with an increase in one year resulting in an average decrease of 0.20% in ribcage contribution and increase of 0.29% in abdominal contribution. Also, gender was found to have a significant impact on thoracoabdominal motion with females demonstrating greater ribcage contribution than males. Similar findings regarding the effect of gender on thoracoabdominal motion were also reported by Romei et al. (2010) in a study using an OEP device in 34 healthy participants (m=17, f=17) where females found to have larger ribcage contribution during quiet breathing than males.

However, Parreira et al. (2010) also examined the impact of age and gender on breathing pattern components by recording breathing pattern using an RIP device in 104 healthy adults (m=41, f= 63, aged between 20-80 years). No significant differences between the different age groups or between genders were found, suggesting that these factors may not produce a measurable impact on breathing pattern components. Yet, consistently high SD deviation values across all age groups were noted 14 (20-39 year olds), 11 (40-59 year olds) and 16 (60-80 year olds, similar to other reports within the literature, suggesting increased variability in older age groups. Though it is worth noting that the total sample of 104 subjects was divided into three separate groups, with 43 (20-39 year olds), 18 (40-59 year olds) and 38 (60-80 year olds), it can be suggested that due to the size and the uneven distribution between groups, there is insufficient power to study subgroups by age and hence, this may have impacted the validity of the results and may increase type II errors (Sullivan & Feinn 2012).

The inconsistency within the literature regarding the effect of age and gender on thoracoabdominal motion and the potential interactions between gender on chest wall kinematics may be related to the device used to record breathing pattern, as Parreira et al. (2010) used RIP, while Mendes et al. (2015) and Romei et al. (2010) used OEP, since the different devices provide different measurements (changes of diameters, perimeters, transversal sections).

2.2.3 Awareness of observation

An additional factor that may affect breathing pattern, and thus add to the complexity of breathing pattern analysis, is the awareness of an individual of their breathing pattern even when a non-invasive device is used. In 1997, Han et al. conducted a study to examine the impact of an individual's awareness on breathing pattern. Seventy-four subjects (f=40, m=34, aged between 22- 63 years) were divided into two groups, a 'younger' group (n= 42, aged 21-26years) and an 'older' group (n= 32, aged between 35-63years). Each group had their breathing monitored under three separate conditions of 5 minutes each. In the first condition participants were told that their breathing was not being monitored and that the time was being used to calibrate the RIP device, this was not the case, the breathing pattern was being monitored by the RIP device during this time, but the participants were unaware of this. In the second condition, the participants were told that their breathing pattern was being monitored by the RIP device. In the third condition, the participants were asked to breath into a mouth piece for their breathing to be monitored using a PNT. Using two-way ANOVA, the results found that there were significant differences in T_i, T_e and V_T between the conditions with p value of <0.01. Notably, it was found that there were significantly longer T_i (1.9±0.6 vs. 2.1±0.8) and T_e (2.6±0.8 vs. 2.8±1.0) once the participants were

made aware that their breathing was being monitored. This indicates that awareness can impact breathing pattern.

2.2.4 Mental state

The impact of mental state on breathing pattern was examined in a study by (Mador & Tobin 1991), which V_{min}, V_T, Bf, T_i and T_e of 9 healthy participants (m=7, f=2, aged 26-35 years) using an RIP device and simultaneous use of a spirometer in the supine position. Participants' breathing pattern was monitored for 10 minutes of resting, quiet breathing, 10 minutes of mental arithmetic, 10 minutes of audio-visual stimulation (watching television) and 2 minutes of noxious stimulation (shining a bright light into the participants' eyes). These interventions where carried out in a randomised manner in order to increase the validity of the findings by reducing bias.

The results showed a significant increase in V_{min} and Bf and significant decreases in T_i during the cognitive stimulating states of mental arithmetic and significant changes in V_{min}, V_T, Bf and T_i during the noxious stimulation intervention. These findings suggest that mental state can significantly affect certain breathing pattern components, particularly during times of increased anxiety or heightened cognitive stimulation. Also, another study by Masaoka and Homma (2001) also showed that increased anxiety (in anticipation a mild electric shock) caused significant increases in various breathing pattern components (V_{min}, V_T, Bf, T_i and T_e).

In a study by Shea et al. (1990), it was noted that the variability of breathing pattern decreases during deep, non-rapid eye movement (NREM) sleep, which is a time when the level of mental activity is considered to be reduced. This may suggest that, although breathing is controlled by metabolic demands, it is also affected by emotions, such as sadness,

happiness, fear and anxiety (Homma & Masaoka 2008), which are more likely to occur during wakefulness. Thus, the available data suggests that breathing pattern may be affected by an emotional response linked to heightened emotional or anxious situations.

2.3 Breathing pattern and asthma

It has been suggested that asthma may alter breathing pattern (Thomas et al. 2001; Thomas et al. 2009). Consequently, dysfunctional breathing pattern is a commonly associated problem in patients with asthma and is likely to impair an individuals' ability to control their asthma symptoms (Thomas et al. 2001; Morgan 2002; Stanton et al. 2008). Dysfunctional breathing incorporates various idiopathic breathing abnormalities that have no clear pathological or biological origin (FBASES 2015). Inevitably, this will have a significantly negative impact on the quality of life of people with asthma (Martínez-Rivera et al. 2011). This is of particular relevance to this research, as the third study incorporates the examination of the responsiveness of breathing pattern in asthma and thus, this section details the characteristics of timing components and thoracoabdominal motion in people with asthma (a detailed discussion of asthma, its pathology, diagnosis and management is included in Appendix J).

2.3.1 Timing component in asthma

Clinical changes of various breathing pattern components (T_i, T_e and Bf) in asthmatics have been examined in a number of studies (Ringel et al. 1983; Tobin et al. 1983b; Gorini et al. 1999; Osborne et al. 2000; Upton et al. 2012; Lo 2013). There is some evidence within the literature, which suggests that patients with asthma display shorter T_i and T_e and faster Bf than healthy individuals (Tobin et al. 1983b; Osborne et al. 2000; Lo et al. 2013); this may be associated with chronic and episodic airway obstruction causing expiration to become active in an attempt by the patient to force

inspired gas out of their lungs, which further increases the work of breathing. In addition, there is increased inspiratory work caused by high airway resistance and hyperinflation (Gong 1990). Chronic inflammation of the airway may also alter the structure of the airway to an extent where airway remodelling occurs (Grainge et al. 2011; Doeing & Solway 2013). These changes are not fully reversible and contribute to airflow obstruction (Niimi et al. 2000b), which may affect breathing pattern. Tobin et al. (1983b) measured breathing pattern in 65 healthy participants alongside 15 'symptomatic' and 17 'asymptomatic' participants with asthma. Symptomatic asthma was defined as having dyspnoea at rest or during moderate exertion, accompanied by wheezing (although, the exact measurement of dyspnoea or wheezing was not reported). Breathing pattern was recorded in a supine position using RIP device for 15 minutes. The results demonstrated shorter T_I and faster Bf in people with asthma compared to the healthy, but these differences were not found to be statistically significant. However, the non-equivalence of sample size between the groups (healthy and non-healthy) may affect the results and might inflate type II error (Rusticus & Lovato 2014).

Similar results were reported in a study by Osborne et al. (2000), which investigated breathing pattern in mild to moderate asthma patients during the stable phase of the condition. Twenty-three individuals with a history of asthma participated and 17 healthy participants with matching age, gender and height were included as controls. V_T, T_I, T_E, Bf and other breathing pattern component, including arterial and expired End-Tidal Carbon Dioxide ($ETCO_2$) were recorded using a PNT and a capnometer for five minutes. Comparisons between the healthy participants and asthmatic participants were made using a t-test. The findings demonstrated that participants with controlled asthma had significantly lower arterial and $ETCO_2$ tension than the healthy participants and this was found to be

related to airway hyper responsiveness rather than airway obstruction, which supports the suggestion that breathing pattern in asthma is altered. However, breathing pattern was recorded using an invasive PNT device, which may have affected breathing pattern.

There is evidence within the literature that demonstrates a difference in the timing components of breathing pattern in asthma in comparison to healthy individuals, which appears to support the notion that timing components are altered in asthmatics. Although the existing literature has not established any significant differences, this may be more due to the methodological procedure of the research or absence of asthma symptoms rather than a lack of actual difference. This notion is also supported by some evidence within the literature suggesting that abnormal breathing pattern is prevalent in asthma. For example, Thomas et al. (2001) conducted a cross-sectional survey of 219 people with asthma and found that approximately one third of women (35%) and one fifth (20%) of men have high scores (>23) on the Nijmegen questionnaire (NQ), which is indicative of the existence of hyperventilation. Also using self-reported questionnaires (Anxiety Sensitivity Index, the Asthma Symptom Checklist, and the Nijmegen questionnaire), Martinez-Moragon et al. (2005) and McLean et al. (1999) both found abnormal breathing pattern to be present in 36% and 42% of asthmatics, respectively. Moreover, Grammatopoulou et al. (2014) also reported a 34% prevalence of hyperventilation in 162 asthma patients (based on NQ scores).

However, the NQ includes items that are common to both anxiety and asthma (shortness of breath, chest tightness) (Ritz et al. 2001; Bruton & Holgate 2005a), so although it might be useful to quantify and assess the normality of subjective sensations, some authors (Keeley & Osman 2001; Ritz et al. 2001) have questioned the validity of using the NQ to identify hyperventilation in an asthma population due to the potential overlap

between the symptoms of anxiety and those of asthma. Moreover, an elevated NQ score is not diagnostic of asthma, but rather is only a reflection of a subjective aspect of dysfunctional breathing. Hence, as van Dixhoorn and Folgering (2015) recommend, a multicomponent assessment which includes ventilatory parameters, such as carbon dioxide tension, breathing movement parameters and other subjective variables in order to fully understand or assess the effect of asthma on breathing pattern, which highlights the need for an objective, reliable and responsive outcome measure.

2.3.2 Thoracoabdominal asynchrony in asthma

During normal quiet breathing in healthy individuals, the rib cage and abdomen move in synchrony with each other, expanding and retracting concurrently, thereby optimising tidal volume (Upton et al. 2012). Thoracoabdominal asynchrony on the other hand, occurs when the rib cage and abdomen do not move in synchrony, but rather there is a time-lag between the motion of the rib cage and abdomen (Hammer & Newth 2009b), and in the most severe cases of thoracoabdominal asynchrony the rib cage and abdominal movements occur in opposite directions (paradoxical breathing).

Thoracoabdominal asynchrony has been found in many respiratory disorders, including COPD and asthma, as patients with asthma have been found to use accessory muscles in an attempt to stabilize respiration (Pascoal et al. 2014). Tobin (1988) assert that the respiratory muscles are placed at a mechanical disadvantage in patients with respiratory disease; this may be because the respiratory muscles are needed to operate at non-optimal lengths (Ratnovsky et al. 2008), which results in the respiratory muscles needing to generate a greater force with each breath; however, the role of thoracoabdominal asynchrony in asthma remains unclear

(Upton et al. 2012). Although, it has been suggested that individuals with respiratory disorders often have a reduction of diaphragm mobility measured using ultrasound (Santana et al. 2016), which may be reflected by asynchrony within thoracoabdominal motion.

The Tobin et al. (1983b) study has been mentioned in detail in the previous section (section 2.3.1), but as an additional finding relevant to this section regarding thoracoabdominal asynchrony, it is worth noting that the rib cage contribution to tidal volume was statistically significantly greater in the participants with asymptomatic asthma (n=17) in comparison to the healthy controls (n=65). In another study, Gorini et al. (1999) measured thoracoabdominal asynchrony during maximal bronchoconstriction (induced by the administration of an aerosol of histamine for two minutes) in seven male participants with mild to moderate asthma, with a mean age of forty years. Breathing pattern was recorded using OEP in the sitting position before and after obstruction. Using a Student's t- test to analyse the data before and after the maximal bronchoconstriction compared with control conditions, the results show that thoracoabdominal asynchrony was evident and was largely associated with an increase in end expiratory rib cage volume (mean increase 0.63L; 95%CI 0.41-0.83; $p<0.001$). Again, this provides evidence that people with asthma often exhibit persistent activity of the rib cage inspiratory muscles even during expiration, which is in contrast to normal breathing pattern observed in healthy individuals. This may be a result of the continued activation of accessory and inspiratory intercostal muscles during expiration (Arnold et al. 2011).

In another study by Upton et al. (2012), breathing pattern in 43 healthy and 43 asthma participants aged between 18 and 65 years (matched by age and gender) was recorded using a Life Shirt® for approximately four hours during the day. Thoracoabdominal asynchrony was quantified using

data derived from the Life Shirt®, while lung function was measured using spirometer and $ETCO_2$ was recorded using capnometry. Data regarding quality of life was collected from the asthma participants using the Mini Asthma Quality of Life Questionnaire (AQLQ) and the Asthma Control Questionnaire (ACQ). Mann–Whitney U-test demonstrated that asthma participants had significantly greater levels of thoracoabdominal asynchrony (14% versus 10.4%, p= 0.012), than the healthy participants. Also, post-hoc exploratory subgroup analysis revealed that the increased thoracoabdominal asynchrony was associated with higher ACQ and AQLQ scores in the females, but not in the male asthma group.

This result may be partially explained or understood by the findings from another study conducted by Weiner et al. (2002), which examined the influence of gender and inspiratory muscle strength by comparing the inspiratory muscle strength, perception of dyspnoea to threshold loads and bronchodilator consumption of asthmatic patients (m= 22, f=22 with mean age of 37.7±3.3 years and 36.2±3.1 years respectively). It was found that females have significantly weaker inspiratory muscles than males (72.1±4.6 versus107.4 ± 6.3, p< 0.01), which may explain the findings from the Upton et al. (2012) study, since females appear to have physiological differences regarding inspiratory muscle strength, which may be a contributing factor to thoracoabdominal asynchrony.

In summary, the findings from the aforementioned studies suggest that thoracoabdominal asynchrony is present in individuals with asthma when compared with healthy individuals. However, the use of thoracoabdominal motion as an outcome measure is not without challenges. For example, thoracoabdominal motion can be affected by several factors; including age, the type and severity of the respiratory disease and the presence of neuromuscular disorders that affect the respiratory muscles and nerves (Hammer & Newth 2009a). Also, there is a lack of pre-defined criteria

within the literature regarding the normative values to detect the degree of asynchrony that indicates abnormality. Moreover, the equipment used to monitor thoracoabdominal asynchrony is largely laboratory based and can be cumbersome or impractical for use within clinical settings. In spite of this, thoracoabdominal motion has the potential to be an important and clinically useful monitoring tool and outcome measure, especially given the emergence of new technology, which is easier to use and more practical for the clinical settings. Yet, if thoracoabdominal motion is to have any value as an outcome measure, it is necessary to establish the reliability and responsiveness of this component.

2.4 Breathing pattern reliability

Reliability is an important feature for any measurement if it is to be useful, i) as an outcome measure for physiotherapy or other interventions and ii) as a means of detecting change in respiratory health. Reliability of breathing pattern can be determined by its ability to remain stable over time. Shea and Guz (1992) conducted a literature review of their own work (8 studies in total), in which they refer to an earlier work by Dejours et al. (1961) which suggests that although breathing pattern differs significantly between individuals, it does remain stable within individuals. In Dejours' words, all individuals are said to have a 'personalite ventilatoire' or in other words, a ventilatory personality that remains stable over time. Shea & Guz (1992) also suggest that breathing pattern varies widely between individuals and that these variations are determined by a number of factors, including neurological functioning, genetic contribution to ventilatory sensitivities and the size and structure of the lungs and airways. Yet, the authors also support Dejours' suggestion that individuals possess a 'ventilatory personality', supporting the notion that individuals maintain stable breathing patterns over time. Shea & Guz's (1992) conclusions highlight the stability of specific breathing pattern components, namely breathing frequency; but importantly, emphasise the lack of research in this area. The limited available research in this area is discussed in the following sections.

2.4.1 Studies examining test re-test reliability of breathing pattern components

There is no recent study within the literature that has examined the test re-tests reliability of breathing pattern and of the limited available research, there are some limitations and heterogeneity regarding the recording devices used, posture during the data collection sessions, statistical

analysis methods, sample sizes and data editing processes. The description and findings of the available studies are summarised in the following table 2-3.

Table 2-3: Summary of studies examining test re-test reliability of breathing pattern components

	Sample size (age) Gender	Recording system & data analysis	Breathing components reported	Procedures	Findings
Adamczyk et al. (2008)	30 (18-28) male only	PNT Freidman Test & Newman Keuls test	VT, Vmin,VT/Ti, Bf Ti, Te and BC	BP recorded 8 times at 3 hourly intervals over a 24-hour period, with each recording session lasting 6 min. (Supine position)	Significant fluctuations $p<0.05$) in group mean for volume components; no significant fluctuations of group mean timing components.
Grossman et al. (2006)	16 (18.2-25.7) (m=8, f=8)	Ambulatory RIP Pearson's r correlation and standard error	Bf, VT and Vmin	BP recorded every week for 6 weeks. Data was collected (for a total of 10 min) before a yoga session, during a yoga session (lasting approx. 60 min) and after the yoga session (for 10 min). Data was averaged across each experimental phases over the six week period. (Sitting position)	Comparisons were made between the adjacent weeks: • Bf in all phases – r between (0.73 – 0.83), SE between (0.7bpm-1.3bpm). • VT in all phases – r between (0.65-0.82), SE between (66.1ml-129ml). • Vmin in all phases – r between (0.65-0.82), SE= (0.5 l/m).
Shea et al. (1990)	18 (19-54) (m=8, f=10)	Conventional RIP paired t-test and Pearson's r	Ti, Te, Bf, VT and Vmin	BP data collected overnight for 5 min during wakefulness and deep sleep stages (Stage 4 sleep). (Supine position)	BP components remained statistically similar ($p>0.05$) and demonstrated high correlation with Pearson's $r > 0.89$ suggesting the reliability of some

		correlation			components during wakefulness and sleep.
Shea et al. (1987)	41 (19-32) (m=16, f=25)	Conventional RIP ANOVA, Kendall's coefficient of concordance correlation And CoV%	VT, Vmin, Ti, Te, Bf and %AB/VT.	BP was measured for 5 min at 4 different times over the course of 2 days. (Supine position)	• The changes in group mean for all BP components were not statistically significant over the 4 sessions with p>0.05. • High correlation r between (0.69 – 0.87). • CoV% of 13.5%, 15.2%, 9.7 % and 22.9 for Ti,Te, Bf and AB/VT respectively.
Benchetrit et al. (1989)	16 (18-55) (m=9, f=7)	PNT Visual inspection of the participants' airflow profiles	VT, Vmin, VT/Ti, Bf Ti, Te and BC.	Two 15-25 min of BP recording sessions took place with an interval of 4-5 years (mean=51.5±4 months) at the same time of year (Feb/March). (Sitting position)	The timing and volume components of BP are reproducible over a prolonged period irrespective of pertinent changes in circumstances and they suggested that BP is an inherent feature of an individuals' respiratory system.

(BP) breathing pattern, (CoV%) Coefficient of Variation; (r) derived from Kendall's coefficient of concordance or Pearson's product-moment to determine correlation, (SD) standard deviation, (SE) standard error, (VT) tidal volume, (Vmin) minute ventilation, (Ti) inspiratory time, (Te) expiratory time, (Bf) breathing frequency and (%AB/VT) abdominal contribution to tidal volume, (RIP) respiratory inductive plthysmography.

Regarding the recording devices, a pneumotachograph (PNT) device was used by Adamczyk et al. (2008) and Benchetrit et al. (1989) to record breathing pattern. While, Grossman et al. (2006), Shea et al. (1990) and Shea et al. (1987) used Respiratory Inductive Plethysmography (RIP). Yet, these two devices measure ventilation in different ways. The RIP device uses elastic bands placed around the abdomen and thorax, which enables estimation of tidal volume (V_T) from rib cage and abdominal displacement (Description of RIP in section 4.3.4). Whereas, PNT involves the use of a facemask that directly measures the differences in airflow across a resistive device; however, the use of a facemask has been found to affect breathing patterns as described in subsequent section (4.2.1). Hence, it may be difficult to compare the findings from these studies due to the different devices used.

Also, regarding the breathing pattern components examined, Adamczyk et al. (2008) and Benchetrit et al. (1989) explored the stability of timing and volume components recorded using a PNT device. And Grossman et al. (2006) and Shea et al. (1990) only reported information regarding timing and volume components, despite using an RIP device, which provides data relating to thoracoabdominal motion. On the other hand, Shea et al. (1987) reported data relating to all three components of breathing pattern: volume, timing and regional contribution. In addition, breathing pattern was recorded in different positions in different studies, participants in the Adamczyk et al. (2008), Benchetrit et al. (1989) and Grossman et al. (2006) studies were in a sitting position, while Shea et al. (1990;1987) recorded breathing pattern in the supine position. The effect of position on breathing reliability is unknown, making comparisons between the findings of the existing literature problematic.

Moreover, regarding the statistical methods used to assess reliability, Grossman et al. (2006) did not perform a statistical significance test, or if

they did, no p-values were reported within the article, but rather reliability was assessed using Pearson's r correlation and standard error. Whereas, Shea et al. (1990) used paired t-test and Pearson's r correlation to assess reliability with no measurement error calculation. While, Adamczyk et al. (2008) only assessed significance using the non-parametric Friedman test to analyse the data, since it was not normally distributed, which is known to be less powerful than ANOVA (DeJuan & Seater 2006). Also, Adamczyk et al. (2008) used the Newman-Keuls test to assess the significance of differences between the mean values of the breathing pattern components. However, the use of Newman-Keuls test with more than four groups is known to increase Type I error (Abdi & Williams 2010) and the Adamczyk et al. (2008) study included 8 recording sessions. Of note, it is not appropriate to use p- value and correlation alone to assess the reliability of measurements (Bland & Altman 1986), since high correlation does not necessarily denote significant reliability.

To accurately examine test re-test reliability, it is necessary to assess three elements: change in mean (p-value), correlation and measurement error Baumgartne (1989). Only Shea et al. (1987) assessed reliability using all of these three elements and demonstrated that an individual's breathing pattern differs greatly from that of others, but that individuals tend to maintain a similar characteristic breathing pattern when measured at different times under the same conditions using ANOVA. This was supported by the Kendall's coefficient of concordance values for their cohort, which is a measure of correlation or association between three or more sets of data (Kendall et al. 1939). The cohort values between sessions ranged from r=0.61 to r=0.87 for all variables, indicating good to high concordance (table 2-3). Consequently, Shea et al. (1987) conclude that breathing pattern components are reproducible and stable within individuals over time, with Bf being the most reproducible component (r=0.87).

However, the conclusions that Shea et al. (1987) report are somewhat contradictory and not fully supported by the statistical data; for example, they report that there is a 'high degree of reproducibility of breathing pattern within a subject', but they fail to state that this is only the case when compared to the degree of between subject differences. Also, the Coefficient of Variation values (CoV%) were 9.7%, 13.5%, 15.2%, for Bf, T_i, T_e and 22.9% for abdominal contribution, which appear to show a degree of variability; however, there is no defined criteria within the literature of what can be considered as high or low CoV% values. Yet, even Shea et al. (1987) concede that these CoV% values may indicate 'significant quantitative differences'. Moreover, the use of CoV% has been discouraged for test re-test reliability studies (Bland 1997) due to criticisms that it assumes that the largest test re-test variation occurs in the individuals scoring the highest values in a test (Atkinson & Nevill 1998).

No statistical methods were used to assess the reliability of breathing pattern in the Benchetrit et al. (1989) study, instead the shape of airflow profile derived from harmonic analysis was analysed, which is a type of mathematical analysis that focuses on the visual representation of signals as basic waves. A visual representation of each breath based on the first four harmonics (waves) providing four amplitudes and four phase angles for each breath. Although the published visual representations does display some similarities, visual inspection is a subjective process and does not allow a quantitative assessment to be performed; this meant that the statistical significance of any differences could not be accurately assessed.

Regarding the data editing processes, Shea et al. (1990), Grossman et al. (2006) and Adamczyk et al. (2008) did not report details of signal editing, so it is unknown as to whether they removed any uncharacteristic signals

or included them within the data analysis. On the other hand, Benchetrit et al. (1989) did report excluded breaths as those including sighing, swallowing or body movement and the subsequent 3 breaths, which resulted in approximately 100 breaths (or more) being removed from the data analysis process. This seems a large number and may increase bias. While Shea et al. (1987) also removed breaths affected by movements and coughs from the data files; however, it is not clear how these breaths were categorised and how many breaths removed. It can be argued that the data editing process is a subjective procedure, which may affect the validity of the results if the researchers are removing a large number of signals.

Another limitation of the available studies within existing literature relates to the sample size. Three studies include a small number of participants of less than 20, which might have insufficient statistical power to detect change; for example, Benchetrit et al. (1989) and Grossman et al. (2006) included 16 participants and Shea et al. (1990) included 18 participants. On the other hand, Adamczyk et al. (2008) had a larger sample size (n=30), but which only included males. Therefore, although these studies are important and contribute relevant information regarding the reliability of breathing pattern components, there are clear limitations, since the sample sizes are small or are unrepresentative.

In addition, there are also some limitations with methodological protocol; for example, a gap of 4-5 years in the Benchetrit et al. (1989) study seems excessive and unrealistic to accurately assess reliability. In addition, the breathing pattern monitoring for the sleep stages in the Shea et al. (1990) study took place overnight; it is possible that the RIP bands may have moved position during the night, which could have interrupted the signals creating noise/artefacts.

Despite the limitations and heterogeneity, the findings within the existing literature appear to suggest that breathing pattern remains stable within individuals over a prolonged period, in both sleep and wakeful states and when recorded using invasive and/or non-invasive devices in different body positions. The limited existing research shows that even though there are some factors that influence breathing pattern variability, the within individual resting breathing pattern does appear to remain stable over time. Nevertheless, it is evident that there is a lack of recent research that focuses on the test re-test reliability of breathing pattern components in healthy and non-healthy individuals, particularly in relation to the variations that may occur in thoracoabdominal motion. Respiratory physiotherapy and other interventions may aim to modify chest wall motion, so evidence regarding the stability of these components within individuals would be valuable. Moreover, establishing the reliability of breathing pattern components could determine its usefulness to be used as an outcome measure. This research aims to address the existing gap in the literature in relation to the test re-test reliability of specific breathing pattern components (T_i, T_e, Bf, %RC, %AB) *(first study).*

2.5 Breathing pattern responsiveness

For breathing pattern to be useful as an outcome measure, it is necessary to establish both reliability *and* responsiveness (Guyatt et a. 1987; Roach 2006). Responsiveness is the ability of a measure to detect change as it occurs (Beaton et al. 2001). Therefore, breathing pattern responsiveness represents the ability of breathing pattern to change in an individual over time, where real change has occurred, or change as a result of a stimulus; however, the definition for clinically meaningful change is not yet defined within the literature (Schuck & Zwingmann 2003). Moreover, there is a limited amount of existing research within the literature that has examined the responsiveness of breathing pattern components. As Beaton et al. (2001) asserts, responsiveness is increasingly becoming a critical criterion

for the selection of outcome measures in clinical research and practice. The following sections discuss the existing literature that has attempted to establish the responsiveness of breathing pattern components.

2.5.1 Responsiveness of breathing pattern to physical exercise stimulus

It is known that timing components of breathing pattern respond and adjust accordingly in order to meet metabolic demand and ventilation has been shown to increase during physical exercise above the levels derived during quiet breathing (Mostert & Kesselring 2002; Burton et al. 2004; Amritsar 2010). Moreover, physical exercise has been shown to cause an increase in tidal volume, breathing frequency and minute ventilation (Aliverti et al. 1997; Pellegrino et al. 1999; Mostert & Kesselring 2002; Amritsar 2010). Therefore, it can be suggested that the responsiveness of timing components in response to physical exercise is well known and well-documented. However, the responsiveness of thoracoabdominal motion components in response to a physical exercise stimulus is not fully understood due to the limited research in this area and due to the lack of homogeneity within research protocols that are available within the literature, which have produced conflicting results.

As can be seen in table 2-4, the existing literature that examines or assesses the changes that occur in thoracoabdominal motion use different systems to collect data, with two using Opto-Electronic Plethysmography (OEP) (Aliverti et al. 1997; Sanna et al. 1999), while (Tamaki et al. 2000) used an RIP and Ohashi et al. (2001) used a three dimensional motion analysis system (Oxford metrics inc., Vicon 370). Each system measures a slightly different area or aspect of the chest wall (see section 4.3); for example, in the Ohashi et al. (2001) study, the three dimensional motion analysis system involves the placement of four markers; one on the

sternoxiphoid process and another directly opposite on the spine, with another marker above the umbilicus and another directly opposite on the spine. Therefore, data regarding the movement that occurs in the upper chest wall is not provided by this system, whereas the OEP (with 86 markers) does provide data regarding this area. Moreover, the RIP only provides data regarding a restricted area of chest wall (just below the axilla and below the lowest vertebral rib). Therefore, the results from these studies may differ slightly and are not directly comparable.

Another limitation of the existing literature is the small sample sizes involved in the studies, Alverti et al. (1997) and Sanna et al. (1999) both included 5 participants, while Tamaki et al. (2000) included 8 participants and Ohashi et al. (2001) collected data from 15 participants. In addition to these small sample sizes, two studies further subdivided the sample into even smaller groups, with the Tamaki et al. (2000) sample (n=8) being divided into two groups (six predominantly rib cage breathers and two predominantly abdominal breathers) and Ohashi et al. (2001) divided the 15 participants into four groups; 7 abdominal group, 2 in the partially abdominal group, 2 in the abdomen-chest group and 4 in a chest group. The small sample sizes confounded by the further subdivisions may affect the validity of these findings due to insufficient power to detect changes by increasing type II error (Marley 2014). Another criticism of the samples in these studies is that they comprise entirely male participants; this means that the findings are not generalisable to both genders and are not representative of the general population and do not allow comparisons to be made between genders.

Another inconsistency within the current existing literature is the difference in physical exercise stimulus. One study Sanna et al. (1999) used a treadmill travelling at a speed of 2 and 4 miles per hour (mph), while three studies used cycle ergometers. In the Aliverti et al. (1997)

study, participants cycled for 10 minutes at increasing increments of 30, 50 and 70W (3 minutes and 20 seconds at each load); while in the Tamaki et al. (2000) study, participants cycled for a total of 15 minutes at increasing increments of 60, 90 and 120W and in the Ohashi et al. (2001) study, participants cycled for 5 minutes at 100W. It is known that the actions of running and cycling use different chest and upper extremity muscles, which may affect chest wall movement and stimulate respiratory muscles differently (Kalsås & Thorsen 2009). Hence, the use of different exercise devices within the studies result in greater heterogeneity within the existing findings regarding the change that occurs in thoracoabdominal motion as a result of exercise.

Moreover, the data analysis involved varying time periods of thoracoabdominal motion recoding; Tamaki et al. (2000) had three 5-minute recordings, while both Sanna et al. (1999) and Ohashi et al. (2001) used 30 seconds of recording and Aliverti et al. (1997) analysed 20 seconds of recording. It might be suggested that 30 or 20 seconds of data is not sufficient time to reflect the changes that occur in thoracoabdominal motion. In addition, there were differences in the participants' posture during data collection with participants in the Ohashi et al. (2001) and Sanna et al. (1999) studies in a standing position, while participants in the Tamaki et al. (2000) and Aliverti et al. (1997) studies were sitting, although in the Aliverti et al. (1997) study participants had to remain in an unnatural position with their hands raised out to their sides. Also, it might be suggested that with increasing work load during cycling, participants may naturally change position, since individuals tend to lean forward moving the centre of gravity anteriorly; this may have an impact on the thoracoabdominal motion, which is found to be significantly altered when the position is changed (Sharp et al. 1975; Verschakelen & Demedts 1995; Estenne et al. 1985). These inconsistencies within the research

methodologies make comparisons of the data difficult and may also mean that the findings are limited largely to the posture of each study.

Furthermore, while three of the studies examined the effect of a physical exercise stimulus on thoracoabdominal motion *during* the exercise itself, one study focused on the changes that occur in thoracoabdominal motion *post* exercise (Ohashi et al. 2001). It is unclear whether the changes that occur during exercise are similar to the changes that occur post exercise; again making comparisons difficult. Also, the recording devices may not be as effective when used during exercise due to the vigorous motion of the participants and the RIP bands may slip or move during exercise (Lo et al. 2013). In addition, there is lack of consistency within the reporting, which makes the interpretation of the data difficult for the reader, with each study presenting their data as either graphs or flow-volume loop diagrams (Aliverti et al. 1997; Senna et al.1999) or as a change in ratio, rather than clear, unambiguous, mean values regarding the actual change that occurred in the thoracoabdominal motion.

Table 2-4: The existing literature that examines or assesses the changes that occur in thoracoabdominal motion

Studies	Sample **size** (age)	Recording system	Type of physical exercise	Period of recording time used for analysis	Position during recording (data collection)	Findings
Ohashi et al.2001	15 Male were divided into 4 groups (22.1)	Three-dimensional motion analysis system. With four markers.	Cycle ergometers	30 second after exercise	Sitting	There were differences among the subjects in terms of the changes in thoracoabdominal motion: (n=7) significantly increase abdominal motion (n=2) Partly increase abdominal motion (n=2) no significant difference in rate of increase between abdominal and chest expansion (n=4) significantly increase chest motion

Studies	Sample **size** (age)	Recording system	Type of physical exercise	Period of recording time used for analysis	Position during recording (data collection)	Findings
Tamaki et al. 2000	8 Male were divided into 2 groups (24.5±3.5)	RIP	Cycle ergometers	5 min at three work rates of 60, 90, and 120w	Sitting	Even as workload increased, tidal volume did not increase significantly. Rib cage motion increased in all participants as workload increased, but the change in abdominal motion was found to be irregular (no p values reported)
Aliverti et al. 2002	5 Male (31-38)	OEP with 86 markers	Cycle ergometers	20 second during exercise at three work load at 30, 50, and 70%$\dot{W}$max	Sitting	Group mean pulmonary rib cage volume progressively increased during exercise and that abdominal volume progressively decreased during exercise.
Sanna et al. 1999	5 Male (35±2)	OEP with 86 markers	Treadmill	30 second during two run of walked at 2 and 4 miles/h (mph) with constant grade (0%).	Standing	During exercise it was found that ribcage were progressively increase while, abdominal were progressively decrease.

(RIP) Respiratory inductive plethysmography, (OEP) Opto-Electronic Plethysmography

All of the aforementioned variations in research methodologies may be a contributing factor to the contradictory and inconsistent findings within the literature. Moreover, thoracoabdominal motion analysis has been a relatively neglected area of enquiry even though there is evidence that thoracoabdominal motion can be used to differentiate between healthy individuals and those with respiratory disease. Therefore, the second study of this research aims to address the existing gap in the literature by examining the responsiveness of thoracoabdominal motion to a moderate physical exercise stimulus in healthy adults.

2.5.1.1 The effects of gender on thoracoabdominal motion responsiveness following physical exercise

A review of the literature by Sheel et al. (2016) demonstrates that there are physiological differences in the anatomy of the respiratory system between

genders, so even when lung sizes are matched with males, females are still found to have smaller-diameter conducting airways. The existing literature shows that the mechanics of airflow generation are affected during conditions of high ventilatory requirements, such as physical exercise (McClaran et al. 1998; Guenette et al. 2007). Moreover, the expiratory flow limitation has been found to be lower in females in comparison to males in a study involving endurance trained athletes (Guenette et al. 2007). Also, females have been found to have upper airway mechanical constraints that could impact chest wall kinematics and change volumes (Martin et al. 1987; Kenyon et al. 1997; McClaran et al. 1998; Guenette et al. 2007; Gonzales & Williams 2010; Guenette et al. 2010). Hence, the effect of gender on the responsiveness of ventilation has been established within the literature (Vogiatzis et al. 2005; Layton et al. 2011). However, more conclusive evidence is needed to determine the effect of gender on the responsiveness of thoracoabdominal motion to physical exercise as there is a limited amount of research that has examined this, which has also derived inconsistent findings.

Vogiatzis et al. (2005) examined the effects of gender on the responsiveness of thoracoabdominal motion during incremental cycling exercise at 30W.min or 40W.min for males (n=10) and 20W.min or 30W.min for females (n=5), where lung volumes and chest wall kinematics were recording using OEP (with 89 markers). The findings showed that during increasing incremental exercise, rib cage contribution to tidal volume progressively increased and abdominal contribution progressively decreased; however, regression analysis of the compartmental contribution for males and females demonstrated that there were no significant differences between genders for either compartment, suggesting that gender does not affect the responsiveness of thoracoabdominal motion. But, the sample size was small and not evenly distributed between genders, which may affect the validity of the results derived from

regression analysis (Maxwell 2000; Harrell 2015). Moreover, Vogiatzis et al. (2005) chose to combine the pulmonary ribcage and abdominal ribcage data, to form one rib cage component data. The impact of this on the validity of the findings is unknown.

Another study conducted by Layton et al. (2011b) investigated the effects of gender and physical endurance on chest wall volume and kinematics at maximal exercise also using an OEP (89 markers). The participants (f=12, m=20, 18-40 years) exercised on an ergometer at increasing increments for 6-12 minutes to attain maximal exertion. The findings derived from ANOVA showed that thoracoabdominal motion responded similarly between the genders, with the only difference in responsiveness being in trained males and females in pulmonary ribcage during expiration, with no statistically significant changes in females, but a statistically significant decrease in males. The findings showed that pulmonary ribcage and abdominal wall contributed equally to tidal volume in males, but not in females suggesting that women breath using predominantly ribcage, while men use equal amounts of ribcage and abdomen during exercise. In the Layton et al. (2011b) study, the data was analysed based on the three separate compartments (as derived from the OEP device); pulmonary ribcage, abdominal ribcage and abdomen. When Layton et al. (2011b) reanalysed the data with pulmonary and abdominal ribcage combined to produce one ‘rib-cage’ data, the findings did not show any differences between males and females; hence, this calls the Vogiatzis et al. (2005) findings into question.

As has been evidenced in this section, the limited existing literature that has attempted to examine the effect of gender on the responsiveness of thoracoabdominal motion has derived contradictory findings; therefore, the effect of gender on the responsiveness of thoracoabdominal motion

remains unclear and consequently, in an attempt to address this gap in the literature, this will be examined as part of the second study.

2.6 Responsiveness of breathing pattern to breathing retraining intervention in asthma

Unlike other automatic systems within the body, individuals are able to exert a certain degree of control over ventilation, which may be an indication of the responsiveness of breathing pattern to certain stimulus (Chakrabarty & Chakrabarty 2006). Correction of abnormal breathing patterns through breathing exercises is a therapeutic method of controlling asthma symptoms (Courtney 2017). The use of breathing exercises as a complementary therapy to pharmacological treatment has been widely used across the globe for people with asthma (Freitas et al. 2013). Breathing exercise is an evidence based, multicomponent, behavioural change intervention for the care of patients with asthma (BTS/SIGN 2016) and other respiratory diseases (Han et al. 1996). It aims to modify breathing pattern by reducing breathing frequency and reducing hyperventilation and comprises a variety of techniques; including the Papworth method, Buteyko breathing technique, yoga or any other similar physiotherapy intervention that involves the manipulation of breathing pattern (Ernst 1998; Ernst 2000; Ram et al. 2003).

However, it is still unknown if breathing retraining significantly changes breathing pattern components in asthma, because all systematic reviews examining the effectiveness of breathing retraining in asthma management rely on questionnaires and medication usage as primary outcome measures to assess the responsiveness of breathing pattern following a breathing retraining intervention (Burgess et al. 2011; O'Connor et al. 2012; Freitas et al. 2013), with only a limited number of studies recording breathing frequency and End-Tidal Carbon Dioxide ($ETCO_2$) (Thomas et al. 2009; Ritz et al. 2014).

Only a case study report by Tehrany et al. (2017) provides objective measurement of breathing pattern before and after three face to face breathing retraining sessions over 16 weeks. Breathing and speech-breathing pattern was recorded during three two minutes periods (quiet breathing, reading and conversational speech) using RIP in one 57 year old female with severe asthma for 10 years. The patient reported a number of improvements, including a reduction in medication (Salbutamol from 9-12 to 6 puffs per day), dyspnoea and hyperventilation (from 39 to 7 according to NQ questionnaire scores). Regarding breathing pattern, reduced Bf (from 20.3 to 14.1 bpm), increased T_e (from 2.4 to 3.4 second) during conversation speech following the breathing retraining programme. Also, there was a small increase in lung volume and flow. However, no change was noted in rib cage and abdominal contribution to respiration following breathing retraining.

Unfortunately, due to corrupted RIP data, no baseline data for quiet breathing before the breathing retraining programme was available. Hence, it was not possible to examine the impact of the breathing retraining programme on breathing pattern during quiet breathing, as only comparisons during the speech tasks could be made. Moreover, the patient's medication was changed during the period of breathing retraining, and it is not known how this may have affected the results. Although the findings suggest that breathing retraining may have a positive effect on breathing pattern and other variables, the findings are based on only one case, which is not representative of the whole population with asthma.

The wide-spread and increasing use of breathing retraining as an adjunct treatment for people with asthma has inevitably generated considerable interest among researchers to develop studies that examine the

effectiveness of breathing retraining in the management of asthma (Freitas et al. 2013). Indeed, the efficacy of breathing retraining in people with asthma has been suggested within the literature in asthma management (Freitas et al. 2013; O'Connor et al. 2012; Burgess et al. 2011; Ram et al. 2003 and Ernst 2000).

Therefore, it can be suggested that there is a lack of reliable, valid and responsive outcome measures, specifically related to respiratory physiotherapy, which objectively measures change that occurs in breathing pattern. This is a barrier to the further development of a strong evidence base in this field. Hence, it is essential to establish the reliability and responsiveness of breathing pattern in order to determine and ascertain its usefulness as an outcome measure. This may add to the existing body of literature and consequently, enable physiotherapists to assess the efficacy of respiratory interventions.

Chapter 3 Outcome Measure Properties

3.1 Introduction

There are a number of properties of an outcome measure that are integral to the evaluation and selection of appropriate outcome measures. These properties include: reliability (the consistency or reproducibility of the measure), appropriateness (the ability of the instrument/ measure to answer the questions asked by any clinical trial), validity (the ability of an instrument or a measure to measure what it is intending to measure), responsiveness (the ability of an instrument to detect a meaningful or clinically important change), precision (the accuracy of an instrument or measure's score), interpretability (the ease with which the data generated by a instrument/measure can be understood) and feasibility (the ease of an instrument or measure to administer or process) (Kabir & Wykes 2010).

In this research, the primary focus is to establish the reliability and responsiveness of specific breathing pattern components, in order to determine their potential usefulness as an outcome measure. Therefore, this chapter comprises a brief overview of the concept of reliability and responsiveness. Followed by details regarding existing outcome measures that are frequently used to monitor respiratory health.

3.2 Reliability

The term reliability is often used interchangeably with the words reproducibility, repeatability and stability. Although, it is acknowledged that these words have slightly different meanings, it can be suggested that these terms are conceptually aligned (Weir 2005), with the differences being mainly linguistic and not different in terms of meaning. Baumgartne (1989) divided reliability into two types, namely: relative and absolute reliability. Relative reliability is defined as 'the degree to which individuals maintain their position in a sample over repeated measures' (Bruton et al. 2000) and absolute reliability is defined as 'the degree to which repeated measurements vary for individuals' (Bruton et al. 2000). Relative reliability is often assessed using correlation coefficient analysis, while absolute reliability is assessed using measurement error calculations. The first study of this research examines the test re-test reliability of breathing pattern components, which is defined as the extent to which the measured value of a given variable remains consistent at different time points (Trochim 2006). There are three important components of test re-test reliability: change in mean, re-test correlation and measurement error (Hopkins 2000). Change in mean can be obtain using t-test and/or analysis of variance (ANOVA), while re-test correlation can be estimated using intra class correlation coefficient. Measurement error can be calculated using Within Subjects Standard Deviation WSSD and Smallest Real Differences SRD, while agreement can be estimated using Bland-Altman analysis (see section 5.2.10 for more details regarding these statistical analyses).

3.3 Responsiveness

Responsiveness is the ability of a measure to detect change that is relevant or meaningful to a researcher or clinician (Husted et al. 2000). de Vet et al. (2006) further defines responsiveness as 'the correct identification of real change according to the external criterion'. For an outcome measure to be

considered useful, it is essential that it can detect changes over time in order to reflect the effects of a therapeutic intervention (Fitzpatrick et al. 1998). However, it is difficult to achieve this when there is a lack of clearly defined, valid external criteria within the existing literature. To determine the responsiveness of a measure without a criterion measure of change in a single group, a pre-post design is often used. Meaning that, participants are measured twice; once before and once after treatment. Although, it is essential that the treatment is effective in producing or inducing change, or else the change might not be meaningful (Lydick & Epstein 1993).

Currently, there is no consensus regarding how best to assess the responsiveness of a measure, several statistical approaches have been proposed (Fitzpatrick et al. 1998; Schuck & Zwingmann 2003). Frequently, inferential statistics are used as an indicators of responsiveness; including, paired t-test and ANOVA (Wyrwich & Wolinsky 2000). However, the results from statistical methods, such as paired t-test and ANOVA, are affected greatly by the sample size (Samsa et al. 1999) and although, the p value may indicate a change, it does not reflect the magnitude of the change that has occurred (Sullivan & Feinn 2012). Hence, effect size calculations have been proposed as alternative indices for determining the importance of change as they do not depend on sample sizes and they provide more detailed statistical information regarding the size of the effect (Schuck & Zwingmann 2003). Effect size is defined as the difference between the mean outcomes in two different groups or at two different time points (Coe 2002; Sullivan & Feinn 2012).

The reliability and responsiveness of outcomes measures frequently used in respiratory physiotherapy has not been decisively established within existing literature. Current outcome measures are discussed in the subsequent sections.

3.4 Current outcome measures for physiotherapy to monitor respiratory health

Respiratory physiotherapists use a variety of outcome measures to monitor and evaluate interventions; however, most outcome measures are not specifically developed or designed to assess or evaluate physiotherapy interventions, but rather are used for diagnostics and are often affected by other confounding factors. Moreover, there is a degree of ambiguity surrounding procedural, physiological and clinical outcomes associated with therapeutic interventions (Lewis et al. 2007). Consequently, there are currently no gold standard outcome measures that are specifically related to respiratory physiotherapy interventions (Marques et al. 2015). Therefore, monitoring respiratory health to detect a significant change following respiratory interventions is challenging due to the lack of reliable, sensitive and valid outcome measures and has been a barrier to the further development of an evidence base in all areas of respiratory physiotherapy.

3.4.1 Respiratory sound – *Auscultation*

Auscultation is a widely-used, conventional method used by physiotherapists as an assessment tool in patient examination. It is commonly utilized because it is practical, simple to use, inexpensive, non-invasive, safe and able to detect abnormalities of the respiratory system (Abbas & Fahim 2010). However, auscultation with a stethoscope has limitations. One issue relates to subjectivity, as the process depends on the clinician's own hearing, experience and ability to differentiate between different sound patterns and to detect adventitious sounds (such as, fine and coarse crackles and wheezes). Moreover, there is a lack of consistency in the terms used when reporting lung sounds (Wilkins et al. 1989; Allingame et al. 1995; Pasterkamp et al. 1997).

There have been some attempts to establish the reliability and accuracy of physiotherapists in interpreting lung sounds. One such study was conducted by Brooks et al. (1992), which investigated the accuracy and inter-rater reliability of 26 cardiorespiratory physiotherapists in identifying and categorising lung sounds using a standardized list of terms. The sounds examined included: high and low pitched wheeze[1], bronchial breath sounds[2], stridor and pleural rub[3]. The findings revealed that physiotherapists were neither accurate (r=0.08) nor reliable (kappa=0.26) in interpreting auscultating tape-recorded lung-sounds and the number of years' experience was not found to have an effect on accuracy. A similar finding was established by Allingame et al. (1995) in a study examining the accuracy and reliability of newly qualified (n=16) and experienced (n=16) cardiopulmonary physiotherapists in interpreting auscultated lung sounds. Both inter-rater and intra-rater reliability were found to be poor, with no significant inter-group differences in reliability; hence, experience was not found to have a significant effect on accuracy or reliability. In both studies, detecting crackles was found to be less accurate than wheeze.

Despite the lack of evidence regarding the accuracy and reliability of respiratory sound, its use in monitoring and defining therapeutic approaches is still wide spread in clinical settings, perhaps due to its simplicity and availability. However, as Warnock et al. (2013) assert, conventional auscultation has not been used as an outcome measure in recent research. Therefore, due to its poor reliability reported within the literature, it can be suggested that respiratory sounds alone are not reliable as an outcome measure for the monitoring and diagnosis of respiratory health.

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[1] High and low pitched wheeze: whistling sound made while breathing and it is always associated with difficult breathing.
[2] Bronchial breath sounds: are tubular, hollow sounds, which are heard when auscultating over the large airways.
[3]stridor and pleural rub: Stridor is a loud, high-pitched crowing breath sound heard during inspiration but may also occur throughout the respiratory cycle most notably as a patient worsens, pleural rub is a 'creaking', coarse, grating or leathery sound, and is similar to the sound of bending stiff leather or treading in fresh snow. From: https://www.mayoclinic.org

3.4.2 Respiratory lung function – *Spirometer*

Lung function components including the (volume and flow of air that can be inhaled and exhaled during specific duration) are important tools in the investigation and monitoring of patients with respiratory diseases (Ranu et al. 2011; Marques et al. 2015). A spirometer is a device commonly used to monitor lung function components (Wanger et al. 2005). The spirometer works by measuring the volume of air that can be forcefully expelled in one second after a maximal inhalation. Several clinical guidelines have recommended the use of spirometry as the gold standard in the diagnosis and management of chronic pulmonary diseases (Pauwels et al. 2001; Burkhardt & Pankow 2014; WHO 2017), which demonstrates the significance of spirometry as an important instrument in the measurement of lung function and accounts for its wide-spread use as the primary instrument to measure pulmonary function within clinical practice. Also, spirometers are small, portable and easy-to-interpret (Miller et al. 2005b).

However, there are disadvantages related to the use of spirometry. In particular, is the invasive nature of the spirometric device, including the use of a nose clip to minimize the loss of air through the nose and the use of a mouthpiece. Moreover, the forced vital capacity manoeuvre can be simple to perform for some people, although most individuals still require some form of training to perform it effectively (Miller et al. 2005a). Additionally, some individuals can find the manoeuvre difficult, particularly children, elderly and those with respiratory disease (Enright 2012). Therefore, spirometry is effort dependent and requires cooperation from the patient and precise administration and training by the clinician.

FEV_1 measured using spirometry has been used within research and clinical settings to assess the effectiveness of respiratory interventions in patients with asthma (Bowler et al. 1998; Slader et al. 2006; Thomas et al. 2009; Grammatopoulou et al. 2011). However, contradictory findings have

emerged from a number of systematic reviews conducted by Burgess et al. (2011), O'Connor et al. (2012) and Freitas et al. (2013) involving randomized and non-randomized controlled trials, which examined the effect of breathing modification techniques (Buteyko Breathing technique, respiratory physiotherapy training and yoga breathing) on FEV_1 when used as an outcome measure following a therapeutic intervention. No significant effects of breathing retraining on FEV_1 in some studies (Bowler et al. 1998, Slader et al. 2006, Holloway and West 2007 and Thomas et al. 2009), while significant improvements in FEV_1 were found in others (Jain et al. 1991; Jain & Talukdar 1993; Santaella et al. 2011).This may be related to the different age groups included within the sample of these studies or the participants' cooperation to perform the spirometer test or relationship between participant and clinician (Drexel et al. 2011). Moreover, participant numbers were generally small and the follow-up times were short. Because each study employed different interventions and applied different protocols, meta-analysis for FEV_1 was not possible because of high heterogeneity. Hence, it can be suggested that lung function parameters measured alone using a spirometer is not sufficient to assess the effectiveness of respiratory physiotherapy interventions (Marques et al. 2015).

3.4.3 Blood gas analysis

Another method of assessing lung function involves determining arterial blood gas tension (Al-Dulymi & Hainsworth 1975). The measurement of arterial blood gas tensions often forms part of the routine assessment of patients with acute and chronic respiratory disorders, particularly those producing abnormalities of gas exchange, including asthma and COPD (Pitkin et al. 1994). However, this method involves arterial catheterisation, which is invasive, time consuming and requires special equipment and skills. More recently, a new, non-invasive method of measuring blood-gas

tension has emerged, which involves measuring End-Tidal Carbon Dioxide ($ETCO_2$), discussed in the next section.

3.4.3.1 End-Tidal Carbon Dioxide- *capnography*

In healthy individuals, $ETCO_2$ reflects metabolism, circulation, and ventilation, and is typically equal to arterial CO_2. Normal $ETCO_2$ values are between 35–45 mmHg (between5-6% Kap) (Bryant 2013). Research has shown concordance between capnography and arterial blood gas (Donald & Paterson 2006) and even with patients experiencing acute bronchospasm, expired CO_2 ($ETCO_2$) is usually within 1 mmHg of arterial CO_2 ($PaCO_2$) (Corbo et al. 2005). $ETCO_2$ has been used as an outcome measure in research and clinical settings to assess respiratory health (Howe et al. 2011; Grayson 2015). $ETCO_2$ is measured using capnography, which provides breath-to-breath ventilation data in quantitative waveform. The wave formation presents a graphical measurement of carbon dioxide partial pressure (mmHg) during expiration (John 2003). Asthmatics often produce a “shark fin” capnography waveform due to the difficulty in emptying the alveoli during acute bronchospasm (Wampler 2011) see figure 3-1.

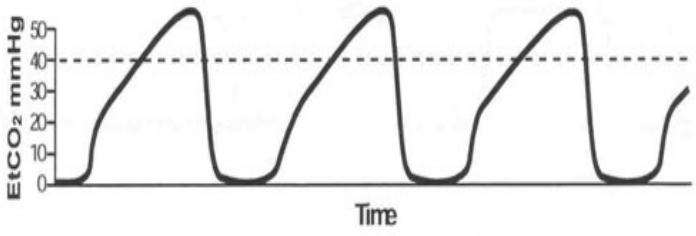


Figure 3-1: Asthma capnography waveform (shark fin)
From: https://emtlife.com/threads/is-petco2-overrated.35487/

An advantage of this method is that it is non-invasive, portable, inexpensive and provides continuous measurement of exhaled carbon dioxide concentration over time (Harigopal & Satish 2008). Moreover, a study by Yosefy et al. (2004) examined the $ETCO_2$ in 73 (m=47, f= 26) emergency department patients with respiratory distress to assess its reliability and accuracy in predicting $PaCO_2$. Comparisons were made between $PaCO_2$ and $ETCO_2$ measured by capnography. Significant correlations were found between $ETCO_2$ measured using capnography and $PaCO_2$ (r=0.79) indicating its reliability. However, correlation is not a sufficiently comprehensive measure for accurately determining reliability (Bland & Altman 1995). Moreover, two factors were found to affect the reliability, including age and temperature. This may suggest a potential limitation of this method, since $ETCO_2$ in patients with unstable cardiac status, unstable body temperature and presence of lung disease will not accurately reflect $PaCO_2$. Hence, the use of capnography in patients with severe respiratory failure should be interpreted with caution (John 2003).

Measuring $ETCO_2$ has been suggested as a potential outcome measure in assessing the effectiveness of breathing retraining interventions in asthma management. However, conflicting data has been reported within the literature regarding the effect of breathing retraining on $ETCO_2$. For example, a study by Grammatopoulou et al. (2011) examined $ETCO_2$ following 12 physiotherapist-led breathing training sessions over 6 months in addition to usual treatment in 20 adults with mild/moderate asthma in comparison to the control group of 20 also with mild/moderate asthma. They found significant increases in $ETCO_2$ in the intervention group (from 34.3 to 38.5, $p< 0.0001$), which took participants from being below the normal $ETCO_2$ levels to within the normal expected $ETCO_2$ range. Whereas, no significant differences were found in the control group that continued with usual treatment only. These findings were in agreement with a study by Meuret et al. (2007) involving 12 asthma patients that were randomly

assigned to either a 4-week Buteyko breathing exercise programme or usual treatment. The experimental group significantly improved asthma control and raised $ETCO_2$ (from 34.4 to 38.5) when compared with the control group. Conversely, no significant differences in $ETCO_2$ have been found in other studies involving various breathing training interventions in comparison with control or other intervention groups; including Bowler et al. (1998), Slader et al. (2006), Holloway and West (2007) and Thomas et al. (2009). The conflicting data within the literature regarding changes in $ETCO_2$ as a result of physiotherapy breathing retraining interventions may suggest this method lacks of the ability to accurately and reliably determine change occurring due to an intervention, but rather is more useful to assess general and immediate respiratory health.

3.4.4 Dyspnoea/ Breathlessness- *scales and questioners*

The American Thoracic Society (1999) defines dyspnoea as "a subjective experience of breathing discomfort that consists of qualitatively distinct sensations that vary in intensity". It is commonly seen in patients affected by respiratory diseases, such as COPD and asthma, and originates from an intricate interaction between physiological and psychological factors (Rose 1999). It is a multidimensional experience that affects many aspects of patients' lives, causing distress and anxiety, limiting activity and independence, and negatively impacting quality of life (Yorke & Savin 2010). Dyspnoea is also an important prognostic indicator of adverse outcomes (Baker et al. 2013). Also, according to Bott et al. (2009) dyspnoea is a key feature of asthma and is the symptom most likely to bring patients to the physiotherapist. The measurement of dyspnoea in asthma is necessary for many reasons: firstly, it is a characteristic of asthma; secondly, dyspnoea represents a warning signal to the patient, making it an essential component in self-monitoring. Thirdly, it is an

important outcome variable within clinical and research settings when a goal is the effective management of symptoms (Yorke et al. 2011).

Dyspnoea is assessed using questionnaires and surveys that have been developed by various researchers in an attempt to capture the various aspects of dyspnoea and to offer standardised clinical descriptors. However, only a limited number of studies have focused on dyspnoea descriptors and their clinical utility (Antoniu 2010). Moreover, most questionnaires were developed using people with COPD and each survey examines various different aspect of the disease. As Yorke et al. (2009) point out, there is currently no questionnaire that incorporates distress and anxiety, limitations on activity and independence and quality of life caused by dyspnoea. Hence, it may be necessary for clinicians and researchers to use a combination of surveys to gain a comprehensive understanding of the symptoms of dyspnoea as perceived by the patient.

Systematic reviews by Burgess et al. (2011), O'connor et al. (2012) and Freitas et al. (2013) examining the effects of breathing retraining interventions in asthma found significant improvements in questionnaire scores (Nijmegen questionnaire [NQ]) within intervention groups involved in breathing retraining programmes in comparison to control groups. The NQ is a screening tool that helps detect patients with hyperventilation complaints (van Dixhoorn & Folgering 2015). The NQ comprises a number of items that relate to both anxiety and asthma (shortness of breath, chest tightness, and palpitations) (Ritz et al. 2001; Bruton & Holgate 2005b). However, the use of NQ for patients with asthma has been questioned, since an elevated NQ score does not provide a diagnosis of asthma and the NQ is only a reflection of a subjective aspect of dysfunctional breathing (van Dixhoorn & Folgering 2015). Nevertheless, the NQ is often used as an outcome measure in clinical research, but due to the limitations, the use of the NQ alone for hyperventilation screening or diagnostic testing is not

sufficient (Li Ogilvie & Kersten 2015). Thus, the assessment of various other factors, including history taking, assessing vital signs and breath sounds, and perhaps breathing pattern are also necessary in order to complete a thorough and comprehensive clinical investigation.

3.5 Summary

This chapter comprised a brief overview of the concept of reliability and responsiveness and detailed the current outcome measures used by respiratory physiotherapists. Evaluating both reliability and responsiveness are essential in determining the usefulness of a potential outcome measure; however, there is currently no gold standard outcome measure specifically related to monitoring changes that occur following respiratory physiotherapy interventions. This lack of reliable, responsive and valid outcome measure is a potential barrier to the further development of respiratory physiotherapy. The aim of this research is to establish the reliability and responsiveness of specific breathing pattern components as a potential outcome measure to address the existing lack.

Chapter 4 Breathing pattern monitoring

4.1 Introduction

Breathing pattern can be monitored using two techniques; visual inspection (subjective) and direct measurement (objective). The clinical assessment of breathing pattern has traditionally been carried out by a visual inspection of respiration, which involves watching the chest rise and fall over a specific period of time (often between 15 and 60 seconds) at bedside. However, this method has a number of limitations due to its subjective nature and has been criticised as being inaccurate, since clinicians often measure chest wall motion for 15 seconds and multiply this by 4 for normal quiet breathing (Tobin 1992). Therefore, there is a chance for a degree of error to be at least 4 breaths per minute. Also, there have been suggestions within the literature that a difference of ±2 breaths per minute may be clinically significant (Cretikos et al. 2008; Smith et al. 2011). Also, a study by Lovett et al. (2005) involving 159 patients (aged 18-89) found that emergency department triage nurses' using visual inspection assessments demonstrated low sensitivity in detecting bradypnoea (abnormally slow breathing) and tachypnoea (abnormally fast breathing), and showed poor agreement with the criterion standard, which was in accordance with WHO recommendations of auscultation or observation for 60 seconds.

Furthermore, Philip et al. (2015) showed that two forms of visual assessment of breathing frequency ('spot' and formal assessment methods) by 159 doctors were inaccurate in 52% and 19% of cases respectively. 'Spot' assessment involved 12 seconds of visual inspection without any form of timer, while 'formal assessment' involved visual inspection for a longer period of either 30 seconds (and multiplying by 2)

or for 60 seconds (in line with the hospital guidelines) and with the use of a timer. Therefore, it can be suggested that visual methods of assessment of Bf by both doctors and nurses are lacking in accuracy. In addition, visual observations and palpation of paradoxical motion of the chest wall can be used to diagnose various respiratory conditions (Clanton & Diaz 1995); however, Kaneko et al. (2015) asserts that due to the difficulties in assessing obstruction, subjective measures of chest wall motion can also be inaccurate.

In an attempt to address the inaccuracies associated with subjective monitoring of breathing pattern, direct measurement of ventilation provides a more objective analysis of breathing pattern. There are currently several devices available to objectively record breathing pattern. These devices can be broadly divided into two categories; firstly, are invasive methods of monitoring breathing pattern that involve the use of an external instrument, which attaches to or covers the route of the airway, such as a face mask or mouthpiece. Secondly, are non-invasive methods, which involve monitoring breathing pattern in ways that do not cover or attach to the airway, such as those using a thoracic band or sensors placed on, near, or around, the trunk. The following section provides an overview of the existing tools used to monitor breathing pattern.

4.2 Invasive devices to measure breathing pattern- Pneumotachograph (PNT)

Within clinical settings, the most widely available and frequently used methods of assessing respiratory health are spirometer and pneumotachograph (the spirometer has been discussed in detail in previous section 3.4.2). The pneumotachograph measures flow in terms of the proportional drop across a fixed resistance consisting of numerous capillary tubes in parallel (Soose et al. 2010). Its precision in the direct

calculation of airflow and volume means that the PNT is currently considered as the gold standard in airflow measurement (Berry et al. 2005). The PNT consists of a facemask with a differential pressure transducer, which is placed directly over the airway and directly measures the differences in pressure of airflow across a resistive device. There are three different types of pneumotachograph, which differ in the type of resistant device that the airflow crosses, namely pressure differential, hot wire, and turbine. Pressure differential is deemed the most reliable (Soose et al. 2010).

Grenvik et al. (1966) found no significant differences between the PNT and a spirometer in an experimental investigation examining the reliability of PNT. Moreover, in a more recent study conducted by Groepenhoff et al. (2011), the smallest detectable change (SDC) in vital capacity (VC) and alveolar volume (VA) in 28 healthy individuals was measured using a PNT and mass-flow sensor. The PNT device derived smaller SDC values than the mass flow sensor. Hence, the researchers concluded that PNT is the preferred instrument to estimate lung volume change over time (Groepenhoff et al. 2011). However, this finding is limited to healthy individuals and consequently, might not be generalisable to patients with respiratory disease.

Among the advantages of the PNT device, it is lightweight, robust, portable and provides continuous measurement of ventilation (Osborne 1974). A limitation of the PNT, however, is that it requires frequent calibration and recalibration in order to ensure accuracy of integration; this can be cumbersome for the PNT operator (Soose et al. 2010). Moreover, this device involves the use of oronasal seal; this is a drawback related to the use of the PNT since the negative impact of facemasks and nose clips on breathing pattern have been established (Golla & Antonovitch 1929; Gilbert et al. 1972; Askanazi et al. 1980). Also, some patients with certain

conditions, such as neuromuscular disease, may have difficulty achieving a proper mouthpiece seal due to muscular weakness. This can result in leakage of air and consequently, an underestimation of volumes (Orlikowski et al. 2009). In addition, the PNT device cannot measure thoracoabdominal motion, which is one component under examination in this research.

4.2.1 Effects of invasive equipment in breathing pattern

There are suggestions within the literature that the type of equipment used to monitor breathing pattern may have an impact on the very components that are under observation; this is found most notably with the invasive methods of breathing pattern monitoring that involve the use of mouthpieces, face masks and nose clips. This is associated with an increase of V_T and reduction in Bf (Gilbert et al. 1972; Askanazi et al. 1980; Perez & Tobin 1985).

Gilbert et al. (1972) examined the influence of respiratory apparatus on breathing pattern in 14 participants (6 healthy, 8 with respiratory disease). Breathing pattern was monitored at rest in the supine position for one hour using a magnetometer, which detects changes in anterior-posterior diameter of the chest and abdomen. This was followed by simultaneous recording of breathing pattern with magnetometer and spirometer with a mouthpiece and nose clips. The findings revealed that Bf decreased in every case with the use of a mouthpiece and nose clip by an average of 6 bpm and V_T increased in all but one case (by an average of 124ml). However, no statistical tests were performed, so the statistical significance of the differences between the two conditions is not known. Also, the use of magnetometer to record breathing pattern is questionable, since it does not measure lateral change of the chest wall, but rather measures anterior-posterior change in the rib cage and abdomen and is therefore restricted

to the 2 degree of freedom assumption, which has some limitations (Konno & Mead 1976, section 4.4.1).

Askanazi et al. (1980) also explored the impact of invasive monitoring equipment on breathing pattern in a study involving 28 healthy participants. Tidal volume (V_T) was recorded as 479 ml ±0.103 ($p<0.001$) with facemasks and 416 ml ±0.126 ($p<0.01$) with the mouthpiece plus nose clip, while minute ventilation (V_{min}) was recorded as 7.7±1.9 L/min and 6.7±1.2 L/min respectively. These recordings were significantly increased in comparison to those measured using the canopy system, which recorded decreased V_T as 362 ml ±0.8 and V_{min} as 5.9±1.6 L/min. No significant change in Bf was found. However, the canopy system involves placing a transparent head chamber around the patient's head. Some individuals may find it restricting and claustrophobic, which may induce anxiety that may affect breathing pattern (Homma & Masaoka 2008). Nevertheless, the Askanazi et al. (1980) study highlights the effect of mouthpieces and nose clips on breathing pattern.

Another study that explored the effect of nose clip and mouthpiece on various breathing pattern components was conducted by Perez and Tobin (1985). The breathing pattern of 46 healthy adults (m=34, f=12) was monitored using different devices and then the data were compared. Firstly, with just a spirometer using a rubber mouthpiece; secondly, a spirometer was used to monitor breathing pattern with a rubber mouthpiece, but with the addition of a nose clip. Then, a non-invasive device RIP was used to monitor breathing pattern using elasticated bands placed around the abdomen and thorax. The impact of the various devices on breathing pattern components was then examined. The data revealed that the most significant changes in breathing pattern occurred when a mouthpiece and nose clip were used simultaneously; with significant increases in V_T (411±83 v. 493±125, $p<0.001$), V_{min} (7.00±1.47 v.

7.56±1.42, $p<0.01$), T_i (1.42± 0.25 v. 1.57± 0.34, $p<0.05$) and T_e (2.28± 0.47 v. 2.51±0.73, $p<0.05$) and a significant decrease in Bf (17.7±2.8 v. 16.5±3.5, $p<0.05$) when compared to the data collected using the non-invasive device. However, the subjects were divided into four groups, which reduces the statistical power to detect differences and could affect the generalisability and validity of the final findings (Button et al. 2013). Nevertheless, Perez and Tobin (1985) concluded that the main determinant of the change in breathing pattern components induced by an invasive device occurred as a result of a change in breathing from nasal to oral route. Han et al. (1997) also examined the effects of breathing pattern recording devices on breathing pattern components. Breathing pattern of 74 healthy adults was monitored using RIP device and a PNT device with mouthpiece and nose clip attached. Breathing pattern was monitored for five minutes. Again, the results revealed significant increases in V_T (575.1±260.2 v. 696.1±373.4, $p<0.001$) when breathing was recorded using the PNT in comparison to the non-invasive RIP device.

The previous studies have investigated the effect of measuring devices on breathing pattern components while at rest; other authors have examined the effect of the device on breathing pattern components during exercise. For example, Bloch et al. (1995) demonstrated the effects of invasive breathing pattern recording methods on breathing pattern components in 6 healthy adult males during exercise. Participants exercised on a cycle ergometer at a rate of 50-60 revolutions per minute for five minutes, which then increased 25W every minute thereafter until they reached volitional exhaustion. Firstly, breathing pattern was monitored using an RIP device and on a second occasion, exactly the same methodological protocol was followed except that nose clips were worn and breathing pattern was monitored using a mouthpiece connected to a spirometer. The results showed significant differences in breathing pattern components between the two conditions (non-invasive and invasive monitoring) during mild

exercise, with significant increases in V_T ($p<0.05$) and Breathing Cycle ($p<0.05$), but no significant differences were noted during maximal exercise states. Total breathing cycle at rest also significantly increased ($p<0.05$) when measured using the mouthpiece and nose clip and V_T at rest was found to be associated with an increase of 37%, although, this increase was not statistically significant. These results indicate the potential impact of invasive apparatus on breathing pattern even during exercise.

The aforementioned studies provide evidence that invasive apparatus associated with breathing pattern monitoring devices, such as face masks, mouth pieces and nose clips, can impact various breathing pattern components. The impact on thoracoabdominal motion, however, remains unknown, partly because of the difficulties in conducting simultaneous recordings using equipment that can measure these components.

4.3 Non- invasive methods of recording breathing pattern from chest wall motion (body plethysmography)

There are a number of devices that enable the monitoring of breathing pattern components that do not require the use of invasive equipment. Particular advantages of these devices are that they limit the amount of pain and discomfort and they do not require the individual to perform any specific breathing manoeuvres. Also it does not change the route of breathing from nasal to oral (Perez &Tobin 1985). Moreover, the effect of these devices on breathing pattern components appears to be less than that of the non-invasive devices. Non-invasive devices that are frequently mentioned within the literature include: Opto-Electronic Plethysmography (OEP), electrical impedance tomography (EIT), Structured Light Plethysmography (SLP) and Respiratory inductive plethysmography (RIP). The following sections comprise a detailed description of each device, including the advantages and disadvantages of their uses.

4.3.1 Opto-Electronic Plethysmography (OEP)

Opto-Electronic Plethysmography (OEP) externally evaluates chest wall motion to estimat pulmonary ventilation. It involves the analysis of the movements of a large number (frequently 86) of retro-reflective markers placed non-invasively on the skin of the chest anterior posterior and lateral (Aliverti & Pedotti 2002). At least four (charge-coupled device) cameras are strategically placed at different points around the room, which emit infrared laser beams that are reflected by the markers. This enables the computation of the three-dimensional X-Y-Z coordinates of each marker using a specific algorithm. Consequently, the OEP has no restriction in relation to the number of degrees of freedom, since it facilitates the measurement of three compartments (pulmonary and abdominal ribcage, as well as the abdomen), and therefore, it is capable of breath-by-breath, three-dimensional, real time assessment of estimate lung volumes in three compartments of the chest wall. This may provide better understanding of breathing mechanisms in patients with respiratory diseases (Parriera et al. 2012).

A number of studies have been conducted attempting to establish the validity and reliability of OEP (Cala et al. 1996; Aliverti & Pedotti 2002; Layton et al. 2011a; Vieira et al. 2013). In a recent review of the literature by Massaroni et al. (2017a), data from 170 studies using OEP devices in healthy/diseased, young/old participants, at rest or during exercise and in different body positions was collated. Many studies collected data relating to V_T measurements using a PNT or spirometer and compared it with the same data collected using an OEP device. The findings from the validity studies within the literature review largely demonstrated good linear correlations between the OEP and the other devices. Moreover, the difference between the V_T data collected using the OEP and the other methods were less than 4% in all cases.

In order to increase the performance of OEP, Massaroni et al. developed a new method of computing volume changes and a new calibration algorithm. In 2017, Massaroni et al. (2017b) examined the validity of a new computing method, which computes the volume enclosed within the chest by defining 82 prisms (246 tetrahedrons) from the 89 reflective markers, called prism-based method. The conventional method computes chest volume by evaluating chest wall motion with a sum of 56 triangles obtained by connecting the tridimensional coordinates of the markers. Breathing pattern in 8 healthy males (mean age of 25±2 years) was recorded for 1 minute in a standing position. The chest volume from both methods were compared with a direct measurement of V_T recorded using spirometer. The findings suggest that V_T derived from the prism-based method demonstrate better agreement and lower difference (r= 0.94, 2.23%) then conventional methods (r= 0.92, 3.56%) when compared with V_T derived from spirometer. During the validation study for the new calibration algorithm, Massaroni et al. (2016) found that the OEP device correlated closely (Pearson's $r > 0.9$) with V_T measurements derived from a Breath-by-Breath gas analyser (BbB) in 5 healthy males and 5 male athletes (mean age of 31.5±5.6 years) during exercise on a cycle ergometer in different body positions. Thus, the researchers concluded that the OEP demonstrates good concurrent validity. However, spirometers and BbB devices measure lung gases, while the OEP measures movement in the chest wall; hence, these devices are not similar in the way they measure ventilation. It may have been more appropriate to compare the OEP with another non-invasive device that measures chest wall motion. Nevertheless, these results appear to indicate that the OEP instrument is a reliable method to assess chest wall volumes.

However, placing 89 markers exactly on specific reference points on the chest wall of each participant/patient is time-consuming for both the researcher and participant and requires practice and training to correctly

identify the appropriate anatomical location for each marker (Layton et al. 2011). This procedure may also increase the participants' awareness of their breathing pattern (Hen et al. 1997). Also, since the markers are set into fixed positions in relation to the cameras, the participants' movement is restricted (Que et al. 2002). Hence, in an attempt to increase the practicality of the OEP for use in research and clinical settings, Massaroni et al. (2017c) evaluated the differences between V_T derived from 32 markers protocol and the V_T obtain from 89 markers with V_T derived from a spirometer. Breathing pattern was recorded for 30 seconds in 10 healthy adult males (5 athletes/5 non-athletes, mean age of 25±3 and 31±5 years respectively) in different postures. High correlation was found between full markers and reduced markers protocol (Pearson's r= 0.99), suggesting that 32 markers derives data comparable with 89 markers.

Although these studies provide useful information suggesting the validity and reliability of the OEP device, the Massaroni et al. studies only including male participants, which may raise questions regarding the practicality of using OEP with female participants, since the reflective markers need to be placed directly onto the skin and not onto clothing. This may be more difficult and/or impractical with female participants/patients. Moreover, the OEP system is not portable and requires a designated operational space and the radiation emitted from the device may interfere with other medical equipment. So although the OEP device appears to be a useful and valid method of monitoring breathing pattern, it may be impractical for clinical and research settings. Moreover, the University of Southampton does not have access to this device.

4.3.2 Electrical impedance tomography (EIT)

The Electrical Impedance Tomography (EIT) is a non-invasive method for monitoring ventilatory movement; it provides a radiation free, cross-

sectional impedance image of the lung that can be used to monitor breathing pattern (Balleza et al. 2007; Costa et al. 2009; Balleza et al. 2010; Muders et al. 2010). It is able to determine the distribution of ventilation, blood supply, and diffused or localized lung defects. It can also be used to detect alterations in assisted ventilation of neonates and estimate therapeutic interventions (Chatziioannidis et al. 2011).

EIT involves the placement of 16 or 32 low alternating current electrodes that are attached to the skin using adhesive material or within an electrode belt placed around the thorax. These electrodes then emit low electrical currents, injected through pairs of adjacent electrodes in a rotating mode. The EIT then transforms the data into a two-dimensional image of the distribution of electrical impedance within the chest wall working on the assumption that the impedance of tissue within the lungs will vary depending on the air content (Hinz et al. 2003).

Balleza et al. (2007 & 2010) examined the validity of EIT for monitoring breathing pattern in 13 healthy individuals (m=6, f=7, mean age 36.7± 13.4years) and 13 male participants (mean age 67±9 years) with COPD in two different studies following the same protocol, using a new generation of EIT, while comparing it to simultaneous measurements obtained using a PNT device. Tidal volume was recorded during quiet breathing during several 30-second slots (which derived approximately 5 to 8 respiratory cycles) with 3 minutes rest between each slot until a total of 25-30 breathing cycles were recorded for each participants.

In the first study by Balleza et al. (2007) involving 13 healthy individuals, the mean±SD V_T measured by the PNT and the EIT was 0.52±0.10 L and 0.53±0.11 L, respectively, which was not found to be statistically significantly different. The correlation coefficient between the 2 measurements was 0.923 and the mean of the differences between the 2

procedures was -0.003 L (95% confidence interval, -0.045 to 0.038) suggesting that the EIT provides an alternative method of monitoring V_T in healthy adults. However, in the second study by Belleza et al. (2010) involving a group of 13 COPD male patients, the mean V_T estimated with EIT and the PNT were found to be statistically significantly different ($p<0.01$); 0.580±0.212 L and 0.774±0.173 L, $r = 0.861$ (respectively). Indicating that EIT is not a valid method to assess ventilation in patients with respiratory diseases. In addition, there were issues with the quality of the EIT readings due to the 'noise' caused by poor cable contact or movement of electrodes and individual physical characteristics were also found to affect the calibration of the EIT and consequently, calibration could only be carried out using the PNT and a complicated, altering equation.

Reifferscheid et al. (2011) examined the reproducibility of repeated EIT measurements with a mean time interval of 8±5 days. The study also investigated the effects of different electrode placement (upper and lower chest planes) and three different postures (sitting, supine and right lateral). The study comprised 10 healthy subjects (m=8, f=2, mean age of 30 ±3 years). Breathing pattern was monitored using an EIT and spirometer during tidal breathing and vital capacity manoeuvre at two different days with a minimum of 48 hours gap. The results indicated that the EIT demonstrated good reproducibility in both upper and lower chest planes, in all 3 positions and during the two different types of breathing with Pearson's r values of above 0.8 in all cases. However, the use of Pearson's r has been actively discouraged for test re-test reliability studies, because correlation can only be determined if the relationship between the variables under examination is linear (Haas 1991; Rankin & Stokes 1998). Moreover, Reifferscheild et al. (2011) stated that it is difficult to draw strong conclusions regarding the inter-rater reliability, since the device used involved placement of a number of individual electrodes onto the

patients' chest wall, this will inevitably lead to some slight differences in electrode placement; although this problem may be resolved through the use of the electrode belt that many EIT devices now utilise. Nevertheless, this study does appear to demonstrate that EIT data obtained on separate occasions relating to regional ventilation is reproducible.

The literature regarding the validity of the EIT is conflicting and inconclusive and the literature regarding its reliability is limited. Another limitation of the EIT relates to the low spatial resolution, which affects the quality of the image produced. The low resolution and the complexity of the regional information provided by EIT systems may cause issues in accurately interpreting the information (Putensen et al. 2007). In addition, EIT provides limited information regarding chest wall motion as the band measures the rib cage area only, which might not represent the full reality of the movement that occurs in chest wall during ventilation.

4.3.3 Structured Light Plethysmography (SLP) - Contactless devices

Recently, Structured Light Plethysmography (SLP) technology has been developed to provide a non- contact monitor for tidal breathing components and chest wall motion. SLP measures displacement that occurs in the anterior chest wall by projecting a structured grid pattern of light onto the anterior surface of the chest wall, while two digital video cameras record the displacement of the grid at 30 frames per second at rest. Recordings can be made in different body positions: sitting, standing or supine (de Boer et al. 2010). Subjects are required to wear a fitted, white t- shirt that follows the contours of the body with as few creases as possible. To correctly align the SLP grid, the individual needs to locate their xiphisternum, this then acts as a guide for the placement of the central point of the grid. During inspiration and expiration, a one-dimensional image of the chest wall is provided from which the tidal

breathing component is calculated using a pre-programmed algorithm built into the existing software of the device which creates a 3D reconstructed image of the chest wall (PneumaView-3DTM software, PneumaCare Ltd). Then numerical data regarding a number of clinically relevant components per each recording period is outputted immediately onto an integrated computer screen (de Boer et al. 2010).

An advantage of the SLP is that it is a completely contactless device, enabling the diagnosis and monitoring of respiratory diseases and ventilation (Hmeidi et al. 2015). Whereas other existing tools for recording breathing pattern are either invasive or are laboratory based and require the use of complex algorithms and/or other software to extract data, which can make them impractical and unsuitable for clinical use. Yet, the design of the SLP is robust, portable and it provides direct numerical data, making it practical for the clinical environment. Since SLP is a new and emerging technology, there is very limited published data regarding its validity and reliability.

Only one full published paper by Motamedi – Fakhr et al. (2017) examined the concurrent validity and repeatability of the SLP device. Firstly, timing and volume components (Bf, T_i,T_e, T_{tot},T_i/T_e, T_i/T_{tot}, and IE50- inspiratory to expiratory flow measured at 50% of tidal volume) were recording for 45 seconds using the SLP and simultaneous PNT in 20 participants (m=13, f=7, mean age 52 ±23.5 years, 4 healthy and 16 with various respiratory disease). No significant differences were found between the measurements for all components derived from the two devices in breath-by-breath analysis and average values suggesting good concurrent validity. Also, the researchers examined the repeatability of the agreement between the two devices in 21 healthy participants (m=12, f= 9, mean age 44.7±14.7 years), both during quiet breathing and following a physical exercise stimulus. The comparisons for quiet breathing demonstrated agreement using

Bland-Altman analysis and high correlation (>0.9) for timing and volume components, indicating the repeatability of SLP at rest. Moreover, following physical exercise, the agreement increased for T_i, T_e and T_{tot} and did not differ for the other components. These findings suggest the validity of the SLP device used at rest and following physical exercise; however, no information was reported regarding the validity and repeatability of thoracoabdominal motion. This is because that SLP was compared with PNT, which does not measure chest wall motion; hence, it would be more appropriate to compare the SLP to a device that provides data regarding these components to obtain a more accurate indication of its validity and repeatability in thoracoabdominal motion.

In order to examine the ability of SLP to detect change following treatment and to differentiate between healthy participants and patients with asthma and COPD, three studies (Hmeidi et al. 2015; Hmeidi et al. 2016; Ghezzi et al. 2017) have examined the change that occurs in breathing pattern following an intervention measured using an SLP device. The results showed that the SLP device was able to detect significant decreases in rib cage contribution and lung function in children with acute asthma. However, no significant change in Bf was noted (Ghezzi et al. 2017; Hmeidi et al. 2015). Moreover, 31 patients with COPD were compared with 31 healthy adults by Motamedi-Fakhr et al. (2017) and the results suggested that participants with COPD had significantly higher thoracoabdominal asynchrony ($p<0.05$), lower T_i ($p<0.001$) and greater variability ($p<0.001$). Similar findings were reported by Hmeidi et al. (2017) where 30 children with asthma were found to have significantly lower ratio of Ti/Te and Ti/Ttot ($p > 0.001$) in comparison to 41 healthy children. Breathing pattern was recorded for 5 minutes at rest using an SLP device following a bronchodilator treatment for those with asthma. Hence, the studies appear to suggest that the SLP device is able to measure change in thoracoabdominal motion in children and adults with asthma and COPD at rest and following a bronchodilator treatment.

There are some limitations of the SLP device; for example, there is limited information provided regarding the algorithm that the SLP uses to extract data from the raw data file. As such, it is difficult to draw conclusions regarding the accuracy of the data. Also, the SLP device records breathing pattern only from an anterior aspect of chest wall, so it provides no information regarding the lateral and posterior aspects of chest wall; this information may be useful in case of tidal volume increase, such as during an asthma attack or during exercise. A potential way to overcome this limitation may be for future designs to include multiple grids to cover different aspects of chest wall.

In addition, most existing published data regarding the SLP validity and reliability has been conducted and written by various members of the SLP development team; this may have the potential to produce a conflict of interest within the research protocol and reporting. However, there is no obvious evidence to suggest that the aforementioned studies have not been carried out in a rigorous and methodical manner. Also, despite the fact that an SLP system is commercially available, it is unclear what level of accuracy that SLP has versus OEP, EIT and RIP. Therefore, it is apparent that there is a need for independent research regarding the validity and reliability of SLP in comparison to other devices. That said, there is no official or valid alternative device that has been validated to record thoracoabdominal motion, since all devices have been validated only against other devices that measure timing and volume components of breathing pattern. Nevertheless, the SLP is a new and emerging technology that is showing potential regarding its clinical usefulness for monitoring breathing pattern within a clinical environment.

4.3.4 Respiratory inductive plethysmography

Respiratory inductive Plethysmography (RIP) was introduced in 1977 by Cohn et al. and since then its use has increased and developed due to its

effectiveness as a ventilation monitoring tool in both research and clinical setting in various populations (Wilhelm et al. 2003). The RIP device is reported to be a valid, semi quantitative, non-invasive method of monitoring breathing pattern (Chadha et al. 1982; Sackner et al. 1989). It estimates respiratory parameters relating to timing, volume and the contribution of rib cage and abdomen to tidal volume by measuring the magnitude of movements in the rib cage and abdominal compartments during inspiration and expiration.

The RIP device comprises two elasticated bands that contain electro-magnetic coils, which are placed around an individual's thorax (rib cage) and abdomen (Figure 4-1). The two bands consist of a Teflon insulated wire sewn in a 'zig zag' pattern, embedded within the elastic belts. The bands are attached to an oscillator module that produces a weak sinusoidal current of approximately 20 millivolts at 300 kHz. A sinusoid is a mathematical curve that depicts a smooth repetitive oscillation.

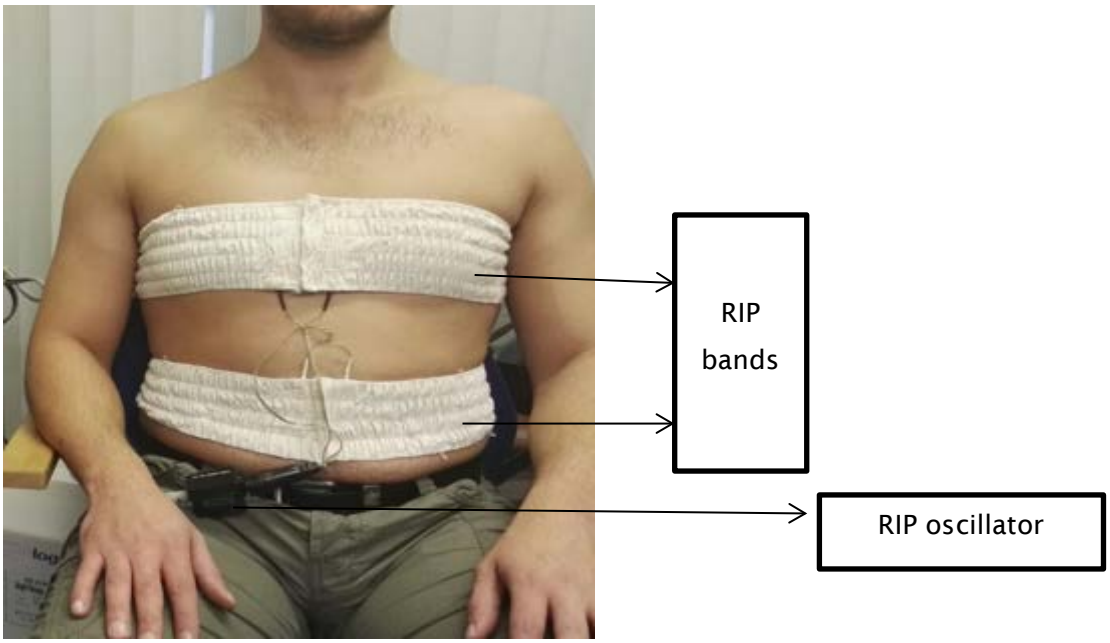


Figure 4-1: A diagram representing the anatomical location of the RIP bands positioning

During inspiration and expiration, an alternating current passes through the bands, which creates a weak electromagnetic field around the cross-sectional area of the abdomen and thorax. An opposing current is created for each compartment as changes in chest wall displacement occurs, measured as a change in voltage; this is converted by a computer to a digital respiration waveform and, after calibration; the amplitude of the waveform proportionally represents the inspired breath volume. The changes can then be stored on a computer for offline breath-by-breath analysis to facilitate estimation of breathing pattern components. The RIP device facilitates the quantification of breathing pattern over time and enables the collection of quantitative and semi quantitative measurements of breath amplitude through the calibration of signals (Stocks 1996).

One difficulty of using the RIP device is that the bands around the rib cage and abdomen are particularly sensitive to an individual's body movements, which may affect the signal quality. Also, regarding belt positioning, the RIP belts must be placed in the correct standard locations (i.e. near the nipple line (or mid-chest) and just above the belly button) to ensure quality signals. Moreover, correct band tension is important; if belts are too tight then the abdomen or chest movement will become restricted, which will affect breathing pattern and if the belts are too loose than they may move and overlap one another (Brüllmann et al. 2010). Hence, the RIP device is inherently flawed due to its design, since it can only measure excursions at the point of the actual transducer bands, and it cannot detect change that occurs in the areas not covered by the bands. Another issue with the RIP device is that its use is based on the Konno and Mead model of respiration (discussed later in this Chapter), and the validity of measurements is only as good as the underlying model. The Konno and Mead model assumes motion of the chest wall is restricted to the 2 degrees of freedom rule; hence, any change in volume is limited to movements that occur anterior-

posteriorly and laterally in the circumference of the rib cage and abdomen, rather than those that occur in the height of each compartment, which is assumed to be fixed.

Despite these limitations, the RIP device has the advantage that is a non-invasive, portable device that does not emit radiation or electrical currents that may interfere with other medical equipment. Moreover, the U.S National Institutes of Health, the International Task force of the European Respiratory Society, the Australian Thoracic Society and the American Thoracic Society have all concluded that the RIP is recommended for the non-invasive monitoring of breathing pattern in adults and infants (Grossman 2004). The methods used to calibrate RIP and the assumption behind its calibration methods are described in the next section, followed by a discussion of the validity of RIP in various scenarios.

4.4 RIP Calibration

Calibration can be understood to be the association between two measurements. This commonly involves one measurement made with one piece of equipment or device with an established degree of accuracy (usually the gold standard device) and another measurement of the same variable made with a second piece of equipment. The main aim of the calibration process is to control, quantify and reduce errors or uncertainties within measurement processes to an acceptable level by ensuring the accuracy of test equipment (Cable 2005).

Calibration of RIP is the process of estimating volume from the motion caused by the regional (rib cage and abdominal) displacement of the thoracoabdominal area. There are a number of different calibration techniques for the RIP device, each attempting to improve and increase the accuracy of the acquired data. Among the most common techniques is the iso-volume manoeuvre (Konno & Mead 1967), which can be referred to as

absolute calibration technique as it directly measures tidal volume using a PNT device. Other calibration techniques have also been developed, including the Qualitative Diagnostic Calibration (QDC) and the Fixed-K method (Banzett et al. 1995; Poole et al. 2000), which are statistical and relative methods of calibrating the RIP device (Sackner et al. 1989).

The calibration of RIP to obtain an estimate of relative or absolute tidal volume, is based on the Konno and Mead model (Konno & Mead 1967), which is discussed in the following section.

4.4.1 Konno and Mead's (1967) Two degree of freedom assumption

In 1967, Konno and Mead proposed a model of the respiratory system, which proposes that it is two separate anatomical compartments, the rib cage and the abdomen, which are separated by the diaphragm. In their theory, each compartment changes its volume as a single, independent unit during normal respiration and each contributes independently to tidal volume. The theory is that it is possible to inspire mainly with the rib cage or with the abdomen and to cause outward displacements of one while moving the other inward. Thus, it should be possible to measure the volume changes of the rib cage and the abdomen separately. Based on this assumption, Konno & Mead (1967) propose that the respiratory system moves with 2 degrees of freedom, since each compartment is considered as one degree of freedom of motion, with any change in volume considered to be linearly related to the anterior/posterior and lateral motion of each compartment. The Konno and Mead two degree of freedom assumption maintains that the volume displacement that occurs during ventilation is proportional to the sum of the displacement in the cross-sectional area of the rib cage and of the abdomen. Thus, tidal volume is estimated using the following equation:

$$V_T = \alpha \Delta RC + \beta \Delta AB \quad (1)$$

In equation 1, V_T represents tidal volume, ΔRC and ΔAB are the changes in the cross sectional area of rib cage and abdomen, and α and β r
the volume/motion coefficients or calibration factors. In order to quantify tidal volume using an RIP device, it is necessary to calculate volume/motion coefficients. So, to quantify the volume/motion coefficient, equation 1 is re-written as:

$$V_T = M [K (\Delta uVRC) + (\Delta uVAB)] \quad (2)$$

V_T = Tidal volume, ΔuVRC and ΔuVAB = changes in the uncalibrated rib cage and abdominal volumes measured by the RIP signal, K and M = the constant factors to be determined by calibration

Hence, in equation 2, M relates to the RIP output to the absolute tidal volume (e.g. in litres) as measured by a PNT device. K represents the constant of proportionality between changes in the rib cage and changes in the abdomen, such that equal output voltages equate to equal changes. Here, it represents the relative anatomical height of the rib cage and abdominal compartments, where the height of the rib cage is considered to be approximately twice the height of the abdomen. If only K is determined and M is assumed to be M=1, then relative calibration can be obtained.

This theory has the advantage of enabling the estimation of tidal volume to within 10% of the tidal volume values measured using invasive devices (that use mouthpieces and facemasks such as PNT) and consequently, it forms a theoretical underpinning of RIP calibration techniques within the literature (Tobin et al. 1983; Shea et al. 1987; Parreira et al. 2010 and Sackner et al. 1989). However, the Konno and Mead theory assumes that the height of the chest wall does not change and is fixed; although it is apparent that this is not necessarily the case, since any change in postural movement of the spine and pelvis (for example, slouching) will result in

displacement of the rib cage and abdomen by changing the distance between the xiphisternal junction and pubic symphysis.

Therefore, researchers examining breathing pattern in the sitting position should be aware that certain postural changes in the sitting position during breathing pattern recording may render the 2 degree of freedom assumption invalid. Furthermore, Tobin (1992) proposed that the respiratory system actually moves with four degrees of freedom, which comprises the changes that occur in the rib cage and abdomen laterally and the changes that occur in the height (Up/down movement) of each compartment. But, Tobin's proposals are not widely used and the assumptions of Konno and Mead are frequently applied. However, more recent, non-invasive methods of monitoring ventilation have been developed that are not limited to the 2 degrees of freedom assumption, such as the OEP and SLP (sections 4.3.1 and 4.3.3)

4.4.1.1 Iso-volume manoeuvre calibration- *Absolute method*

To calculate the volume/motion coefficient, Konno and Mead introduced the iso-volume manoeuvre. The iso-volume manoeuvre is based upon two key principles: firstly, that the respiratory system functions with a two degree of freedom assumption when it is configured as an open system, assuming that the change in volume at the mouth is equal to the sum of the volume changes that occur within the rib cage and abdominal compartments. Hence, the relative gains of the RIP are adjusted so that the amplitude of the rib cage and abdominal signal were equal. The second principle is that a closed respiratory system (with occluded airways) works with one degree of freedom and volume changes that occur in the rib cage will be equal to and opposite to volume changes that occur within the abdomen.

This principle is used to obtain the volume/motion coefficients for the rib cage and abdominal compartments. In order to carry out the iso-volume manoeuvre, an individual is required to voluntarily shift volumes (a known volume of air measured by PNT) back and forth between the rib cage and abdomen without flexing or extending the spine; it takes approximately 5 to 10 seconds to complete one cycle. In this manoeuvre, the airways are occluded (one degree of freedom) so the total volume of the respiratory system is unchanged and the volume of one compartment is equal and opposite to the other; this involves contraction of the abdomen to cause an equal expansion in the ribcage.

There are, however, some disadvantages associated with this technique. In particular, it has been found that even after accurate calibration with the iso-volume manoeuvre, changes in chest wall motion can occur due to a change in position; this suggests that the volume/motion coefficient is subject to error with change in body position (Konno & Mead 1967; Robertson et al. 1980). Moreover, in order to carry out the iso-volume manoeuvre, as already described, an individual is required to shift volumes between the rib cage and abdomen with occluded airways using a PNT; this requires practice and can be difficult for some individuals to perform, particularly the very young and the elderly (Stocks 1996). In order to acquire valid measurements, it is important that participants are trained on how to correctly perform the iso-volume maneouvre (Ricieri & Rosário Filho 2009).

4.4.1.2 Qualitative diagnostic calibration (QDC)-*statistical method*

Sackner et al. (1989) proposed a statistical calibration method for the RIP device during quiet breathing known as the qualitative diagnostic calibration (QDC). The QDC method uses the Konno & Mead (1967) assumption and depends on variation that occurs in relative contribution

of the rib cage and abdomen during normal breathing. QDC is based on the assumptions that tidal volume remains approximately constant over five minute's periods and that breath-to-breath variations of ΔVRC and ΔVAB are always normally distributed. Since it is impossible to keep a constant VT during quiet breathing, the QDC method excludes from the calibration process breaths that have large or smaller (e.g. greater than ±1 SD) differentiation from the mean breath size. Thus, the QDC calibration is as follows:

$$K = -SD\,[(\Delta\,uVAB) \,/\, SD\,(\Delta\,uVRC)] \qquad (3)$$

K = calibration factor (volume/motion coefficients), SD indicates standard deviation, ΔVAB = changes in uncalibrated volume of the abdomen (AB,) Δ uVRC = change of uncalibrated volume of the ribcage (RC),

Sackner et al. (1989) validated the QDC calibration method by finding tidal volume values that were not statistically significantly different from those derived using the RIP device calibrated using the Iso-volume maneouvre and also a spirometer in 10 healthy, non-smoking adults during various respiration simulations. These findings suggest that the QDC method is a valid calibration method that facilitates the calculation of reliable K values (volume/motion coefficients) that enable the setting of an RIP device to accurately detect rib cage and abdominal excursion, particularly during normal quiet breathing and in the supine position (This study is discussed in more detail in section 4.5). In addition, Brown et al. (1998) found that during normal, quiet breathing, the RIP device calibrated with the QDC technique is also a valid and useful measure of tidal volume in infants.

A particular advantage of using the QDC calibration method is that it does not involve active participation in the form of specific breathing manoeuvres from the subject, but rather it can be carried out during quiet breathing. Also, it does not necessitate the use of a facemask (De Groote et al. 2001). However, the QDC method has faced some criticisms; De

Groote et al. (2001) applied the QDC method to uncalibrated data from a simulated set of thoracoabdominal motions. The findings revealed that the QDC method could only provide an accurate calibration factor (K) when an entire set of breaths had a constant V_T level. This is unrealistic, since an individual is unlikely to maintain a constant V_T, but will have some variability (Banzett et al. 1995; Thompson 1999). Moreover, using the initial five minutes of breathing pattern recording to determine a natural breathing pattern for the individual seems unrealistic and may not be fully representative, since participants may feel anxious and overly aware of their breathing at the beginning of the recording session due to unfamiliar laboratory surroundings. Removing uncharacteristic breaths based on this calibration period seems to be problematic since this is an arbitrary criterion for size.

4.4.1.3 Fixed-K Calibration- *relative method*

The fixed-K technique is a simple and reliable method that enables users to infer respiratory volume changes and determine the gains for the rib cage and abdomen signals. The fixed-K method was developed by Banzett et al. (1995) in an attempt to reduce issues that occured with other calibration methods, such as the QDC and iso-volume manoeuvre method. Banzett et al. (1995) proposed the theory that the height of the rib cage is approximately double the height of the abdomen when measured vertically (in ‘normal’ individuals). The relationship between surface excursion and volume displacement depends mainly on the area of the moving wall (rib cage or abdomen) and the relative extent of these two areas might be quite similar in ‘most people'. Therefore, Banzett et al. (1995) proposed a fixed ratio of 2:1 (ribcage-to-abdomen) to weight RC and AB gains. This standard gain ratio is based on the principle notion that volume displacement of the rib cage and the abdomen depends linearly on surface motion at the rib cage and abdomen.

Since the volume of the rib cage is larger than that of the abdomen, any change in the surface of the rib cage produces a greater change in lung volume; hence, a larger gain is afforded to the rib cage motion signal before the two signals are added to estimate volume as in equation 4:

$$VT = K \times \Delta RC + \Delta AB \quad (4)$$

V_T= tidal volume, K = fixed ratio of 2:1 (ribcage-to-abdomen), ΔRC= change in rib cage, ΔAB = change in abdomen

Banzett et al. (1995) examined the validity of the fixed K calibration method in 11 healthy subjects (m=6, aged 22-46 years; f=5 females, 23-31 years) that were specifically chosen to represent a diversity of 'normal' body types in terms of height and weight. Banzett et al. (1995) compared values obtained by an RIP device calibrated using the Fixed K method with tidal volume values derived from a spirometer. The results demonstrated that the standard gain ratio (pre-set Fixed-K factor) method provided tidal volume estimates with a mean error of V_T of approximately 35ml, which was within 1 to 8% of the spirometric tidal volume values in quiet breathing in normal, healthy subjects. As a result, the researchers concluded that the Fixed-K method is an acceptable alternative to other widely used calibration techniques in healthy adults. However, this finding cannot be generalized in patients with respiratory diseases.

In relation to this research, Banzett et al. (1995) has demonstrated the effectiveness of the Fixed-K calibration method in healthy adults, which is the sample participating in the first study, making it a particularly suitable method. There are also other advantages of using the Fixed-K calibration technique in comparison to other methods, the main one being the ease of application for participants, as it does not require the use of any another device, nor does it require training to learn difficult breathing manoeuvres. Thus, the Fixed-K method has been selected to calibrate the RIP device for the first study due to its advantages.

4.5 Validity of RIP device

Validity is the extent to which a measurement device is measuring the thing it was designed to measure (Bailey & Pearson 1983; Weiner & Hopkins 2007). There are two main types of validity that apply to quantitative measurement tools, internal and the external validity. Internal validity refers to the validity of a measurement, device or test itself, while external validity refers to the ability to generalise findings to a target population (McDermott 2011). Various research has been conducted examining the validity of the RIP device, which is presented in this section.

Sackner et al. (1989) simultaneously measured tidal volume using a spirometer and RIP in a variety of postures during normal and abnormal breathing (Cheyne-Stokes) in 10 healthy adults. Cheyne-Stokes breathing is characterised by a breathing cycle that involves progressively deeper and faster breaths followed by slower and shallower breaths that result in a brief period of apnoea (Hanly et al. 1993). A t-test showed no statistically significant differences between the mean tidal volume value derived from the RIP device and that of the spirometer in all scenarios. These findings suggest that the RIP is a valid device for estimating tidal volume; however, the t-test is not considered as a sufficiently comprehensive method for comparing methods of measurement (Bland & Altman 1986). Also, smaller standard deviation figures were collected with the RIP device in comparison to the spirometer with increasing increments of time and during normal breathing (5 minute = 3.4% ±0.6; 3 minute = 4.2% ± 2.4; 1 min = 5.0% ± 7.7). Overall, these findings support the validity of the RIP device and may even suggest that the RIP is better able to detect variability when used for a longer period of time for breathing pattern recording (i.e. 5 minutes or more).

Another study conducted by Fiamma et al. (2007) also established the validity of the RIP device when measuring breathing pattern in comparison

to a PNT device. A Visuresp® was used, which has RIP bands embedded within it (similar to the LifeShirt®). Breathing pattern data was recorded for 10 minutes, following a 15-minute stabilisation period in 8 healthy individuals (m=6, f=2, aged 26.5±2 years). Data were obtained during three separate recordings; one with simultaneous RIP and PNT recordings, one using only the RIP and another using only the PNT. Also, in each of the three recordings, measurements were obtained with subjects in two positions: sitting and supine.

All breathing pattern component values (V_{min}, V_T, BC, T_i, T_e and mean inspiratory flow) collected during simultaneous RIP and PNT monitoring were found to be significantly correlated in both positions. Pearson's correlation coefficient r values were all above 0.75 ($p<0.0325$) in sitting position and r values of 0.83 ($p<0.0114$) were found in the supine position. When the data obtained from the two separate consecutive RIP and PNT recordings were compared, it was found that there were no significant correlations in any of the breathing pattern values, except for T_i in the sitting position, which demonstrated a weak r value of 0.54, but a significant p value of 0.032. When recording breathing pattern with a PNT device separately, V_T was found to be significantly higher than that recorded using an RIP.

The findings from the Fiamma et al. (2006) study suggest that RIP demonstrated good concurrent validity when compared with data recorded using a PNT device. However, correlation alone is also an inappropriate choice of analysis for comparing two methods of measurement (Bland & Altman 1986). In addition, there were other limitations with this study. The sample size was small (n=8), and it is not clear how the '15 minute period of stabilisation' was implemented. Was there 15 minutes between the sitting and supine recordings, or was there 15 minutes between the consecutive RIP and PNT recordings, or both? Despite a lack of clarity,

however, Fiamma et al. (2007) concluded that the RIP device (Visuresp®) is valid for measuring breathing pattern.

Establishing the validity of the RIP in healthy adults is insufficient to conclude that it is also valid in patients with respiratory disorders, especially given that the calibration technique for the RIP device relies on the assumption of 2df (degrees of freedom of motion) (section 4.4.1), whereas the 2df assumption is not necessarily applicable to patients suffering from respiratory disorders. Therefore, Tobin et al. (1983c) conducted a study to test the validity of an RIP device against simultaneous spirometry in patients with respiratory disorders. The study involved 21 patients with chronic airway obstruction, including asthma, bronchitis and emphysema (m=10, f=11, mean age of 61 years), 9 patients with restrictive lung disease (m=6, f=3, mean age of 60 years) and 19 patients receiving mechanical ventilation (m=10, f=9, mean age of 73). The results demonstrated that the mean difference in V_T obtained with the RIP device were within ±10% of those collected with the spirometer in all cases, except the mechanically ventilated patients, where 96% were within ±10% of the spirometer readings. However, the value of ±10% difference was considered as acceptable to indicate adequate levels of validity, there is, however, no justification within the literature explaining that this level indicates validity, but rather these figures rely on the subjective assessment of the researchers. Also, the analysis was only based on 6 breathing cycles, which is approximately 20 seconds; this may not have been sufficient time to enable comprehensive detection of variability. Nevertheless, the results appear to indicate that the RIP device demonstrates acceptable concurrent validity in patients with pulmonary disease, although its use in mechanically ventilated patients may be viewed with more caution. The general consensus within the literature is that the RIP is a valid, non-invasive tool for monitoring breathing pattern in healthy individuals and those with respiratory disease.

Overall, there is an issue with all the validation studies involving the non-invasive devices (namely, RIP, OEP, SLP, EIT), which is that the data is usually compared with data collected using invasive devices, often a PNT or spirometer. But, the values derived from the non-invasive devices cannot be exactly equated to the values obtained using a PNT or spirometer, this is because there is a difference in the volumes that are being compared; the non-invasive devices measures changes in chest wall motion, while the PNT and spirometer devices measure lung gas volume (Motemadi-Fakhr et al. 2017). Moreover, the non-invasive devices may inaccurately detect changes that are resulting from shifts in non-gaseous volumes, such as blood, rather than ventilation.

4.6 Rationale for using RIP and SLP

The overall aims of all three studies included in this research are to examine the reliability and responsiveness of specific breathing pattern components in healthy and asthma individuals. Hence, a method of recording breathing pattern is required; the two devices selected as data collection methods (RIP and SLP) in these studies were chosen for a number of reasons.

Tang et al. (2002) asserts that invasive methods of breathing pattern recording, such as PNT and spirometer, have the disadvantage of causing the patient to change their breathing pattern due to the resulting discomfort that they experience because of the change in the route of breathing from nasal to oral. As Criner (2010) asserts breathing pattern monitoring should not be a source of pain or discomfort for the patient. This is perhaps the most significant advantage and main rationale for using non-invasive devices for recording breathing pattern in this research. Hence, two different non-invasive methods of breathing pattern recording devices, RIP and SLP, were selected to reduce the possibility of causing

pain and/or discomfort to the participants and to avoid the potential unwanted effects of using facemasks and mouthpieces.

Regarding the rationale behind the selection of the RIP device for the first study, this device was readily available for use by the researcher within the University of Southampton. In addition, it is relatively easy and practical to use and has undergone a large amount of empirical testing to establish its validity with a variety of participants and in various settings (Grossman et al. 2004). The RIP device requires calibration to extract the data, the Fixed-K method of calibration (section 4.4.1.3) was selected for use due to its recognised advantages to the participants of the study who, as a result, would not have to perform the difficult iso-volume manoeuvre or use face-mask or mouthpiece (as is necessary in other calibration methods). In addition, previous studies have indicated the feasibility of the Fixed-K method as an acceptable calibration method in healthy adults and so it was deemed a suitable method for use in first study.

Although the RIP device was used for the first study, an SLP device was selected to collect data in the second and third study since it is a new and emerging contact-less technology that has recently become available to the University of Southampton. Like the RIP, the SLP provides data regarding thoracoabdominal motion and other breathing pattern components relevant to this research. In addition, it is easy to use for both researcher and participant and its contact-less nature also makes its comfortable and completely non-invasive. Thus, it is less likely to increase participants' awareness of their breathing pattern during recording, which might present a more realistic and accurate representation of breathing pattern. Moreover, unlike RIP, the SLP is an auto-calibrated device that provides direct numerical data and hence does not require complex algorithms to extract the data, making the SLP particularly relevant and practical for use within clinical settings. Since it is a new technology, the existing literature

regarding its validity and reliability is limited, but what is available demonstrates an agreement between PNT and SLP (Motemadi-Fakhr et al. 2017). Although the exact validity and reliability of the SLP has not been extensively established within the literature, the main aims of the second and third studies are to measure the changes that occur in breathing pattern after a physical exercise stimulus and after a breathing retraining intervention and not to establish the validity of any device. Moreover, the aim is not to make comparisons between the data collected in the first study with the data collected in the second and third studies and so it is not deemed problematic to collect the data using a different device. Therefore, the SLP was selected for use to record breathing pattern in the second and third study.

It is acknowledged that breathing pattern recording devices are not without some limitations regarding validity, reliability and/or practicality issues; however, the RIP and SLP devices were selected due to their relative advantages. To clarify, this study does not aim to validate the SLP or RIP device or compare the data derived from the two devices, but rather aims to examine the reliability and responsiveness of specific breathing pattern components in order for these components to be considered as potentially useful outcome measures.

Chapter 5 First study- Breathing pattern reliability in sitting and supine (recorded using RIP)

5.1 Introduction

In the **first study**, an observational single group test re-test design was applied to examine whether any significant measurable change occurs in specific breathing pattern components in both the sitting and supine positions in order to determine the test re-test (relative and absolute) reliability of breathing pattern components in healthy adults.

Performing multiple recordings of breathing pattern for the same participant can provide useful information regarding the changes that occur in the respiratory system; hence, this study examined the reliability of breathing pattern in three different occasions: within session, between session and between days.

This study also aims to make comparisons between the data collected in the sitting and supine position in order to examine the impact of position on the reliability of breathing pattern components in healthy adults since the impact of posture on the reliability of breathing pattern components is not known.

A heterogeneous group of 50 adults were recruited from a university population. The sample comprised 38 female, 12 male with a mean age of (31.12±6.83 years).

5.2 Methods

The methodology for the first study, including the study protocol, the equipment, the inclusion/exclusion criteria, sample sizes and the recruitment processes, are outlined in the following sections and the statistical analysis processes are also described.

5.2.1 Design

An observational single group test re-test design was used to test the reliability of breathing pattern components in sitting and supine positions.

5.2.2 Participants

Adult males and females aged 18 years or over were considered eligible for this study since most of the research on reliability to date has involved adults (Shea et al. 1987; Grossman et al. 2006), thus enabling comparisons with published data. The factors that affect the stability of breathing pattern are unknown, so this work was exploratory with broad inclusion criteria. As no safety issues were identified, the exclusion criteria was minimal.

Inclusion criteria

1. Healthy adults aged 18 years (and over) and free from respiratory diseases, injury and illness.
2. Able to sign a consent form.

Exclusion criteria

Participants that were excluded:

1. Reported history of uncontrolled respiratory disease and chest wall deformity or heart diseases (defined as diagnosed by a health professional).

2. Individuals with chest infections.
3. Anyone unable to read and understand written English.

5.2.3 Sample size

A statistician (Dr. Sean Ewings) at the University of Southampton programmed a reliability sample size calculator (Bonett 2002) using Microsoft Excel programme. The calculation includes four pieces of information; the repeated measures (i.e. the number of measurements taken), the ICC (based on the data derived from the pilot study, which involved 20 participants), the significance level (5%), and a 95% confidence interval (CI) width of 0.5 for Te and 0.3 for other components. Appendix A depicts an example of the Excel spread sheet used for the sample size calculation. As shown in table 5-1, the highest number of required participants were 51; hence, the decision was taken to recruit 51 participants to the first study. The largest existing study examining the reliability of breathing pattern in adults included 41 individuals (Shea et al. 1987); so, a sample size of 51 is considered acceptable.

Table 5-1: Power calculation outcome for each component based on pilot work (n=20)

Breathing components	ICC value (derived from pilot study)	Width of CI (derived from pilot study)	Sample size
Ti (s)	0.681	0.3	51
Te (s)	0.829	0.5	18
Total breathing cycle (s)	0.685	0.3	50
%RCexp	0.704	0.3	45

(Ti) inspiratory time, (Te) expiratory time, (%RCexp) rib cage relative expired contribution, (ICC) intra class correlation coefficient

5.2.4 Equipment

Breathing pattern was recorded using a Respiratory Inductive Plethysmography (RIP) device. At the time of the first study, the RIP was the only available non- invasive device to be used by the researcher.

5.2.5 Measurement of breathing pattern using Respiratory Inductive Plethysmography (RIP) device

An Inductotrace ® system (Model 10.9000) based on RIP technology was used to acquire respiratory signals. Two elasticated bands with insulated wires were placed around the participants' rib cage and abdomen and connected to a calibration unit via a transducer oscillator. A custom-built analogue-to-digital (A-D) converter was used to convert the signals into digital form on a laptop computer. Each recording is represented by a 15 minute long time series acquired with 12-bit resolution and a sampling frequency of 10 kHz using a USB data acquisition module (USB-1208FS, frequency sampling up to 50 kbit/s). In order to record the data, a daqpilot.m program built by Professor Anna Barney from the Institute of Sound and Vibration Research was used and the measured data were acquired using the Matlab Data Acquisition Toolbox and stored in a MATLAB format for data analysis at a later date (Figure 5-1).

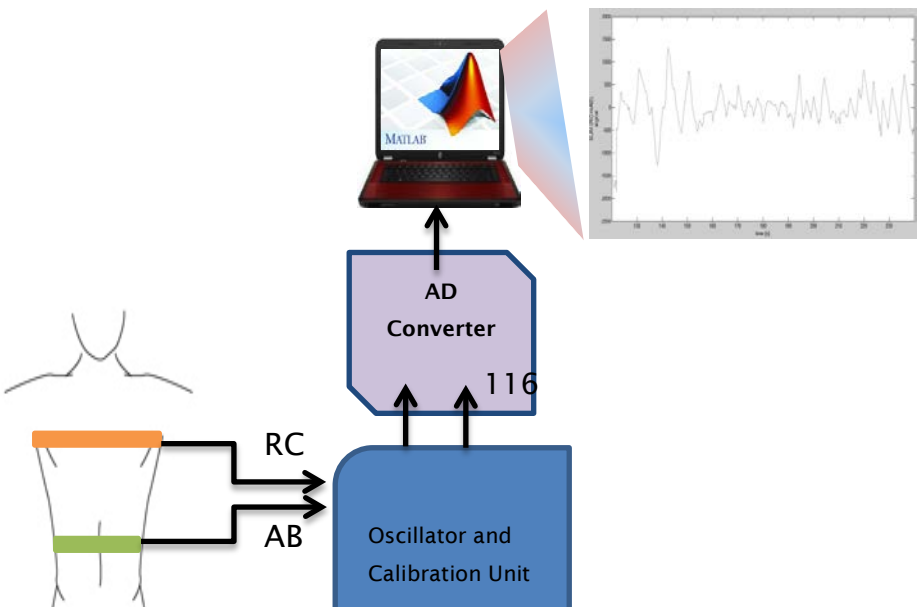


Figure 5-1: Experimental equipment set up (RIP)

5.2.6 Recruitment

After obtaining the appropriate ethical approval from the Ethics and Research Governance Online (ERGO) at University of Southampton, the researcher advertised the study on a poster that was placed around Highfield campus. The poster contained contact details for the researcher (Appendix A.4). Interested volunteers were sent (by e-mail) an information sheet explaining what was expected of participants (Appendix A.1). Those that had read the information sheet and still expressed an interest in taking part were given convenient appointments for the data collection to take place.

5.2.7 Data collection and equipment set up procedure

Willing participants were invited to attend an appointment for the first data collection session, which took place at a research laboratory located in the Faculty of Health Sciences, University of Southampton at a mutually convenient time. At this time, the researcher answered any further questions regarding the study and written, informed consent was obtained (Appendix A.2).

Demographic data (age, gender) were collected through a researcher-administered questionnaire (Appendix A.3). Details relating to height and

weight were obtained using an EKS electronic scale to weigh and a Stanley Lever lock tape measure to record height (this data were only used to characterise the sample). The questionnaire included questions relating to other factors that the researcher thought might affect breathing pattern, for example: whether or not they take part in regular physical or breathing exercise, and general health at the time of data collection. Additionally, questions regarding any respiratory problems and medication used were included. The breathing pattern data were then collected while the participants sat quietly in a chair (with an upright back 90 degrees) for 15 minutes. Data were collected using an RIP device, which collects data relating to rib cage and abdominal excursions. From this data, measurements relating to inspiratory (T_i) and expiratory time (T_e), breathing frequency (Bf) and relative expired contribution of rib cage and abdominal to tidal volume can be extrapolated ($\%RC_{exp}$ and $\%AB_{exp}$).

Participants were asked to remove clothing from their upper body (or undress to minimal undergarments) in order to allow the inductobands belts to be applied close to the skin around the abdomen and the thorax as demonstrated in figure 5-2. They were given the opportunity to wear garments over the bands if they wished to cover up. Using a standard tape measure, the circumference of the rib cage (just below the axilla) together with circumference of the abdomen (below the lowest vertebral rib) was measured in order to determine the correct size of RIP belt for the participants. Once the inductobands were secured in place with a Velcro fastening, both inductobands were connected to the RIP system via the transducer oscillator, and then into the corresponding input channel (RC and AB) of the custom-built A/D converter (a full discussion of the RIP device, its clinical usefulness and the rationale behind using the RIP for data collection in *first* study is included in Chapter 4).

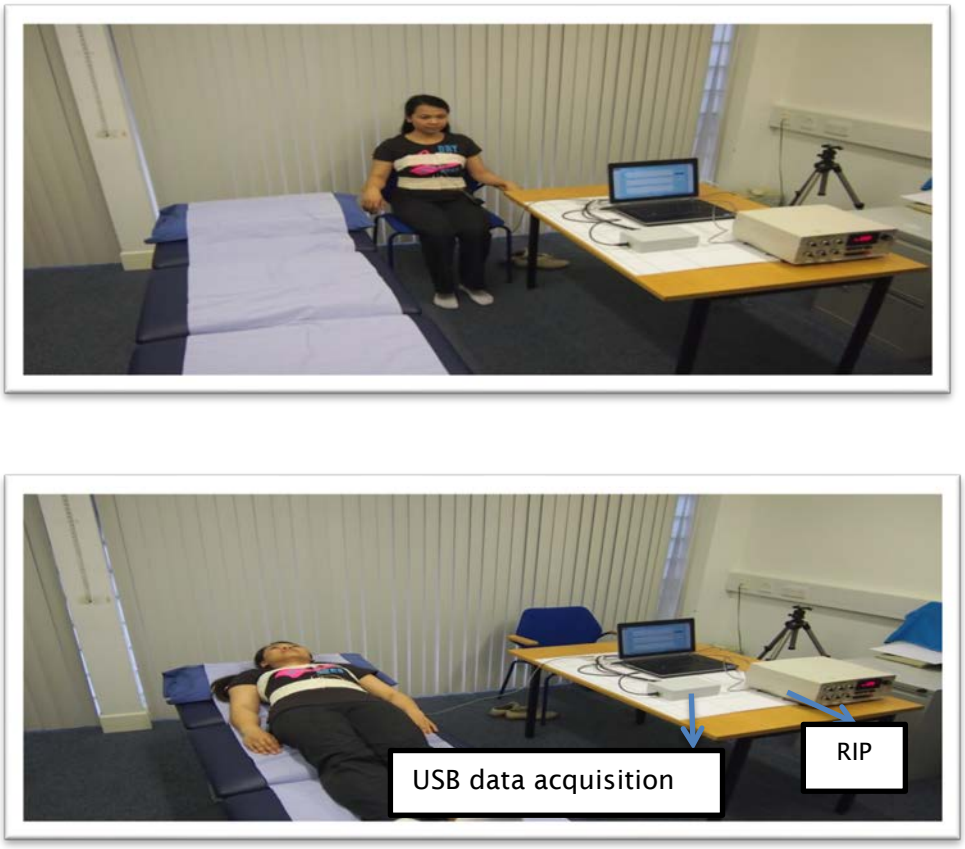


Figure 5-2: Participant wearing RIP device during a breathing pattern recording session in sitting and supine position

For the first part of the data collection process, participants were in a comfortable, sitting position similar to other studies involving the RIP device (Tobin et al. 1983; Parreira et al. 2010). This data collection procedure lasted for 15 minutes. To facilitate the recording of an accurate reflection of resting breathing pattern, as recommended by Shea et al. (1987), the participants were encouraged to relax. Participants were not given any sensory and cognitive stimulation and were asked not to fall asleep during the RIP data collection process, as these can all impact an individual's resting breathing pattern in both positions (Shea et al. 1990).

The researcher also collected data following the same procedure while participants were in the supine position. After 15 minutes of breathing pattern recording was completed with participants in the sitting position,

the participants were asked to lie down and 15 further minutes of breathing pattern data were recorded with the participants in the supine position. Sitting and supine order was randomized.

Once the first RIP monitoring had taken place (in both positions), the RIP device bands were removed and participants were given a 15 minute break to move around if they wished. The researcher considered a 15 minute break sufficient length of time between sessions to allow valid assessment of the stability of breathing pattern components. After the 15 minute break, the second data collection session commenced, which involved the participants reconnecting to the RIP device. Breathing pattern monitoring then took place following the same procedure as in the first phase; 15 minutes in a comfortable, supine position followed by 15 minutes in the sitting position (or vice versa). This protocol enabled the researcher to examine the test re-test reliability of specific breathing pattern components within sessions and between sessions on one day in both positions.

The second day of data collection (third and fourth data collection sessions) took place 4-10 days later at approximately the same time of day, according to participants' availability. These third and fourth data collection sessions followed exactly the same procedure as the first and second, except that it was not necessary to obtain demographic data or gain consent. This enabled the researcher to examine the test re-test reliability of specific breathing pattern components between days (Figure 5-3 for outline of the *first* study format).

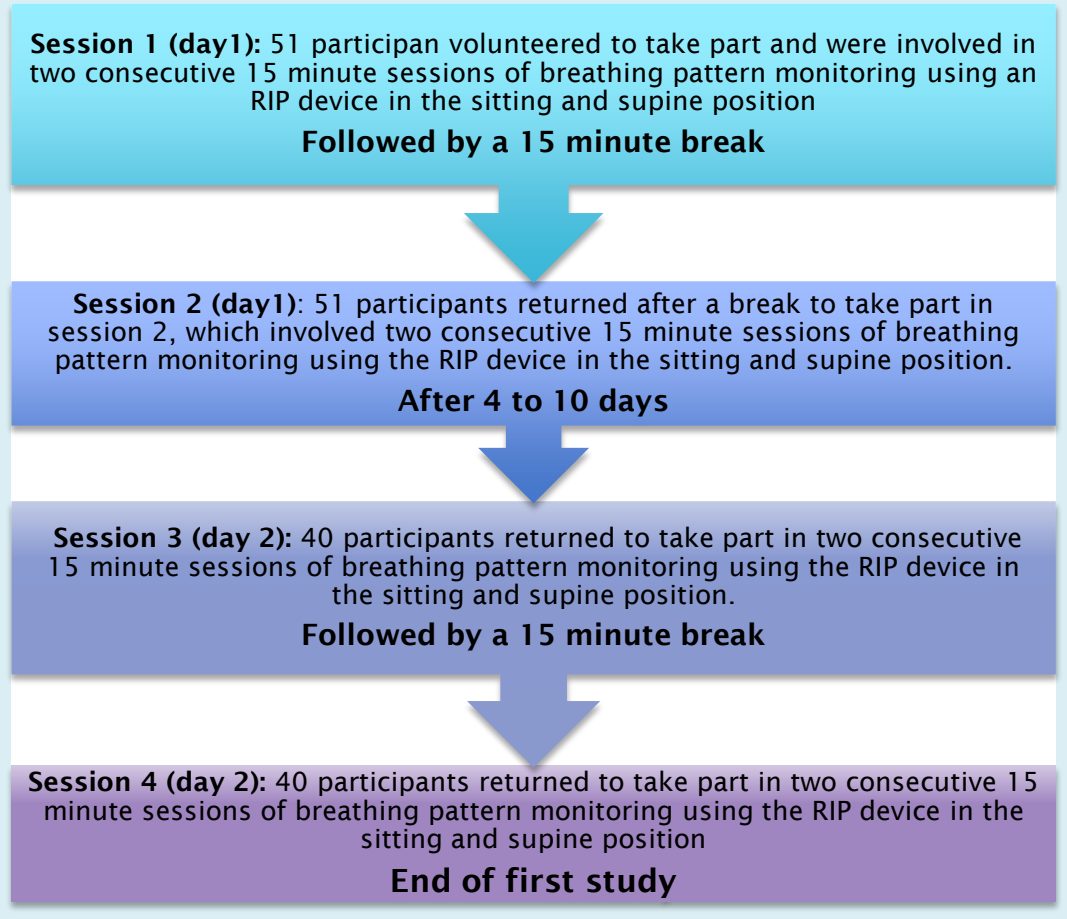


Figure 5-3: Overview of the First study protocol

5.2.8 Components of breathing pattern recorded by RIP

Three timing components (Ti, Te and Bf) and two thoracoabdominal motion components (%RC$_{exp}$ and %AB$_{exp}$) were selected since they reflect some of the key elements of breathing pattern that have been found to alter during respiratory disease and to reduce the possibility of type I error that occurs due to a high number of multiple tests. The specific breathing pattern components under examination were extracted using a specially designed algorithm and are defined as follows:

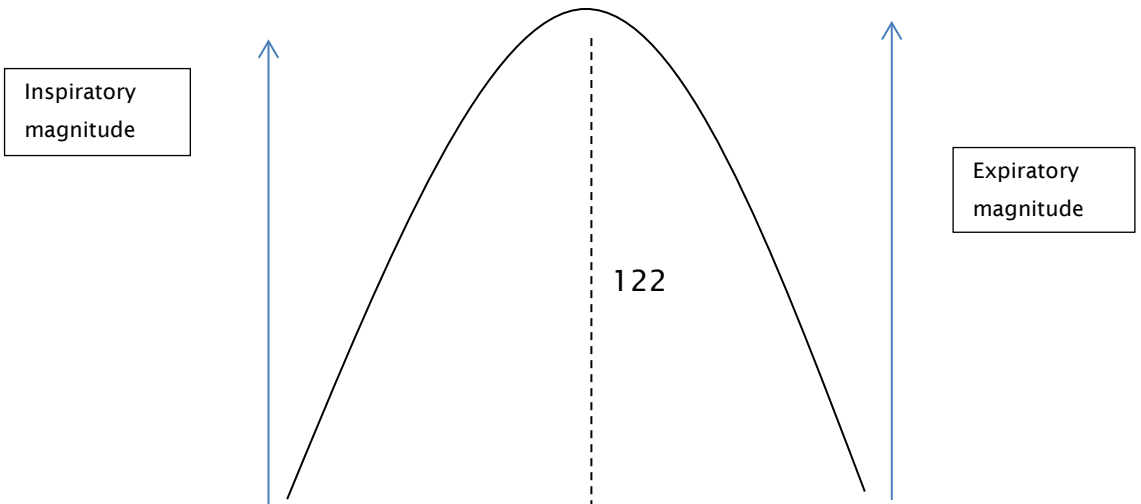
Timing components

- **Inspiratory time (Ti) (sec)** - Inspiratory time can be defined as the duration of the inspiratory phase. As illustrated in figure 5, inspiration time was measured as the duration in seconds from the beginning to the end of the inspiration phase; indicated by an upward slope (left to right) in the RIP signal.
- **Expiratory time (Te) (sec)** - Expiratory time is the duration of time in seconds from the end of inspiration to the beginning of inspiration of the next cycle measured.
- **Breathing frequency (Bf)** – Breathing frequency is the number of breath cycles* that an individual makes per minute. Bf was calculated using the calculation: Bf=60/breathing cycle

  ***Breath cycle= Ti+Te**

Thoracoabdominal motion components

- **Rib cage relative expired contribution% (%RCexp)** – The magnitude of the movement that occurs in the rib cage band during expiration to the amplitude of the sum of the two (rib cage and abdomen) and is expressed as a percentage (as measured by the RIP device).
- **Abdominal relative expired contribution% (%ABexp)** – The magnitude of the movement that occurs in the abdomen band during expiration to the amplitude of the sum of the two (rib cage and abdomen) and is expressed as a percentage (as measured by the RIP device) (Figure 5-4).



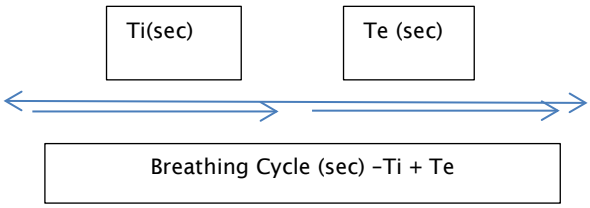


Figure 5-4: Illustration of breathing pattern components measured in the first study (pauses not included)

5.2.9 RIP data extraction procedure

The algorithm was used to calibrate the RIP signals, extract the data relating to breathing pattern components and then calculate the mean values for the each component using a semi-automatic process (in MatLab software). The mean for each component was calculated through the detection of the minimum and maximum of each inspiratory phase for the duration of the recording session. The minimum and maximum of each inspiratory phase were defined as the lowest and the highest point of the signal. These points were then used to detect a breathing cycle in each file. The mean for each breathing pattern component was calculated based on the full breathing cycles contained in the signal, starting with the first detected inspiration in recording; partial breathing cycles at the start or finish were not included in the calculation.

The data comprised a total of 15 minutes of RIP measurements in the sitting position and 15 minutes in the supine position taken at different times. Each 15 minute recording was divided into 5 sections of 3 minutes; this was for two reasons. Firstly, it was more manageable for the MatLab software, since dividing the session into 3 sections of 5 minutes made the

programme run slowly; hence it was considered more practical to record signals in five, 3-minue sections. Secondly, it enabled the researcher to divide the breathing pattern recording time into five, 3-minute sections to facilitate comparisons to be made for the within session data.

Each 3 minute section was saved as a separate file and is referred to as 1st, 2nd, 3rd, 4th and 5th section. The first and fifth sections of data were excluded from the data analysis process for all scenarios; this enabled the participants to settle at the beginning of the breathing pattern monitoring session and eliminated data collected at the end of the session in an attempt to avoid the effects of participants' becoming restless and fidgeting when they knew the session was nearly completed. The 2nd and 4th sections of 3 minutes of data were compared to evaluate the within session reliability of the breathing pattern components (Figure 5-5). Figure 5-6 shows that for the between sessions and between days data analysis, the 2nd, 3rd and 4th sections were combined to give 9 minutes of data. Each raw data file was stored in Matlab format and was provided with an individual identification code for analysis.

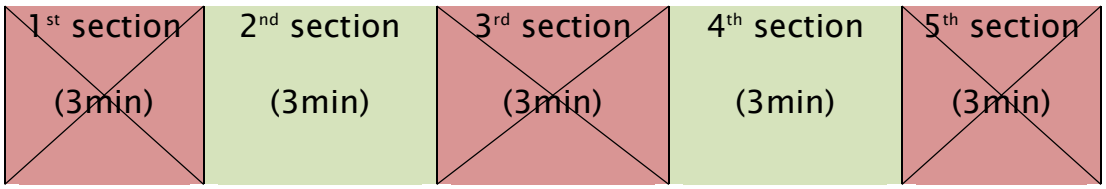


Figure 5-5: Data recording division process to enable within session comparisons, which compares the 2nd and 4th sections of data recording

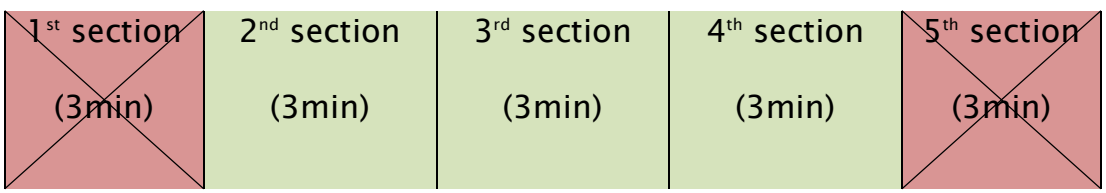
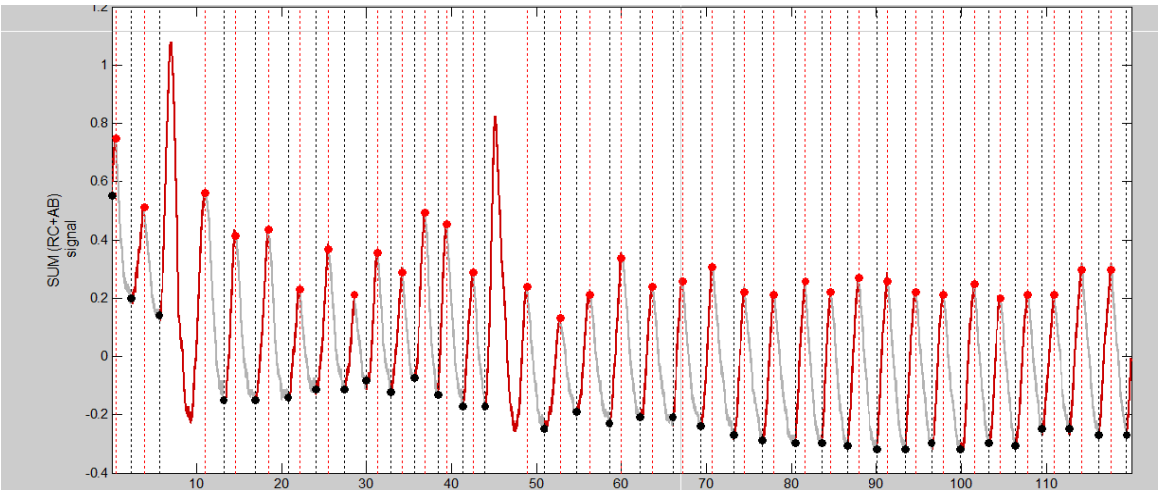


Figure 5-6: Data recording division process to enable between session and between day comparisons, which uses the 2nd, 3rd and 4th sections of data recording combined

A limitation of the algorithm was that on some occasions it incorrectly identified the start or the end of inspiration phase, due to various factors, including movement, coughing, yawning etc. Therefore, the researcher was required to edit/remove the signals. During the entire data recording sessions, the researcher closely observed the participants and made detailed notes of any factor that caused an uncharacteristically large or small signal on the RIP signals; for example, any excessive movements (such as fidgeting/shifting) and coughing, yawning or swallowing. The MatLab programme allows the user to edit the markers manually if necessary, by deleting already set markers in the signal by locating the cursor at the beginning or the end of the inspiration phase and deleting where necessary. This process can be repeated as many times as necessary. Approximately 2 and 8 signals was removed per participant from a total of approximately 45 breathing cycle signals (for the 3 minute data) and between 5 and 16 signals were removed from a total of 135 breathing cycle signals (for the 9 minute data).

Once the uncharacteristic signals (caused by coughing, yawning, swallowing and moving) were removed, the breathing pattern data were calculated to extract the mean values for each participant in relation to breathing pattern components. An example of uncharacteristic signals can be seen at approximately 10 and 47 seconds in figure 5-7. Subjective editing of the data is a limitation of this study, which is discussed in more details in section 8.5.6. Another limitation of the MatLab programme is that it does not enable the detection of pauses; however, the first study examines the reliability of breathing pattern in healthy participants at rest,

which is not associated with the number of pauses, which may be frequent during other states e.g during speech (Mitchell et al. 1996).



Key: Black dot = Beginning of inspiration duration; Red Dot = End of inspiration duration; the vertical dotted line = time in seconds

Figure 5-7: An example of an individual's RIP signals depicting two uncharacteristic signals at approximately 10 and 47 seconds

5.2.10 Plan for statistical analysis

Test re-test reliability involves administering the same measurement to the same individual at two (or more) different times (Shi 2008). There are three important components of test re-test reliability: change in mean

(systematic bias), re-test correlation and measurement error (Hopkins 2000), which were all performed in this first study to assess test re-test relative and absolute reliability.

5.2.10.1 Breathing pattern comparison (Change in Mean)

One-way repeated measures analysis of variance (ANOVA) was used to detect statistically significant differences in group mean value of each breathing pattern component (T_i, T_e, Bf, $\%RC_{exp}$ and $\%AB_{exp}$) for the within, between session and between day comparisons in both sitting and supine positions with a 95% confidence level and a p-value of < 0.05. The Bonferroni adjustment for multiple comparisons was used in an attempt to account for the increased probability of any type I errors occurring due to multiple tests being carried out (7 tests). Bonferroni adjustment for multiple comparisons multiplies the p value of the Least Significant Difference (LSD) (which is equivalent to performing multiple tests) by the number of tests being performed and produces a new 'adjusted' p value (Meier 2006). In this first study, seven paired comparisons were performed for each breathing component in each position. This would increase the probability of type I error rate from 20 to 30%, which was considered unacceptable. Post hoc comparisons were therefore performed for each component that was identified as being statistically significant from the one-way repeated measures ANOVA.

However, measuring change in mean alone is not sufficient to assess reliability, as the information provided is limited to changes in mean. Therefore, other statistical analyses were performed to determine relative and absolute reliability.

5.2.10.2 Breathing pattern relative reliability estimate

Relative reliability is defined as 'the degree to which individuals maintain their position in a sample over repeated measures' (Bruton et al. 2000). The intra class correlation coefficient (ICC) was used to calculate the

relative reliability of each breathing pattern component at different time points. There are six different formulae for calculating the ICC, which were developed by Shrout & Fleiss (1979), which are selected for use depending on the purpose of the study, the design of the study and the type of measurements taken. These formulae are referred to as (1, 1) (2, 1) (3, 1) (1, k) (2, k) (3, k). The first number in each bracket (1, 2, and 3) refers to the type of study design. In design (1), each subject is assessed by a different set of randomly selected raters. In design (2), each rater assesses each subject and raters are randomly selected. In design (3), each rater assesses each subject; however, only the raters are of interest. In relation to the second integer in each bracket (1 and k), this refers to the unit of analysis, with 1 being a single measurement and k being an average of 2 or more measurements.

These classic descriptions of designs based on the Shrout & Fleiss (1979) guidelines may cause some confusion in relation to test re-test reliability studies that do not involve a number of different researchers (raters). However, this need not cause confusion, the description above relates to a slightly different perspective, but regarding the research within this first study there is just one source of variability, the participants (i.e. people differ from each other in their scores). The common link between this study and the description above is that we cannot assess another source of variation. In this case, it is because there is none (the same researcher assessed the participants at each time point). The description here attempts to differentiate between those times where we can separate out the effect of certain raters and those cases where we cannot. Hence, a (1, k) ICC design was used to determine relative reliability, with 1 being individual scores and k being mean scores of each breathing pattern component taken at different points.

Thus, the ICC equation for this study using the (1, k) design was:

$$ICC(1, k) = (BMS - WMS)/BMS \quad (5)$$

BMS =mean sum of squares (a measure of the total variability of a set of scores) for between-groups; WMS =mean sum of squares (a measure of the total variability of a set of scores) for within-groups as derived from one-way ANOVA.

An ICC value of 1.00 represents perfect correlation and 0.00 represents no correlation (Hopkins 2003). Strength of agreement for ICC values was assessed as <0.20 poor, 0.20–0.40 low, 0.40–0.60 moderate, 0.60–0.80 good, 0.80–1.00 very good (Bland & Altman 1996). However, the ICC in isolation does not provide a comprehensive guide to reliability, since it is a one-point estimate of reliability based on one selected sample. Therefore, it is essential to report the 95% confidence interval to gain a more rounded understanding of reliability.

The main limitation of this method is its reliance on the variance of the assessed population. Consequently, higher ICC values may be derived when applied to a more heterogeneous population as compared with a more homogeneous one. This is in part due to the relative nature of the ICC, which tends to reflect the magnitude of an ICC depending on the between-subjects variability (Weir 2005). However, an advantage of the ICC, according to Hopkins (2003) and Weir (2005), it is particularly useful in research that involves 2 or more tests as it can be calculated as a single correlation, thereby facilitating simplification during the data analysis process.

ICC has been used to determine relative reliability, but it is also necessary to examine the absolute reliability in order to gain a more comprehensive representation of reliability. Methods that can be used to assess absolute reliability (measurement error) are discussed in the following section.

5.2.10.3 Breathing pattern absolute reliability estimate

Absolute reliability is defined as ‘the degree to which repeated measurements vary for individuals’ (Bruton et al. 2000) and was calculated

using the Within Subjects Standard Deviation (WSSD) and Smallest Real Differences (SRD).

WSSD values provide an indication of a measurements' reliability. The WSSD is the same as the standard error of measurement (SEM). It is an effective way of presenting measurement error and is used in reliability studies to facilitate the interpretation and reporting of test scores and score differences on tests (Bland & Altman 1990; Stratford & Goldsmith 1997). The WSSD is reported in the unit of measurement of what is being measured. A smaller WSSD value provides an indication that the measurements are more reliable, since it reflects less variability (Tighe et al. 2010). In this first study, the WSSD was selected for use to determine absolute reliability, since it provides an indication of variability in repeated tests regardless of the rank of the individual within a particular sample. Therefore, this statistic is unaffected by the range of measurements. In addition, the SPSS calculation for ICC produces an ANOVA table, which includes the value of the within subject mean square. The square root of the within subject mean square value produces the WSSD value.

Regarding Smallest Real Differnces (SRD), Pfennings et al. (1999) introduced the SRD calculation as a way of estimating sensitivity to change. However, due to the lack of external criterion, the SRD value is used as a baseline data set in order to determine how much change needs to occur between two or more measures to be considered as a ‘real change’, rather than a change that occurs due to measurement error (Schuck & Zwingmann 2003). The SRD is calculated as $1.96 \times \text{WSSD} \times \sqrt{2}$. A limitation of using the WSSD and SRD is that there are no defined criteria within the literature as to what constitutes a high or low WSSD and SRD value (Baumgartne 1989), and this is determined according to the subjective opinion of the user.

5.2.10.4 Breathing pattern agreement

The Bland-Altman 95% limits of agreement (LA) method was used to assess the agreement between the measurements for the within session, between session and between day comparisons in both positions. Bland & Altman (1986) described a graphical method to analyse the agreement between two methods of measurement as an indicator of absolute reliability, as it provides an indication of measurement error. In the Bland-Altman analysis, the differences between two measurements and the mean values are inputted onto a scatter plot as the y and x axis respectively. This provides a visual representation to facilitate the construction of judgments regarding the extent to which the two measures agree (or not). The Bland-Altman scatter plot reference lines are created to indicate the zero bias line and the 95% upper and lower limits of agreement (see below for calculation of upper and lower limits). Each point marked on the scatter plot graph represents one observation from a data set; this attribute makes this analysis different to the others (mentioned above) where cohort variables are considered. The direction and magnitude of the scatter around the zero line provides an indication of the systematic bias and random error, respectively.

Heteroscedasticity can be defined as a 'positive relationship between the degree of measurement error and the magnitude of the measured value' (Atkinson & Neville 1998, p. 229). So, heteroscedasticity occurs when the standard deviations of a variable are not constant when measured over a period of time. If this occurs, a funnel shaped pattern appears on the scatter plot graph. The degree of heteroscedasticity on the scatter plots determines whether the data requires logarithmic transformation before calculating the limits of agreements.

When using Bland-Altman analysis, it is necessary to calculate the mean and the standard deviation of the mean differences between measures. The more reliable the measure, the closer the mean differences will be to

zero and the standard deviation will be smaller. The Bland-Altman analysis also involves calculating the 95% Limits of Agreement (LA), which reflects 95% of the differences between the two measures (Myles & Cui 2007). This is calculated using the mean and standard deviation of the differences in the following equation:

$$95\%\ LA = d \pm 2SD \quad (6)$$

LA = Limits of Agreement, d = Mean difference, SD = Standard deviation of the differences.

A narrower range between these two limits indicates closer agreement. However, there are no clearly defined criteria regarding what represents narrow or wide LA, and this is determined by the subjective opinion of the researcher and depends largely on the clinical context; this could be interpreted as one of the limitations of this method. Another consideration when using Bland-Altman analysis is the sample size, a sample size of at least 50 or more is recommended to facilitate generalisability of the limits of agreement beyond the study population. Nevertheless, Bland-Altman 95% limits of agreement analysis are appropriate for reliability studies (Wood 1989) and it provides a useful indicator of absolute reliability.

5.3 Results

Data gathered for the first study aimed to explore the reliability of specific breathing pattern components in sitting and supine position in a sample of 51 healthy adults with no previous history of uncontrolled chronic respiratory disease.

5.3.1 Demographic data and sample size

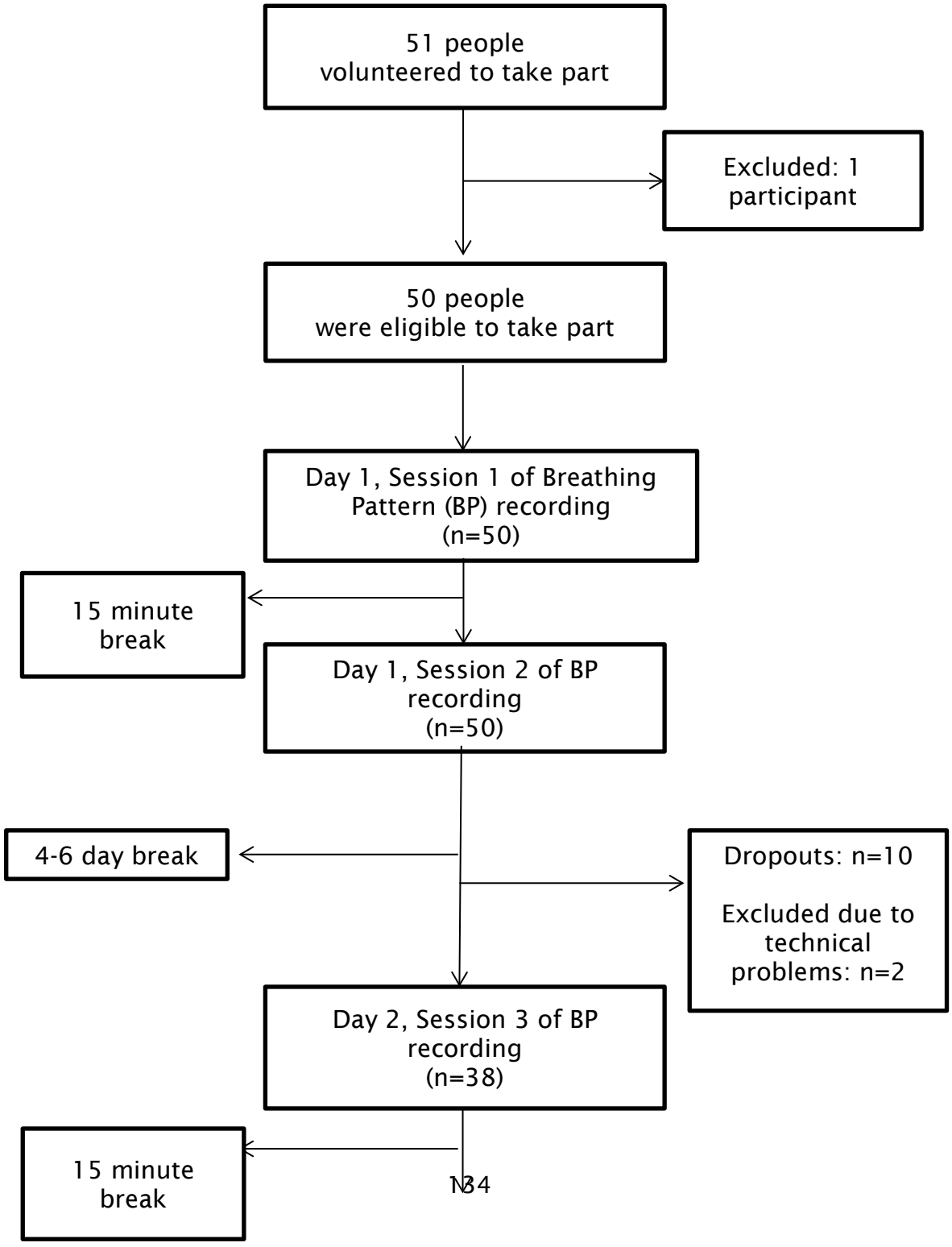
The final sample comprised 50 individuals (m=12, f=8; mean age 31.12±6.83years) aged between 19 and 52 years, four participants had

self-reported controlled asthma. The body mass index for participants ranged from 16.5 to 44.1 BMI with a mean BMI of 24.89 (SD±4.47) kg/m^2. The demographic data are presented to provide a description of the whole sample (n=50), although this information was only used to characterise the sample and not to measure the effect of any variable on breathing pattern.

The original aim was to recruit 51 participants to complete both days of breathing pattern recording as derived from the power calculation (section 5.2.3). On day one, 51 participants (m=12, f=39) completed two breathing pattern recording sessions (session one and two). Although, upon analysing the data, one participant was found to be breathing in an unusual manner and was found to be an extreme outlier, with an unusually long inspiratory and expiratory time of 8.1 (sec) and 7.2 (sec) respectively and with an extremely slow breathing frequency of 3.8 (bpm), which seems to be non-realistic. This may be due to an error with the RIP device or due to some other reason; although, the exact reason for this result is not known. Therefore, the data from a total final sample of 50 participants was analysed for the first day.

On day two, only 40 participants (m=8, f=33) returned for session three and four of recording. Reasons for non-attendance may include time taken for the overall breathing pattern recording session (with a break), which was quite long (75 minutes in total); this may have contributed towards non-attendance for the second day of recording. In addition, the data for 2 participants had to be excluded from the analysis due to technical problems with the RIP oscillator, resulting in a final second day sample of 38 (m=7, f=32). The smaller sample size on day two is likely to affect the statistical power, which is a limitation of this study, and is discussed further in section 5.3.7.1. Figure 5-8 shows the data collection flow chart for the first study.

Figure 5-8: Data collection flowchart (first study)



Day 2, Session 4 of BP recording
(n=38)

5.3.2 Within session comparisons - Descriptive analysis and One-way repeated measures ANOVA

5.3.2.1 Sitting position (within session)

The Shapiro-wilk test and histograms were used to test the normality of the distribution of the data for each breathing pattern component there were generally found to be normally distributed in both sitting and supine positions (Appendix A.7). Therefore, as the same group of participants completed all sessions, one-way repeated measure ANOVA was used to test for any statistically significant differences Mauchly's Test of Sphericity as not violated.

One-way repeated measures ANOVA determined that the changes in the cohort mean of T_i, T_e and Bf for all 50 participants were not statistically significantly different within session 1, with p values of more than 0.05 and F ratio values of (F= 0.41, *df*=1, p=0.53), (F=0.00, *df*=1, p=0.99), and (F=0.05, *df*=1, p=0.77) respectively (table 5-2). The change in cohort means of $\%RC_{exp}$ and $\%AB_{exp}$ were not statistically significantly different within session 1 with F ratio values of (F=0.76, *df*=1, p=0.39), and (F=0.55, *df*=1, p=0.46) respectively (table 5-2). Since the rib cage and abdomen work reciprocally, any change that occurs in the rib cage movement data, should also be reflected in abdominal change, so as expected, there was a reciprocal relationship to the changes that occurred in the thoracoabdominal motion components; if the $\%RC_{exp}$ increased then the $\%AB_{exp}$ decreased (and the opposite). Similarly, no statistical significant differences in cohort mean values for within session 2 and 3 comparisons for all breathing pattern components (table 5-2).

In session 4, however, the only cohort mean value found to be statistically significantly different was Bf, with a p value of 0.009 (table 5-2). Yet, it is

important to note that this difference in Bf was 0.59 (bpm) and a study by Smith et al. (2011) comparing a device that monitors Bf with the manual method of counting breath excursions, a pre-defined protocol limit to evaluate equivalence was defined as ±2 breaths per minute. This criteria (of ±2 breaths per minute) was also adopted to measure meaningful change in Bf in a study by Smith et al. (2011). Hence, the change in Bf (of 0.53bpm) for the within session 4 comparison may not large enough to be considered as meaningful change according to the predefined protocol limit of Smith et al. (2011). However, there is a general lack of specificity within the literature regarding defined criteria that represents meaningful change in breathing pattern components.

In addition, multiple testing for one breathing pattern component may increase the possibility of type I error by more than 5% chance. Therefore, the Bonferroni correction was used to give a new level of significance 0.0025, so these significant changes in Bf cohort mean may have occurred due to chance rather than real change. Although, the Bonferroni Correction has been criticised as being too conservative (Narum 2006) and can not always be considered as a definitive indicator of p value (Perneger 1998).

In summary, one-way repeated measures ANOVA did not find any statistically significant differences in the cohort means for most components in most scenarios in the sitting position (with the exception of Bf for within session 4 comparison).

Table 5-2: Descriptive statistic and one –way repeated measure ANOVA results for breathing pattern components for within session comparisons in SITTING (RIP)

		Descriptive statistics		Result of the One- way repeated measure ANOVA			
	Breathing components	**2nd section (M±SD)**	**4th section (M±SD)**	**Mean squares**	**F**	***df***	***P* Value**
Within session one n=50	Ti (sec)	1.66±0.64	1.69±0.72	0.04	0.41	1	0.53
	Te (sec)	2.55±0.79	2.55±0.82	0.08	0.00	1	0.99
	Bf (bpm)	15.57±4.59	15.49±4.28	1.861	0.09	1	0.77
	%RCexp	60.38±12.59	60.98±13.62	11.68	0.76	1	0.39
	%ABexp	39.54±12.59	39.03±13.21	11.55	0.55	1	0.47
Within session two n=50	Ti (sec)	1.64±0.61	1.55±0.51	0.06	3.86	1	0.06
	Te (sec)	2.55±0.80	2.49±0.68	0.05	1.80	1	0.19
	Bf (bpm)	15.52±4.11	15.81±3.71	1.37	1.57	1	0.22
	%RCexp	61.44±11.95	60.63±12.96	7.90	2.10	1	0.15
	%ABexp	38.59±12.01	39.37±13.23	8.24	1.79	1	0.19
Within session three n=38	Ti (sec)	1.59±0.59	1.58±0.59	0.03	0.34	1	0.56
	Te (sec)	2.55±0.81	2.47±0.72	0.04	3.01	1	0.91
	Bf (bpm)	15.59±3.93	15.43±4.41	1.14	0.96	1	0.33
	%RCexp	60.58±11.4	61.02±13.09	8.31	0.45	1	0.51
	%ABexp	39.52±11.52	39.00±13.14	8.04	0.62	1	0.44
Within session four n=38	Ti (sec)	1.58±0.57	1.56±0.68	0.04	0.18	1	0.68
	Te (sec)	2.56±0.78	2.44±0.71	0.07	4.47	1	0.09
	Bf (bpm)	15.61±4.01	16.19±4.01	1.01	7.60	1	0.009*
	%RCexp	60.28±12.02	60.19±12.97	6.03	0.02	1	0.88
	%ABexp	39.75±12.11	39.96±12.99	5.87	0.13	1	0.72

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes. (M) Mean; (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase,(*df*) degree of freedom,* starred results significant at the 0.05 alpha level.

5.3.2.2 Supine position (within session)

The following table (5-3) details the descriptive data and ANOVA results relating to the mean (±SD) for all breathing pattern components for the within session data in the supine position.

No statistically significant differences were found for any of the cohort means values for all components (T_i, T_e, Bf, $\%RC_{exp}$ and $\%AB_{exp}$) in any of the four sessions, with the exception of thoracoabdominal motion components for the within session 3 comparisons (table 5-3). The reciprocal nature of the rib cage and abdomen explains why cohort mean values for both rib cage contribution and abdominal contribution parameters were found to be statistically significant for the within session 3 comparison. This finding may be related to type I error that can occur in a design with multiple tests.

However, one-way repeated measures ANOVA is not alone considered sufficient to conclusively determine reliability (Atkinson & Alan 1998); thus, ICC was used to examine the relative reliability, which is presented in the following section.

Table 5-3: Descriptive statistic and one –way repeated measure ANOVA results for breathing pattern components for within session comparisons in SUPINE (RIP)

		Descriptive statistics		Result of the One- way repeated measure ANOVA			
	Breathing components	**2nd section (M±SD)**	**4th section(M±SD)**	**Mean square**	**F**	***df***	***P* Value**
Within session one n=50	Ti (sec)	1.77±0.91	1.83±1.04	0.14	0.68	1	0.42
	Te (sec)	2.52±1.1	2.45±0.97	0.22	0.55	1	0.46
	Bf (bpm)	15.81±5.0	15.41±6.05	7.85	0.51	1	0.48
	%RCexp	38.20±19.17	39.12±19.57	32.23	0.63	1	0.43
	%ABexp	61.65±19.16	60.57±19.59	29.92	0.97	1	0.33
Within session two n=50	Ti (sec)	1.74±0.93	1.79±0.85	0.0	0.92	1	0.34
	Te (sec)	2.39±0.99	2.38±0.79	0.08	0.14	1	0.71
	Bf (bpm)	16.26±4.84	15.68±4.09	3.21	2.81	1	0.10
	%RCexp	36.22±17.39	36.46±17.75	20.57	0.07	1	0.79
	%ABexp	63.68±17.52	63.49±17.69	20.20	0.05	1	0.83
Within session three n=38	Ti (sec)	1.69±0.79	1.65±0.69	0.05	0.85	1	0.36
	Te (sec)	2.47±1.15	2.38±1.06	0.11	1.48	1	0.23
	Bf (bpm)	16.21±4.8	16.11±6.86	2.08	0.08	1	0.78
	%RCexp	39.52±19.99	42.05±19.49	23.91	5.72	1	0.02*
	%ABexp	60.71±19.94	58.19±19.37	23.49	5.81	1	0.02*
Within session four n=38	Ti (sec)	1.83±0.79	1.92±1	0.17	1.01	1	0.32
	Te (sec)	2.54±0.96	2.51±0.92	0.12	0.14	1	0.71
	Bf (bpm)	15.23±4.69	15.27±4.78	4.08	0.01	1	0.93
	%RCexp	41.98±19.39	41.20±19.71	21.90	0.51	1	0.48
	%ABexp	57.99±19.29	58.78±19.82	22.17	0.52	1	0.48

(Ti)Inspiratory time, (Te) Expiratory time, (sec) second, (BF) Breathing frequency, (bpm) breath per minutes. (M) Mean; (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase,(df) degree of freedom,* starred results significant at the 0.05 alpha level.

5.3.3 Relative reliability estimates for cohort mean using ICC- Within session reliability

5.3.3.1 Sitting position (within session)

Regarding within session 1 in sitting position, the ICC (1, k) (using random method, type consistency, average measure) for the cohort mean T_i was found to be 0.958 (with a 95% confidence interval from 0.925-0.976), which demonstrates high relative reliability. Also, an ICC value of 0.939 (with a 95% confidence interval from 0.893-0.966) was found for the cohort mean T_e measurements, indicating a high relative reliability and Bf measurements demonstrated a high relative reliability, with an ICC of 0.951 (with a 95% confidence interval from 0.914-0.972). Regarding thoracoabdominal motion, ICC values of 0.964 (with a 95% confidence interval from 0.937- 0.980 respectively) were derived for $\%RC_{exp}$; this demonstrates high correlation. Also, $\%AB_{exp}$ demonstrated a high ICC value with measurements of 0.946 (with a 95% confidence interval from 0.937- 0.980). Additionally, for within session 2, 3 and 4 comparisons, ICC values denoting high correlation were derived for all breathing pattern components, indicating high relative reliability in the sitting position (table 5-4).

5.3.3.2 Supine position (within session)

For the within session 1 comparison in supine, high relative reliability was indicated for cohort mean T_i measurement with ICC values of 0.923 (with a 95% confidence interval from 0.864-0.956). An ICC score of 0.888 (with a 95% confidence interval from 0.790-0.932) was found for the cohort mean T_e measurements, indicating a high relative reliability. Cohort mean Bf measurements also demonstrated a high relative reliability, with an ICC of 0.854 (with a 95% confidence interval from 0.743-0.917). Regarding the thoracoabdominal motion components, the ICC for $\%RC_{exp}$ and $\%AB_{exp}$

cohort mean values were found to be 0.955 (with a 95% confidence interval from 0.921- 0.974) and 0.959 (95%CI 0.927- 0.976) respectively, indicating high relative reliability. As demonstrated in the table 5-5, ICC values of > 0.7 (high correlation) were found in all scenarios, indicating high relative within session reliability for all breathing pattern components in the supine position.

5.3.4 Absolute reliability estimate using Within Subjects Standard Deviation (WSSD) and Smallest Real Differences (SRD) for - Within session comparisons

This section presents the data regarding the measurement error calculation using Within Subjects Standard Deviation (WSSD) and Smallest Real Differences (SRD) to determine the absolute reliability of breathing pattern components in both sitting and supine positions (tables 5-4 and 5-5).

5.3.4.1 Sitting position (within session)

The WSSD values for the timing components displayed both increases and decreases within the various sessions. The WSSD for T_i, T_e and Bf ranged from 0.17(sec)–0.22(sec), 0.27(sec)-0.3(sec) and 1.0(bpm)–1.4(bpm) respectively. Regarding thoracoabdominal motion components, it was noted that the WSSD values decreased progressively for the within session comparisons with the WSSD ranging from 3.4%- 2.4% across all 4 sessions. WSSD% is calculated by dividing WSSD by the mean of the two tests multiplied by 100. The WSSD% values were all less than 20% of the mean values, which might be considered low, indicating low variability; however, it is not possible to judge high or low absolute reliability due to lack of criteria within the literature.

The SRD for Ti, Te and Bf ranged from 0.47(sec)–0.61(sec), 0.77(sec)-0.83(sec) and 2.77(bpm)-3.9(bpm) across all four sessions. Regarding the

thoracoabdominal motion components, the SRD ranged from 6.65% to 9.4%.

5.3.4.2 Supine position (within session)

The WSSD and SRD values in the supine position were found to be higher than those in the sitting suggesting a lower absolute reliability in the supine position.

The WSSD for T_i, T_e and Bf ranged from 0.22(sec)–0.41(sec), 0.28(sec)-0.47(sec) and 1.79(bpm)-2.8(bpm) across all four sessions, while thoracoabdominal motion components ranged from 4.49 to 5.68%. All WSSD% values for all components were within 20% of the mean value. With the exception of T_i for within session 1 and 4, which were 20.7% and 22% respectively.

The SRD for T_i, T_e and Bf ranged from 0.6(sec)–1.03(sec), 0.7(sec)-1.3(sec) and 3.99(bpm)-7.7(bpm) across all four sessions and thoracoabdominal motion components ranged from 12.4 to 15.7%.

Table 5-4: Relative and absolute reliability of breathing pattern components for within session comparisons in SITTING (RIP)

	Breathing components	ICC (95% CI)	WSSD (%)	SRD	*d*	SD diff	SE diff	95% CI for diff	95 % LA
Within session one n=50	**Ti (sec)**	0.958 (0.925- 0.976)	0.2 (11.7)	0.55	-0.03	0.28	0.04	-0.09, 0.06	-0.59, 0.50
	Te (sec)	0.939 (0.893- 0.966)	0.3 (11.8)	0.83	-0.00	0.39	0.06	-0.10, 0.11	-0.78, 0.78
	Bf (bpm)	0.951 (0.914- 0.972)	1.4 (8.8)	3.9	0.08	1.95	0.28	-0.53, 0.58	-3.80, 4.00
	%RCexp	0.964 (0.937- 0.980)	3.4 (5.6)	9.4	-0.6	4.85	0.66	-1.92, 0.63	-10.3, 9.10
	%ABexp	0.946 (0.937- 0.980)	3.4 (8.6)	9.4	0.51	4.83	0.66	-0.73, 1.82	-9.2, 10.2
Within session two n=50	**Ti (sec)**	0.903 (0.829- 0.945)	0.24 (15.1)	0.66	0.09	0.33	0.05	0.01, 0.19	-0.57, 0.75
	Te (sec)	0.956 (0.921- 0.975)	0.22 (8.7)	0.61	0.06	0.30	0.04	-0.02, 0.15	-0.54, 0.66
	Bf (bpm)	0.954 (0.918- 0.974)	1.2 (7.6)	3.32	-0.29	1.64	0.24	-0.77, 0.13	-3.57, 2.99
	%RCexp	0.974 (0.955- 0.986)	2.8 (4.6)	7.76	0.84	3.97	0.56	-0.24, 1.99	-7.10, 8.78
	%ABexp	0.974 (0.954- 0.985)	2.8 (9.3)	7.76	-0.77	4.07	0.58	-1.98, 0.31	-8.71, 6.72
Within session three n=38	**Ti (sec)**	0.963 (0.930- 0.981)	0.16 (9.9)	0.44	0.02	0.22	0.04	-0.05, 0.09	-0.42, 0.46
	Te (sec)	0.964 (0.932- 0.981)	0.2 (7.9)	0.55	0.08	0.28	0.04	-0.002, 0.17	-0.48, 0.64
	Bf (bpm)	0.960 (0.923- 0.979)	1.2 (6.8)	3.32	-0.24	1.51	0.24	-0.69, 0.211	-3.26, 2.76
	%RCexp	0.972 (0.947- 0.986)	2.9 (4.7)	7.97	-0.45	4.11	0.66	-1.76, 0.85	-8.67, 7.77
	%ABexp	0.974 (0.950- 0.986)	2.8 (7.2)	7.84	0.51	4.03	0.65	-0.75, 1.77	-7.55, 8.57
Within session four n=38	**Ti (sec)**	0.964 (0.931- 0.981)	0.17 (10.7)	0.47	0.02	0.24	0.04	-0.06, 0.09	-0.46, 0.5
	Te (sec)	0.932 (0.870- 0.965)	0.27 (10.8)	0.75	0.12	0.36	0.06	0.008, 0.24	-0.6, 0.84
	Bf (bpm)	0.968 (0.940- 0.984)	1.0 (6.3)	2.77	-0.59	1.31	0.21	-1.02, -0.16	-3.21, 2.03
	%RCexp	0.981 (0.963- 0.990)	2.5 (4.08)	6.93	0.09	3.5	0.56	-1.01, 1.1	-6.91, 7.09
	%ABexp	0.982 (0.965- 0.990)	2.4 (6.09)	6.65	-0.21	3.5	0.55	-1.26, 0.87	-7.21, 6.79

ICC (95%CI) intra class correlation coefficient with 95% confident intervals, (WSSD) within subjects standard deviation (%) , SRD smallest real differences, (*d*) mean of the differences and standard deviation (SDdiff) of the differences, Standard Error of the mean difference (SE diff), 95% confident interval for the mean differences and 95% LA limit of agreement.

Table 5-5: Relative and absolute reliability of breathing pattern components for within session comparisons in SUPINE (RIP)

	Breathing components	ICC (95% CI)	WSSD (%)	SRD	*d*	SD diff	SE diff	95% CI for diff	95 % LA
Within session one n=50	**Ti (sec)**	0.923 (0.864- 0.956)	0.37 (20.7)	1.03	-0.06	0.53	0.07	-0.21, 0.09	-1.17, 0.98
	Te (sec)	0.888 (0.970- 0.932)	0.47 (18.9)	1.31	0. 07	0.67	0.09	-0.09, 0.26	-1.25, 1.39
	Bf (b/min)	0.854 (0.743- 0.917)	2.80 (17.9)	7.76	0.40	3.98	0.55	-0.59, 1.5	-7.47, 8.29
	%RCexp	0.955 (0.921- 0.974)	5.68 (14.6)	15.72	-0.90	8.06	1.08	-2.92, 1.20	-17.02, 15.22
	%ABexp	0.959 (0.927- 0.976)	5.47 (8.8)	15.15	1.1	7.7	1.03	-1.03, 2.99	-14.3, 16.5
Within session two n=50	**Ti (sec)**	0.961 (0.931- 0.978)	0.25 (13.9)	0.69	-0.05	0.35	0.05	-0.14, 0.05	-0.75, 0.65
	Te (sec)	0.949 (0.910- 0.971)	0.28 (11.8)	0.77	0.02	0.4	0.06	-0.09, 0.13	-0.78, 0.82
	Bf (b/min)	0.915 (0.850- 0.951)	1.79 (11.2)	4.95	0.59	2.5	0.35	-0.04, 1.3	-4.33, 5.54
	%RCexp	0.966 (0.939- 0.980)	4.54 (12.5)	12.58	-0.24	6.47	0.9	-1.99, 1.59	-13.06, 12.58
	%ABexp	0.966 (0.941- 0.981)	4.49 (7.1)	12.43	0.19	6.42	0.9	-1.6, 2.0	-12.65, 13.03
Within session three n=38	**Ti (sec)**	0.954 (0.911- 0.976)	0.22 (13.3)	0.61	0.05	0.31	0.05	-0.05, 0.15	-0.58, 0.67
	Te (sec)	0.955 (0.913- 0.976)	0.32 (13.4)	0.89	0.05	0.46	0.07	-0.06, 0.23	-0.81, 0.99
	Bf (b/min)	0.947(0.899-0.972)	1.44 (8.9)	3.99	0.09	2.06	0.33	- 0.58, 0.77	-04.03, 4.21
	%RCexp	0.968 (0.940- 0.984)	4.9 (12.0)	13.6	-2.53	6.52	1.06	-4.53, -0.48	-15.57, 10.53
	%ABexp	0.969 (0.940- 0.984)	4.8 (8.2)	13.3	2.53	6.46	1.04	0.52, 4.48	-10.39, 15.45
Within session four n=38	**Ti (sec)**	0.884 (0.778- 0.939)	0.41 (22.04)	1.1	-0.09	0.58	0.09	-0.29, 0.08	-1.25, 1.07
	Te (sec)	0.929 (0.862- 0.962)	0.31 (13.6)	0.94	0.03	0.49	0.08	-0.14, 0.17	-0.95, 1.01
	Bf (b/min)	0.900 (0.808- 0.948)	2.02 (13.3)	5.6	-0.04	2.89	0.47	-0.96, 0.89	-5.82, 5.74
	%RCexp	0.971 (0.944- 0.985)	4.68 (11.2)	12.9	0.77	6.66	1.07	-1.2, 2.96	-12.55, 14.09
	%ABexp	0.970 (0.943- 0.948)	4.7 (8.1)	13.0	-0.78	6.70	1.07	-3.02, 1.18	-14.18, 12.62

ICC (95%CI) intra class correlation coefficient with 95% confident intervals, (WSSD) within subjects standard deviation (%) , SRD smallest real differences, (*d*) mean of the differences and standard deviation (SDdiff) of the differences, Standard Error of the mean difference (SE diff), 95% confident interval for the mean differences and 95% LA limit of agreement.

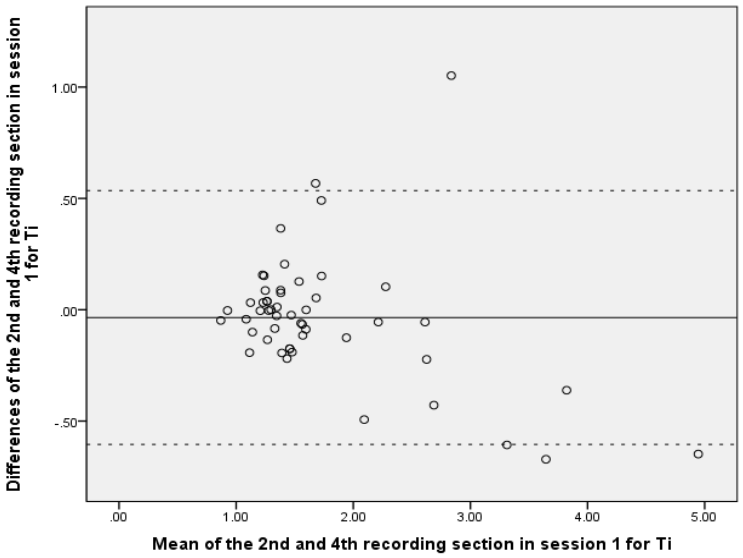
5.3.5 Bland-Altman 95% limit of agreement for within session comparisons

Bland-Altman (1986) developed a graphical method for analysing the agreement between measurements. Using the Bland-Altman method, a scatter plot was produced for each variable in each recording session in both sitting and supine positions. This study produce a large number of scatter plots, only one example will be included in the following figures 5-9 to 5-13, which show the scatter plot for all breathing pattern components in the sitting position for the within session one comparisons. All other Bland-Altman plots for all other comparisons in both positions are including in Appendix D.

The mean differences were plotted using a solid line and the 95% limit of agreement and upper and lower were plotted using dotted lines. The 95% confidence intervals for the mean difference demonstrates the magnitude of the systematic bias are presented in previous tables 5-4 and 5-5. The results from the Bland–Altman analysis demonstrated an agreement for all breathing pattern components with no systematic bias, although there were some outliers (shown as data points outside the lower and upper limits of agreements).

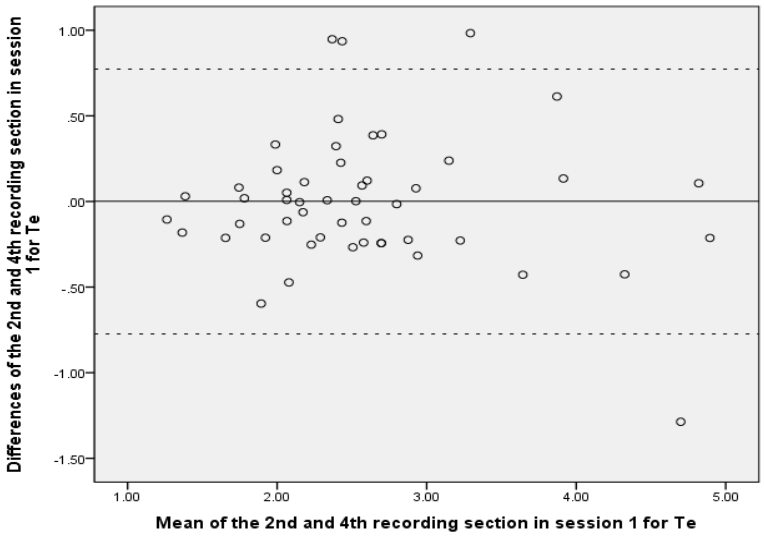
Bland-Altman plots for breathing pattern components for within session 1 in SITTING position

Figure 5-9**: Results from the Bland- Altman 95% limit of agreement for inspiratory time (Ti)**



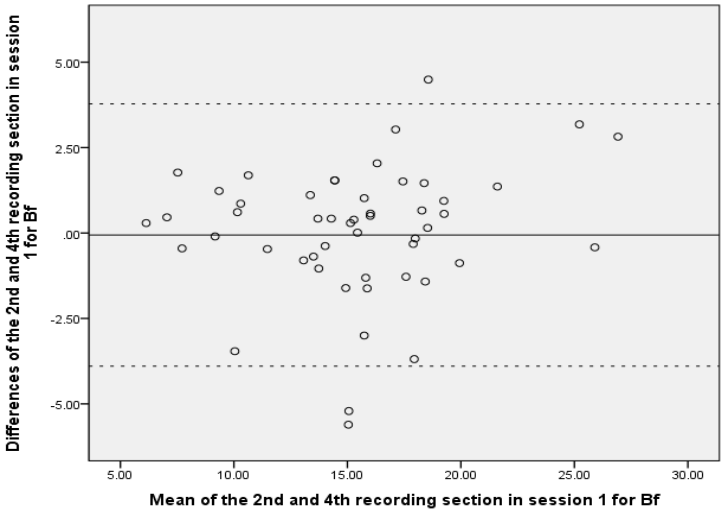
The Bland-Altman analysis shows a 95% limit of agreement (LA) between -0.59 and 0.5 and 5 outliers (10% of the total number of participants).

Figure 5-10: Results from the Bland- Altman 95% limit of agreement for expiratory time (Te)



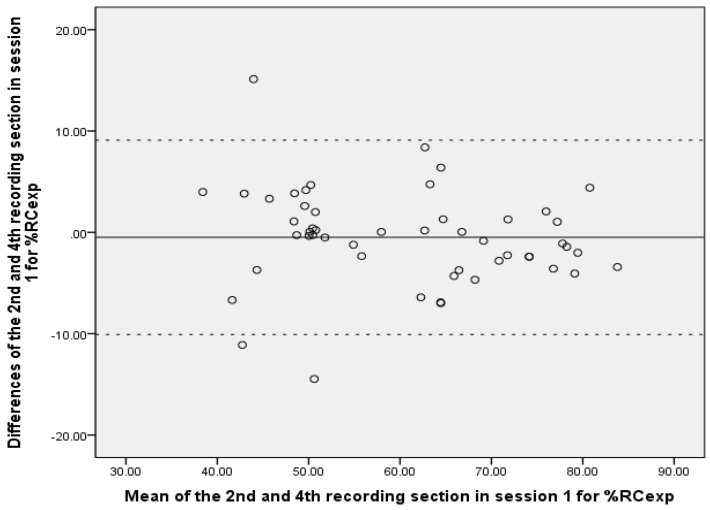
The Bland-Altman analysis demonstrates a 95% limit of agreement (LA) between -0.78 and 0.78 and 4 outliers (8% of the total number of participants).

Figure 5-11: Results from the Bland- Altman 95% limit of agreement for breathing frequency (Bf)



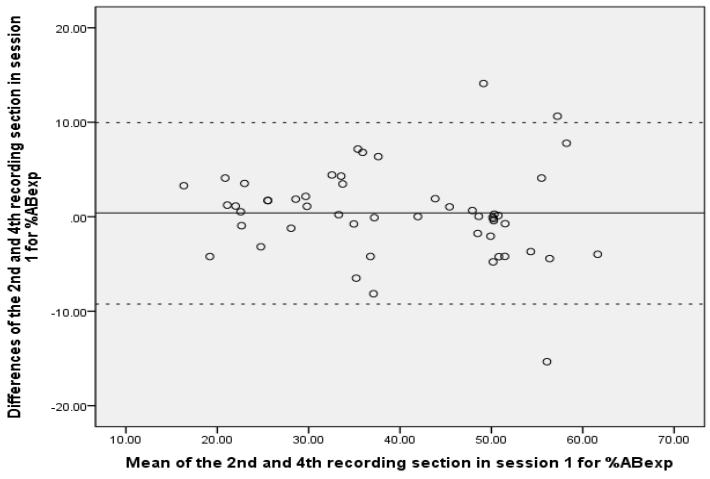
The Bland-Altman analysis demonstrates a 95% limit of agreement (LA) between -3.77 and 4 and 3 outliers (6% of the total number of participants).

Figure 5-12: Results from the Bland-Altman 95% limit of agreement for (RCexp).



The Bland- Altman analysis demonstrates a 95% LA between -10.3 and 9.1 and 3 outliers (6% of the total number of participants).

Figure 5-13: Results from the Bland-Altman 95% limit of agreement for (ABexp)



The Bland- Altman analysis demonstrates a 95% LA is between -9.2 and 10.2 and again 3 outliers (6% of the total number of participants).

5.3.6 Between session reliability

The previous section outlined the data for the within session reliability; this section presents the data for the between session reliability based on 9 minutes (sections two, three and four combined) of breathing pattern recording that took place on two separate sessions in the sitting and supine position on the same day with a 15 minute break in between.

5.3.6.1 Descriptive analysis and One- way repeated measure ANOVA for between sessions reliability

Sitting position (between session)

One-way repeated measured ANOVA was used to compare the cohort mean values for each breathing pattern component between session one and two (both on day one) in the sitting position.

Table 5-6 shows that there were no statistically significant differences in the cohort mean values for all the breathing pattern components (T_i, T_e, Bf, $\%RC_{exp}$ and $\%AB_{exp}$) in the between session comparisons.

Supine position (between session)

It is apparent in table 5-7, that there were no statistically significant differences in the cohort mean values for all breathing pattern components for the between session comparisons (session one and two) in the supine position. However, between session three and four, the one-way repeated measures ANOVA demonstrated significant differences in the cohort means for two of the timing components, namely T_i and Bf ($p= 0.02$).

Descriptive between sessions SITTING

Table 5-6: Results from analysis of variance ANOVA for breathing pattern components for the between session comparisons in SITTING (RIP)

		Descriptive statistics		Result of the One- way repeated measure ANOVA			
	Breathing components	**Session one**	**Session two**	**Mean square**	**F**	***df***	***P* Value**
Between session one and two n=50	Ti (sec)	1.75±0.81	1.70±0.62	0.21	0.27	1	0.61
	Te (sec)	2.59±0.80	2.59±0.75	0.10	0.02	1	0.90
	Bf (bpm)	15.25±4.45	15.07±4.036	5.48	0.15	1	0.69
	%RCexp	60.15±13.26	60.90±12.56	35.38	0.39	1	0.53
	%ABexp	39.82±13.21	39.15±12.66	34.67	0.34	1	0.57
Between session three and four n=38	Ti (sec)	1.59±0.56	1.61±0.61	0.02	0.39	1	0.54
	Te (sec)	2.54±0.80	2.55±0.73	0.03	0.01	1	0.93
	Bf (bpm)	15.57±3.62	15.50±3.82	1.35	0.06	1	0.81
	%RCexp	58.77±12.13	59.42±12.96	15.06	0.52	1	0.47
	%ABexp	41.33±12.17	40.70±13.04	15.9	0.47	1	0.49

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes. (M) Mean; (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase,(df) degree of freedom,* starred results significant at the 0.05 alpha level.

Descriptive between sessions SUPINE

Table 5-7: Results from analysis of variance ANOVA for breathing pattern components for between session comparisons in SUPINE (RIP)

		Descriptive statistics		Result of the One- way repeated measure ANOVA			
	Breathing components	**Session one**	**Session two**	**Mean square**	**F**	***df***	***P* Value**
Between session one and two n=50	Ti (sec)	1.86±1.02	1.79±0.91	0.18	0.69	1	0.41
	Te (sec)	2.56±1.06	2.39±0.89	0.24	3.06	1	0.09
	Bf (bpm)	15.54±5.27	15.79±4.17	6.69	0.25	1	0.62
	%RCexp	35.60±16.64	37.23±17.75	36.93	1.83	1	0.18
	%ABexp	64.04±16.42	62.65±17.81	39.22	1.23	1	0.27
Between session three and four n=38	Ti (sec)	1.64±0.69	1.82±0.85	0.114	5.76	1	0.02*
	Te (sec)	2.39±0.98	2.53±0.89	0.21	1.13	1	0.29
	Bf (bpm)	16.39±4.30	15.52±4.56	3.06	5.59	1	0.02*
	%RCexp	40.51±19.51	40.89±18.48	22.57	0.13	1	0.72
	%ABexp	59.63±19.45	59.12±18.46	22.70	0.21	1	0.65

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes. (M) Mean; (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase,(df) degree of freedom,* starred results significant at the 0.05 alpha level.

5.3.6.2 Relative reliability estimates for cohort mean using ICC for between session comparisons for sitting and supine

The ICC values for the timing and thoracoabdominal motion components between session one and two and between session three and four in sitting, all demonstrated high correlation, ICC value >0.7 (see table 5-8).

Regarding supine position data, Table 5-9 shows that the ICC values for timing and thoracoabdominal motion components demonstrated high correlation (ICC >0.8) and (ICC > 0.9) respectively. These ICC values suggest high relative reliability in both the sitting and supine position.

Between session SITTING

Table 5-8: Relative and absolute reliability of breathing pattern components for between session reliability in SITTING (RIP)

	Breathing components	ICC (95% CI)	WSSD (%)	SRD	*d*	SD diff	SE diff	95% CI for diff	95 % LA
Between session one and two n=50	**Ti (sec)**	0.742 (0.547-0.853)	0.5 (26.7)	1.27	0.05	0.66	0.09	-0.13, 0.24	-1.27, 1.37
	Te (sec)	0.908 (0.838-0.948)	0.3 (12.3)	0.89	-0.01	0.46	0.05	-0.14, 0.13	-0.93, 0.91
	Bf (bpm)	0.821 (0.685-0.898)	2.3 (15.4)	6.48	0.19	3.34	0.42	-0.68, 1.1	-6.49, 6.87
	%RCexp	0.881 (0.791-0.932)	5.95 (9.8)	16.48	-0.75	8.46	1.12	-2.9, 1.7	-17.7, 16.17
	%ABexp	0.884 (0.797-0.934)	5.9 (14.9)	16.35	0.68	8.38	1.1	-1.67, 2.9	-16.08, 17.44
Between session three and four n=38	**Ti (sec)**	0.969 (0.941-0.948)	0.14 (9.1)	0.39	-0.02	0.21	0.03	-0.09, 0.05	-0.43, 0.39
	Te (sec)	0.971 (0.944-0.985)	0.18 (7.1)	0.52	-0.01	0.26	0.04	-0.09, 0.08	-0.53, 0.52
	Bf (bpm)	0.949 (0.902-0.973)	1.16 (7.5)	3.21	0.07	1.7	0.26	-0.48, 0.55	-3.33, 3.47
	%RCexp	0.950 (0.904-0.974)	3.88 (6.6)	10.75	-0.65	5.5	0.89	-2.4, 1.1	-11.65, 10.35
	%ABexp	0.947 (0.899-0.973)	3.99 (9.7)	10.75	0.63	5.7	0.91	-1.2, 2.4	-10.77, 12.04

ICC (95%CI) intra class correlation coefficient with 95% confident intervals, (WSSD) within subjects standard deviation, SRD smallest real differences, (*d*) mean of the differences and standard deviation (SDdiff) of the differences, Standard Error of the mean difference (SE diff), 95% confident interval for the mean differences and 95% LA limit of agreement.

Between session SUPINE

Table 5-9: Relative and absolute reliability of breathing pattern components for between session reliability in SUPINE (RIP)

	Breathing components	ICC (95% CI)	WSSD (%)	SRD	*d*	SD diff	SE diff	95% CI for diff	95 % LA
Between session one and two n=50	**Ti (sec)**	0.893 (0.812-0.939)	0.42 (23.1)	1.7	0.07	0.60	0.08	-0.08, 0.25	-1.13, 1.27
	Te (sec)	0.861 (0.756-0.921)	0.48 (19.6)	1.33	0.17	0.67	0.09	-0.018, 0.36	-1.17, 1.51
	Bf (bpm)	0.826 (0.694-0.901)	2.59 (16.5)	7.17	-0.26	3.68	0.52	-1.22, 0.84	-7.62, 7.1
	%RCexp	0.934 (0.883-0.962)	6.08 (16.7)	16.84	-1.63	8.52	1.21	-4.05, 0.79	-18.67, 15.44
	%ABexp	0.928 (0.874-0.959)	6.26 (9.9)	17.34	1.38	8.84	1.25	-1.13, 3.89	-16.32, 19.08
Between session three and four n=38	**Ti (sec)**	0.897 (0.802-0.946)	0.34 (19.5)	0.94	-0.39	1.5	0.23	-0.89, -0.06	-3.39, 2.61
	Te (sec)	0.868 (0.747-0.931)	0.45 (18.6)	1.25	-0.19	0.79	0.13	-0.44, 0.06	-1.77, 1.39
	Bf (bpm)	0.916 (0.839-0.956)	1.75 (11)	4.84	1.3	3.3	0.51	0.33, 2.35	-5.3, 7.9
	%RCexp	0.968 (0.938-0.983)	4.75 (11.7)	13.16	-0.39	6.79	1.1	-2.63, 1.84	-13.97, 13.19
	%ABexp	0.967 (0.938-0.983)	4.76 (8)	13.18	0.5	6.81	1.1	-1.73, 2.74	-13.12, 14.12

ICC (95%CI) intra class correlation coefficient with 95% confident intervals, (WSSD) within subjects standard deviation, SRD smallest real differences, (*d*) mean of the differences and standard deviation (SDdiff) of the differences, Standard Error of the mean difference (SE diff), 95% confident interval for the mean differences and 95% LA limit of agreement.

5.3.6.3 Absolute reliability estimate using WSSD and SRD for between session comparisons

Sitting position (between session)

The previous table 5-8 demonstrates the WSSD% values for all breathing pattern components for the between session one and two comparisons were less than 20% of the mean, with the exception of T_i, which was 26.7% of the mean value. WSSD% values for session three and four for all breathing pattern components were lower than those derived during session one and two (as shown in table 5-8) with all values within 10% of the mean. This finding may be explained due to the impact of the 'White coat effect' or learning effect, where participants perhaps felt more relaxed and less apprehensive during the 3rd and 4th sessions (on the second day) in comparison to the first day. However, the level of anxiety for participants was not measured using any instrument; therefore, it is impossible to confirm this assumption (this will be discussed in more detail within the Chapter 8).

The SRD value for the within session data were used as a baseline data set that provided an estimate of how much change needed to occur in the between session comparisons' group means in order to be considered as real change rather than change that occurred due to measurement error. So if the changes that occur exceed the 'baseline' value derived from the SRD data set, then this can be considered as a real change rather than as a result of measurement error. However, if the mean differences are less than the 'baseline' data set derived from the SRD calculation, then it would indicate that no real change has occurred. All the group mean differences for the between session comparisons were less than the 'baseline' data suggesting that no real change occurred (see table 5-2 for within session 'baseline' SRD values and table 5-8 for mean differences values for between session data).

Supine position (between session)

Table 5-9 shows that the WSSD% values relating to the between session one and two comparison were all less than 20% of the mean, with exception of Ti, which was 23.1%. Again, the WSSD% values for the between session three and four comparison were lower than those derived from the between session one and two comparison, and were all within 20% of the mean. Also, all the group mean differences for the between session comparisons were less than the 'baseline' data set derived from the SRD values for the within session comparisons indicating no real change occurred.

5.3.6.4 Bland-Altman 95% limit of agreement for between session comparisons

The results from the Bland-Altman analysis indicated agreement and no systematic bias for all breathing pattern components in both the sitting and supine position, with the exception of Ti and Bf for the between session 3 and 4 comparison in the supine position. All Bland-Altman plots are included in Appendix D.

5.3.7 Between day reliability

This section presents the data relating to the between day reliability in the sitting and supine position, based on the group mean of both sessions on day 1 compared with the group mean of both sessions on day 2. An important consideration when interpreting the data for the between day comparisons is that the data collected on day 1 (session 1and 2) is based on a sample size of 50, while only 38 participants returned for the second day (session 3 and 4) (retention rate of 78%).

5.3.7.1 Missing data

Two participants' data were removed from analysis due to equipment failure. Also, due to unknown reasons, 10 participants did not return for the second day of recording (third and fourth recording sessions). Therefore, some data sets are missing from the analysis. This directly affects the between day comparisons because to conduct analysis with ANOVA, complete data sets throughout all time points are necessary and the SPSS will remove data sets if any parts are missing. Since only 38 participants returned (from an original sample of 50), the number of complete data sets is reduced for the between day comparisons. This may affect the statistical power, which in turn may contribute to the possible occurrence of Type II error (false negative).

5.3.7.2 Descriptive statistics and One- way repeated measures ANOVA for between day reliability in sitting and supine positions

Regarding the between day comparisons, table 5-10 demonstrates that the cohort mean values of the timing components T_i and T_e decreased from day 1 to day 2 in both sitting and supine positions, while Bf slightly increased. In relation to the thoracoabdominal motion components in sitting, the $\%RC_{exp}$ decreased from day 1 to day 2, while the $\%AB_{exp}$ increased from day 1 to day 2. In the supine position, the $\%RC_{exp}$ increased from day 1 to day 2, while the $\%AB_{exp}$ decreased from day 1 to day 2. Inspiratory time was found to be longer in supine position, which may be due to physiological changes that occur in the rib cage and abdomen in the supine position (discussed further in Chapter 8).

In both sitting and supine positions, one-way repeated measured ANOVA demonstrated no statistically significant differences in cohort means for any of the breathing pattern components ($p>0.05$) (table 5-10).

Between day comparison (SITTING AND SUPINE)

Table 5-10: Descriptive statistics and One- way repeated measure ANOVA for breathing pattern components for the between days comparison in SITTING and SUPINE (RIP)

	Breathing components	Descriptive statistics		Result of the One- way repeated measure ANOVA			
		Day one (n=50)	Day two (n=38)	Mean square	F	*df*	*P* value
SITTING	**Ti (sec)**	1.69±0.65	1.60±0.59	0.09	1.8	1	0.19
	Te (sec)	2.66±0.77	2.55±0.77	0.09	2.26	1	0.14
	Bf (bpm)	14.93±3.77	15.54±3.63	3.45	2.09	1	0.16
	%RCexp	62.07±12.15	59.09±12.26	59.19	2.99	1	0.09
	%ABexp	38.05±12.24	41.01±12.29	59.59	2.19	1	0.09
SUPINE	**Ti (sec)**	1.90±1.01	1.84±0.96	0.09	0.22	1	0.64
	Te (sec)	2.56±0.97	2.49±0.89	0.19	2.92	1	0.09
	Bf (bpm)	14.83±4.14	15.65±4.28	3.76	3.74	1	0.06
	%RCexp	37.06±17.83	39.69±17.75	76.98	1.75	1	0.19
	%ABexp	62.76±17.79	60.34±17.73	77.31	1.52	1	0.22

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (BF) Breathing frequency, (bpm) breath per minutes. (M) Mean; (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase,(df) degree of freedom,* starred results significant at the 0.05 alpha leve

5.3.7.3 Relative reliability estimates for cohort mean using ICC for between day comparisons in sitting and supine positions

All timing components demonstrated high correlation with ICC values of > 0.849 for the between days comparison in both positions. The thoracoabdominal motion components also showed high correlation with ICC values of > 0.755 (see table 5-11) indicating high relative reliability for all breathing pattern components in both positions.

5.3.7.4 Absolute reliability estimate using WSSD and SRD for the between days comparison in sitting and supine positions

The WSSD% values for all breathing pattern components in the sitting and supine positions were less than 20% of the mean. With the exception of $\%RC_{exp}$ in the supine position, which was 22.9% of the mean value. The WSSD% values for thoracoabdominal motion components were higher in the supine position. Regarding the SRD, the values derived from the between session comparisons was used as the 'baseline' data set. All group mean differences for the between day comparisons were less than the 'baseline' data set (see table 5-8 & 5-9 for between session SRD 'baseline' values and tables 5-11 for mean differences values for between day data). From this, it can be suggested that no real change occurred for any of the breathing pattern components under examination.

5.3.7.5 Bland-Altman 95% limit of agreement for within session comparisons

The results from the Bland-Altman analysis indicated agreement and no systematic bias for all breathing pattern components in both positions. All Bland-Altman plots are included in Appendix D.

Between day comparison (sitting and supine)

Table 5-11: Relative and absolute reliability of breathing pattern components for between day's reliability in sitting and supine (RIP)

	Variable	ICC (95% CI)	WSSD (%)	SRD	*d*	SD diff	SE diff	95% CI for diff	95 % LA
SITTING	**Ti (sec)**	0.849 (0.712 -0.922)	0.3 (18.3)	0.83	0.09	0.42	0.06	-0.05, 0.23	-0.75, 0.93
	Te (sec)	0.905 (0.817 -0.950)	0.31 (11.5)	0.86	0.01	0.44	0.07	-0.03, 0.25	-0.77, 0.99
	Bf (bpm)	0.857 (0.726 -0.925)	1.9 (12.2)	5.26	-0.61	2.59	0.41	-1.4, 0.19	-5.79, 4.57
	%RCexp	0.755 (0.532-0.872)	7.69 (12.7)	21.3	2.98	10.61	1.72	-0.51, 6.46	-18.24, 24.2
	%ABexp	0.756 (0.533-0.873)	7.72 (19.5)	21.4	-2.77	10.65	1.73	-6.47, 0.53	-24.07, 18.53
SUPINE	**Ti (sec)**	0.949 (0.903-0.973)	0.29 (15.5)	0.80	0.06	0.85	0.14	-0.21, 0.34	-1.64, 1.76
	Te (sec)	0.875 (0.760-0.935)	0.44(17.12)	1.2	0.02	0.61	0.09	-0.03, 0.37	-1.05, 1.39
	Bf (bpm)	0.882 (0.777- 0.938)	1.94 (12.68)	5.4	-0.89	2.64	0.43	-1.7, 0.03	-6.17, 4.39
	%RCexp	0.862 (0.736-0.928)	8.8 (22.9)	24.4	-2.64	12.29	1.99	-6.68, 1.40	-27.22, 21.94
	%ABexp	0.861 (0.734-0.928)	8.8 (14.29)	24.4	2.42	12.25	1.99	-1.61, 6.45	-2.08, 26.92

ICC (95%CI) intra class correlation coefficient with 95% confident intervals, (WSSD) within subjects standard deviation, SRD smallest real differences, (*d*) mean of the differences and standard deviation (SDdiff) of the differences, Standard Error of the mean difference (SE diff), 95% confident interval for the mean differences and 95% LA limit of agreement

5.3.8 Comparison between supine and sitting positions reliability

Table 5-12 compares the within session, between session and between day data collected in both sitting and supine positions in order to compare the effect of posture on breathing pattern reliability. From this table, it is possible to conclude that all breathing pattern components demonstrated high relative reliability for the within session, between session and between day comparisons in both positions. Regarding the absolute reliability, the range of WSSD and SRD values were lower for all components in all comparisons in the sitting position; indicating a higher absolute reliability in the sitting position in comparison to supine. This may be as a result of certain factors that are linked to the physiological changes that occur in the rib cage and abdomen in the supine position (Wade 1954; Konno & Mead 1967; Sharp et al. 1975; Estenne et al. 1985 and Verschakelen & Demedts) (discussed further in Chapter 8).

Bland-Altman analysis showed agreement for all timing and thoracoabdominal motion components for within session, between session and between day comparisons in both positions with no systemic bias; however, the 95% LA were narrower in the sitting position indicating greater agreement in the sitting position in comparison to supine.

Table 5-12: Comparison between sitting and supine position reliability

Estimate	SITTING			*SUPINE*		
	Within session	***Between session***	***Between day***	***Within session***	***Between session***	***Between day***
One way ANOVA	No Statistically Significantly Different (NSSD) in cohort mean for all breathing components with exception of Bf in session 4	NSSD was found in cohort mean for all breathing components	NSSD in cohort mean for all breathing components	NSSD with exception of Thoracoabdominal motion in within session 3.	NSSD except Ti and Bf in between session 3and 4	NSSD in cohort mean for all breathing components
ICC	High correlation for all BP components in all comparisons with ICC value >0.7			High correlation for all BP components in all comparisons with ICC value >0.7		
WSSD	**Timing component** Ti, Te range from 0.16(sec) to 0.48 (sec). Bf range from 1.01 (bpm) to 1.35(bpm). **Thoracoabdominal motion** Range from 2.23% to 3.7%.	**Timing component:** Ti and Te range from 0.14 (s) to 0.5 (s). Bf range from 1.16 (bpm) to 2.3 (bpm). **Thoracoabdominal motion:** range from 3.88% to 5.9%.	**Timing component:** Ti =0.33(s) and Te =0.3(s) Bf= 1.9(b/min) **Thoracoabdominal motion:** %RCexp= 7.39% to %ABexp= 7.4%.	**Timing component** Ti, Te range from 0.22(sec) to 0.47 (sec). Bf range from 1.79 (bpm) to 3.9 (bpm). **Thoracoabdominal motion** Range from 4.25% to 5.65%.	**Timing component:** Ti and Te range from 0.34 (s) to 4.8 (s). Bf range from 1.75 (bpm) to 2.59 (bpm). **Thoracoabdominal motion:** range from 4.75% to 6.26%. WSSD values were higher in the supine	**Timing component:** Ti =0.39 (s) and Te = 0.53(s) Bf= 2.2 (b/min) **Thoracoabdominal motion:** %RCexp = 9.32% to %ABexp = 9.35%. WSSD values were higher in the supine position (compared to sitting) indicating lower absolute reliability in the supine position.
95%LA	All breathing components showed agreement with no systematic bias			All breathing components showed agreement with no systematic bias. The 95%LA is wider than sitting results.		

(NSSD) No Statistically Significantly Different, (Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minute, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase, ICC intra class correlation coefficient, (WSSD) within subjects standard deviation, of the differences, and 95% LA limit of agreements.

5.3.9 First study findings summary

This study examined the reliability of breathing pattern components in order to establish whether these components can be considered useful as a potential outcome measure.

The findings demonstrated that for ***within session reliability in both sitting and supine positions***, all breathing pattern components showed no statistically significant differences using ANOVA, with the exception of Bf for within session 4 in the sitting position and thoracoabdominal motion for within session 3 in the supine position. In addition, for ***the between session reliability in the sitting position***, all breathing pattern components showed no statistically significant differences. While for the ***between session reliability in the supine position,*** no statistically significant differences in any breathing pattern components were found except for T_i and Bf in the between session 3 and 4 comparisons. For ***between day comparisons in the sitting and supine position***, all breathing pattern components showed no statistically significant differences. Moreover, high relative reliability with high ICC values were noted for all breathing pattern components in all scenarios and no systematic bias was found with Bland–Altman analysis demonstrating good agreement. Thus, hypothesis HP1a has been found to be supported.

Overall, the data collected in the sitting position demonstrated higher ICC values, lower WSSD and SRD and narrower 95%LA than that collected in the supine position. Also, SD values were always less in the sitting position data, in comparison to that collected in the supine position. Hence, this suggests that breathing pattern components demonstrated slightly better relative and

absolute reliability in the sitting position in comparison to the supine position. Consequently, hypothesis HP1b is rejected.

Therefore, it can be suggested that the breathing pattern components have demonstrated reliability. However, for an outcome measure to be considered useful it should demonstrate both reliability and responsiveness, as responsiveness should join reliability as necessary requirements for a measure that detects change over time (Guyatt et al. 1987). Thus, the second and third studies in this thesis explores the responsiveness of breathing pattern components following a stimulus in healthy adults and those with asthma.

Chapter 6 Responsiveness of breathing pattern (thoracoabdominal motion) during recovery from physical exercise in healthy adults (recorded using SLP)

6.1 Introduction

Since the significant effect of physical exercise on timing components has been widely researched and is known (Mostert & Kesselring 2002; Burton et al. 2004; Amritsar 2010), the main aim of the second study was to examine the effect on thoracoabdominal motion components. Thoracoabdominal motion analysis is a neglected area of study, even though there is evidence suggesting that thoracoabdominal motion can be used to differentiate between healthy individuals and those with respiratory disease (Tobin et al. 1983a; Tobin et al. 1983b). However, there is a degree of contradiction and inconsistency within the existing literature, which may be due to heterogeneity in methodological protocol. Hence, the clinical evaluation of thoracoabdominal motion components during recovery from physical exercise is important to add to the evidence base to further understanding of the relationship between respiration and chest wall motion, which could be used to assess the provision of therapeutic intervention in order to improve respiratory health. Consequently, the effect of a 10 minute physical exercise stimulus on breathing pattern was examined.

In addition, the effect of gender on the responsiveness of thoracoabdominal motion in healthy adults was examined and the relationship between cohort mean thoracoabdominal motion and cohort mean timing components at rest

and during recovery from physical exercise in healthy adults due to limited and contradictory literature in this area.

6.2 Methods

6.2.1 Design

This is an experimental study involving healthy adults following a test re-test design. If thoracoabdominal motion analysis is to be considered as an outcome measure to monitor respiratory health, there is a need to establish whether thoracoabdominal motion can be used to detect any significant change following a stimulus before it is applied to a patient population.

6.2.2 Participant selection

Like the first study, healthy adults (aged 18 years or over) were recruited from the University of Southampton population. The ***inclusion criteria*** for this second study included individuals aged 18 years or over, free of any respiratory diseases, injury or illness, physically able to pedal on static bike for 10 minute and with normal BMI (between 18.5 and 29).

Regarding the ***exclusion criteria***, individuals suffering from chest wall deformity and respiratory disease (defined as a diagnosis by a health professional), such as asthma, were excluded in order to reduce the impact of exercise-induced bronchoconstriction following physical exercise, which may impact on the data and to avoid any discomfort/difficulties for participants. Also, participants with reported musculoskeletal pain and high BMI (of more than 29) were excluded as it might affect their ability to use a static bike.

6.2.3 Sample size

The sample size was calculated using the Cohen *d* effect size criteria. The researcher assumed that the effect size would be medium (0.5) based on data from previous research, which demonstrates that the volume component of breathing pattern and breathing frequency are significantly affected by physical exercise (Mostert & Kesselring 2002; Burton et al. 2004; Amritsar 2010); therefore, it can be suggested that a moderate physical exercise stimulus will have a medium impact on thoracoabdominal motion. With a significance level of 5% and 90% power, a target sample size of 43 was required to demonstrate statistically significant and meaningful results.

6.2.4 Recruitment

Similar to the first study, posters were placed around the University of Southampton Highfield campus after gaining permission (Appendix B.2). In addition, the recruitment poster was posted on the official University of Southampton's online forum, which details information regarding upcoming research projects and events. Moreover, posters were distributed to students attending lectures and some posters were left in lecture theatres after taking appropriate permission to increase promptness of response rate. Additionally, posters were placed in the Jubilee sports centre and swimming pool (on the University of Southampton Highfield campus) after obtaining the necessary permission. Interested volunteers contacted the researcher via email or phone and were sent an information sheet explaining what would be expected of them (Appendix B.1). Those who read the information sheet and still wanted to take part were invited to attend an appointment for the data collection procedure to take place.

6.2.5 Data collection procedure

Participants were required to attend one data collection session lasting approximately 30-35 minutes at Research Laboratory 0003 located in Building 45 (University of Southampton). After reading the information sheet and signing a consent form (Appendix A.2), demographic data were obtained.

Then participants were asked to sit down on a comfortable, high backed chair with feet on the floor and a Structured Light Plethysmography (Thora-3Di, Pneumacare Ltd) (SLP) device was used to record breathing pattern (a full description of the SLP device is included in section 4.3.3). The SLP works by projecting a grid pattern of light onto the anterior chest (Chen et al. 2010). Participants were required to wear a fitted, white sleeveless t-shirt that followed the contours of the body in order to correctly align the SLP's projected grid. There are three different grid sizes: 14 x 10, 12 x 8 and 10 x 6, which vary according to the size of the participants' chest wall. In order to determine the appropriate grid size, the researcher measured the participants' chest wall using a tape measure. Participants were asked to locate their xiphisternum, which acted as a guide for the placement of the central point of the grid. Such that the grid covered an equal area above and below the xiphisternum from the clavicles to the umbilicus (Figure 6-1).

Participants were then asked to sit as still as is possible and breath naturally while 5 minutes of breathing pattern recording took place using the SLP device, which was placed approximately two metres away from participants. Two digital video cameras recorded the changes that occurred in the dynamic 3D reconstruction of the chest wall during inspiration and expiration, which provides immediate numerical data on an integrated computer screen regarding timing and relative contributions of rib cage and abdomen (Figure

6-1). The SLP sampling rate was set at 30 Hz through the integrated algorithm written by the SLP's developers and installed into the Pneumacare software.

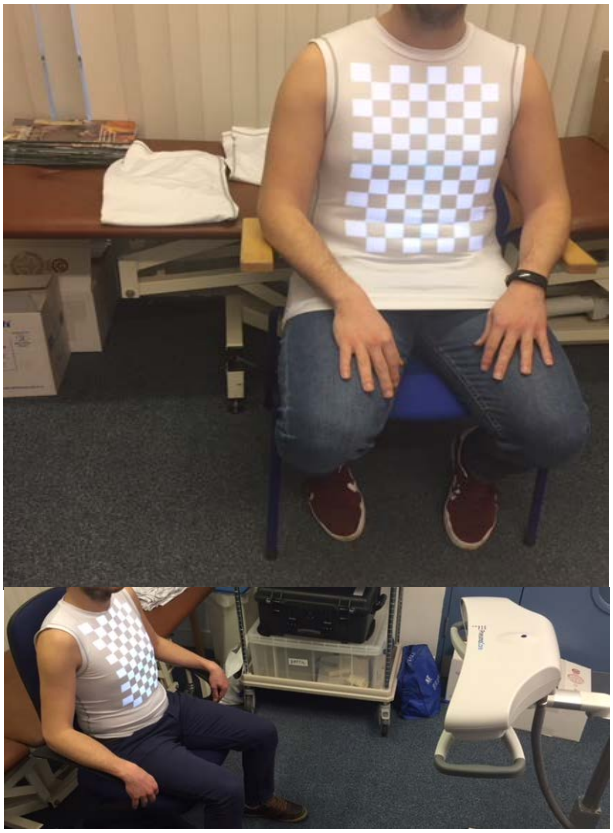


Figure 6-1: SLP projected light grid pattern on participant

Once the initial breathing pattern recording at rest was completed, participants were asked to pedal on a cycle ergometer at a pace of 70/80 revolutions per minute (rpm) (which could be viewed on an integrated display screen on the ergometer) and were encouraged to give a submaximal effort (depending on each the individual's physical limits). Also, two Borg scales were used throughout the data collection session; The Borg Scale of Perceived Exertion for Exercise and The Borg Scale for Perceived Dyspnoea (Borg &

Kaijser 2006), which were used to check the intensity of exercise and breathlessness. The Borg scale is a measure designed to monitor an individual's level of exercise intensity and breathlessness as shown in figure (6-2). A Borg scale rating of 4 or 5 is required to ensure an adequate level of breathlessness, while maintaining the exercise at a moderate intensity. Participants were advised to immediately cease the physical exercise if they felt they had reached a heightened level of intensity of sensation of breathlessness according to the scale (at level 6 or above). This is to prevent any adverse or dangerous effects of becoming overly breathless. This was entirely a precautionary measure as the exercise level was moderate and no adverse effects were anticipated. To increase participants' comfort during exercise, a fan was used to blow cool air throughout the cycling phase. Moreover, in accordance with the first aid policy of the University of Southampton, access to first aid treatment was available.

The first 3 minutes of exercise was set at an exercise intensity of 30 Watt, followed by steadily increasing increments of 25 Watts every two minutes for a total of 10 minutes. This method is in line with the guidelines for submaximal incremental cycle ergometry protocol as recommended by the American Thoracic Society/American College of Chest physicians (ATS/ACCP 2003). Moreover, it is suggested that 10-minute incremental cycling exercise causes a sufficient increase in tidal volume and breathing frequency to be considered as an adequate physical exercise stimulus in this study (ATS/ACCP 2003). It would have been useful to monitor the participants' heart rate using an Electrocardiogram (ECG) in order to check intensity between participants; however, an ECG device was not available for use during the research study.

Once the 10 minute of incremental cycling was completed, breathing pattern was immediately recorded for a period of 5 minutes following the same

procedure as mentioned for the first breathing pattern recording using the SLP device. This marked the end of the study for the participants.

Since the SLP does not enable the researcher to edit the data and remove any uncharacteristic signals, it is essential to assess the screen to identify any errors in the 3D reconstruction during and after the recording. These errors can be caused by excessive movement, a lack of contrast in the projected image and/or extreme creases in the fitted shirt, which can cause flickering or loss of some reconstructed points. To limit potential errors, participants were requested to sit as still as possible during recording and if necessary, some data collection sessions were repeated, rescheduled to take place on a different day (this occurred in 3 participants).

For exercise

Classification	Descriptor
0	Rest
1	Very, very easy
2	Easy
3	Moderate
4	Somewhat hard
5	Hard
6	
7	Very hard
8	
9	Very, very hard
10	Maximum

For Dyspnoea

Rating	Intensity of Sensation

0	No symptoms
0.5	Very, very slight sensation of symptoms
1	Very Slight
2	Slight
3	Moderate
4	Somewhat Severe
5	Severe
6	
7	Very severe
8	
9	Very, very severe
10	Maximal

Figure 6-2: Borg Scale of Perceived Exertion for Exercise and Dyspnoea

6.2.6 Components of breathing pattern recorded by Structured Light Plethysmography (SLP)

The breathing pattern data for the second and third studies were directly derived from an SLP device using PneumaView-3D™ software (PneumaCare, Ltd.), which is integrated into the system. The SLP device calculates breathing pattern mean values from the regional movements of the chest wall. A 3D reconstruction of the chest wall is created by the SLP software onto a screen and is divided into an upper and lower region as well as right and left thorax (Hamedi et al. 2017). Individual breaths on all traces were automatically detected using a breath detection algorithm (Matlab, R2015b) derived from work by Bates et al. (2000) and Schmidt et al. (1998).

Similar to the RIP trace, the SLP device produces a wave-like movement trace over time that provides numerical data regarding a number of breathing pattern components. To be consistent with the first study, the same five breathing pattern components were selected for data analysis in the second and third study. However, the main focus of the second study is to examine

the responsiveness of thoracoabdominal motion, because the responsiveness of timing components are well documented. The definition of the breathing pattern components are defined by Hmeidi et al. (2017) and Motamadi et al. (2017) as desicribe in section 5.1.8.

6.2.7 SLP data and signal processing

The SLP device is automatically calibrated to provide numerical data regarding mean values for all breathing pattern components directly to the integrated output screen. Inspiratory start time, expiratory start time and expiratory end time are direct outputs of the breath detection algorithm. The minimum and maximum of each inspiratory phase were defined as the lowest and highest points of the displacement signal and are seen as a trough (a local minimum) on the thoracoabdominal movement time trace for T_i and a peak (local maximum) for T_e. The peaks and troughs are detected using the zero-crossing of the first signal. In order to be classified as one complete breath, the peak-to-peak amplitude had to be >25% of the median peak to-peak amplitude of the entire trace. Any breathing cycle with excessive large or small inspiratory and/or expiratory times are automatically excluded from analysis. However, it is not known whether SLP is capable of accurately detecting pause time within a breath cycle, since there is limited information available regarding the specification of the algorithm that the SLP uses to extract data from the raw data file.

6.2.8 Plan for statistical analysis

Once the mean values were obtained for each breathing pattern component for each individual participant, group mean values with standard deviation were calculated using SPSS software.

6.2.8.1 Comparison of thoracoabdominal motion data before and during recovery from physical exercise in healthy adults measured with SLP

In the second study, a paired sample t-test was used to estimate how much cohort mean values vary over two test conditions (Field 2009). It is a widely used measure in clinical research that is considered to provide accurate results regarding the statistical significance of any change in mean (Pauole et al. 2000). A 95% confidence level and a p-value of < 0.05 is used to indicate a statistically significant difference in the group mean of the two measures.

Although the p value may indicate a change, it does not reflect the magnitude of the change that has occurred (Sullivan & Feinn 2012). Hence, an effect size calculation was used to provide more detailed statistical information regarding the size of the effect. The calculation used to determine effect size varies depending on the type of comparisons that are under study and fall into two main study categories. Firstly, are studies looking at effect sizes between different groups and secondly, those looking at measures of association between variables (Sullivan & Feinn 2012). The method of calculating effect size used in the present study is the Cohen's *d* calculation, where effect size is calculated by dividing the mean change score by the standard deviation scores (after) in the same subjects. According to the Cohen's *d* criteria, an effect size of >1.3 is very large, >0.8 is large, >0.5 is medium, and >0.2 is small (Ferguson 2009).

The effect size is calculated as follows:

Cohen's *d* formula = (Mean before - Mean after)/ SD after.

6.2.8.2 Variability of thoracoabdominal motion before and during recovery from physical exercise

A paired sample t-test was used to compare the cohort mean thoracoabdominal motion from two different time-periods; 5 minutes prior to physical exercise and 5 minutes post physical exercise. It is reasonable to assume that the data collected prior to exercise was recorded during a stable period of breathing, whereas data collected after exercise may be from a period of change. Hence, Coefficient of Variation calculation was used since it enables comparisons to be made between different sets of data. This enabled the researcher to examine the effect (if any) of a moderate physical exercise stimulus on the variability of thoracoabdominal motion. The Coefficient of Variation (CoV%) calculation is derived by dividing the standard deviation by the mean multiplied by 100.

6.2.8.3 The effects of gender on the responsiveness of thoracoabdominal motion

The effect of gender on thoracoabdominal motion was examined using simple linear regression analysis. Regression analysis was chosen for its ability to provide information about whether gender has any significant influence on thoracoabdominal motion responsiveness. The simple linear regression analysis model provides additional information about the predicted change in the expected value in the outcome when the independent variable is increased by one unit.

6.2.8.4 The relationship between the cohort mean thoracoabdominal motion and cohort mean timing components at rest and during recovery from physical exercise

Pearson's r correlation coefficient was used to assess the strength and direction of a linear relationship (if any) between the cohort mean thoracoabdominal motion and cohort mean timing components at rest and during recovery from physical exercise. Pearson's r is based on five assumptions that the data must adhere to, including: variables must be either interval or ratio measurements and must be approximately normally distributed, there should be a linear relationship between the two variables, outliers must be either kept to a minimum or are removed entirely and there must be homoscedasticity of the data. An advantage of using Pearson's r correlation is that it is able to assess the direction (positive or negative) and the strength of any relationship. An r value from 0 to 0.3 represents a small correlation, from 0.3 to 0.5 demonstrates medium correlation and 0.5 to 1.0 shows large correlation (Mukaka 2012).

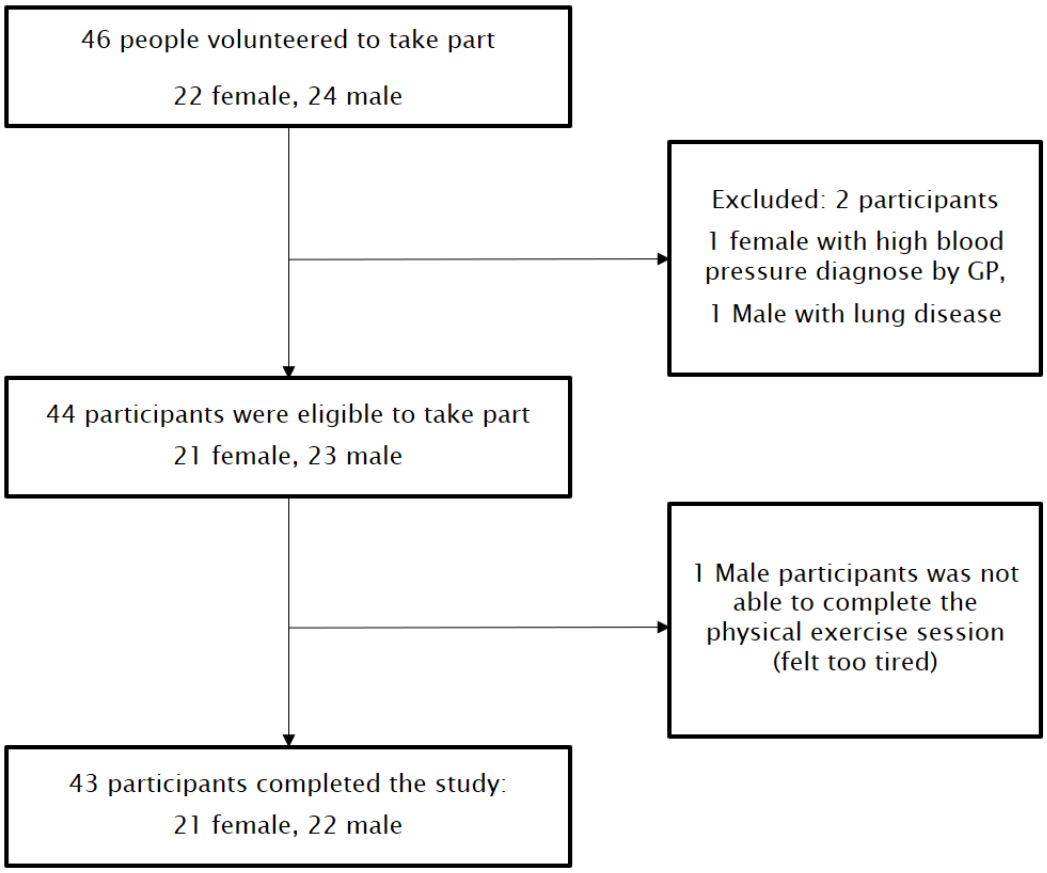
6.3 Results

6.3.1 Demographic data and sample size

Data from forty-three healthy adults (males=22; females=21; mean age=33.36±8.14 years; height=168.14±11.13cm; weight=68.91±11.52kg; BMI=24.32±2.96 kg/m^2) was used to examine the change, if any, that occurs in thoracoabdominal motion components during recovery from a moderate physical exercise stimulus. No participants withdrew, but three participants were excluded from the study due to health conditions and inability to

complete the physical exercise task (Figure 6-3). Demographic data relating to gender were used to examine any differences on thoracoabdominal motion responsiveness between males and females; however, the information relating to height, weight and BMI is presented merely to characterise the sample (Appendix H).

Figure 6-3: Data collection flowchart (second study)



6.3.2 Thoracoabdominal motion components before and during recovery from physical exercise in healthy adults (n=43) - Results from paired sample t-test and the Coefficient of Variation (CoV%) calculation

Since the data from the breathing pattern components T_i, T_e, Bf, $\%RC_{exp}$ and $\%AB_{exp}$ were found to be normally distributed when examined with histogram and Shapiro-Wilk test (p value =0.142, 0.06, 0.230, 0.922, 0.884 respectively), paired sample t-tests were used to compare the mean differences of breathing pattern components before and following 10 minutes of moderate

physical exercise. CoV% calculation was used since it enables comparisons to be made between different sets of data. Table 6-1 presents the descriptive statistics, paired samples t-test results, the Coefficient of Variation and effect size calculation.

Table 6-1: Breathing pattern components (thoracoabdominal motion) in healthy adults (n=43) - Descriptive statistics and results from paired sample t- test (SLP)

	Mean ±SD		Paired differences						
					95% confident interval				
Breathing components	Before Mean ±SD (CoV %)	After Mean ±SD (CoV %)	Mean± SD	SE	Lower	Upper	*t*	*p*	Effect size (*r*)
Ti (sec)	1.49±0.36 (24.2)	1.26±0.30 (23.8)	0.23±0.25	0.04	0.15	0.30	5.897	**0.00***	0.8
Te (sec)	2.21±0.77 (33.9)	1.68±0.41 (24.6)	0.54±0.56	0.08	0.37	0.71	6.338	**0.00***	1.3
Bf (bpm)	17.33±4.02 (23.2)	22.43±5.83 (25.9)	5.1±4.33	0.66	-6.41	-3.85	-7.731	**0.00***	0.9
%RCexp	52.48±9.89 (18.8)	53.90±9.98 (18.5)	1.42±6.83	1.04	-3.52	0.68	-1.363	0.18	0.2
%ABexp	47.51±9.89 (20.8)	46.30±10.05 (21.7)	1.21±7.19	1.09	-1.00	3.42	1.103	0.28	0.1

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes. (M) Mean; (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase, (df) degree of freedom, * starred results significant at the 0.05 alpha level.

As expected, significant changes in mean value for all timing components were found during recovery from physical exercise, with significant decreases in cohort mean T_i (t= 5.897, *df*= 42, p= 0.00) and cohort mean T_e (t= 6.338, *df*= 42, p= 0.00). Also, the cohort mean Bf increased significantly (t=-7.731, *df*= 42, p=0.00). The timing components, T_i and T_e, showed less variability with lower CoV%, while Bf showed greater variability following exercise. The effect size for all timing components were found to be large; (T_i, *r*= 0.8, T_e, *r*= 1.3 and Bf, *r*= 0.9).

Regarding thoracoabdominal motion components, no statistically significantly differences in cohort mean of $\%RC_{exp}$ and $\%AB_{exp}$ were found following exercise (t=-1.363, *df*= 42, p= 0.18, *r*= 0.2) and (t=1.103, *df*= 42, p= 0.28, *r*= 0.1) respectively. Regarding CoV%, $\%RC_{exp}$ showed slightly less variability following exercise and $\%AB_{exp}$ demonstrated slightly greater variability following exercise. Even though the results from the group mean showed no statistically significant change in $\%RC_{exp}$ and $\%AB_{exp}$, the individual participants demonstrated some changes as can be seen in table 6-2. The change in mean $\%RC_{exp}$ and $\%AB_{exp}$ in each individual ranged from 2% - 19%, indicating that some change did occur in some individuals' thoracoabdominal motion; however, because the results are based on the group mean, the change was not found to be statistically significant. Moreover, as the work-load increased not all participants responded in the same way; 25 participants increased ribcage motion, while15 participants decreased ribcage and 3 participants demonstrated no change in ribcage or abdominal motion.

Table 6-2: The direction and the amount of change in thoracoabdominal motion for each individual participant (SLP)

Participants No.	gender	age	%RCexp before	%RCexp after	The mean change
1	f	39	52	62	+10
2	f	27	47	44	-3
3	f	36	61	55	-6
4	m	39	53	53	-0
5	f	38	37	24	-13
6	m	27	54	60	+6
7	m	39	49	52	+3
8	m	48	40	38	-2
9	m	39	57	58	+11
10	m	35	47	51	+4
11	f	35	53	49	4
12	f	23	44	48	+4
13	m	39	56	55	-1
14	m	33	56	63	+7
15	m	39	66	57	-9
16	m	31	40	43	+3
17	f	36	63	66	+3
18	f	39	51	56	+5
19	f	35	61	64	+3
20	m	41	57	46	-11
21	f	32	43	49	+6
22	m	36	52	42	10
23	m	45	47	51	+4
24	f	34	49	59	+10
25	f	34	69	63	-6
26	f	26	72	77	+5
27	f	27	68	67	+9
28	f	26	50	54	+4
29	f	29	51	58	+7
30	f	30	52	52	-0
31	m	62	59	52	-7
32	m	30	54	65	+11
33	m	39	44	43	-1
34	f	24	26	45	+19
35	m	40	34	40	+6
36	m	30	58	58	-0
37	m	36	63	60	-3
38	f	28	42	48	+6
39	f	27	62	58	-4
40	f	35	62	63	+11
41	f	23	55	72	+17
42	m	19	39	41	+2
43	m	19	62	57	-5

(f) Female, (m) Male, (%RCexp) Rib Cage Contribution during expiratory phase.

6.3.3 Thoracoabdominal motion analysis for each minute during recovery from physical exercise for 5 minutes - Results from paired sample t–test and CoV% calculation

In order to avoid under-estimation of the change that occured in thoracoabdominal motion in the fitter participants who may be able to recover to baseline quicker than less fit participants, cohort mean data were extracted from the SLP for each minute following the physical exercise stimulus (for a total of 5 minutes) for all participants. This data was compared with the pre-exercise data using paired sample t-test and CoV% (see table 6-3 and 6-4). Multiple t-tests were performed (5 tests); therefore, the Bonferroni adjustment was used for multiple comparisons to reduce the probability of type I error.

Table 6-3 shows the descriptive data for each breathing pattern component during each minute following recovery from a physical exercise stimulus. While table 6-4 shows the mean (SD) of the differences that occurred for each breathing pattern component in comparison to the baseline data.

The results from the paired sample t-test for each minute during recovery from exercise in comparison with the pre-exercise data showed no statistically significant differences in cohort mean thoracoabdominal motion in any comparison. In addition, the CoV% did not indicate any clear regular pattern of the variability change.

Table 6-3: Breathing pattern components in healthy adults (n=43) - Descriptive statistics and CoV% for each minute during recovery from physical exercise (for 5 minutes) (SLP)

Breathing pattern components	At rest M±SD (CoV%)	1st min M±SD (CoV%)	2nd min M±SD (CoV%)	3rd min M±SD (CoV%)	4th min M±SD (CoV%)	5th min M±SD (CoV%)
Ti (sec)	1.49±0.36(24.2)	1.14±0.22(19.3)	1.25±0.29(23.2)	1.29±0.29(22.5)	1.31±0.29(22.1)	1.32±0.32(24.2)
Te (sec)	2.21±0.77(33.9)	1.40±0.32(22.9)	1.60±0.36(22.5)	1.77±0.47(26.6)	1.8±0.51(28.3)	1.89±0.58(30.7)
Bf (bpm)	17.33±4.02(23.2)	25.35±6.71(26.5)	22.25±4.99(22.4)	21.16±5.12(24.2)	20.58±4.49(21.8)	19.96±4.02(20.1)
%RCexp	52.48±9.89(18.8)	56.16±10.45(18.6)	54.56±10.17(18.6)	55.49±9.57(17.2)	55.16±8.7(15.8)	54.69±9.08(16.6)
%ABexp	47.51±9.89(20.8)	43.84±10.45(23.8)	45.44±10.17(22.4)	44.51±9.57(21.5)	44.84±8.7(19.4)	45.37±9.09(20.0)

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes. (M) Mean, (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase, (CoV%) Coefficient of Variation.

Table 6-4: Breathing pattern components (thoracoabdominal motion) in healthy adults (n=43) - Results from paired sample t- test for each minute (for 5 minutes) during recovery from physical exercise (SLP)

Breathing components	1st min			2nd min			3rd min			4th min			5th min		
	M±SD	95%CI	*P*	M±SD	95%CI	*p*	M±SD	95%CI	*p*	M±SD	95%CI	*p*	M±SD	95%CI	*p*
Ti (sec)	0.34± 0.42	0.22,0.48	0.00	0.24± 0.45	0.1,0.38	0.00	0.19± 0.47	0.05,0.34	0.00	0.18± 0.47	0.04,0.33	0.00	-2.63± 6.69	0.02,0.32	0.01
Te (sec)	0.8± 0.78	0.57,1.1	0.00	0.61± 0.84	0.35,0.87	0.00	0.44± 0.85	0.18,0.71	0.01	0.39± 0.95	0.11,0.69	0.02	0.17± 0.49	0.01,0.63	0.03
Bf (bpm)	-8.0± 7.67	-10.4,-5.6	0.00	-4.9± 6.49	-6.91,2.92	0.00	3.8± 6.7	-5.89,-1.75	0.00	-3.24± 6.42	-5.22,-1.27	0.01	0.32± 1.01	-4.69,-0.56	0.04
%RCexp	-3.7± 12.8	-7.6,0.28	0.07	-2.07± 13.08	-6.09,1.95	0.31	-3± 13.6	-7.23,1.23	0.16	-2.67± 13.93	-6.96,1.61	0.22	-2.21± 13.89	-6.49,2.07	0.30
%ABexp	3.7± 12.8	-0.28,7.6	0.07	2.07± 13.08	-1.95,6.09	0.31	3± 13.6	-1.23,7.23	0.16	2.67± 13.93	-1.61,6.96	0.22	2.14± 13.9	-2.14,6.42	0.32

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes. (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase, (M) Mean the difference, (SD) Standard Deviation of the differences, 95%Confident Interval of the differences.

6.3.4 Effect of gender on thoracoabdominal motion responsiveness (Linear regression analysis results)

Linear regression analysis was used to assess the relationship between each outcome variable (breathing pattern components) and independent predictors (gender). The histograms and P-P plots were assessed for linearity, independence of errors, homoscedasticity and normality of error distribution for each breathing pattern component. The P-P plots demonstrated reasonably distributed residuals and the regression standardised residual histograms showed normal distribution and looked approximately bell-shaped. The randomly dispersed data points throughout the plot met the assumption of homoscedasticity.

Based on the summary findings shown in table 6-5, the linear regression analysis showed that there was no evidence that gender has any significant effect on responsiveness of any breathing pattern component. By looking at the R^2 values (the proportion of variance in the dependent variables that could be explained by the independent variables), the independent variables explained between 5% and 4% of the variability of the rib cage and abdomen contributions during expiration (respectively), and this variance was not found to be significant for gender. Also, the correlation was found to be small (0.2).

For the variable gender following physical exercise, females increased $\%RC_{exp}$ by 4.38 and decreased $\%AB_{exp}$ by 3.97. Furthermore, the regression standardised residual histograms appeared to be normally distributed, and the P-P plots demonstrated a minor deviation from normality. But, such a minor deviation is not enough to question the validity of the regression and may be due to sample size. There was no obvious change in the variation of the residuals across the range of predicted values and the data points were randomly spread around zero; hence, the assumption of the homoscedasticity was met. Since the

regression standardised residual histograms, P-P plots and scatter plots of the residuals were similar for each component, only one component (%RCexp) is presented below in order to avoid repetition.

Table 6-5: The effect of gender on the responsiveness of breathing pattern following physical exercise (SLP)

Breathing components	R	R^2	Constant (SE)	B (SE)	SC	95% CI for B	p
Ti (sec)	0.24	0.06	1.49(0.15)	-0.15 (0.09)	-0.24	-0.33,0.04	0.12
Te (sec)	0.10	0.01	1.80(0.21)	-0.08 (0.13)	-0.10	-0.35,0.18	0.53
Bf (bpm)	0.17	0.03	19.44(2.82)	1.98(1.77)	0.17	-1.60,5.56	0.27
%RCexp	0.22	0.05	47.29(4.78)	4.38(3.01)	0.22	-1.69,10.45	0.15
%ABexp	0.20	0.04	52.30(4.84)	-3.97(3.04)	-0.20	-10.11,2.17	0.19

(B) Unstandardised Beta; (SE) Standard Error; (R2)Coefficient of determination; SC Standardized Coefficients; (Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase.

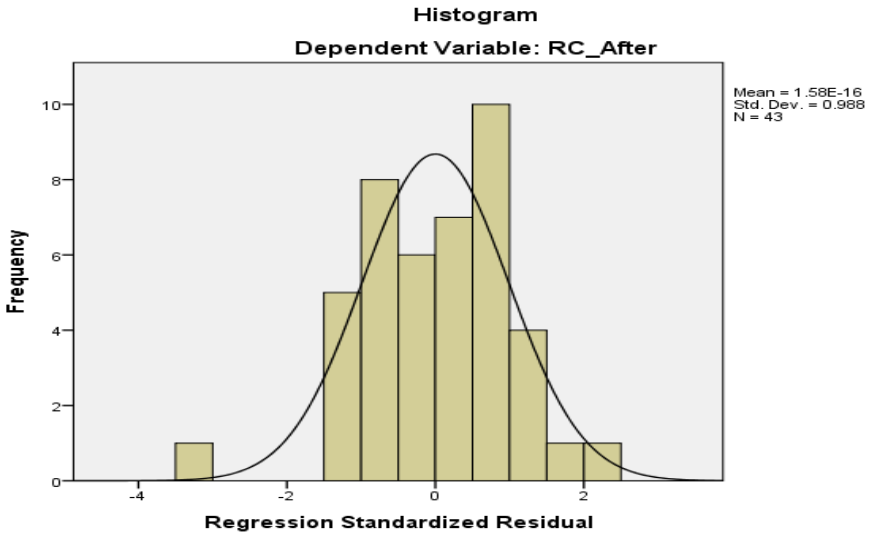


Figure 6-4: Regression standardised residual histogram of ribcage data (%RCexp) following physical exercise demonstrated normal distribution.

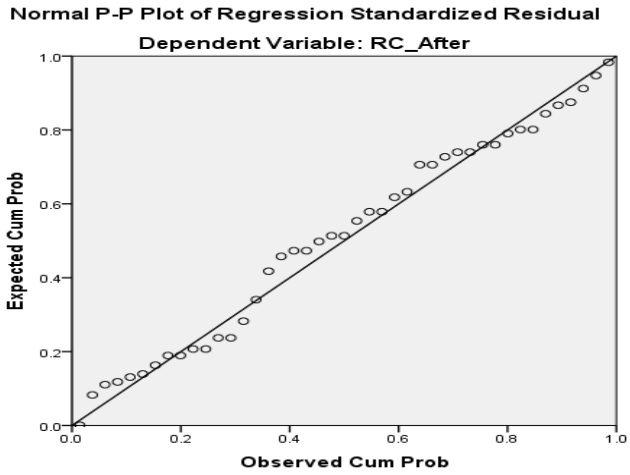


Figure 6-5: P-P plot for regression model for %RCexp following physical exercise demonstrating minor deviation from normality

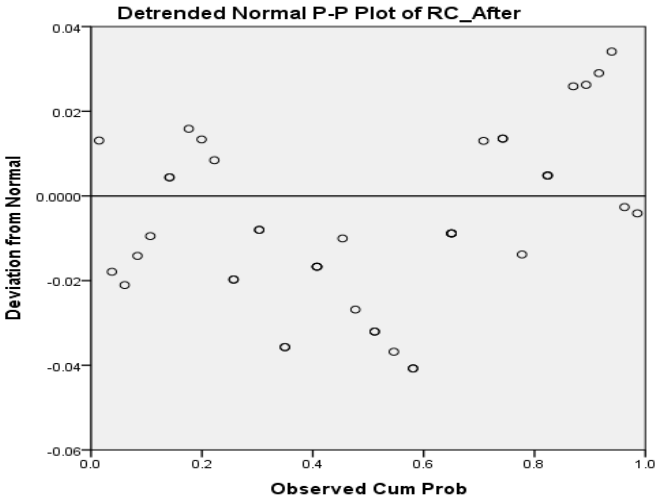


Figure 6-6: Scatter plot of the residuals of the regression model for %RCexp following physical exercise.

6.3.5 The relationship between thoracoabdominal motion and timing components at rest and following physical exercise (Pearson's correlation coefficient)

Pearson's r correlation coefficient was used to assess the strength and direction of a linear relationship (if any) between the cohort mean thoracoabdominal motion and cohort mean timing components at rest and following physical exercise. The results (shown in table 6-6) demonstrate low correlations between the cohort mean rib cage and abdomen with the cohort mean of the timing components (T_i, T_e and Bf) indicating that these components may be largely independent of each other; meaning that a change in one may not necessarily induce a change in the other.

Table 6-6: Pearson's correlation coefficient **for thoracoabdominal motion and timing components at rest and following physical exercise (SLP)**

	Pearson's r		p value	
	At rest	**After exercise**	**At rest**	**After exercise**
%RCexp				
Ti (sec)	-0.07	-0.04	0.66	0.8
Te (sec)	0.09	0.09	0.56	0.53
Bf (bpm)	-0.08	-0.11	0.62	0.49
%Abexp				
Ti (sec)	0.07	-0.01	0.66	0.93
Te (sec)	-0.09	0.11	0.56	0.43
Bf (bpm)	0.08	0.09	0.62	0.59

Inspiratory time, (Te) Expiratory time, (sec) second, (Bf) Breathing frequency, (bpm) breath per minutes, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase.

In order to avoid the inclusion of a vast number of scatterplots, figures 6-7, 6-8 and 6-9 are included here as just one example depicting the relationship between cohort mean %RC_{exp} and the cohort mean timing

components (T_i, T_e and Bf) following physical exercise (Appendix I includes the scatterplots of all the other correlations between all other components at rest and during recovery from exercise). All scatterplots derived from Pearson's r correlation test showed low correlation between thoracoabdominal motion and timing components.

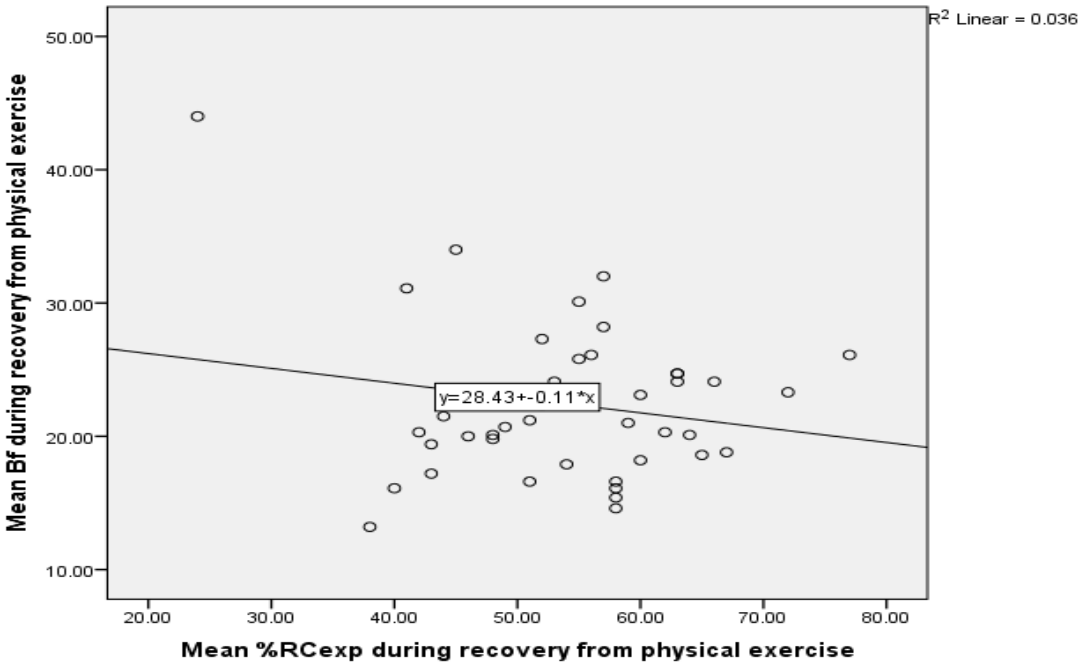


Figure 6-7: Scatterplot for the relationship between cohort mean %RCexp and Bf following exercise.

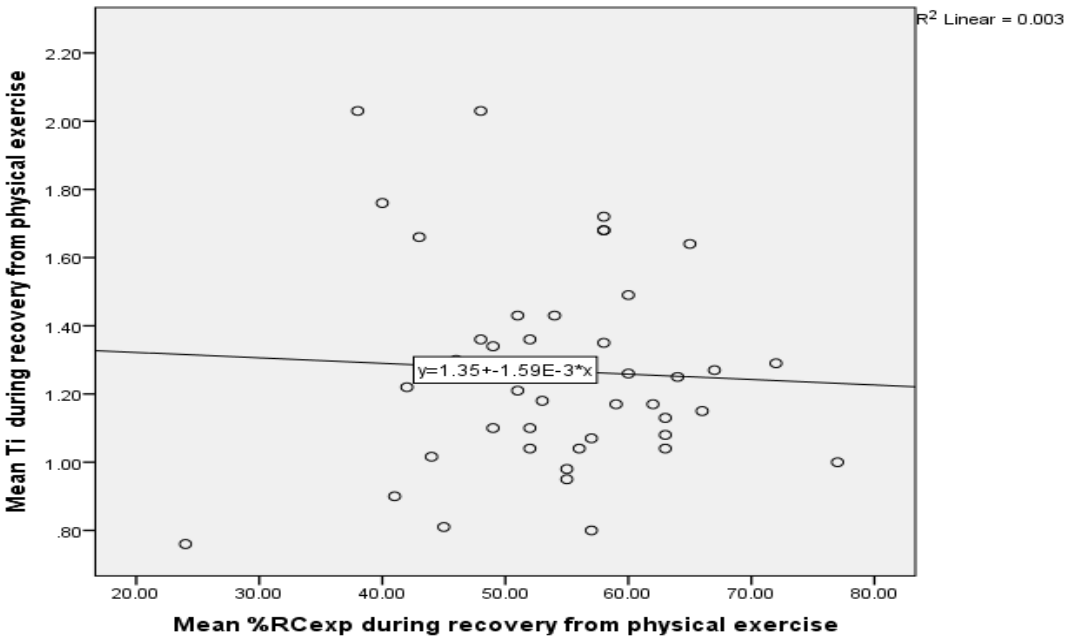


Figure 6-8: Scatterplot for the relationship between cohort mean %RCexp and Ti following exercise.

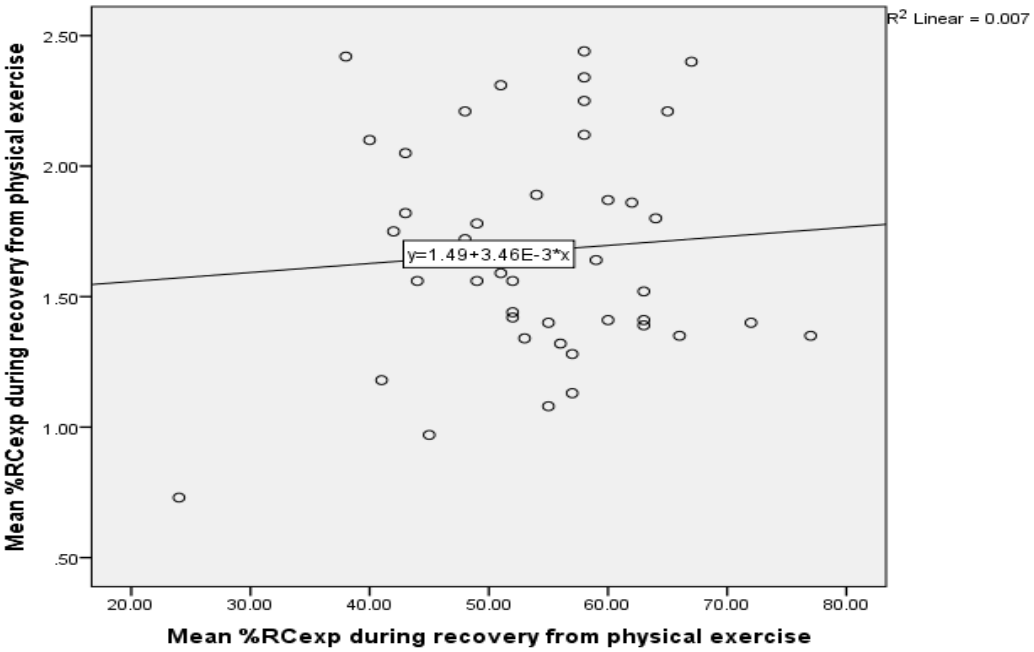


Figure 6-9: Scatterplot for the relationship between cohort mean %RCexp and Te following exercise.

The results showed perfect negative correlation between cohort mean $\%RC_{exp}$ and cohort mean $\%AB_{exp}$ before (r= -1.00, p=0.00) and following exercise (r= -0.99, p=0.00) and high correlation was found between cohort mean Bf and cohort mean T_i and T_e before (r= -0.82, -0.85; p=0.00, 0.00) and following exercise (r=0.81, 0.93; p= 0.00, 0.00) (as shown in the scatterplots in Appendices I). This indicates robustness of the data, as it is known that a reciprocal relationship between ribcage and abdomen exists and T_i and T_e are used to calculate Bf. Hence, these results suggest that the data is robust.

6.3.6 Summary of Second study results

This study examined the responsiveness of thoracoabdominal motion of breathing pattern components in response to a physical exercise stimulus in healthy adults.

No statistically significant change in thoracoabdominal motion cohort mean was found following a physical exercise stimulus. Nevertheless, changes within individual thoracoabdominal motion were observed; however, the changes that did occur within individuals did not demonstrate any regular pattern or consistency. This may suggest that one, 10 minute physical exercise stimulus is not sufficient to bring about a change in thoracoabdominal motion.

In addition, gender was not found to affect the responsiveness of thoracoabdominal motion. Moreover, a low correlation was found between timing components and thoracoabdominal motion components both at rest and following physical exercise indicating that these components are independent of each other. Consequently, all hypotheses (HP2a, b and c) are rejected.

In order to further examine the responsiveness of breathing pattern, the third study in this thesis explores the responsiveness of breathing pattern components in patients with asthma in response to a therapeutic breathing retaining intervention. This is of particular relevance for physiotherapists aiming to alter any of the breathing pattern components during therapeutic interventions.

Chapter 7 Third study - Responsiveness of breathing pattern following breathing retraining in patients with asthma (recorded using SLP)

7.1 Introduction

Asthma is an increasingly prevalent and common condition across the globe, which increases the likelihood of hospitalisation, increased morbidity and has a significantly negative impact on the sufferers' quality of life (Mukherjee et. al 2014; Bruton &Thomas 2014). The use of breathing exercises as a complementary therapy to pharmacological treatment has been widely used across the globe for people with asthma (Freitas et al. 2013; BTS/SIGN 2016). However, the change that occurs in breathing pattern components as a result of breathing re-training is largely unreported within the literature and those that are available rely primarily on questionnaires as the primary outcome measure to assess the responsiveness of breathing pattern following an intervention.

To assess the change that occurs due to a physiotherapy intervention (of breathing exercises) in order to improve respiratory health, it is important to be able to measure and register detailed, objective information about breathing pattern. There are few studies relating to dysfunctional breathing in which changes in breathing patterns associated with interventions are objectively described and evaluated (Bruton & Thomas 2011). Hence, the third study aims to examine the responsiveness of

breathing pattern following breathing retraining intervention in patients with asthma.

7.2 Methods

7.2.1 Design

This third study is an uncontrolled exploratory study with an observational repeated measure design to collect data before and after a breathing retraining intervention. It is part of a larger on-going study with wider research aims within the University of Southampton that had already been through ethics and research governance procedure. Currently, there is no published literature documenting responsiveness of asthma breathing patterns at rest before and after any clinical intervention.

It would have been preferable to include a control group that performed a different intervention, which did not include breathing retraining (perhaps an education programme alone); this would enable the researcher to examine the change that occurs in breathing pattern as a result of breathing retraining in comparison to other interventions. The inclusion of a control group enables researchers to determine the effect of the specific experimental treatment and is ideal for hypothesis testing. If there is no control group, then the effect of the intervention may be less clear (Ho et al. 2008). However, recruitment of a control group in this study would have been challenging, as recruitment, and subsequent retention, in community-based asthma studies are often cited as problematic (Thomas et al. 2009). In attempt to reduce the limitation of not including a control group in the third study, the first data collection session was used as baseline data to enable comparisons to be drawn

7.2.2 Participant selection

Adult males and females (aged 18 years or over) with a clinical diagnosis of asthma were selected to participate. To participate in this study, participants were referred to the physiotherapy breathing retraining programme at Southampton General Hospital (SGH).

Inclusion criteria

1. Aged over 18 years
2. Have a clinical diagnosis of asthma (defined as self-reporting a physician's diagnosis of asthma and having used asthma medications in the previous 12 months)
3. Individuals referred to breathing retraining programme at SGH
4. Able to sign consent form

Exclusion criteria

1. Individuals taking part in other clinical study involving new clinical interventions.

7.2.3 Sample size

The data collected for the third study are from a larger study examining the effect of breathing retraining on a number of outcome measures in patients with asthma. Based on the primary outcome measure in the larger study (AQLQ), it was estimated that a sample size of 48 participants was required to demonstrate a difference in AQLQ scores of 0.5 or greater with 90% power and a type I error rate of 5%. However, the primary outcome measure in this third study is the specific breathing pattern components under observation (and not AQLQ). A separate power calculation was, therefore, carried out. Since the participants were to be involved in a therapeutic intervention, it was assumed that there would be a medium

effect size. Thus, assuming a medium effect size of 0.5, with a significance level of 5% and a 90% power, the required sample size would be 43.

7.2.4 Recruitment

The recruitment process was pre-defined by the wider study. Eligible participants were patients with asthma who had been referred by a physician to participate in a physiotherapy breathing retraining programme. Once referred, eligible individuals were sent a study information pack to their home address. The information pack was sent by the respiratory centre administrative team to the patient and comprised an invitation letter (Appendix C.1), a detailed information sheet (Appendix C.3), reply form (Appendix C.2) and an initial physiotherapy appointment letter. Any individuals wishing to take part in the study, provided their contact details using the stamped addressed envelope provided.

Once this was received, if the participant met the inclusion criteria, the interested individual was contacted directly by the research team and invited to take part in the study, which was arranged to take place in a physiology laboratory within the Welcome Trust Clinical Research (located in SGH) one hour before the scheduled physiotherapy appointment. This was confirmed by letter and a reminder text message in an attempt to decrease the 'Did Not Attend' rate, which is currently reported to be approximately 30% for breathing retraining in this centre.

7.2.5 Data collection

As mentioned previously, this third study is part of a wider on-going study at Southampton University and Southampton General Hospital; hence, data were collected by different members of the research team (discussed in more detail in section 7.3.1). In total, data were collected from each

participant on two or three separate data collection sessions depending on the individual case and the number of physiotherapist appointments (Figure 7-1). The breathing retraining programme involved two or three face-to-face physiotherapy sessions over a period of eight to sixteen weeks. The content of the programme was similar to that published by Thomas & Bruton (2014). All data collection sessions were scheduled to coincide with the physiotherapist appointment at SGH.

At the initial data collection session, the aims and the procedure of the study were explained and then informed consent was obtained by asking participants to sign a consent form (Appendix C.5). Participants were invited to ask questions and were informed that they could end the session at any time without reason or consequence. Breathing pattern data, lung function and $ETCO_2$ was then recorded. Also participants were asked to complete asthma related questionnaires Hospital anxiety and Depression Scale (Appendix C.7) and Nijmegen questionnaire (Appendix C.8). After the baseline data collection session, participants were invited to attend one or two further data collection sessions scheduled to take place one hour before the second and/or the fourth physiotherapist breathing retraining sessions. Each data collection session lasted approximately 45 minutes and followed the same procedure. The researcher was not present during the actual physiotherapists' breathing retraining sessions.

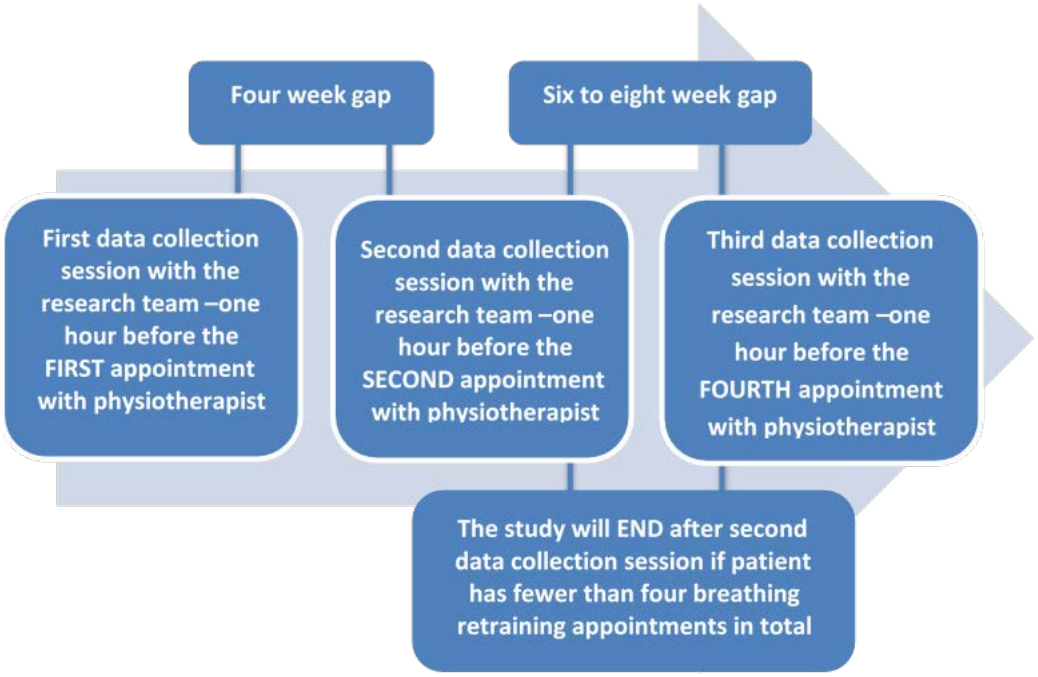


Figure 7-1: Overview of the third study protocol

7.2.5.1 Demographic data

Demographic and anthropometric data (including age, gender, height and weight) was obtained (Appendix C.9) at the beginning of the first data collection session. Although this data were only used to characterise the sample.

7.2.5.2 Breathing pattern data

Breathing pattern data were recorded using SLP device at each data collection session for a total of 5 minutes of quiet breathing in a comfortable, sitting position. Participants were given some privacy and asked to change into the necessary tight-fitting, white clothing as required by the SLP device. The procedure was explained fully to the participants and the SLP device was used according to the detailed description provided in section 6.3.5 for the second study.

7.2.5.3 Measurement of Lung function, End Tidal CO_2, Hospital Anxiety and Depression questionnaire (HADS) and Nijmegen questionnaire (NQ)

Although, lung function, $ETCO_2$, HADS and NQ are not the primary outcome measures in this study, these parameters were required by the wider study and have been included to characterise the participants as they reflect the physiological and psychological changes that occur following breathing retraining.

Lung function parameters - Forced Expiratory Volume in one second (FEV1) and Forced Vital capacity (FVC), were measured using spirometry in accordance with published guidelines set out by the American Thoracic Society (Miller et al. 2005). The required procedure was demonstrated by a member of the research team and involved participants taking in a maximum deep breath and then forming a tight seal around the disposable mouthpiece. Participants then exhaled forcefully through the mouthpiece attached to the spirometer as hard and as fast as possible, until their lungs were fully emptied. Tests were carried out three times with short rest intervals between tests. The ratio of FEV1 to FVC is calculated by dividing FEV1 by FVC and provides a standard measure of lung function used to characterise the participants.

End-tidal CO_2 - was measured using capnography (Smiths Medical, Sleep Capnocheck) at each session. A nasal cannula was placed in front of the participants' nose in order to measure the $ETCO_2$ in a sample of expired air for approximately three minutes.

Hospital Anxiety and Depression Scale (HADS) - was used to determine the levels of anxiety and depression that participants felt and experiencing. Also, the *Nijmegen questionnaire (NQ)* was used to assess the presence of

hyperventilation by asking patients to rate the frequency they experience a series of symptoms associated with hyperventilation.

7.2.6 Components of breathing pattern and SLP data extraction and analysis

The breathing pattern components were recorded using the SLP device and have been defined in section 6.3.6.

Due to the small sample size (n=5), group mean values for each component were not considered as meaningful, so no statistical analysis (using SPSS software) was conducted. Rather, breath- by-breath analysis was selected as appropriate to extract and analyse the data relating to each breathing cycle to gain detailed and in-depth information for each individual participant. The raw data from SLP was saved in Comma-Separated Values (CSV) files and the same algorithm (developed for the first study described in section 5.2.9) was used to extract the mean values from each breath for each breathing pattern component. As with the first study protocol, the breath using semi-automatic detection process was measured through the identification of the local minimum and maximum of each breathing cycle using a specifically designed algorithm programme with MatLab software, which required data editing, as presented in table 7-1 below. In addition, the Coefficient of Variation was calculated in order to examine any changes in variability of breathing pattern components.

Table 7-1: Data editing for third study

Participants no	No. of	Before breathing	After breathing

	breathing cycle	retraining	retraining
1	50	0	1
2	88	1	8
3	111	3	0
4	93	0	0
5	76	0	3

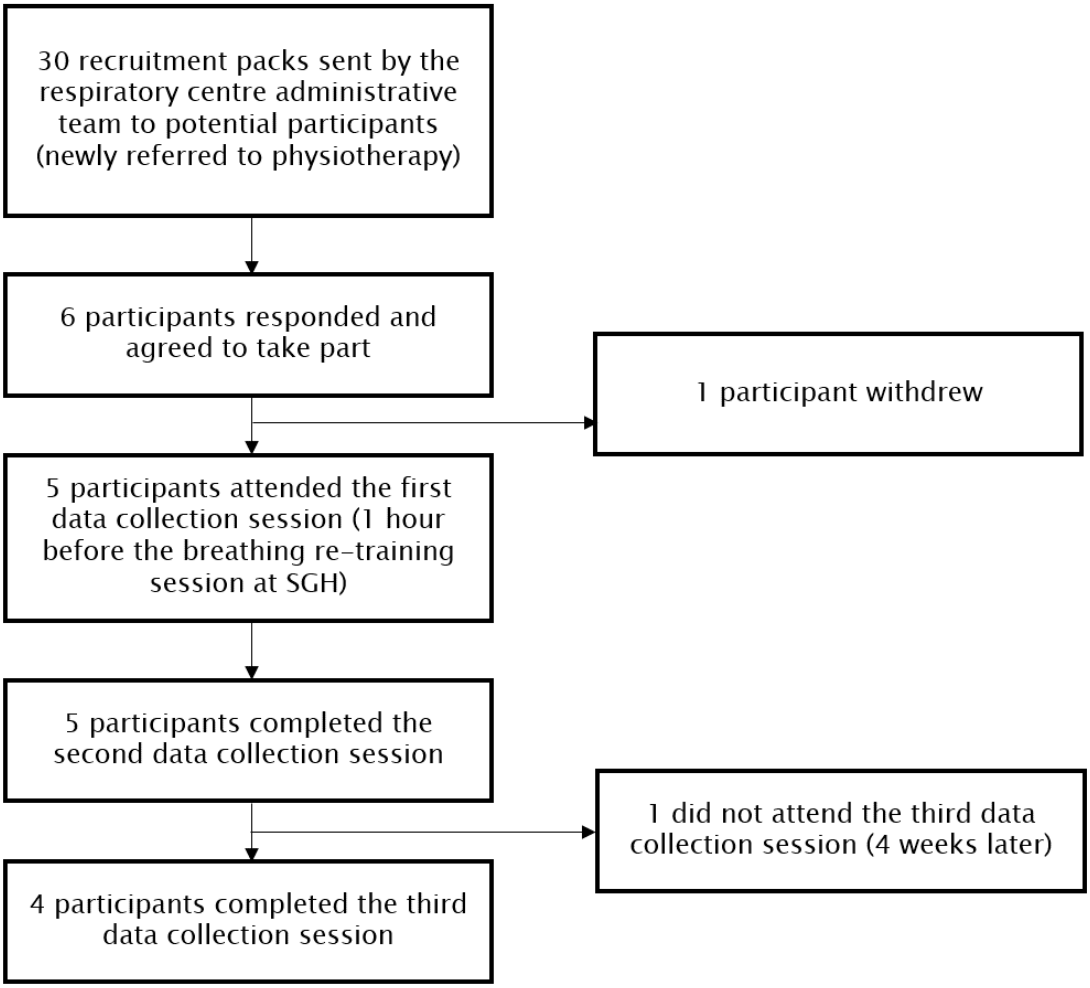
7.3 Results

7.3.1 Demographic data and sample size

Six adult patients with asthma were recruited into the study. However, one participant withdrew from the study before taking part in any data collection sessions; hence, five participants took part in the initial data collection session (m=2, f=3, mean age=51.67±6.25 years; height=165.77±4.89 cm; weight=106.63±22.02 kg; BMI=38.9±3.8 kg/m^2). Three participants were regularly taking 6 puffs of Fostair inhaler, which is a combination inhaler containing long acting beta-agonist and corticosteroid, 4 participants were taking 2 puffs daily of Tiotropium (Alvesco), which is a long-acting muscarinic receptor antagonists and 1 participant regularly took 2-10 puffs of Salbutamol (reliever inhaler) on a daily basis.

Four participants completed the first, second and third data collection sessions; however, one of the participants only completed the first and second data collection sessions (Figure 7-2). Data were collected by a research team, of which I attended all of the first data collection sessions for all participants, three of the second data collection sessions and none of the third.

Figure 7-2: Data collection flowchart (third study)



7.3.2 Breathing pattern components before and after breathing retraining intervention in patients with asthma (n=5) results from breath-by-breath analysis

Based on a power calculation, the original intention was to recruit a sample of 43 individuals for this third study. However, this was not possible for a variety of reasons, which are mentioned in detail within (section 8.4.3) and the final sample size was 5. Hence, the focus of this study changed to provide more preliminary data to be used to inform future, continued research in this area. As the sample size was 5, a paired samples t-test became inappropriate to be used for a number of reasons. Firstly, with only five participants, there is insufficient power to detect change and type II error would be inflated. Secondly, a paired samples t-test treats the first breath as independent from the second, so with such a small sample size, the relationship between the breaths become arbitrary and not clear. Therefore, breath-by-breath analysis was selected as a more appropriate data analysis method given the small sample size. This involved in putting all breathing cycles into the SPSS statistics editor and chart builder, which produced a mean value for each breathing pattern component for each individual breath and also produced a graph depicting a visual representation of the breath-by-breath change for each breathing pattern component before and after the breathing retraining intervention. In addition, Coefficient of Variation (CoV%) was calculated to examine the variability that occurred in each breathing pattern component before and after breathing retraining.

The following table 7-2 shows the cohort mean values, standard deviation and CoV% for each breathing pattern component before and after the breathing retraining programme for each participant. Since breath-by-breath analysis was used, Bf becomes inappropriate, so the mean Bf

including in table 7-2 is based on 5 minutes of breathing pattern recording derived directly from SLP.

Table 7-2 Means and standard deviation for each breathing pattern component before and after the breathing retraining programme for each individual participant derived from breath-by-breath analysis (SLP)

Breathing components	Participant 1 M±SD (CoV%)	Participant 2 M±SD (CoV%)	Participant 3 M±SD (CoV%)	Participant 4 M±SD (CoV%)	Participant 5 M±SD (CoV%)
Ti (sec)					
Before	1.26±0.24 (19)	1.69±0.71 (42.0)	1.29±0.28 (21.7)	0.99±0.11 (11.1)	1.38±0.39 (28.3)
After	1.74±0.49 (28.2)	1.41±0.69 (48.9)	1.70±0.26 (15.3)	2.47±0.41 (16.6)	1.48±0.30 (20.3)
Te (sec)					
Before	2.03±0.33 (16.3)	1.94±0.74(38.1)	1.84±0.56 (30.4)	2.03±0.4 (19.7)	2.74±1.56 (56.9)
After	2.72±0.84 (30.9)	1.58±0.82(51.9)	3.04±0.45 (14.8)	4.58±1.01 (22.1)	2.26±0.68 (30.1)
Bf (bpm)					
Before	18.2	23.65	19.38	15.45	14.55
After	10.61	16.76	11.54	8.51	16.02
%RCexp					
Before	75.49±15.83 (21)	59.08±5.51 (9.3)	57.99±13.84 (23.9)	45.78±11.48(25.1)	51.15±17.59 (34.4)
After	65.44±10.10 (15.4)	37.99±12.23 (32.2)	56.06±7.42 (13.2)	53.55±9.45(17.6)	46.72±13.01 (27.8)
%ABexp					
Before	24.37±15.94 (65.4)	41.08±5.48 (13.3)	42.20±13.97 (33.1)	54.29±11.45 (21.1)	49.79±14.07 (28.3)
After	34.61±10.41 (30.1)	62.78±14.49 (23.1)	43.89±7.34 (16.7)	46.42±9.45 (20.4)	53.26±13.21 (24.8)

(Ti) Inspiratory time, (Te) Expiratory time, (sec) second, (M) Mean; (SD) Standard Deviation, (%RCexp) Rib Cage Contribution during expiratory phase, (%ABexp) Abdominal Contribution during expiratory phase

7.3.3 Breath-by-breath analysis graphs

The figures below show the results from the breath-by-breath analysis for each component, before breathing retraining (green) and after breathing retraining (blue). Breathing was recorded for 5 minutes, where differences are seen in the length of lines, this reflects a difference in number of breaths (Bf) during the 5 minutes recording period (as 4 of the 5 participants decreased Bf following breathing retraining). The breath-by-breath analysis graphs for each component for Participant One are included below, while the remaining graphs for all other participants are included in Appendix G.

Figure 7-3: Breath-by-breath data for the mean Inspiratory time (Ti) before & after breathing retraining

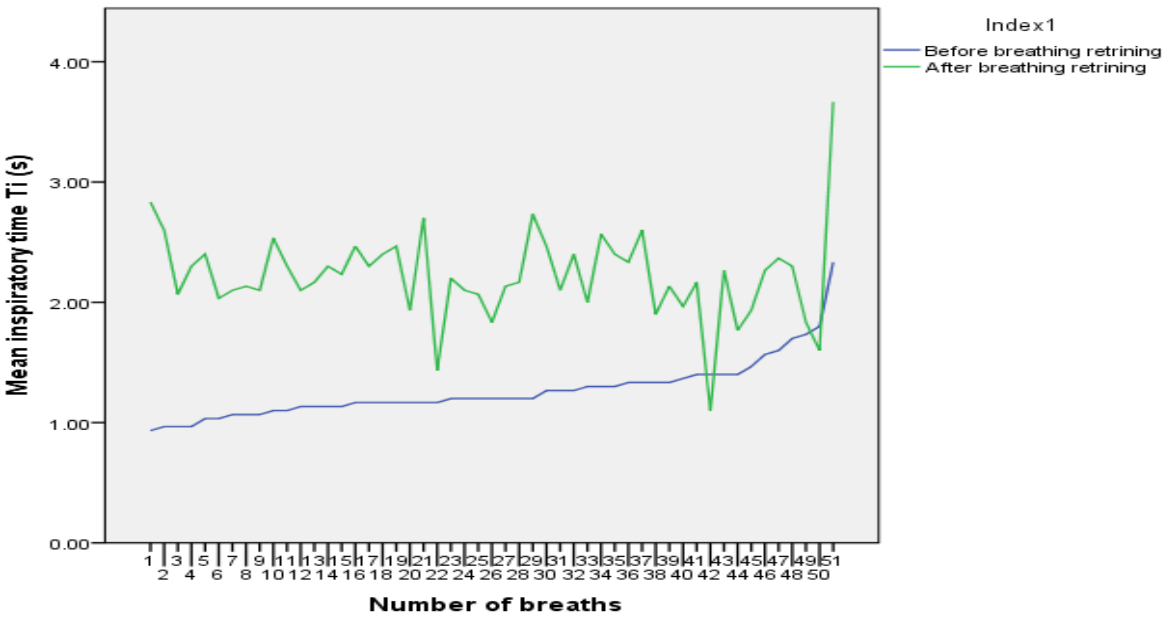


Figure 7-4: Breath-by-breath data for the mean expiratory time (Te) before & after breathing retraining

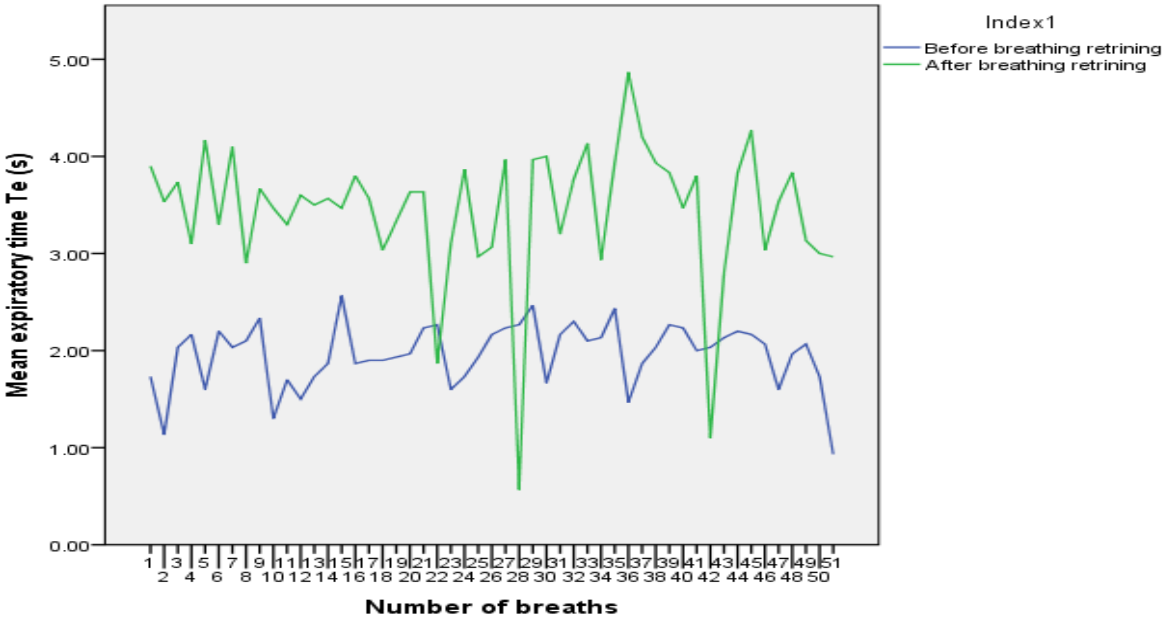


Figure 7-5: Breath-by-breath data for mean %RC$_{exp}$ before & after breathing retraining

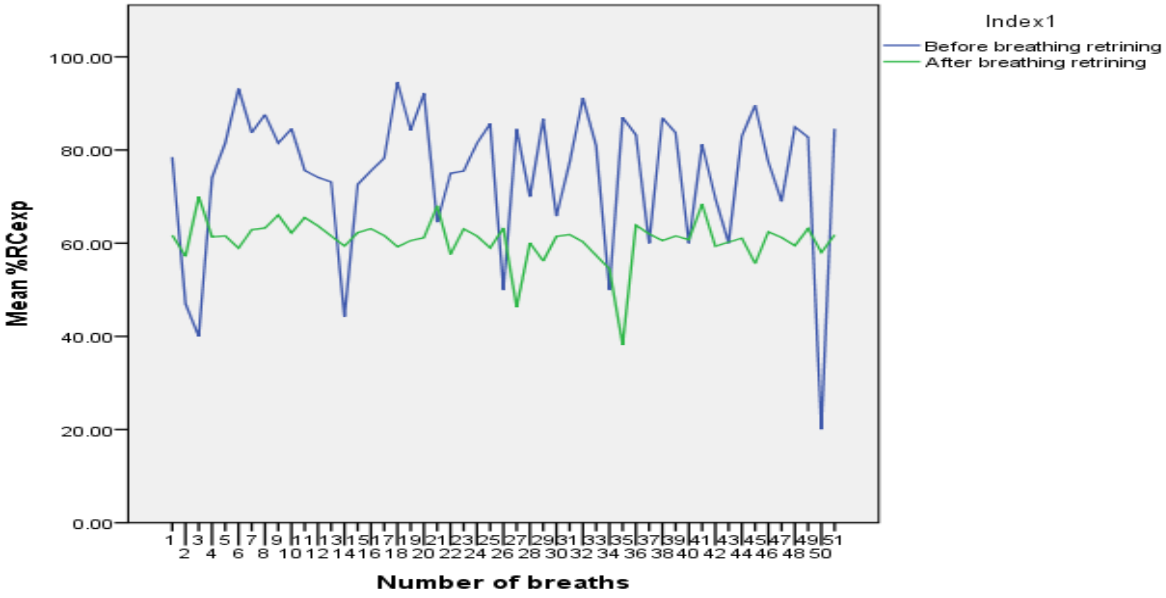
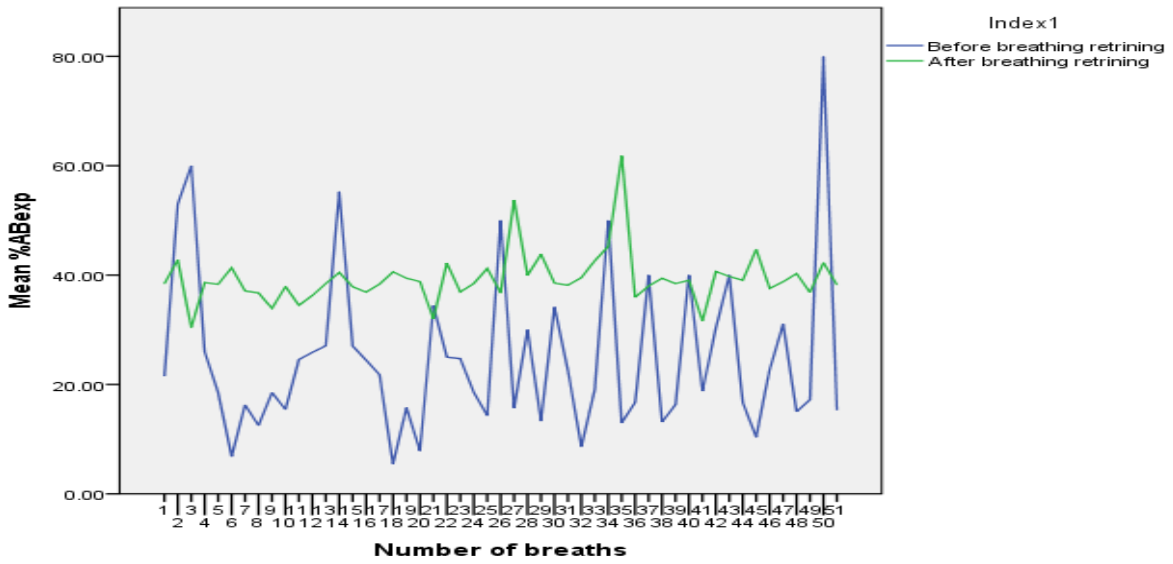


Figure 7-6: Breath-by-breath data for the mean %ABexp before & after breathing retraining



As shown in the table 7-3 and graphs 7-3 to 7-6 for the breath-by-breath analysis, there does not appear to be any consistency regarding the changes that occur in the timing components of breathing pattern. For participant 1, 3, 4 and 5, the T_i and T_e increased following the breathing retraining programme; whereas, participants 2 and 5 showed decreases in T_i and T_e. Regarding thoracoabdominal motion, the changes were also found to be inconsistent, with decreases in %RCexp and increases in %ABexp following breathing retraining in participants 1, 2, 3 and 5. However, participant 4 decreased in %ABexp and increased %RCexp; although participant 4 was the oldest participant (70 years old) and it has been acknowledged that age can affect thoracoabdominal motion due to physiological changes associated with age (Tobin et al. 1983a; Parreira et al. 2010).

7.3.4 Variability of breathing pattern after breathing retraining in patients with asthma (n=5)

The CoV% calculation showed that two participants (3 & 5) decreased variability in breathing pattern components following breathing retraining, while two participants (1 & 4) increased variability in timing components and decreased variability in thoracoabdominal motion following breathing retraining. One participant (2), increased variability in all breathing pattern components following breathing retraining. Hence, this preliminary finding indicates that there is no consistent pattern regarding the effect of breathing retraining on breathing pattern variability.

7.3.5 Lung function, End Tidal CO_2 and questionnaire data after breathing retraining

Data regarding FEV1/FVC, $ETCO_2$ and scores for HADS Anxiety and Depression and NQ are included in table 7-3. Based on the data, the change in both physiological and psychological data shows inconsistencies, with no clear pattern detectable. Regarding the route of breathing, 4 participants were nasal breathers and 1 was a mouth breathing and no change occurred following breathing retraining. However, regarding region of breathing, all participants were upper thoracic breathers before the breathing retraining and changed to abdominal breathers following retraining.

Table 7-3: lung function, $ETCO_2$ and Questionnaire descriptive data for five participants before and after breathing retraining.

Lung function and questioners data	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5
FEV1%					
Before	0.84	0.90	0.79	0.96	0.98
After	0.83	0.93	0.70	0.99	0.99
FEV1 (Litters)					
Before	2.62	2.62	1.05	2.86	1.99
After	2.74	2.34	1.61	2.86	1.91
FEV1/FVC (Litters)					
Before	0.81	0.88	0.76	0.91	0.79
After	0.83	0.91	0.69	0.97	0.99
$ETCO_2$ (kPa)					
Before	3.82	2.55	4.3	4.2	4.7
After	6.3	2.8	6.1	4.5	4.5
HADS Anxiety scale					
Before	4	17	11	13	11
After	6	15	10	7	13
HADS Depression scale					
Before	10	13	19	13	7
After	5	16	17	8	10
NQ					
Before	29	42	44	33	26
After	5	28	35	18	22

FEV1= Forced Expiratory Volume in one second, FVC= Forced Vital capacity, ETCO2= End Tidal CO_2 , HADS= Hospital Anxiety and Depression questionnaire and NQ= Nijmegen questionnaire.

Lung function data: Asthma is characterised by airflow obstruction, which is shown by reduced FEV1 and reduced FEV1/FVC. Therefore, an increase in FEV1 and FEV1/FVC would be favourable following breathing retraining. Yet, only three participants were found to increase FEV1, while two decreased. Four participants increased FEV1/FVC, but participant number three decreased.

Variable and inconsistent changes were noted in FEV1. A value of 0.23L is reported to be the average patient perceivable improvement for FEV1 (Santanello et al. 1999), however, only participant 3 was found to change by that level following breathing retraining.

End Tidal CO_2: $ETCO_2$ represents the amount of CO_2 in exhaled air and is indicative of ventilation. An increase in $ETCO_2$ was found in four participants, but participant number 5 was found to decrease $ETCO_2$. However, a limitation of capnography (used to measure $ETCO_2$) is the use of a nasal cannula, which may not accurately measure the outgoing breath in participants that are habitual mouth breathers.

Hospital Anxiety and Depression questionnaire (HADS): Lower scores represent lower levels of anxiety and depression. For the anxiety scale, the scores for all participants decreased with the exception of participant number one who was found to increase. For the depression scale, all participants decreased, with exception of participant two who was found to increase. Despite these decreases, 3 participants (2, 3 & 5) still remained in borderline and abnormal levels for anxiety and depression.

Nijmegen (NQ): A decrease in NQ score indicates reduced levels of symptoms relating to hyperventilation as self-assessed by the participant. This is the only assessment that demonstrated a consistent change in all participants following breathing retraining. NQ scores decreased for all

participants after breathing retraining, indicating a reduction in self-assessed hyperventilation symptoms. Despite decreasing, however, two participants (2 & 3) remained within the threshold indicating hyperventilation.

The significance of the change that occurred in lung function, $ETCO_2$ and questionnaire data after breathing retraining were not assessed using any statistical tests due to the small sample size (n=5). Also, this information was not the primary outcome measure for the third study, where the main outcome was the breathing pattern components measured using an SLP. However, this data were included since it may reflect the physiological and psychological changes that occur following breathing retraining.

7.3.6 Section Summary - Third study

The data collected in this third study does not appear to show a consistent pattern of change. Although the initial data does indicate that changes did occur following breathing retraining, due to the small sample size, it is too early to draw any firm conclusions regarding the responsiveness of breathing pattern components following breathing retraining at this stage. Therefore, these findings can be considered as preliminary data to be used to inform future research in this field. Hence, further large controlled studies are needed to test the responsiveness of breathing pattern following breathing retraining in asthma.

Chapter 8 Discussion

8.1 Introduction

For an outcome measure to be useful, it must be reliable and responsive. Hence, this research has set out to examine the reliability and responsiveness of specific elements of breathing pattern to determine its potential usefulness as an outcome measure for therapeutic physiotherapy interventions and general respiratory health. This chapter discusses the findings from the three separate studies and outlines the difficulties and challenges that have been faced throughout the studies, along with how the findings relate to existing literature.

This chapter is divided into four parts; the first three parts discuss the findings derived from each of the three separate studies and their implications. This is followed by a detailed discussion of the limitations and ethical considerations associated with all three studies.

8.2 First study - Breathing pattern reliability in the sitting and supine position in healthy adults

There is little published research regarding the reliability of breathing pattern components and specifically thoracoabdominal motion; this gap was evident during an examination of the literature, but was also highlighted by Clifton-Smith & Rowley (2011). Consequently, there is no published data that can be used to compare and contrast the findings derived from this first study regarding the within session reliability of certain breathing pattern components. Another issue that was a frequent challenge throughout this study was the lack of pre-defined protocol limits to enable critical evaluation of the change that occurs in breathing pattern components to determine whether the change was clinically meaningful. Moreover, there was a general lack within the literature regarding criteria

to define high and low absolute reliability of breathing pattern components. This presented difficulties regarding the drawing of firm conclusions regarding the absolute reliability of breathing pattern components. In order to overcome this challenge, a number of statistical analysis tests were carried to gain a comprehensive view of the reliability of breathing pattern components. Moreover, this difficulty regarding a lack of pre-defined criteria highlights the need for this study, since it contributes important information to the literature regarding the amount of variability in breathing pattern components.

Nevertheless, the findings from this first study demonstrate that overall, all breathing pattern components remain stable for the within session, between session and between day comparisons in both the sitting and supine position, as evidenced by: the high correlation, the lack of statistically significant differences in cohort means, WSSD% values less than 20% and no systematic bias within the Bland-Altman analysis for most components in most scenarios. Moreover, the mean differences between sessions and between days for all components were found to be less than the baseline data set (as derived from the SRD values for the within session data and the between session data) indicating that no real change occurred. However, T_i and Bf differed slightly from the other breathing pattern components, as it showed some discrepancies in a few scenarios and this is discussed in detail in the subsequent sections.

As mentioned previously, there is no published research within the literature that has examined the within session reliability of breathing pattern components, making it impossible to compare these findings with existing data. Yet, the findings regarding timing and thoracoabdominal motion for the between session and between day comparisons is in line with previous authors; Shea et al. (1987 &1990) conducted studies of breathing pattern in both awake and sleeping healthy adults in the supine position. In their awake study, the breathing pattern of 41 healthy adults aged between 19 and 32 years were recorded four times for 5 minutes each over the course of 2 days using RIP. Tidal volume, inspiratory and

expiratory time, breathing frequency and the proportion of time spent on inspiration (expressed as a percentage) were examined. They reported high degree of reproducibility of breathing pattern within individuals. Similar findings were reported for their sleep study. Benchetrit et al. (1989) used PNT to assess the stability of components of breathing pattern over a longer period of time. Breathing patterns were recorded twice with a 5 year gap between recording sessions, and analysis was based on 50 breaths per participant, but with any sighs or pauses being manually removed from the recordings. They concluded that differences within individuals were significantly smaller than those between individuals despite changes in some participants' circumstances (including increases in weight, respiratory illnesses and learning wind instruments). It, therefore, seems that irrespective of the measurement tool used to record breathing patterns, timing and thoracoabdominal motion components remain stable within healthy individuals, which is in line with the findings from the first study.

Also, the overall reliability for all breathing pattern components was found to be greater in the comparisons that took place on day two, than the comparisons that took place on day one. The reason for this unclear, although a possible suggestion could be that participants felt more familiar, and consequently less anxious, with the research protocol on the second day, which may have affected their breathing pattern (Masaoka & Homma 2001; Labbé et al. 2007). However, anxiety was not assessed using any specific questionnaire or test for e.g. HADS, so it is difficult to confirm this assumption. Nevertheless, the effect of anxiety on breathing pattern has been reported within the literature by Tobin et al. (1983b), where healthy participants (n=65) had an inspiratory time of 1.62 (±0.31) and those (n=13) with chronic anxiety had T_i of 1.44 (±0.24). Similar reports regarding the effect of anxiety on inspiratory time were reported by Mador & Tobin (1991) who found that inspiratory time significantly changed during stressful situations with p value of < 0.0001.

From the findings of the first study, it is possible to suggest that the breathing pattern components under examination remain stable over time and therefore, are reliable.

8.2.1 Inspiratory Time (T_i)

The findings from the first study highlighted inspiratory time (T_i) as displaying varying degrees of absolute reliability for various scenarios in both positions. For example, in the between session 1 and 2 comparison in the sitting position, a WSSD% of greater than 20% was derived. Nevertheless, it still showed good correlation, no statistically significant differences in cohort mean and no systematic bias in Bland-Altman analysis in this scenario. For the between session 3 and 4 comparison in the supine position, one- way repeated measures ANOVA showed that cohort mean T_i was significantly different and the 95% LA were wide.

The findings may appear to suggest that T_i has lower reliability than other breathing pattern components. This may be because T_i is based on a diminutive measure (of only approximately 1 or 2 seconds), thus any slight change may become statistically and clinically meaningful. Nevertheless, it is important to reiterate that lower reliability of T_i was only found in only 2 scenarios (out of 14 scenarios in total), while throughout the majority (n=12) of comparisons, T_i did demonstrate good reliability and the inconsistent findings may be related to type I error that can occur in a study design with multiple tests (Goldman 2008).

The apparent overall reliability of T_i findings is consist with evidence found within the literature; Shea et al. (1987) reported good Kendall's coefficient of concordance values of 0.69 for T_i, while Adamczyk et al. (2008) demonstrated no significant differences in the cohort mean values of T_i based on 8 separate, 6 minute breathing pattern recording sessions that took place over 24 hours with 3 hourly intervals between each session. Moreover, Benchetrit et al. (1989) reported that T_i did not change significantly between recording sessions, therefore, all the aforementioned

literature conclude that T_i is a reliable measure over a period of time. From the first study's findings, it is possible to draw similar conclusions regarding the reliability of T_i, since variability was only found in 2 scenarios.

8.2.2 Breathing frequency (Bf)

During the data analysis, Bf was highlighted as showing varying levels of reliability in comparison to other breathing pattern components. One way repeated measures ANOVA showed statistically significant differences for the within session 4 comparison in the sitting position and between session 3 and 4 in the supine position. However, when these findings are put into the context of the whole of the first study, which involved comparisons made in 14 different scenarios in both the sitting and supine position with 5 different data analysis estimations in each scenario, making a total of 70 tests that took place for the component Bf, it becomes apparent that Bf did demonstrate good overall reliability in the majority (94%) of tests. Hence, the inconsistent findings regarding Bf in the two scenarios may be related to type I error that can occur in a study design with multiple tests (Goldman 2008).

Moreover, the differences that did occur in cohort mean Bf were always less than the baseline SRD value, indicating that no real difference occurred. Furthermore, there have been suggestions within the literature that a limit of variance of ±2 (bpm) might be used as a pre-defined protocol limit to evaluate the equivalence in Bf (Smith et al. 2011). The difference that occurred within session 4 was 0.53 (bpm) in the sitting position and the difference in between session 3 and 4 in the supine position was 1.87 (bpm). Hence, the difference in Bf may not be considered as clinically meaningful. Given the fact that in the majority of cases, Bf showed no statistically significant differences, high correlation and no systematic bias and when notable differences did that occur (in the

two scenarios) it was always smaller than ±2 (bpm), it may be concluded that Bf demonstrates good reliability.

This finding is in line with reports within the existing literature, where Shea et al. (1987) found that Bf demonstrated high reproducibility in a study involving 41 healthy individuals with a Kendall's coefficient of concordance values of 0.87. Also, in the Grossman et al. (2006) study, which examined breathing pattern in 16 healthy individuals (m=8; f=8, mean age= 21.8 years range 18.2-25.7 years) involved in a six week Yoga exercise programme, Bf demonstrated high correlation with Pearson's r values of between 0.73 and 0.83. The finding from the first study regarding the reliability of Bf is useful since Bf is reported as being a key vital sign in detecting early changes in an individuals' condition, particularly in critically ill patients (Sage & Gough 1998, Folke et al. 2003 and Cretikos et al. 2008, Smith et al. 2011). Fieselmann et al. (1993) found that a Bf of 27 bpm or more is an important predictor of cardiac arrest, while Goldhill et al. (2005) reported that patients with a Bf of 25-29 bpm assessed by clinical outreach service had a 21% mortality rate, which further increased as Bf increased. Thus, it is apparent that Bf is an important clinical indicator and it might be clinically useful to monitor within individual changes.

8.2.3 Thoracoabdominal motion components

Thoracoabdominal motion were found to be reliable, which is in line with findings reported in other studies within the literature regarding rib cage contributions in supine position. For example, Tobin et al. (1983) reported RIP data from 47 healthy adults (with similar ages to the sample in this first study), which showed average rib cage contributions to be 42%. Parreira et al. (2010) also used RIP to record breathing pattern in 104 individuals aged 20 to 39, 40 to 59, and 60 to 80 years (41 males and 63 females) and reported rib cage percentage contributions of 44%, 36% and 40% respectively. Binazzi et al. (2006) used OEP and reported rib cage

contributions between 40% and 53%. The findings from this first study found rib cage contributions of 36-41% in the supine data, which is in line with those reported within existing literature.

Regarding the reliability of thoracoabdominal motion components in the sitting position, the one- way repeated measures ANOVA did not find any statistically significant differences, showed high intra class correlation coefficient, WSSD values within 20% and no systematic bias indicated by Bland-Altman analysis, for within session, between session and between day comparisons. Also, any change in mean differences that did occur was always lower than the baseline values derived from the SRD calculation for all comparisons. From these findings, it can be suggested that thoracoabdominal motion components remain stable in the sitting position.

For the supine position, the thoracoabdominal motion components remained stable in all comparisons, with the exception of the within session 3 comparison, where significant differences in cohort mean were found with one- way repeated measures ANOVA; which may be due to the impact of posture on breathing pattern in the supine position (Estenne et al. 1985); the effect of posture on thoracoabdominal motion is discussed in more detail in a later section (8.2.5) or it may be related to type I error that can occur in a multiple test study design (Goldman 2008).

Following visual inspection of the data, it can be suggested that, in both positions, the thoracoabdominal motion components demonstrated greater relative and absolute reliability than the timing components, since cohort mean values were found to be statistically significantly different in only one scenario (which was within session 3 in the supine position), whereas it was found to be statistically significantly different in 3 scenarios for the timing components. Although, this may be due to the nature of the RIP device, which is specifically designed to directly measure the thoracoabdominal motion components, whereas it relatively estimates the timing components.

These novel findings regarding the stability of thoracoabdominal motion are in line with those reported in the only other existing study that evaluated the reliably of thoracoabdominal motion, which was conducted by Shea et al. (1987). Abdominal motion was found to have high correlation with a Kendall's coefficient of concordance value of 0.73 and a CoV% of 22.9%. Overall, the findings from the first study indicate the reliability of thoracoabdominal motion.

8.2.4 The 3 and 9 minute of recording

An important finding from this study relates to the amount of data acquisition time that was analysed. The within session tests were based on 3 minutes of recorded data, while the between session and between day tests were based on 9 minutes of recorded data. The results derived from 9 minutes were consistent with the results derived from 3 minutes of recording. This may suggest that 3 minutes of recording is a sufficient amount of time for recording breathing pattern in order to sufficiently detect variability. This finding is in line with existing research that has recorded breathing pattern for a duration of 5 minutes or less (Parreira et al. 2010; Verschakelen & Demedts 1995 and Benchetrit et al. 1989). This is useful information, as 9 minutes of breathing pattern recording may be impractical for participants and patients having their breathing pattern recorded using certain devices that require a restricted amount of movement. Hence, this is an important finding as it may inform future research regarding the duration of time needed to sufficiently detect change in breathing pattern.

8.2.5 Breathing pattern reliability in healthy adults in sitting and supine

The effect of posture on thoracoabdominal motion has been examined extensively within the literature; however, this is the first study to examine the effect of posture on the *reliability* of breathing pattern components.

The findings from this first study suggest that the reliability of breathing pattern components was affected by posture. Visual inspection of the data showed higher WSSD values and the wider 95% LA in the supine position data in comparison to the sitting position data, suggesting more variability and lower agreement in the supine position for all comparisons. Moreover, in general, the standard deviations within the descriptive data were greater for the supine position, than the sitting position, again indicating more variability of breathing pattern components when recorded in the supine position.

This change in reliability from the sitting to supine position may be due to the kinematic changes that occur within thoracoabdominal compartments due to a change in posture; for example, the data showed rib cage contribution was greater in the sitting position, while abdominal contribution was greater in the supine position. This increase in rib cage contribution in the sitting position may relate to an increase in tonic activity of abdominal muscles resulting from an increase in intra-abdominal pressure (attributed to gravity) and this activity serves to prevent a shift in the length-tension relation by shortening the diaphragm (DeTroyer 1983). Thus, it can be suggested that posture has a strong influence on chest wall kinematics.

Similarly reports within the literature by Wade (1954); Konno & Mead (1967); Sharp et al. (1975); Estenne et al. (1985) and Verschakelen & Demedts (1995) also support this notion, demonstrating that changes from the sitting to supine position is associated with a decrease in rib cage compliance and an increase in diaphragm-abdomen compliance. Moreover, Velody et al. (1978) added that rib cage and abdomen diameters were affected by changes in gravitational forces that result from a change in posture from sitting to supine positions. Hence, tidal excursions of the rib cage were found to decrease, while abdominal excursions increased. This may be due to the reduced elasticity of the diaphragm and abdominal wall in the supine position in comparison to the sitting position (Barnas et al. 1993) and increased abdominal compliance in the supine position (Estenne

et al. 1985). In a study using an OEP device with 34 healthy participants in 5 different postures, Romei et al. (2010) also reported that posture has an influence on the displacement of the rib cage, which decreased from sitting to supine positions.

Although the diaphragm is the primary muscle of inspiration, there is evidence that the diaphragm is involved in the control of postural stability during movement of the limbs and during changes in posture by minimizing displacement of abdominal contents into the thorax, thus maintaining the hoop-like geometry of the abdominal muscles. These muscles could then increase spinal stability via tension in the thoraco-lumbar fascia (Parian 1973; McGill & Norman 1987; Tesh et al. 1987 and Hodges et al. 1997). Moreover, during quiet breathing, in the supine position only the abdomen varies its static characteristic by increasing the compliance (Agostoni & Rahn 1960). Furthermore, Barnas et al. (1993) argues that the abdominal wall distends in the sitting position due to the weight of the abdominal content, which increases the elasticity of the diaphragm-abdomen and lengthens the diaphragm's fibres in the supine position. This concurs with the findings of this study, which demonstrated that abdominal contribution was greater in the supine position.

There may be other factors brought about as a result of being in the supine position. For example, a total of 4 participants fell asleep in the supine position during various tests in the first study (despite being asked not to), which was presumably due to being in a relaxed, supine position, which induced sleepiness. Deep sleep is known to impact breathing pattern by decreasing T_e and Bf (Shea et al. 1990). However, removal of these participants did not have any notable effect on ANOVA, ICC, WSSD values or 95% LA for the timing or thoracoabdominal motion components. This may be explained by the fact that participants fell asleep during different sessions; hence, the effect of removing them was not significant enough to affect the data. Also, in the Shea et al. (1990) study involving sleeping participants, it was found that breathing pattern was only affected during the deep sleep phase, rather than the Rapid Eye Movement (REM)

stage of sleep (i.e. light sleep) and it is unlikely that the participants were asleep for long enough to enter a deep sleep phase.

Another reason may be related to the accuracy of the RIP device when recording breathing pattern in the supine position, which might reduce when used in the supine position. Also, the accuracy of RIP is likely to be violated if the bands slip during recording causing 'noise' in the signal leading to inaccurate measurements and this may be more likely in the supine position (Caretti et al. 1994). This suggestion is further supported in a study by Grossman et al. (2010), which examined the validity of Ambulatory RIP (LifeShirt System; Vivometrics Inc., Ventura, CA) compared with mobile ergospirometry in 9 healthy participants (m=4, f=5; mean age 37.3 ±10.2). Simultaneous measurements were made during daily life in a range of normal activities. In post hoc analyses (ANOVA), V_T was found to be statistically significantly different when measured with the two different devices when in the supine position (698 vs. 602 ml respectively, $p< 0.05$). These findings appear to suggest that RIP may not be particularly suited to recording breathing pattern in the supine position or it may be necessary to perform separate calibration procedures for each posture.

The findings derived from this first study suggest that breathing pattern reliability is slightly affected by posture and is greater when recorded in the sitting position. This contributes important information to the existing body of literature, since supine is often the preferred position in research studies (Tobin et al. 1983a; Tobin et al. 1983b; Parreira et al. 2010); however, this finding suggests that sitting position is a useful alternative for recording breathing pattern, as it produces less measurement error.

8.2.6 Summary of section 8.2

Despite a number of challenges presented regarding the lack of pre-defined criteria relating to clinically meaningful change and absolute reliability, the findings from this study appear to suggest that the breathing pattern components under examination remain stable when

measured within session, between sessions and between days in both the sitting and supine position. However, according to the findings, sitting may be the preferred position for recording breathing pattern, since all components demonstrated greater reliability in the sitting position in comparison to the supine position. The findings from this study contribute useful information to the literature in this field and address the existing gap regarding within session reliability. These findings are important as they indicate that breathing pattern may be useful as an outcome measure; however, for breathing pattern to be considered as a useful for outcome measure, it must also demonstrate responsiveness (as well as reliability). The following sections discuss the findings from the second and third study, which examined the responsiveness of breathing pattern.

8.3 Second study - Thoracoabdominal motion responsiveness during recovery from 10 min of moderate physical exercise in healthy adults

As expected, the inspiratory and expiratory time significantly decreased, whereas breathing frequency significantly increased during recovery from physical exercise with a large effect size, suggesting that timing components are responsive to a physical exercise stimulus. An alteration in ventilation is to be expected following physical exercise and is related to the increased metabolic demand to increase ventilation (Aliverti et al. 2009; Neder et al. 2003). Moreover, during exercise, individuals may adapt breathing pattern to optimise respiratory breathing capacity in order to meet ventilatory requirement (Chanavirut et al. 2006). Similar findings have been widely reported within the literature (Mostert & Kesselring 2002; Burton et al. 2004; Amritsar 2010).

The main finding of this second study showed that although there was some change in cohort mean thoracoabdominal motion components during recovery from 10 minutes of physical exercise, this change was not found to be statistically significant indicating that one session of 10

minute physical exercise does not appear to induce a significant change in thoracoabdominal motion. However, it was apparent that there was some change in thoracoabdominal motion within the individual participants, but the change was not consistent in all participants; for example, rib cage contribution increased in 25 participants, while abdominal contribution increased in 15 participants and no difference was found in 3 participants. The change in thoracoabdominal motion seen within individuals in this second study might have occurred as a result of the higher pressure generated by the inspiratory intercostal muscles during inspiration and the recruitment of abdominal muscles during expiration as suggested by Aliverti et al. (2002). Moreover, as Grimby et al. (1968) asserted, the increasing demand for ventilation during incremental cycling brings about increases in rib cage motion as this is the most compliant compartment utilised and thus, this causes a decrease in abdominal motion during exercise, as the relationship between the rib cage and abdomen is known to be reciprocal, which may explain this finding.

The inconsistent change in rib cage and abdominal motion demonstrated in the second study is similar to that reported in the literature. For example, Tamaki et al. (2000) found that rib cage motion increased in all 8 participants exercising using a cycle ergometer for 15 minutes at increments of 60, 90 and 120W. However, the p value was not reported. Also, Grimby et al. (1968) reported increases in rib cage motion during moderate to heavy exercise (600-900kpm/min using a cycle ergometer) in 4 participants, while 2 had no change and 2 were not able to perform high intensity exercise. Moreover, increases in abdominal motion were found during rest to light exercise (0-300kpm/min) in 5 participants, while rib cage motion increased in 2 and remained the same in one. In addition, Ohashi et al. (2001) reported increases in abdominal motion in 9 of his 15 participants, while 2 remained the same and 4 increased ribcage motion following 5 minutes of cycling on an ergometer at 100W. However, the amount of change for individuals was not reported in any of the

aforementioned studies, which would facilitate comparison with the present study.

It is apparent that the existing literature exhibits heterogeneity in methodology, as most studies recorded breathing pattern using a variety of devices, for varying time periods, with various exercise stimuli, in different body positions and with different sample sizes. For example, Grimby et al. (1968) used a magnetometer (a pair of coils attached to the anterior and posterior body surface) to record a total of 10 breathing cycles in 8 participants (m=6; f=2). However, magnetometers estimate tidal volume based on the anterior-posterior displacements of the chest, but inspiration and expiration causes a cross-sectional expansion of the thorax as well as anterior-posterior movements (Konno & Mead 1967), which raises questions regarding the accuracy of magnetometers to estimate breathing pattern components. While Ohashi et al. (2001) recorded 30 seconds of thoracoabdominal motion in 15 male participants using a 3D motion analysis system with 4 markers positioned on the surface of the body (at the sternoxiphoid process and above the umbilicus and at the corresponding positions along the spine). However, no markers were placed at the upper chest/rib cage regions, so no data regarding the upper rib cage displacement was recorded. Tamaki et al. (2000) used RIP to record thoracoabdominal motion for 3x one minute (at each workload), in 8 male participants; yet, it is known that the RIP bands can slip or move during exercise and the abdominal signals may be interrupted by the participants' leg movements during exercise (Lo et al. 2012). Moreover, it has been reported that during cycling, participants tend to lean forward, which may also affect thoracoabdominal motion by increasing RC motion and using accessory muscles during exercise (Grimby et al. 1968; Romei et al. 2010). Furthermore, it is difficult to standardise this 'forward-leaning' cycling position on the ergometer.

This heterogeneity within the existing literature can make it difficult to compare the findings derived from this second study; nevertheless, there

are some similarities. For example, Aliverti et al. (1997) and Sanna et al. (1999) all reported changes in thoracoabdominal motion during physical exercise; however, similar to this second study, the changes were not found to be statistically significant and were also inconsistent. Of note, all of the aforementioned studies had small sample sizes and since no power calculation has been reported it is not known whether the sample sizes were sufficient to detect meaningful changes, which may affect the validity of their findings (Marley 2014). Nevertheless, the cohort mean obtained from this second study, which included 43 participants (as derived from a power calculation using Cohen's *d* formula) still showed no statistically significant and inconsistent change in thoracoabdominal motion during recovery from 10 minutes of physical exercise.

8.3.1 Potential reason for non-statistically significant change in thoracoabdominal motion during recovery from physical exercise

The results from this second study demonstrated that 10 minutes of physical exercise did not produce a statistically significant change in thoracoabdominal motion. The change during recovery from physical exercise was not found to be significant: this section discusses some of the possible reasons for this finding.

8.3.1.1 Chest Wall kinematics

Ventilation increases primarily through an increase in tidal volume when the energy cost of the respiratory muscles is minimised during low and moderate levels of exercise. Although, at high levels of exercise, breathing frequency changes are primary and tend to minimize the elastic work of breathing with greater rigidity of the respiratory system (Gallagher et al. 1987). Thus, during incremental exercise, a breaking point might exist when the mechanical adaptation of the respiratory system to hyperventilation becomes less efficient, which forces an individual to utilise more breathing frequency than tidal volume; this may explain the

statistically significant changes in timing components and non-statistically significant changes in thoracoabdominal motion.

Moreover, since the diaphragm length is dependent on both lung volume and chest wall configuration, the diaphragm performance is optimised during exercise by increasing its pre-inspiratory length and preventing excessive shortening during inspiration, as shown by the constant end-inspiratory volume reported within the literature (Romagnoli et al. 2004; Aliverti et al. 1997; Kenyon et al. 1997). Moreover, the inspiratory muscles approach their maximum length with increasing ribcage volume; hence, excessive pre-inspiratory lengthening of inspiratory rib cage muscles is prevented by a constancy of maximal rib cage volume (Alerviti et al. 1997). Therefore, the non-statistically significant change in thoracoabdominal motion may be attributable to the basic mechanical function of the chest wall, which does not change significantly as a result of a single physical exercise stimulus. Or as Dejours et al. (1961) and Shea & Guz (1992) suggest, it may be that individuals' possess an ‘personalite ventilatoire’ meaning that an individuals' breathing pattern remains stable over a long period of time, in spite of brief and immediate changes as a result of metabolic demands to maintain respiratory homeostasis (Chiras 2011) or in response to a stimulus. Perhaps change in thoracoabdominal motion may be brought about by more long-term physical exercise training, which is discussed further in the following section.

8.3.1.2 Participants’ physical endurance

Another possible reason behind the non-statistically significant change in thoracoabdominal motion may be related to the participants' ability to perform physical exercise. In a study by Layton et al. (2013), it was found that 14 untrained participants (m=9, f= 5) did not change pulmonary rib cage contribution from rest to maximal exercise when compared with 18 endurance trained athletes (m=11, f=7) measured using OEP, during cycling for 6-12 minutes. Untrained participants were defined as those performing aerobic exercise less than 2 days per week and having never

competed in an endurance sport. Endurance trained athletes were defined as performing more than 10 hours of cycling per week and were competitive athletes. Increases in rib cage motion were significantly different between trained and untrained subjects. Since inhalation is an "active" process, the trained subjects' ability to increase end-inspiratory volumes were greater than the untrained subjects and this may be due to better conditioned respiratory muscles. This may also explain how trained athletes are able to substantially increase their tidal volume in comparison to untrained individuals (Myrianthefs & Baltopoulos 2013). However, the p value was not reported within the article and it may be the significant change occurred because of the multiple test protocol rather than real change.

Since the majority of participants involved in the second study stated that they were not performing regular formal exercises (as measured by a questionnaire, see Appendix A.3), this may have contributed towards the non-statistically significant change in thoracoabdominal motion; however, a limitation of this second study is that physical endurance was not formally assessed and so this cannot be assumed.

8.3.1.3 Change in recording device

Due to a change in recording devices from the first to the second study, it is not possible to be completely certain how stable the SLP measures thoracoabdominal motion. The two devices measure chest wall motion in different ways. The RIP device uses elastic bands placed around the abdomen and thorax; hence, it is limited to recording breathing pattern based only on this limited area, which is also restricted to the 2 degrees of freedom assumption (Konno & Mead 1967). The SLP device counters this problem by recording breathing pattern via a projected grid that covers the entire anterior aspect of the chest wall and is not limited to the 2 degrees of freedom assumption. In spite of this, the SLP device is not able to record the changes that occur in the lateral and posterior aspects and combines

the two ribcage compartments (ribcage pulmonary and ribcage abdomen). Since the RIP and SLP measure chest wall motion in different ways, it cannot necessarily be assumed that SLP measures will behave in the same way in terms of stability over time. Thus, it may not be certain what differences are due to measurement error and which reflect real change and perhaps if RIP was used in the second study, a different outcome regarding the significance of change in thoracoabdominal motion may have occurred. However, SLP is a new and emerging technology with many advantages especially regarding its ease of use within clinical settings. Moreover, the aim was not to directly compare the data collected from these two devices, which is why it was selected for use in the second study.

8.3.2 Variability of thoracoabdominal motion in healthy adults at rest and during recovery from physical exercise

The CoV% calculation showed that ribcage motion variability very slightly increased and abdominal motion variability very slightly decreased during recovery from moderate physical exercise with less than 1% change in both. The only available study within the existing literature that reported mean±SD of rib cage and abdominal motion at rest and during exercise was Layton et al. (2013), from which the CoV% can be calculated. The CoV% for the data collected by Layton et al. (2013) demonstrated decreases in rib cage and abdominal motion variability during sub-maximal and peak exercise. This contradiction in results may be due to the sample, since Leyton et al. (2011) included trained athletes (n=18) and non-athletes (n=14), while the present study's sample comprised wholly of non-athletes. Moreover, the difference in findings may be due to the recording, which was conducted during exercise for the Layton et al. (2013) study, while the present study recording breathing pattern during recovery from exercise.

However, in line with the Leyton et al. (2013) study, the findings from this second study appear to indicate that abdominal contribution is consistently more variable than rib cage contribution at rest and during

recovery from physical exercise with high CoV% in all scenarios. Also, the data from the second study demonstrated that T_e variability was greater than T_i both at rest and during recovery from exercise; a similar finding was reported by Tehrany et al. (2016), where T_e showed a CoV% of 26.23%. While T_i CoV% was lower at 22.83% and abdominal contribution variability was greater at 14.98% than rib cage contribution variability, which was 3.71% in a study examining breathing pattern at rest and during various speech tasks in healthy and non-healthy individuals.

Some variability in breathing pattern in normal healthy adults would be expected and has been related to a number of physiological factors; such as, chemo reflexes (Aardweg & Karemaker 2002), the regulatory system of metabolism and temperature (Iberall 1986), rhythm-generating systems within the brainstem (Von Euler 1983) or by higher cortical centres (Haruki et al. 2011). Consequently, breathing pattern may naturally exhibit complex variability (Goldberger et al. 2002) due to the interactions that take place between several respiratory pattern generating neuronal networks within central nervous systems (Smith et al. 2000) or by mechanical and chemical afferent feedback modulations (Sammon 1994; Van den Aardweg & Karemaker 2002). Therefore, normal breathing pattern during quiet breathing is expected to exhibit some degree of random variability in order to maintain respiratory homeostasis, and is a demonstration of the complexity of any healthy pathological systems that must exhibit adaptability and functionality (Clancy & McVicar 1996).

8.3.3 The effect of gender on thoracoabdominal motion responsiveness

The effect of gender on thoracoabdominal motion at rest has been extensively examined (Fugl-Meyer 1974; Gilbert et al. 1981; Romei et al. 2010; Binazzi et al. 2006); the findings consistently show that females have greater rib cage contribution and lower abdominal contribution. While males tend to have equal ribcage and abdominal contribution. These

gender differences in thoracoabdominal motion may be related more to body size rather than gender per se, as females have smaller radial rib cage dimensions in relationship to height than males and a greater inclination of the ribs. This was shown in a study by Bellemare et al. (2003) who used chest radiography to measure thoracic dimensions and diaphragmatic length in 40 healthy participants (m=21, f=19) and found a significant difference in chest wall dimensions with the sixth rib being more inclined in females and a shorter diaphragmatic length in females when compared to males, which may affect thoracoabdominal motion.

Research examining the effect of gender on the responsiveness of thoracoabdominal motion is limited. The findings from simple linear regression analysis in the second study revealed that gender has no effect on the responsiveness of thoracoabdominal motion, both males and females were found to respond in a similar manner. This finding is in line with a study by Vogiatzis et al. (2005) who recorded breathing pattern using OEP in the sitting position and found no gender differences in the responsiveness of thoracoabdominal motion during four minutes of cycling in 15 healthy adults (m=10, f=5; with a mean age 24 years). Although this finding should be viewed with caution due to the small number of females within the sample (n=5), which may affect the statistical power of this sub group (Button et al. 2013). However, in another study by Layton et al. (2013), it was shown that the responsiveness of pulmonary ribcage (RCp) and abdominal ribcage (RCa) contribution was significantly greater in women than men, but abdominal contribution was similar in both men and women; this conflicting finding may be due to the inclusion of trained athletes within the sample. Nevertheless, the findings from this second study indicate that gender does not affect the responsiveness of thoracoabdominal motion.

8.3.4 Relationship between thoracoabdominal motion and timing components at rest and during recovery from exercise

The findings from the Pearson's r correlation demonstrated low correlation between the cohort mean thoracoabdominal motion and timing components both at rest and during recovery from physical exercise. This is a novel finding as there are no studies within the literature that assess the relationship between thoracoabdominal motion and timing components. There are two available studies that assess the relationship between thoracoabdominal motion and tidal volume (V_T), which were conducted by Tamaki et al. (2000) and Ohashi et al. (2001). The results from Tamaki et al. (2000) revealed that V_T correlated more with rib cage motion (r= 0.87) than abdominal motion (0.69). Conversely, the Ohashi et al. (2001) findings derived from two-way ANOVA suggested that V_T increased more by abdominal motion than rib cage motion. These contradictory results may be related to heterogeneity within the methodology, as discussed earlier in section (2.5.1) especially as the device used in the Ohashi et al. (2001) study does not provide data relating to the upper rib cage motion.

Hence, it might be suggested that there is a relationship between thoracoabdominal motion and tidal volume (Ohashi et al. 2000;Tamaki et al. 2001), but the findings from this second study indicate that there does not appear to be a relationship between thoracoabdominal motion and timing components. It may be useful to clarify the relationships between respiratory movement, respiratory timing and tidal volume, as this often relates to the physical therapy approach to improve respiratory health. Thus, when designing a respiratory training programme it may be necessary to consider the notion that a change in thoracoabdominal motion may not be dependent on the time that an individual needs to inspire and/or expire air and may rely on the volume that is inhaled and/or exhaled into the lungs during breathing. This is certainly an area of study

that requires further research to confirm the relationship between thoracoabdominal motion and timing components.

8.3.5 Summary of section 8.3

This second study examined the responsiveness of thoracoabdominal motion components of breathing. Although the results showed changes in thoracoabdominal motion within individuals, the changes that did occur within individual participants did not demonstrate any regular pattern or consistency. Moreover, cohort mean thoracoabdominal motion was not found to change significantly following a single 10 minute physical exercise stimulus. A lack of a significant change in cohort mean thoracoabdominal motion may indicate that for change in thoracoabdominal motion to occur a more long term training approach is necessary, rather than one short physical exercise stimulus. This notion has been alluded to within the literature, where highly trained athletes and swimmers have been found to demonstrate better coordinated action of both inspiratory and expiratory muscles in comparison to non-swimmers (Sarro et al. 2008) and long-term physical endurance training was found to have a significant impact on ventilatory kinematics (Leyton et al. 2013). Also, the findings from this second study have shown that gender does not have an effect on the responsiveness of thoracoabdominal motion and there is a low correlation between the thoracoabdominal motion and timing components.

8.4 Third study - Breathing pattern responsiveness following breathing retraining in patients with asthma

The initial data indicates that some change does occur in breathing pattern following a breathing retraining programme. However, there are inconsistencies within the change for both the timing and thoracoabdominal motion components. Regarding the changes that occurred in T_i and T_e, there were inconsistencies across all participants,

despite the aim of the breathing retraining programme, which encouraged participants to reduce breathing frequency and increase inspiration and expiration time. Nevertheless, two participants (1 & 2) decreased T_i, and the other three increased. While three participants (1, 3 & 4) increased T_e and the other two decreased (participant 2 & 5). These two participants (that decreased T_e, 2 & 5) were noted as scoring the highest HADS Anxiety scores (which were above the threshold of clinical significance) after breathing retraining. In addition to this, participant no. 5 was also found to increase Bf after breathing retraining. Indeed, anxiety has been shown to affect breathing pattern (Mador &Tobin 1991; Masaoka & Homma 2001; Homma & Masaoka 2008), which may explain this finding.

Regarding thoracoabdominal motion, all participants decreased $\%RC_{exp}$ and increased $\%AB_{exp}$ following breathing retraining, with the exception of participant 4, who increased $\%RC_{exp}$ and decreased $\%AB_{exp}$. This may be due to the aim of the breathing retraining programme, which encouraged participants to breath with more emphasis on their abdominal muscles. Of note, the one participant who showed a difference in change in thoracoabdominal motion was 70 years old; there is evidence within the literature that increasing age results in changes in breathing mechanism, particularly regarding weaker diaphragmatic muscles, which may result in a breathing pattern dominated by rib cage displacement (Kaneko & Horie 2012).

This is the first study to examine the effect of breathing retraining on breathing pattern components in asthma patients during quiet breathing; hence, there is no research within the literature to allow comparisons to be drawn. However, similar inconsistent findings were reported in a case study by Tehrany et al. (2017), where $\%RC_{exp}$ was found to decrease during a loud reading task, but increased during conversation following a breathing retraining programme. Nevertheless, the general trend in the direction of change for the thoracoabdominal motion components in the 4 participants in the present study appears to be a positive finding, since

increased ribcage motion with restricted abdominal activation has been associated with respiratory disease (Lavorini et al. 2009). Therefore, increased use of abdominal diaphragm during quiet breathing can be viewed as a potentially positive outcome, since the breathing retraining programme encourages a predominantly abdominal pattern of breathing.

Nevertheless, these preliminary findings must be viewed with caution and no firm conclusions can be drawn regarding the effect of breathing retraining on breathing pattern in asthmatics for a number of reasons, which are discussed in the following sections (8.4.3, 8.4.4 and 8.4.5).

8.4.1 Breathing pattern variability before and after breathing re training

Healthy breathing pattern is expected to exhibit some degree of random variability within individuals and this is a measure of complexity that accompanies any healthy systems enabling it to display greater adaptability and functionality (Papaioannou & Pneumatikos 2012). It is acknowledged that respiratory disease can affect breathing pattern variability (Khoo 2000) and an excessive increase or decrease in variability is indicative of the onset of disease or dysfunction (Bokov et al. 2016). Hence, the variability of each breathing pattern component for each individual participant was examined at baseline and following the breathing retraining programme. Despite large changes in variability shown for some components for some participants, no clear consistent pattern in variability was observed in the data with various increases and decreases throughout the various participants and components.

In a recent study within the literature, it was found that people with asthma can demonstrate greater variability in comparison to healthy individuals. Hmeidi et al. (2017) recorded breathing pattern using SLP for 5 minutes in 30 children (7-16 years) with asthma and compared it to breathing pattern in 41 healthy children with similar age. Asthma patients

showed greater variability in Te (0.21 v. 0.35 seconds) and RC contribution components (6.52% v. 8.03%) in comparison to healthy children.

8.4.2 Sample size

The respiratory centre administrative team sent a total of 30 recruitment packs; 6 individuals responded (approximately 20% response rate) and 4 participants completed the first, second and third recording sessions; one participant completed only the first and second recording session and one participant withdrew from the study before any data were collected. Thomas et al. (2009) highlighted the difficulties often associated with recruitment and retention in community based asthma studies, which is mainly due to the inconvenience for the participant regarding an increase in medical visits and general disruption to participants' lives. Similarly, Holloway & West (2007) specified the practical and logistical difficulties that prevented the retention of some participants in their study, which examined the effect of breathing exercise in asthma patients.

Another factor contributing to the small sample size related to the duration of recruitment time, which was restricted (from August 2016 to November 2017), which proved to be insufficient time to recruit the necessary numbers. Within current literature, recruitment for community based asthma studies is often a period of 6 months or more (Holloway & West 2007; Thomas et al. 2009; Grammatopoulou et al. 2011). Clearly, the sample size of five participants is a major limitation of the third study.

8.4.3 The duration and frequency of breathing retraining programme

This preliminary data is based on three face to face breathing retraining sessions lasting approximately 30 minutes each for 4 participants and only one session for 1 participant; plus whatever home practice each participant undertook during the intervening weeks. This may not have been sufficient time or sufficient number of sessions to significantly alter and/or modify

breathing pattern. It might be suggested that increasing the frequency and duration of the breathing retraining instructional sessions may have favourable effects on breathing pattern as has been suggested in scientific, evidence based clinical guidelines, in which it is recommended that a breathing retraining programme comprising five hours of instructional sessions can be beneficial for patients with asthma (BTS/SIGN 2016). Although Thomas & Bruton (2014) suggest three to four instructional breathing retraining sessions over a period of six-weeks is sufficient to modify breathing pattern. However, the optimal length and number of instructional sessions required to modify breathing pattern is unclear within the literature as no study has examined the effect of a low number versus a high number of sessions.

A study by Tehrany et al. (2016), which examined breathing pattern following a pulmonary rehabilitation programme in 20 participants with respiratory diseases (14 patients with COPD and 6 patients with bronchiectasis), showed no statistically significant differences in all breathing pattern components measured using RIP. However, this may have been due to the lack of a sufficient number of instructional breathing retraining sessions, as it only included one 60-minute breathing retraining session. Indeed, there are some suggestions within the literature that asthma symptoms might improve, QOL may increase, medication usage can reduce and/or ETCO2 can improve when an individual receives 3 or more instructional breathing retraining sessions either face to face or through video/DVD (Slader et al. 2006; Holloway & West 2007; Meuret et al. 2007; Thomas et a.l 2009; Grammatopoulou et al. 2011). Hence, a newly designed pulmonary rehabilitation programme, which includes a greater number of instructional breathing retraining sessions may have favourable effects on breathing pattern. Clearly, more research is needed in this area, which may require commitment and, importantly, funding from the NHS and government bodies.

Another potential issue relates to participants' adherence (or possible lack of) to the self-administered part of the programme. A WHO report states that in the general population, adherence to long-term therapies for chronic disease is approximately 50% and even less in developing countries (Sabaté 2003) and in a study that explored 29 asthmatic participants' perceptions of a self-administered breathing retraining programme, the main barriers mentioned were ‘remembering to do it’ and ‘perseverance’ (Arden-Close et al. 2013). A number of studies have reported various ways to increase adherence, including providing participants with detailed instructions as to how to practice their breathing exercises (Thomas et al. 2009), providing social support and tracking progress (Arden-Close et al. 2013; Slader et al 2006), another provided instructional video/DVD material to assist the participant (Slader et al. 2006), while others have given booklets and specific asthma action plans (Grammatopoulou et al. 2011).

The research team asked the participants about their adherence, and one participant reported not performing any home exercises. Four of the five participants explained that they are performing the breathing exercises consistently on a daily basis (between 1 and 3 times a day), although they may have said this in order to satisfy the researchers. Fendrich & Johnson (2008) suggest that this phenomenon may relate to the Socially Desirable Response (SDR) theory, which is defined as “the tendency for people to present a favourable image of themselves”. Hence, participants in this study may have provided positive responses regarding their level of adherence. A way to overcome this problem, may be to ask participants to keep a diary to record their self-administered breathing exercises and/or to allow them to anonymously select the amount of times a week they perform the breathing exercises within a questionnaire item. Moreover, a qualitative study to measure participants' adherence may also provide useful information regarding adherence to independent breathing retraining programmes, although this may require some sort of digital device to record participants' daily breathing pattern practice.

8.4.4 The influence of asthma severity on breathing pattern responsiveness

Participants in this third study have all been diagnosed with asthma for many years (mean = 27.4 years) and asthma symptoms were all at a relatively high intensity (hence the referral to a respiratory physiotherapist). There has been some suggestion within the literature that the severity of an individuals' asthma symptoms may affect the efficacy of a breathing retraining programme. For example, Slader et al. (2006) included patients with moderate to severe asthma and found no significant change in lung function and $ETCO_2$ following a breathing exercise programme. However, Meuret et al. (2007) and Grammatopoulou et al. (2011) included patients that were characterised as mild to moderate asthma and found a significant change in lung function and $ETCO_2$ following a breathing exercise programme (the respective changes in lung function and $ETCO_2$ may be reflected in changes in breathing pattern if this variable had been examined). This conflicting finding may be related to the fact that breathing retraining does not improve the chronic underlying physiological causes (inflammation) of asthma, but rather their manifestation (Holloway & West 2007). The other reason behind the different findings within the literature may be due to the different breathing retraining interventions, as all of the aforementioned studies used a different type of breathing exercise programme, which differed in length, duration, frequency and breathing exercise used. This heterogeneity is another challenge, since there is a lack of consistency and uniformity across breathing retraining programmes, as each hospital has it is own programme, which differs from others; this may be another reason behind the conflicting results regarding alterations in lung function and $ETCO_2$ within the literature.

8.5 Research Limitations

There are a number of limitations with each of the studies in this research, which in the interests of fairness and impartiality and to assist future research are presented and discussed in detail as follows.

8.5.1 Sample method

A limitation of this research relates to the sampling method utilised in the first and second studies (convenience sampling), while the third study was part of a wider study and involved a purposive sampling method as it was necessary to recruit particular pre-defined participants (with asthma and having been referred to the breathing retraining programme at SGH). A random sampling technique would have been preferable for the first and second as it is understood to be more representative of the population (Trochim 2006); however, the researcher was limited to a convenience sample method for the first two studies due to limitations in accessing funds and was limited to recruiting colleagues from the University of Southampton.

8.5.2 Sample diversity, completeness and size

The sample size differs on the first day of data collection (n=50) to the second day (n=38) in the first study. It could be suggested that this affected the results; however, in attempt to explore the potential impact of this, the researcher re-analysed the data to included only the 38 participants that attended both day one and day two data collection sessions (Appendix E). The data analysis involving these 38 participants was not largely different from the data collection involving all 50 participants. Hence, it can be suggested that the effect of this differing sample size on the two days is minimal. Also, the sample in the third study is lacking in statistical power, as the total number of participants is five. This was largely due to time constraints, which prevented the further

recruitment and inclusion of additional participants; this is clearly a limitation of this third study and as such, the data and findings are to be considered as preliminary in this stage.

8.5.3 Study methodology and design

In the first study, the researcher would have preferred to record breathing pattern at the same time of day on each of the two days; so for example, if the data collection on the first day was in the morning, the researcher made an effort to record the data in the morning (at the same time) on the second day, and likewise for the afternoon or evening recordings. However, of the 39 that returned for the second day of data recording, 9 participants (23%) could not come at the same time of day. A study by Adamczyk et al. (2008) noted that some breathing pattern components can be significantly affected by circadian fluctuations; however, the Adamczyk et al. (2008) findings suggested that volume components are more subject to change, while the timing components appeared less affected by daily fluctuations. Therefore, the impact of the difference in the time of day that recordings took place in the present study is unclear.

Regarding the second study, it could be argued that placing additional workload on the male participants ergometer in recognition of the physiological differences between males and females, would have been interesting. Leyton et al. (2011) and Vogiatzis et al. (2005) both gave males greater exercise intensity during exercise (in comparison to the female participants) in order to induce greater physical exertion to determine how increased ventilatory demand impacts ventilatory kinematics. It might have been useful to perform a PPO (peak power output) test, which measures the total amount of time that an individual can hold the PPO of between100 to 400 watts over a period of 4-6 minutes. However, it was considered more simple for each participant to perform incremental cycling for 10 minutes Nevertheless this may be a consideration for future research. In this study, both males and female

exercised at the same intensity, which may not have provided a fully accurate reflection of the responsiveness of thoracoabdominal motion in males, although this is not fully known and has not been explored within the literature.

8.5.4 Blinding

Another possible limitation of this research was the lack of participant blinding in all three studies, all participants were fully aware of the aims of the studies and knew that their breathing pattern was being recorded and investigated. In 1997, Han et al. conducted a study to examine the impact of an individual's awareness of the recording of breathing pattern on the actual breathing pattern. Participants had their breathing monitored under three separate conditions of 5 minutes each; in the first condition participants were told that their breathing was not being monitored and that the time was being used to calibrate the RIP device, this was not the case. In the second condition, the participants were told that their breathing pattern was being monitored by the RIP device. In the third condition, the participants were asked to breath into a mouth piece for their breathing to be monitored using a PNT. The results found that there were significant differences in all of the breathing pattern components between the conditions. Notably, it was found that there were significantly longer inspiration and expiration durations once the participants were made aware that their breathing was being monitored.

All possible measures were taken during the protocol in this to avoid the participants' awareness having an effect on their breathing pattern, by asking participants to avoid focusing attention on their breathing and requesting them to breathe as normally as possible. Also, in the first study, the first three minutes of each breathing pattern recording session data were discarded from analysis, in the hope that participants would have settled into a natural (less conscious) breathing pattern after 3 minutes had passed. Moreover, the second and third study used the contactless SLP

device, which may reduce the participants' awareness and produce a more natural, realistic breathing pattern. Nevertheless, it is conceivable to assume that participants' awareness may have had some impact on their breathing pattern, which consequently may not have been natural/normal. However, since the aim of this research was to examine the reliability and responsiveness of specific breathing pattern components, it is hoped that the data in this regard were not affected greatly.

8.5.5 Technical issues with recording devices

Due to a malfunction of RIP Oscillator (loose connections of wires), data of two participants had to be removed from the analysis of second day, which highlights one of the technical challenges related to the RIP device since it is sensitive to be being transported from one laboratory to another. Regarding the SLP, it is a new and emerging technology, which means that it has not been subject to extensive validity and reliability trials (although these are ongoing). Also, there is little information regarding the integrated algorithm software used to extract and process the data; hence, the validity of the SLP algorithm is not known. Moreover, although SLP provides direct numerical data, it only provides the mean value of each component and does not include the standard deviation value. Mean values are useful in determining average values, but are more meaningful if the standard deviation values are also included.

8.5.6 Data editing

Another potential limitation with the first and third studies involve the process of editing the data, in particular, the process of removing the uncharacteristic signals, which occur as a result of excessive movement, coughing and/or yawning. This process relied on a visual inspection of the signals on the trace, and removal of any obviously large, uncharacteristic signals (explained in section 5.2.9) that matched the notes made by the researcher during the breathing pattern recording session at specific

points when an uncharacteristic signal was produced that was obviously a result of the participants' movements, coughing and/or yawning.

In each study, the majority of uncharacteristic signals that were removed were 2 times that of the average signal size. It can be argued that this is a very subjective process, which relies wholly on the researcher's opinion. In an attempt to control for this limitation, the researcher practised extreme caution when it came to the removal of unmatched signals and ensured that only very obvious and extreme differences between high and low signal peaks and troughs were removed, any signals that were thought to be different, but not excessively different were not removed and also only those signals that matched the researcher's notes were removed.

8.6 Ethical considerations

Ethical approval for the first and second studies was obtained from Southampton University's Ethics Committee ID 20200 and 5269 respectively and the third study was reviewed by a NHS Ethical Committee ethic number 16/SC/0083; ID RHM MED 1324.

8.6.1 Data protection and confidentiality

Participants were assured anonymity for all three studies, with only the researcher and supervisors (and research team for the third study) having access to breathing pattern data, which were kept securely on a private computer that could only be accessed using a password known by the researcher. All paper documents including sign consent forms and demographic data were securely stored in a locked filing cabinet within the university, in compliance with the University of Southampton policy for postgraduate research. No participants' names have been included in any report and numbers have been used to represent participants (P1, P2).

8.6.2 Health and safety

A risk assessment was carried out prior to any data collection procedure following the University of Southampton's risk assessment protocol. The data collection only took place if no risks or hazards were identified and all equipment was checked and used in accordance with the manufacturer's safety guidelines. Data collection procedures for the first and second study took place in a well-ventilated room at the University of Southampton and for the second study, there was the addition of a fan, to increase participants' comfort during the exercise stimulus. Moreover, the Borg scale was clearly displayed throughout, and participants were informed to stop the exercise at any time if they felt over-exerted or overly breathlessness (in accordance with the Borg scale).

Moreover, if the researcher had assessed a participant as experiencing difficulty or discomfort during any of the data collection sessions, or during exercise phases, the data collection would have been stopped and the participant advised to attend their usual primary care practitioner as appropriate. However, no problems of this kind were experienced and it was not necessary to advise any participant to seek medical assistance. In addition, a first aid kit was on site at all times.

For the data collection at Southampton General Hospital (third study), the data collection was carried out in a well-ventilated physiology laboratory within the Welcome Trust Clinical Research. Risk assessment was conducted by the research team before each data collection session in order to identify any safety hazard. In the unlikely event of discomfort or distress, a respiratory consultant could be contacted and presented as the study' medical cover.

Chapter 9 Conclusion

9.1 Introduction

The overall aim of this research was to examine the potential for using breathing pattern as an outcome measure for respiratory physiotherapy intervention. Three studies have been conducted to examine the reliability (first study), and responsiveness of breathing pattern components in healthy adults and in asthma patients (second and third study).

9.2 Main Conclusions

From the information obtained during the first study, it can be concluded that the breathing pattern components under examination are reliable in healthy adults, suggesting that breathing pattern does have the potential to be used as an outcome measure for assessing respiratory interventions within clinical and research settings. The results suggested that posture can slightly effect reliability; consequently, the optimal position to record breathing pattern may be the sitting position. However, for an outcome measure to be considered as clinically useful, it should demonstrate reliability *and* responsiveness (Guyatt et al. 1987; Beaton et al. 2001; Roach 2006). Regarding the responsiveness, no statistically significant change in cohort mean thoracoabdominal motion was found following a single physical exercise stimulus. Nevertheless, changes in thoracoabdominal motion within individuals were observed in both the second and third studies, but the changes were inconsistent and did not demonstrate any clear pattern or direction of change making it too soon to draw firm conclusions regarding the responsiveness of breathing pattern.

The lack of a reliable and responsive outcome measure specifically related to assess respiratory physiotherapy interventions is a particular challenge that respiratory physiotherapists face and could potentially be a barrier to the further development of an evidence base in respiratory physiotherapy. Although, this research has contributed valuable evidence to the existing body of literature regarding the reliability of specific breathing pattern components in healthy adults, it was unable to establish the responsiveness of thoracoabdominal motion. Consequently, further future research is required to examine the responsiveness of breathing pattern components with a more long-term physical exercise intervention and with a breathing retraining intervention with a larger sample size.

Chapter 10 Recommendations and Future Research

The specific recommendations derived from the findings of this research that may inform future work can be summarised as follows:

- Since the first study has established the reliability of specific breathing pattern components in healthy adults, future research examining reliability of breathing pattern in patients with respiratory disease is necessary to confirm the reliability of breathing pattern to be used as an outcome measure in patients with respiratory disease. This is of relevance since the prevalence of respiratory diseases is overwhelming and has consequences for countries' economies as well as individuals' quality of life and morbidity rate. Hence, reliable and responsive outcome measures specific to respiratory physiotherapy may improve the efficacy of therapeutic interventions.

- The findings from the second and third studies were unable to establish the responsiveness of thoracoabdominal motion to specific stimuli; therefore, more research in this area is needed. An example of potential future work could involve examining the responsiveness of thoracoabdominal motion components to a more long-term physical exercise programme and to long-term breathing retraining programme.

- For a number of reasons, the third study in this research had a very small sample size, which had insufficient power to detect any significant changes that occurred in breathing pattern following a

breathing retraining intervention. This prevented the drawing of firm conclusions regarding the responsiveness of breathing pattern in people with asthma following breathing retraining. Therefore, another recommendation would be to continue the original work of the third study to increase the sample size.

- A recommendation for future research examining breathing pattern would involve attempts to blind the participants (for example, researchers could inform the participant that the recording device is being calibrated and that breathing pattern recoding is not occurring for a specified duration when in fact, breathing is being recorded). This may reduce the participants' awareness of their breathing pattern and will reduce the likelihood of them consciously altering it during the breathing pattern recording session (Han et al. 1997).

- From experience gained during the first study, it can be recommended that breathing pattern recording sessions last approximately 3 to 5 minutes, as 15 minutes seemed to be long and caused some participants to fidget or fall asleep and it may be a potential barrier to participants returning for further recording sessions. Moreover, the results derived from 3 minutes of recording were consistent with the results derived from 9 minutes, suggesting that 3 minutes of recording is a sufficient time to sufficiently detect variability.

- To assist further development in both research and clinical settings, further work would be useful to establish and create a normative value database for breathing pattern components in healthy adults. At present, this is largely lacking. This would require extensive future research involving a large and varied, randomly selected sample.

- The lack of homogeneity between studies within the existing literature in the field of respiratory health has resulted in difficulties in drawing firm conclusions regarding the responsiveness of breathing pattern. Hence, the challenge now is to establish methodological homogeneity within the future research in order to facilitate meta-analysis and therefore, ultimately improve respiratory health.

These are the main recommendations from this research that would assist in the future development in the field of respiratory physiotherapy.

Appendix A Ethic documents first study

A.1 Participant Information Sheet

Study Title: The test re-test reliability of specific elements of Breathing Pattern (BP)

Researcher:
Fatimah AL-Shaikh
MPhil/PhD student
Faculty of Health Sciences
University of Southampton
SO17 1BJ
Fja1e09@soton.ac.uk
Tel: 07742160189

You are being invited to take part in a research study. Before you decide whether you would like to participate, it is essential that you understand the purpose of the research and what it will involve if you wish to take part. Please take time to read the following information and discuss it with others if you wish. It is important that you understand all of the information before you decide whether or not you would like to take part in the research. Please contact us if there is any more information that you require or if anything is unclear. If you are happy to participate you will be asked to sign a consent form.

What is the research about?

One of the ways that health care professionals assess lung health is to observe people's breathing pattern. It is now also possible to make objective measurements of breathing pattern using various pieces of equipment. One of these is called Respiratory Inductive Plethysmography

(RIP for short). Although this equipment has been used by researchers for a long time, we still do not know whether breathing pattern is stable within individuals (or does it vary from day to day). If it is stable, then it may be useful as an outcome measure for health interventions. In this research we will take some measurements of 40 people's breathing pattern over 2 separate days to see if it stays the same or not.

Why have I been chosen?

You have been chosen because we would like to record breathing patterns from a group of 40 adults.

Do I have to take part?

It is entirely your decision whether or not you decide to participate in this study. If you do decide to take part, you will be asked to sign a consent form. In addition, you are free to withdraw from the study at any point during the procedure without having to give a reason.

What will happen to me if I take part?

If you indicate that you would like to take part in this study, the researcher (Fatimah Al Alshaikh) will contact you to organise a convenient time and date to attend a breathing pattern recording session at the University of Southampton. This will last approximately 90 minutes. When you arrive you will be given a chance to ask any questions. You will then need to fill in and sign a consent form. In order for the breathing apparatus to record your breathing pattern, two elastic belts with built in sensors will be attached around your upper chest and abdomen (tummy). The belts will need to be attached close to your skin in order to record your breathing pattern, therefore you will need to wear a vest or minimal undergarments on your top half to ensure that the sensors make close contact with your skin. If you wish, your outer garments (like a t-shirt) can then be replaced over the top of the belts to cover you up. As you breathe, signals from the belts are sent down some wires for recording. You will not feel anything while this is happening. We will ask you to sit quietly in a chair and

complete a short questionnaire about your age, height, weight, gender and general health. You will then be asked to remain seated without speaking for a further 10-15 minutes. After this you will be asked to lie down on a bed/couch for a further 15 minutes (still wearing the belts). The belts will then be removed and you will be free to move around or take a bathroom break. The belts will then be replaced on your body as before and you will be asked to sit and lie down again for 15 minutes each, as before. The belts will then be removed and you will be free to go.

You will be asked to return for a second recording session on a day about one week after the first recording session (may be 4 -10 days, depending on your availability). At the second session all the breathing pattern measurements will be repeated

What are the side effects of any treatment received when taking part in this study?

There are no known side effects from taking part in this study.

What are the possible disadvantages in taking part in this study?

There are no known disadvantages or risks from taking part in this study.

What are the possible benefits of taking part in this study?

There are no direct benefits from you taking part in this study. It is hoped that the information gained from this study may be used to help us to monitor breathing patterns in patients with chronic lung disease. This could lead to improved understanding of breathing patterns by health professionals and patients, as well as improved management of patients with chronic lung disease.

Will my taking part in this study be kept confidential?

All information collected during the research process will remain confidential. Any data that is collected from you will have your name removed and will be allocated with an individual code so that you will not be able to be identified. The information will be stored on a password-

protected laptop which will be stored in a locked cupboard with in the university.

What to do if you want to complain?

In the unlikely event of anything going wrong or if have a complaint or concern, you can contact Dr Martina Prude of Research & Enterprise Services, at the Faculty of Health Sciences (Address: University of Southampton, Building 67, Highfield, Southampton, SO17 1BJ; Tel: +44 (0)2380 595058Email: mad @soton.ac.uk). Martina Prude is completely independent of this study and will be happy to deal with any problems or concerns that may arise and can provide you with an official complaints form.

What will happen to the results of the research study?

The information recorded from your breathing pattern will be converted into figures for analysis. Some of the information may be used to develop future research ideas. The findings may also be written up in the form of reports or research articles and published at conferences or in academic journals. If this happens, you will not be identifiable.

Who has reviewed the study?

The study has been reviewed by the Ethics committee of the Faculty of Health Sciences. Ethics number: xxx

Thank you for taking time to read this information sheet

If you would like any further information please contact:

Contact details:

Researcher
Fatimah Alalshaikh
PhD student
Faculty of Health Sciences
University of Southampton
SO17 1BJ
fja1e09@soton.ac.uk

Supervisors
Prof Anne Bruton
Professor of Respiratory Rehabilitation
Faculty of Health Sciences
University of Southampton
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ab7@soton.ac.uk

Prof Anna Barney
Professor of Biomedical Acoustic Engineering
Faculty of Engineering and Environment
University of Southampton
SO17 1BJ
ab3@soton.ac.uk

A.2 Participant consent form (used for both first and second studies)

UNIVERSITY OF Southampton

CONSENT FORM

Study title:

The test-retest reliability of specific elements of Breathing Pattern (BP)

Researcher name:

Fatimah ALALShaikh

Study reference:

Ethics reference:

Please initial the box (es) if you agree with the statement(s):

I have read and understood the information sheet (date /version no. of participant information sheet) and have had the opportunity to ask questions about the study.	☐
I agree to take part in this research project and agree for my data to be used for the purpose of this study	☐
I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected	☐
I am happy to be contacted regarding other unspecified research projects. I therefore consent to the University retaining my personal details on a database, kept separately from the research data detailed above. The 'validity' of my consent is conditional upon the University complying with the Data Protection Act and I understand that I can request my details be removed from this database at any time.	☐

I understand that information collected about me during my participation in this study will be stored on a password protected computer and that this

information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Name of participant (print name)……

Signature of participant……..

Date……

A.3 Questionnaire (used for both first and second studies)

1. Demographic Data

Gender	
Date of birth	
Height	
Weight	

2. Other information:

Do you have asthma?

If 'yes' Do you have day time asthma symptoms?

Are you receiving any current medication?

Do you have any other respiratory problems?

If 'yes' please state the problem.

Are you receiving any prescribed medication?

What medication are you taking?

Have you taken part in any other study today that involved the use of any respiratory medications?

Are you involved in physical exercise during this week?

Are you involved in breathing exercises during this week?

Is your general health is good today?

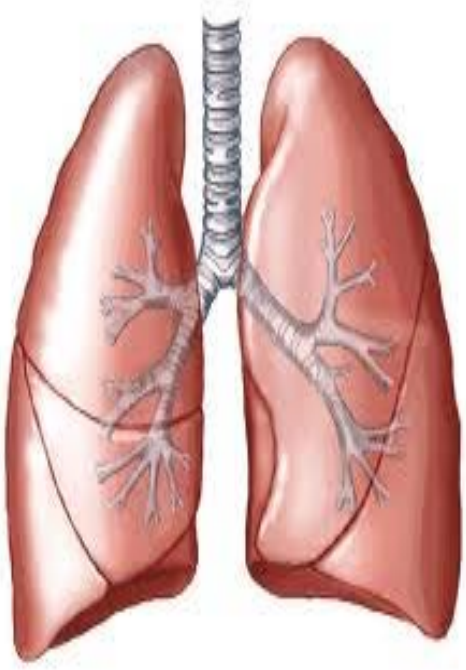
A.4 The recruitment poster

UNIVERSITY OF Southampton

School of Health Sciences

The study has been approved by ethics committee of the Faculty of Health Sciences

The test- retest reliability of specific components of Breathing Pattern



Would you like to help health care professionals understand more about breathing pattern?

- ✓ Adults over 18 years are invited to take part in this study to test the stability of breathing pattern.

Taking part in this study will involve:

- Coming to the Faculty of Health Sciences and having a lie down
- Two sessions of breathing pattern recording.
- Maximum 2 1/2 hours of your time

For more information and to participate contact Fatimah AL Shaikh:

Email address: (removed)

Mob no: (removed)

A.5 Faculty of Health Science ethical approval letter (first study)

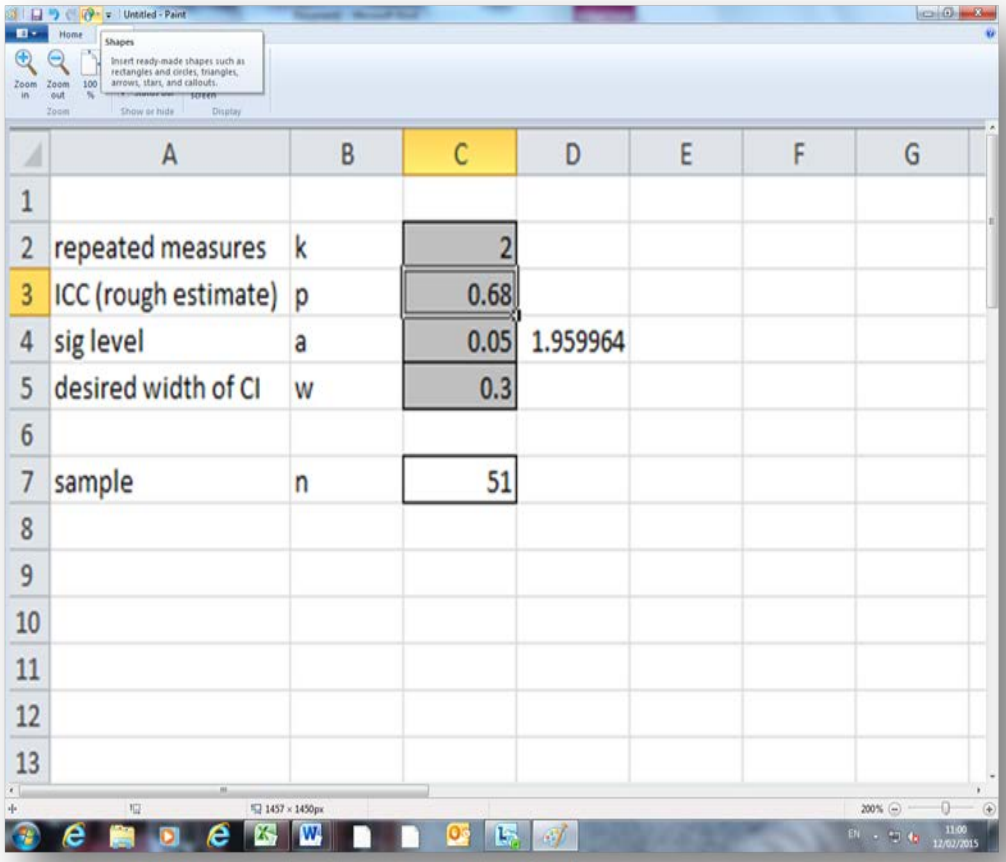
Submission Number: 5269
Submission Name: The test-retest reliability of specific elements of Breathing Pattern (BP)
This is email is to let you know your submission has been reviewed and approved by your supervisor.
It has now been sent to the Ethics committee for review.

Comments
None
Click here to view your submission
Coordinator: Fatimah Al Alshaikh

ERGO : Ethics and Research Governance Online
http://www.ergo.soton.ac.uk

DO NOT REPLY TO THIS EMAIL

A.6 Example of the Excel spread sheet used for sample size calculation.



	A	B	C	D	E	F	G
1							
2	repeated measures	k	2				
3	ICC (rough estimate)	p	0.68				
4	sig level	a	0.05	1.959964			
5	desired width of CI	w	0.3				
6							
7	sample	n	51				
8							
9							
10							
11							
12							
13							

A.7 Normality figures derived from Shapiro-wilk test for the first study

Table 1: Normality of breathing pattern component within session sitting

Breathing Components	within session 1	within session 2	within session 3	within session 4
Ti (s)	0.00	0.00	0.00	0.00
Te(s)	0.07	0.03	0.01	0.00
Bf (bpm)	0.617	0.634	0.44	0.741
%RCexp	0.07	0.72	0.05	0.07
%ABexp	0.065	0.088	0.05	0.06

Table2: Normality of breathing pattern component within session supine

Breathing Components	within session 1	within session 2	within session 3	within session 4
Ti (s)	0.05	0.03	0.00	0.02
Te(s)	0.08	0.06	0.00	0.06
Bf (bpm)	0.595	0.853	0.076	0.910
%RCexp	0.210	0.083	0.192	0.134
%ABexp	0.228	0.081	0.174	0.104

Table 3: Normality of breathing pattern component between session sittings

Breathing Components	session 1	session 2	session 3	session 4
Ti (s)	0.03	0.03	0.00	0.04
Te(s)	0.07	0.05	0.08	0.07
Bf (bpm)	0.188	0.803	0.161	0.493
%RCexp	0.081	0.25	0.126	0.162
%ABexp	0.061	0.24	0.164	0.172

Table 4: Normality of breathing pattern component between sessions supine

Breathing Components	session 1	session 2	session 3	session 4
Ti (s)	0.04	0.01	0.00	0.05
Te(s)	0.07	0.06	0.06	0.08
Bf (bpm)	0.485	0.974	0.209	0.877
%RCexp	0.184	0.245	0.071	0.067
%ABexp	0.166	0.229	0.071	0.063

Appendix B Ethic documents for second study

B.1 Participant Information Sheet (PIS)

Study title: The extent of change that occurs in breathing pattern before and during recovery from physical exercise in healthy adults

Researcher: Alalshaikh Fatimah, PhD student

You are being invited to take part in this research study. Before you decide whether you would like to participate in this research, please read this information sheet carefully to understand the aim of this research and what it will involve for you. If you are happy to participate, you will be asked to sign a consent form. Please feel free to discuss it with others if you wish. Also, please do not hesitate to contact me if there is any more information that you would like, or if anything is unclear.

What is the purpose of this study?

Some elements of breathing pattern (*thoracoabdominal motion* in this study*)* have the potential to be used to monitor respiratory health and used as an outcome measure for specific interventions designed to improve respiratory health. We believe that breathing pattern can provide useful information about a person's lung health, but the effect of moderate exercise on thoracoabdominal motion components is largely unknown as this has not been examined fully.

Also, this study will involve the use of a relatively new device called Structured Light Plethysmography (SLP). SLP monitors breathing pattern by projecting a grid onto your chest and so is a completely "contactless"

measurement device that uses cameras and the reflected light to record the movements of your chest wall.

Why I have been chosen?

You have been chosen because you are 18 years old or over, with no health problems that might prevent you from pedaling a static exercise bike. We would like to record breathing patterns from about 43 people like you, using the SLP recording device.

Do I have to take part in this research?

It is entirely up to you whether or not you would like to be a participant in this study. Please feel free to decide if you want to take part in this study and if you do, then you will also be asked to sign a consent form. Please remember that you are free to withdraw from the study at any time during this research without giving any specific reason.

What will happen to me if I choose to take part in the research?

If you decide that you would like to take part in this study, you will be invited to attend a one recording session at the Faculty of Health Sciences Building 45 of the Highfield Campus at the University of Southampton at a time and day that is mutually convenient for you and the researcher. The recording session will last approximately 30-35 minutes. When you arrive, I will run through the study again, and if you are still willing to take part, then you will be asked to sign a Consent Form. After this the researcher will ask you some questions relating to your age, gender, height, weight and general health. Please remember that all of your personal details will be kept entirely securely and all data will be anonymous.

For the breathing pattern recording, you will be required to wear a close-fitting white stretchy T-shirt (this is to enable the SLP device to project the grid onto your chest wall). You will be able to dress/undress in complete privacy in the laboratory. You are very welcome to bring a friend/relative

with you if this would make you feel more comfortable during the recording session. You will then be asked to sit as still as possible in a high-back chair for approximately 5 minutes. After the first recording session, you will be asked to sit on a static bike and pedal for about 10 minutes. The resistance of the bike may gradually be made harder as you pedal, depending on your fitness.

After 10 minutes of pedaling on the static bike, you will be asked to sit in the high backed chair and have your breathing pattern recorded for another 5 minutes using the SLP device again. Once this is completed, you will then be able to remove the T-shirt and will be free to leave.

What are the side effects of breathing pattern recording?
As mentioned previously, the SLP device is a completely contactless method of measuring breathing pattern and is commercially available and currently in use in clinics and in research. As such, this is a safe device and there are no known side-effects from device. During the exercise phase, you will need to pedal a static bike for 10 minutes. So there may be some small potential risks associated with exercise; however, you will be closely monitored and supervised at all times throughout the exercise phase and will not be asked to over exert yourself during exercising.

What are the possible disadvantages in taking part in this study?
There are no potential disadvantages associated with taking part in this research, with the exception of a small potential risk of exercising on a static bike. But, if at any time during the study, you feel uncomfortable, you are free to stop the exercise immediately with no repercussion for yourself.

What are the possible benefits of taking part in this research?

By taking part in this study, you will be helping to contribute important information in breathing pattern research, which may be relevant to future research and developments in the field of respiratory health.

Will my participation in this study be kept confidential?

All information collected during this research process will remain confidential. Data relating to breathing pattern will be anonymized (have your name removed) and stored in files in a laptop locked by a password. All other data will also be anonymized and coded to ensure your information will not be able to be identified. Personal information and signed consent forms will be securely stored in a locked cabinet within the University of Southampton in accordance with the policy of the University.

What to do if you want to complain?

If you have a concern or a complaint about this study you should contact the Research Governance Office (Address: University of Southampton, Building 37, Highfield, Southampton, SO17 IBJ; Tel: +44 (0)23 8059 5058; E-mail rgoinfo@soton.ac.uk. If you remain unhappy and wish to complain formally the Research Governance Office can provide you with details of the University of Southampton Complaints Procedure.

Where can I get more information?

If you would like to ask any more information about the study please contact Fatimah ALalshaikh at fja1e09@soton.ac.uk

Thank you for taking your time to read this Information Sheet.

Contact details:

Researcher
Fatimah Alalshaikh
PhD student
Faculty of Health Sciences
University of Southampton
SO17 1BJ
fja1e09@soton.ac.uk

Supervisors
Prof Anne Bruton
Professor of Respiratory Rehabilitation
Faculty of Health Sciences
University of Southampton
SO17 1BJ
ab7@soton.ac.uk

Prof Anna Barney
Professor of Biomedical Acoustic Engineering
Faculty of Engineering and Environment

University of Southampton
SO17 1BJ
ab3@soton.ac.uk

B.2 The recruitment poster

UNIVERSITY OF Southampton

We would like to find out how breathing pattern change after physical exercise in healthy adults

- **Are you able to help us to examine the extent of change that occurs in the chest wall motion component of breathing pattern following a moderate physical exercise?**

- ✓ **You can take part if you are 18 years old or over, with no problems that might prevent you from pedalling a static exercise bike.**

- ✓ **A single recording session will take place where breathing pattern will be monitored twice including 1) 5-minute recording at rest and 2) for 5 minutes immediately after a 10-minute session of incremental exercise on a static bike**

- ✓ **The study will take place in Building 45 at the University of Southampton, Highfield Campus.**

For more information, please contact:

Fatimah ALalshaikh

fja1e09@soton.ac.uk

B.3 Faculty of Health Science ethical approval letter

Submission Number: 20200
Submission Name: The extent of change that occurs in breathing pattern before and after physical exercise in healthy adults
This is email is to let you know your submission has been reviewed and approved by your supervisor.
It has now been sent to the Ethics committee for review.

Comments
None
Click here to view your submission
Coordinator: Fatimah Al Alshaikh

ERGO : Ethics and Research Governance Online
http://www.ergo.soton.ac.uk

DO NOT REPLY TO THIS EMAIL

Appendix C Ethic documents for third study

C.1 Participant invitation letter and reply slip

Title: Breathing pattern recordings before and after physiotherapy breathing retraining for asthma

Ethics Number: 16/SC/0083; ID RHM MED 1324.

You are receiving this letter and information because you have been referred for physiotherapy to help you with your breathing. My name is Roxy Tehrany and I am carrying out a research study at the University of Southampton, which aims to look at how breathing patterns are affected by physiotherapy breathing retraining. I would like to invite you to take part in this study.

I have enclosed a copy of an Information Sheet that will provide you with more detailed information about the study and what taking part would involve for you. If you would like to take part in the study, I would like you to attend a maximum of three research appointments which will all take place on the same day as your scheduled appointments with the physiotherapist.

If you are interested in taking part, or would like further information, I would be grateful if you could **complete the enclosed reply slip and post it to me using the pre-paid envelope provided**. I will contact you as soon as I receive the reply-slip on the contact details that you provide. Alternatively, **you can contact me, Roxy Tehrany, on xxxxxxxxxx for further information.**
Whether you decide to take part or not will not affect your current or future treatment.Yours sincerely,

Roxy Tehrany, PhD, MSc, BSc, MCSP

Research Fellow and Physiotherapist
Postgraduate Office,
Faculty of Health Sciences
University of Southampton,
Southampton
SO17 1BJ

Direct tel: xxxxxxxxxxxxxxx
email: r.tehrany@soton.ac.uk

C.2 Participant reply slip

If you are interested in taking part in this study, or would like further information about it, please fill out this reply-slip. You can return it by post, using the pre-paid envelope, pre-addressed. The researcher will then contact you on the telephone number or email address that you provide.
Alternatively, you can contact the researcher directly on 07541679251 or R.tehrany@soton.ac.uk for further information.

Your Name: .....

Your Telephone Number: .....

Your Email address (if preferred).....

Please indicate a convenient time and date for the researcher to

telephone you: .....

Thank you
Roxy Tehrany
Research Fellow

C.3 Participant Information Sheet

Title: Breathing patterns in asthma

You are being invited to take part in a research study. Before you decide whether you would like to take part, it is important that you understand the purpose of the research and what it will involve if you wish to take part. Please take time to read the following information and discuss it with others if you wish. It is important that you understand all of the information before you decide whether or not you would like to take part in the research.

Please contact us if there is any more information that you require or if anything is unclear.

What is the purpose of this study?

Physiotherapy breathing retraining is a form of treatment that can benefit some people with asthma, by helping them to control their breathing and reduce their asthma symptoms. At present, we do not know if, or how, this therapy affects people's breathing patterns. We would like to record your breathing pattern before and after a physiotherapy breathing retraining programme to see if there are any measurable changes.

Why have I been invited?

You have been approached because you have been referred for physiotherapy breathing retraining by your consultant. We would like to record breathing and speech patterns from a group of 48 people like you, before and after a physiotherapy breathing retraining programme.

Do I have to take part?

It is entirely your decision whether or not you decide to take part in this study. If you do decide to take part, you will be asked to sign a consent form. You are also free to withdraw from the study at any

time without having to give a reason. This decision will not affect your current or future treatment in any way.

What will happen to me if I take part?

If you would like to take part in this study, you will be invited to attend a minimum of two, and maximum of three additional breathing pattern recording sessions. Each recording session will take approximately 45 minutes and these will take place on the same days as your breathing retraining appointments with the physiotherapist, just before the physiotherapy session.

When you arrive for your first recording session you will be given a chance to ask any questions you may have about the study, and will then be asked to fill in and sign a consent form. You will then be asked to give information about your age, gender and general health. We would also like to ask you about any medicines you may have taken. After this you will be asked to carry out some simple lung health tests. For these you will be asked to blow as hard as you can through a tube, for as long as possible. You will then be asked to wear a white t-shirt (which we will provide) while we record your breathing patterns. You will be given privacy while you change your clothing, and females may still wear their undergarments. Please feel free to bring a friend, or family member, if this would help you to feel more comfortable. To record your breathing patterns, we will ask you to remain seated while a breathing pattern recording device is positioned in front of you, and lights are shone onto your chest. This is why we will require you to wear a white t shirt, so that the lights can be clearly seen on your chest. You will not feel anything while your breathing patterns are being recorded because the technology is completely contactless. You will also be asked to wear a microphone so that we can record your speech patterns. This will be similar to the ones used by people working in call centres. We would then like to

record your breathing for five minutes while you sit quietly, and for two minutes while you are talking. We will ask you to speak about any topic of your choice (for example, you could describe what you did the day before). Your voice will be recorded during this time so that we can examine what happens to your breathing patterns while you speak. We will not use these recordings for anything else before they are destroyed. After this the microphone will be removed, and replaced by a small tube placed near your nose to measure the air that you breathe in and out. You will be asked to complete some simple questionnaires about your health while wearing this tube. After that you will be able to remove the white t-shirt and you will be free to go to your breathing retraining appointment with the physiotherapist. We will make sure the physiotherapist knows when you are on your way.

What are the side effects of any treatment received when taking part in this study?

There are no known side effects to taking part in this study.

What are the possible disadvantages in taking part in this study?

There are no known disadvantages or risks in taking part in this study.

What are the possible benefits of taking part in this study?

There are no direct benefits for you personally from taking part in this study, although it may be interesting for you to see if your own breathing pattern changes at all. It is hoped that the information gained from this study may be used to gain knowledge about how breathing retraining affects patients. This could lead to improved understanding of who might benefit most from this type of therapy.

Will my taking part in this study be kept confidential?

All information collected during the research process will remain confidential. Any data that is collected from you will have your name removed and will be allocated with an individual code so that you will not be able to be identified. The information will be stored on a password protected laptop that will be stored in a locked cupboard within the university.

What will happen to the results of the research study?

The information recorded from breathing and speech patterns will be converted into figures for analysis. Some of the information may be used to develop future research ideas. The findings may be written up in the form of reports or research articles and published at conferences or in academic journals. If this happens, you will not be identifiable. If you would like a copy of the research findings, we can send you a summary after the study is completed.

Who has reviewed the study?

The study has been reviewed by the South Central-Hampshire B Research Ethics Committee.

What to do if you want to complain.

If you have a concern or a complaint about this study you should contact the Research Governance Office (Address: University of Southampton, Building 37, Highfield, Southampton, SO17 1BJ
Tel: +44 (0)23 8059 5058
Email: rgoinfo@soton.ac.uk .
If you remain unhappy and wish to complain formally they can provide you with details of the University of Southampton formal Complaints Procedure.

Thank you for taking the time to read this Information Sheet

If you would like any further information please contact:

Roxy Tehrany PhD, MSc, MCSP
Research Fellow
r.tehrany@soton.ac.uk

C.4 Letter of access (research passport)

University Hospital Southampton NHS
NHS Foundation Trust

Clinical Governance
R&D Department
SCBR Level E, Laboratory & Pathology Block
Mailpoint 138
Southampton General Hospital
Southampton
SO16 6YD

Tel: 023 8079 8591
Taru.Jussila-Knappett@uhs.nhs.uk

ALALShaikh, Fatimah
Faculty of health Sciences, Building 45,
University of Southampton,
Highfield Campus
Southampton
SO17 1 BJ

14 July 2016

Dear Fatimah ALALShaikh

Letter of access for research
(RHM* Med1324, *involving Non-invasive data collection for breathing pattern with no likely impact on diagnosis or treatment)

This letter confirms your right of access to conduct research through **University Hospital Southampton NHS Foundation Trust (UHS)** for the purpose and on the terms and conditions set out below. This right of access commences on **14 July 2017** and ends on **1 September 2017** unless terminated earlier in accordance with the clauses below.

You have a right of access to conduct such research as confirmed in writing in the letter of permission for research from this NHS organisation. Please note that you cannot start the research until the Principal Investigator for the research project has received a letter from us giving permission to conduct the project.

The information supplied about your role in research at **UHS** has been reviewed and you do not require an honorary research contract with this NHS organisation. We are satisfied that such pre-engagement checks as we consider necessary have been carried out.

You are considered to be a legal visitor to **UHS** premises. You are not entitled to any form of payment or access to other benefits provided by this NHS organisation to employees and this letter does not give rise to any other relationship between you and this NHS organisation, in particular that of an employee.

While undertaking research through **UHS**, you will remain accountable to your employer **(University of Southampton)** but you are required to follow the reasonable instructions of **Local Collaborator, Physiotherapist Charlotte Church** in this NHS organisation or those given on her/his behalf in relation to the terms of this right of access.

Where any third party claim is made, whether or not legal proceedings are issued, arising out of or in connection with your right of access, you are required to co-operate fully with any investigation by this NHS organisation in connection with any such claim and to give all such assistance as may reasonably be required regarding the conduct of any legal proceedings.

You must act in accordance with **UHS** policies and procedures, which are available to you upon request, and the Research Governance Framework.

You are required to co-operate with **UHS** in discharging its duties under the Health and Safety at Work etc Act 1974 and other health and safety legislation and to take reasonable care for the health and safety of yourself and others while on UHS premises. You must observe the same standards of care and propriety in dealing with patients, staff, visitors, equipment and premises as is expected of any other contract holder and you must act appropriately, responsibly and professionally at all times.

You are required to ensure that all information regarding patients or staff remains secure and *strictly confidential* at all times. You must ensure that you understand and comply with the requirements of the NHS Confidentiality Code of Practice (http://www.dh.gov.uk/assetRoot/04/06/92/54/04069254.pdf) and the Data Protection Act 1998. Furthermore you should be aware that under the Act, unauthorised disclosure of information is an offence and such disclosures may lead to prosecution.

You should ensure that, where you are issued with an identity or security card, a bleep number, email or library account, keys or protective clothing, these are returned upon termination of this arrangement. Please also ensure that while on the premises you wear your ID badge at all times, or are able to prove your identity if challenged. Please note that this NHS organisation accepts no responsibility for damage to or loss of personal property.

We may terminate your right to attend at any time either by giving seven days' written notice to you or immediately without any notice if you are in breach of any of the terms or conditions described in this letter or if you commit any act that we reasonably consider to amount to serious misconduct or to be disruptive and/or prejudicial to the interests and/or business of this NHS organisation or if you are convicted of any criminal offence. Your substantive employer is responsible for your conduct during this research project and may in the circumstances described above instigate disciplinary action against you.

UHS will not indemnify you against any liability incurred as a result of any breach of confidentiality or breach of the Data Protection Act 1998. Any breach of the Data Protection Act 1998 may result in legal action against you and/or your substantive employer.

If your current role or involvement in research changes, or any of the information provided in your Research Passport changes, you must inform your employer through their normal procedures. You must also inform your nominated manager in this NHS organisation.

I also enclose a copy of this letter for you to forward on to your employer's HR Department.

Yours sincerely,

Taru Jussila-Knappett
Research Governance Officer

C.5 Participant consent form

Patient Identification Number for this study:

Title of Project: Breathing pattern recordings before and after breathing retraining for adults with asthma.
Name of Researcher:
Please initial boxes:

1. I confirm that I have read and understand the information sheet dated 27.01.2016
for the above study and have had the opportunity to ask questions.

2. I understand that my participation is voluntary and that I am free to withdraw at
any time, without giving any reason.

3. I understand that my data may be looked at by responsible individuals Involved in the study where it is relevant to my taking part in research.
I give permission for these individuals to have access to my research records.

4. I understand that the study will include the use of voice recordings, but nothing I say will
appear in any research report or publication.

5. I agree to take part in the above study.

_____	_____	_____
Name of patient	Date	Signature
_____	_____	_____
Researcher	Date	Signatur

C.6 Patient confirmation letter

Patient Name
Address

Dear
RE: Breathing pattern study – confirmation of times/dates
Thank you for your taking part in the breathing pattern study. As discussed, we would like to see you before your first breathing retraining appointment with the physiotherapist:

Date: XXXX
Time: XXXX
Location: NIHR Wellcome Trust Southampton Clinical Research Facility, C level West Wing, Southampton General Hospital, Tremona Road, Southampton, SO16 6YD

We will assist you to your appointment with the physiotherapist immediately after the research session. If you have any further questions about the study, please do not hesitate to contact me on xxxxxxx.

I will look forward to meeting you on XXXX

Yours sincerely,

Name

C.7 Hospital Anxiety and depression scale (HADS)

D	A		D	A	
		I feel tense or 'wound up':			**I feel as if I am slowed down:**
	3	Most of the time	3		Nearly all the time
	2	A lot of the time	2		Very often
	1	From time to time, occasionally	1		Sometimes
	0	Not at all	0		Not at all
		I still enjoy the things I used to enjoy:			**I get a sort of frightened feeling like 'butterflies' in the stomach:**
0		Definitely as much		0	Not at all
1		Not quite so much		1	Occasionally
2		Only a little		2	Quite Often
3		Hardly at all		3	Very Often
		I get a sort of frightened feeling as if something awful is about to happen:			**I have lost interest in my appearance:**
	3	Very definitely and quite badly	3		Definitely
	2	Yes, but not too badly	2		I don't take as much care as I should
	1	A little, but it doesn't worry me	1		I may not take quite as much care
	0	Not at all	0		I take just as much care as ever
		I can laugh and see the funny side of things:			**I feel restless as I have to be on the move:**
0		As much as I always could		3	Very much indeed
1		Not quite so much now		2	Quite a lot
2		Definitely not so much now		1	Not very much
3		Not at all		0	Not at all
		Worrying thoughts go through my mind:			**I look forward with enjoyment to things:**
	3	A great deal of the time	0		As much as I ever did
	2	A lot of the time	1		Rather less than I used to
	1	From time to time, but not too often	2		Definitely less than I used to
	0	Only occasionally	3		Hardly at all
		I feel cheerful:			**I get sudden feelings of panic:**
3		Not at all		3	Very often indeed
2		Not often		2	Quite often
1		Sometimes		1	Not very often
0		Most of the time		0	Not at all
		I can sit at ease and feel relaxed:			**I can enjoy a good book or radio or TV program:**
	0	Definitely	0		Often
	1	Usually	1		Sometimes
	2	Not Often	2		Not often
	3	Not at all	3		Very seldom

Scoring Total score: Depression (D) _____ Anxiety (A) _____ 0-7 = Norma 8-10 = Borderline abnormal (borderline case) 11-21 = Abnormal (case)

C.8 Nijmegen Questionnaire

A score of over 23 out of 64 suggest a positive diagnosis of hyperventilation syndrome.

	Never 0	Rarely 1	Sometimes 2	Often 3	Very Often
Chest pain					
Feeling tense					
Blurred vision					
Dizzy spells					
Feeling confused					
Faster or deeper					
Short of breath					
Tight feelings in					
Bloated feeling in					
Tingling fingers					
Unable to breathe					
Stiff fingers or					
Tight feelings					
Cold hands or					
Palpitations					
Feeling of anxiety					

C.9 Breathing pattern recordings before and after breathing retraining for asthma

Case Report Form
Baseline

Participant ID				

Participant Initials			

Date of Visit	D	D	M	M	y	Y	

Patient demographics

Day/Month/Year of Birth | M | M | M | Y | Y | Y | Age | | |

Sex Male | | Female | |

Weight (Kg) | |

Height (cm) | |

Ethnicity | |

Age first diagnosed with Asthma | |

Medication usage

Currently taking any medication? | | **Yes** | | No

if 'yes' please provide the names of the medications you are currently taking, and the amount administered each day. If taking inhalers, please state the number of puffs taken each day

……

……

……

……

……

……

……

……

……

Questionnaires

Have the following questionnaires been completed:

All participants:

Nijmegen	☐ yes	☐	No –If no, give reason ……
Mini AQLQ	☐ yes	☐	No ……
HADs	☐ yes	☐	No ……
ACQ	☐ ye	☐	No……

Breathing pattern recordings

Have breathing patterns been recorded during the following conditions:

Quiet breathing	☐ yes	☐	No (reason)……
Spontaneous speech	☐ yes	☐	No (reason)……

Breathing parameters during QUIET BREATHING:

	Values (full body)
RR	
TI/TE	
TI	
TE	
TI/Ttot	
Ttot	

	Values	Overall phase	Principle angle	Spread
Ribcage				
Abdomen				
Left				
Right				
Upper left		**n/a**	**n/a**	**n/a**
Upper right		**n/a**	**n/a**	**n/a**
Lower left		**n/a**	**n/a**	**n/a**
Lower right		**n/a**	**n/a**	**n/a**

Breathing parameters during a SPONTANEOUS SPEECH TASK:

	Values (full body)
RR	
TI/TE	
TI	
TE	
TI/Ttot	
Ttot	

	Values	Overall phase	Principle angle	Spread
Ribcage				
Abdomen				
Left				
Right				
Upper left		**n/a**	**n/a**	**n/a**
Upper right		**n/a**	**n/a**	**n/a**
Lower left		**n/a**	**n/a**	**n/a**
Lower right		**n/a**	**n/a**	**n/a**

Spirometry:

	1st	2nd	3rd
FEV_1			
FVC			
FEV_1%			
PEFR			
FEV_1 predicted			
FEV_1% predicted			

Physiological measurements obtained from Capnograph:

$ETCO_2$ (kPa)	
SpO_2 (%)	
RR (bpm)	
HR (bpm)	

Case Report Form

Session 3 and 4

Medication usage

Currently taking any medication? ☐ **Yes** ☐ No

if 'yes' please provide the names of the medications you are currently taking, and the amount administered each day. If taking inhalers, please state the number of puffs taken each day

……

……

……

……

……

……

……

……

……

Questionnaires

Have the following questionnaires been completed:

All participants:

Nijmegen ☐ yes ☐ No –If no, give reason

……

Mini AQLQ ☐ yes ☐ No ……

☐ ☐

HADs yes No ……..

ACQ ☐ ye ☐ No……..

Breathing pattern recordings

Have breathing patterns been recorded during the following conditions:

Quiet breathing ☐ yes ☐ No (reason)……

Spontaneous speech ☐ yes ☐ No (reason)……..

Breathing parameters during QUIET BREATHING:

	Values (full body)
RR	
TI/TE	
TI	
TE	
TI/Ttot	
Ttot	

	Values	Overall phase	Principle angle	Spread
Ribcage				
Abdomen				
Left				
Right				
Upper left		**n/a**	**n/a**	**n/a**
Upper right		**n/a**	**n/a**	**n/a**
Lower left		**n/a**	**n/a**	**n/a**
Lower right		**n/a**	**n/a**	**n/a**

Breathing parameters during a SPONTANEOUS SPEECH TASK:

	Values (full body)
RR	
TI/TE	
TI	
TE	
TI/Ttot	
Ttot	

	Values	Overall phase	Principle angle	Spread
Ribcage				
Abdomen				
Left				
Right				
Upper left		**n/a**	**n/a**	**n/a**
Upper right		**n/a**	**n/a**	**n/a**
Lower left		**n/a**	**n/a**	**n/a**
Lower right		**n/a**	**n/a**	**n/a**

Spirometry:

	1st	2nd	3rd
FEV_1			
FVC			
FEV_1%			
PEFR			
FEV_1 predicted			
FEV_1% predicted			

Physiological measurements obtained from Capnograph:

$ETCO_2$ (kPa)	
SpO_2 (%)	
RR (bpm)	
HR (bpm)	

Appendix D Bland-Altman analysis graphs (first study)

In the attached CD

Appendix E Breathing pattern reliability in healthy participant (first study)

Table 1: Descriptive statistics (mean and SD) for breathing parameters in the SITTING position during each session (n=38)

Breathing parameter	Day 1		Day 2	
	Session 1 (n=38)	Session 2 (n=38)	Session 3 (n=38)	Session 4 (n=38)
TI (s)	1.73±0.73	1.82±1.18	1.59±0.56	1.61±0.61
TE (s)	2.66±0.76	2.77±1.08	2.54±0.80	2.559±0.73
BC (s)	4.39±1.43	4.59±2.23	4.13±1.33	4.16±1.29
RR (b/min)	15±4.05	15±4.24	16±3.63	16±3.83
%RCInsp	63±12.15	62±12.84	59±11.85	60±12.87
%ABInsp	38±12.18	38±12.98	41±11.91	40±12.94
%RCExp	63±12.21	62±12.77	59±11.90	60±12.91
%ABExp	38±12.25	38±12.912	41±11.96	40±12.98

Table 2: Descriptive statistics (mean and SD) for breathing parameters in the SUPINE position during each session

Breathing parameter	Day 1		Day 2	
	Session 1 (n=38)	Session 2 (n=38)	Session 3 (n=38)	Session 4 (n=38)
TI (s)	1.97±1.06	1.88±1.00	1.67±0.68	1.88±0.87
TE (s)	2.78±1.10	2.59±0.94	2.43±0.96	2.55±0.89
BC (s)	4.75±2.06	4.47±1.88	4.10±1.59	4.43±1.69
RR (b/min)	14±4.32	15±4.13	16±4.02	15±4.44
%RCInsp	38±16.86	39±17.89	42±18.29	43±17.11
%ABInsp	62±16.73	61±17.95	58±18.23	57±17.05
%RCExp	37±16.79	39±17.93	42±18.37	43±17.18
%ABExp	62±16.78	61±17.99	58±18.31	57±17.14

TI=Inspiratory time, TE=Expiratory time, BC=Breathing Cycle duration, RR= Respiratory rate, %RCInsp=Ribcage contribution to tidal volume during inspiratory phase, %RCInsp= Ribcage contribution to tidal volume during inspiratory phase, %RCExp=Abdominal contribution to tidal volume during expiratory phase, %ABExp= Abdominal contribution to tidal volume during expiratory phase.

Table 3: Within session descriptive statistics (Mean and SD) for all breathing parameters in the SITTING position

Breathing Parameters	Session 2 (day 1)		Session 4 (day 2)	
	2nd section	4th section	2nd section	4th section
TI	1.71±0.68	1.71±.77	1.57±0.57	1.55±0.68
TE	2.67±0.78	2.63±0.83	2.55±0.78	2.44±0.72
BC	4.39±1.42	4.36±1.55	4.13±1.31	4.00±1.35
RR	15±4.05	15±4.05	16±4.02	16±4.02
%RCInsp	62±11.74	63±12.08	61±12.07	61±13.04
%ABInsp	38±11.81	37±112.03	39±12.16	40±13.04
%RCExp	62±11.65	63±12.05	60±12.07	60±13.06
%ABExp	38±11.70	37±11.98	40±12.14	40±13.07

Table 4: Within session descriptive statistics (Mean and SD) for all breathing parameters in the SUPINE position

Breathing Parameters	Session 2		Session 4	
	2nd section	4th section	2nd section	4th section
TI	1.82±1.02	1.88±.92	1.85±.79	1.92±1.00
TE	2.57±1.05	2.53±.82	2.56±.96	2.49±.92
BC	4.40±2.02	4.43±1.72	4.43±1.66	4.43±1.86
RR	15±4.62	15±3.77	15±4.74	15±4.78
%RCInsp	37±18.54	38±18.56	43±19.20	42±19.36
%ABInsp	63±18.62	62±18.56	57±19.09	58±19.42
%RCExp	37±18.50	38±18.91	43±19.08	42±19.48
%ABExp	63±18.64	62±18.88	57±18.97	58±19.59

TI=Inspiratory time, TE=Expiratory time, BC=Breathing Cycle duration, RR= Respiratory rate, %RCInsp=Ribcage contribution to tidal volume during inspiratory phase, %RCInsp= Ribcage contribution to tidal volume during inspiratory phase, %RCExp=Abdominal contribution to tidal volume during expiratory phase, %ABExp= Abdominal contribution to tidal volume during expiratory phase

Table 5 Reliability estimates of breathing parameters in the SITTING position

Breathing parameter	Estimate	Within sessions		Between sessions		Between days
		Session 2	Session 4	Session 1 & 2	Session 3 & 4	Session 2 & 4
TI (seconds)	ANOVA	p=0.88, F=0.02	p=0.63, F=0.24	p=0.21, F=1.60	p=0.59, F=0.30	p=0.73, F=0.13
	ICC	0.95(0.91,0.98)	0.96(0.93,0.98)	0.84(0.70,0.92)	0.97(0.94,0.98)	0.86(0.72,0.93)
	WSSD	0.22	0.17	0.34	0.14	0.29
	SRD	0.61	0.47	0.94	0.39	0.8
	Mean Difference	0	0.02	0.1	0.02	0.21
	Bland-Altman	-0.66,0.89	-0.47, 0.49	-0.87, 1.05	-0.43, 0.39	-0.82, 1.09
TE (seconds)	ANOVA	p=0.61, F=0.26	p=0.10, F=2.78	p=0.44, F=0.62	p=0.87, F=0.02	p=0.13, F=2.40
	ICC	0.93(0.86,0.96)	0.93(0.86,0.96)	0.75(0.52,0.87)	0.97(0.94,0.99)	0.70(0.43,0.84)
	WSSD	0.94	0.28	0.59	0.18	0.63
	SRD	2.6	0.78	1.63	0.49	1.75
	Mean Difference	0.04	0.01	0.11	0.01	0.22
	Bland-Altman	-0.50, 0.65	-0.66, 0.87	-1.89, 1.68	-0.53, 0.52	-1.52, 1.96
RR (breaths per minute)	ANOVA	p=0.50, F=0.47	p=0.02, F=5.69	p=0.49, F=.50	p=0.81, F=0.06	p=0.43, F=0.63
	ICC	0.94(0.88,0.97)	0.97(0.94,0.98)	0.91(0.82,0.95)	0.95(0.90,0.97)	0.82(0.66,0.91)
	WSSD	1.41	1.01	1.64	1.16	2.10
	SRD	3.91	2.79	4.54	3.21	5.82
	Mean Difference	0	0	0	0	1
	Bland-Altman	-3.38, 2.66	-3.24, 2.19	-4.95, 4.41	-3.28, 3.40	-6.36, 5.9
%RCExp (percentage)	ANOVA	p=0.25, F=1.36	p=0.92, F=0.01	p=0.70, F=0.15	p=0.57, F=0.32	p=0.25, F=1.40
	ICC	0.97(0.94,0.98)	0.98(0.96,0.99)	0.89(0.79,0.94)	0.95(0.91,0.97)	0.69(0.40,0.84)
	WSSD	2.98	2.46	5.57	3.82	8.89
	SRD	8.25	6.81	15.43	10.58	24.62
	Mean Difference	1	0	1	1	2
	Bland-Altman	-6.43, 7.57	-7.09, 7.09	-15.42, 16.42	-11.44, 10.44	-22.62, 27.4

Table 6 Reliability estimates of breathing parameters in the SUPINE position

Breathing parameter	Estimate	Within sessions Session 2	Session 4	Between sessions Session 1 & 2	Session 3 & 4	Between days Session 2 & 4
TI (seconds)	ANOVA	p=0.35, F=0.89	p=0.46, F=0.55	p=0.35, F=0.89	p=0.02, F=6.25	p=0.94, F=0.01
	ICC	0.96(0.92,0.98)	0.88(0.77,0.94)	0.93(0.87,0.96)	0.86(0.73,0.93)	0.93(0.87,0.96)
	WSSD	0.27	0.42	0.37	0.39	0.34
	SRD	0.75	1.16	1.02	1.08	0.94
	Mean Difference	0.06	0.07	0.09	0.21	0
	Bland-Altman	-0.82, 0.70	-1.27, 1.13	-0.98, 1.14	-1.24, 0.82	-0.94, 0.98
TE (seconds)	ANOVA	p=0.62, F=0.25	p=0.48, F=0.51	p=0.11, F=2.62	p=0.26, F=1.29	p=0.71, F=0.14
	ICC	0.94(0.89,0.97)	0.92(0.85,0.96)	0.85(0.71,0.92)	0.86(0.72,0.93)	0.89(0.78,0.94)
	WSSD	0.31	0.36	0.53	0.46	0.41
	SRD	0.86	0.99	1.47	1.27	1.14
	Mean Difference	0.04	0.07	0.19	0.12	0.04
	Bland-Altman	-0.85, 0.93	-0.97, 1.09	-1.27, 1.66	-1.43, 1.18	-1.15, 1.23
RR (breaths per minute)	ANOVA	p=0.17, F=2.00	p=0.68, F=0.17	p=0.24, F=1.40	p=0.02, F=5.98	p=0.70, F=0.16
	ICC	0.89(0.79,0.94)	0.89(0.79,0.94)	0.86(0.73,0.93)	0.90(0.81,0.95)	0.85(0.71,0.92)
	WSSD	1.89	2.11	2.09	1.82	2.19
	SRD	5.24	5.84	5.79	5.04	6.07
	Mean Difference	0	0	1	1	1
	Bland-Altman	-4.69, 5.90	-6.22, 5.82	-6.44, 5.32	-3.87, 5.79	-6.48, 6.08
%RCExp (percentage)	ANOVA	p=0.3, F=0.88	p=0.36, F=0.87	p=0.25, F=1.36	p=0.40, F=.72	p=0.14, F=2.24
	ICC	0.97(0.94,0.98)	0.97(0.94,0.98)	0.92(0.85,0.96)	0.96(0.92,0.98)	0.80(0.63,0.90)
	WSSD	4.65	4.72	6.59	4.99	10.07
	SRD	12.88	13.07	18.25	13.82	27.89
	Mean Difference	1	1	2	1	1
	Bland-Altman	-14.17, 12.19	-12.37, 14.39	-20.29, 16.79	-15.16, 13.20	-31.44, 24.64

Appendix F Breathing pattern reliability in participant with self-reported asthma (first study)

Table 1: Descriptive statistics (mean and SD) for breathing parameters in the SITTING position for within session in participants with self-reported asthma (n=4)

Breathing components	Session 1		Session 2	
	2nd section	4th section	2nd section	4th section
TI (seconds)	1.51±0.16	1.52±0.13	1.63±0.36	1.43±0.12
TE (seconds)	2.31±0.45	2.31±0.23	2.34±0.61	2.11±0.43
RR (breaths per minute)	16.02±2.4	15.69±1.44	15.76±4.24	17.19±2.56
%RCExp (percentage)	50.45±7.36	47.63±8.80	49.47±3.22	46.10±7.87
%ABexp(percentage)	49.57±7.37	52.27±8.89	49.99±2.89	53.78±7.72

Table 2: Descriptive statistics (mean and SD) for breathing parameters in the SITTING position for between session in participants with self-reported (n=4)

Breathing components	Session one	Session two
TI (seconds)	1.54±0.17	1.67± 0.47
TE (seconds)	2.33±0.31	2.39±0.41
RR(breaths per minute)	15.69±1.94	17.38±2.89
%RCExp (percentage)	45.47±5.81	48.26±9.84
%ABexp (percentage)	54.41±5.82	51.63±9.91

Table 3 Reliability estimates of breathing parameters in the SITTING position for self-reported asthma (n=4)

	Estimate	Within sessions		Between sessions 1&2
		Session 1	Session 2	
TI (seconds)	**ANOVA** **ICC** **WSSD** **SRD** **Mean Difference** **Bland-Altman**	P= 0.57, F=0.42 0.974(0741, 0998) 0.03 0.08 -0.12 -0.08, 0.08	P=0.27, F=1.84 0.381(-5.177,0.959) 0.24 0.66 0.21 -0.45, 0.87	P= 0.47, F=0.69 0.697(0.465, 0.986) 0.21 0.58
TE (seconds)	**ANOVA** **ICC** **WSSD** **SRD** **Mean Difference** **Bland-Altman**	P= 0.99, F=0.00 0.879 (-0.210,0.992) 0.16 0.44 -0.00 -0.54, 0.54	P= 0.52, F=0.53 0.496 (-4.029,0.967) 0.43 1.19 0.23 -1.05, 1.51	P= 0.32, F=1.4 0.974 (0.744,0.998) 0.08 0.22
RR(breaths per minute)	**ANOVA** **ICC** **WSSD** **SRD** **Mean Difference** **Bland-Altman**	P=0.4, F=0.57 0.939 (0.396, 0.996) 0.67 1.86 0.33 -1.73, 2.39	P=0.49, F=0.63 0.674(2.25, 0.978) 2.4 6.6 -1.4 -8.63, 2.17	P=0.36, F=1.15 0.288(-6.1, 0.953) 2.3 6.37
%RCExp (percentage)	**ANOVA** **ICC** **WSSD** **SRD** **Mean Difference** **Bland-Altman**	P=0.7, F=7.62 0.957 (0.572, 0.997) 2.4 6.65 2.82 -1.3, 6.92	P=0.39, F=0.99 0.539 (-3.60, 0.969) 4.78 13.24 3.37 -10.16, 16.89	P=0.50, F=0.58 0.765 (-1.348, 0.984) 4.93 13.66
%ABexp (percentage)	**ANOVA** **ICC** **WSSD** **SRD** **Mean Difference** **Bland-Altman**	P=0.09, F=6.36 0.959 (0.593, 0.997) 2.3 6.37 -2.69 -6.95, 1.57	P=0.31, F=1.47 0.551(-3.48, 0.970) 4.67 12.94 -3.78 -16.26, 8.7	P=0.51, F=0.56 0.763 (-1.37, 0.984) 4.97 13.77

Table 4: Descriptive statistics (mean and SD) for breathing parameters in the SUPINE position for within session in participants with self-reported (n=4)

Breathing components	Session 1		Session 2	
	2nd section	4th section	2nd section	4th section
TI (seconds)	1.71±0.33	1.93±0.86	1.48±0.13	1.56±0.04
TE (seconds)	2.06±0.24	2.11±0.28	1.95±0.41	1.96±0.41
RR(breaths per minute)	15.89±1.13	13.22±7.76	17.73±2.47	17.28±2.13
%RCExp (percentage)	32.84±19.94	47.75±14.26	42.12±9.67	37.69±12.90
%ABexp (percentage)	67.28±19.78	58.59±9.17	57.88±9.57	62.23±12.89

Table 5: Descriptive statistics (mean and SD) for breathing parameters in the SUPINE position for between session in participants with self-reported (n=4)

Breathing components	Session one	Session two
TI (seconds)	2.13±1.195	1.51±.07
TE (seconds)	2.259±.36	1.98±.36
RR(breaths per minute)	14.63±3.79	17.4±2.21
%RCExp (percentage)	36.25±13.33	40.69±11.01
%ABexp (percentage)	63.84±13.28	59.50±11.07

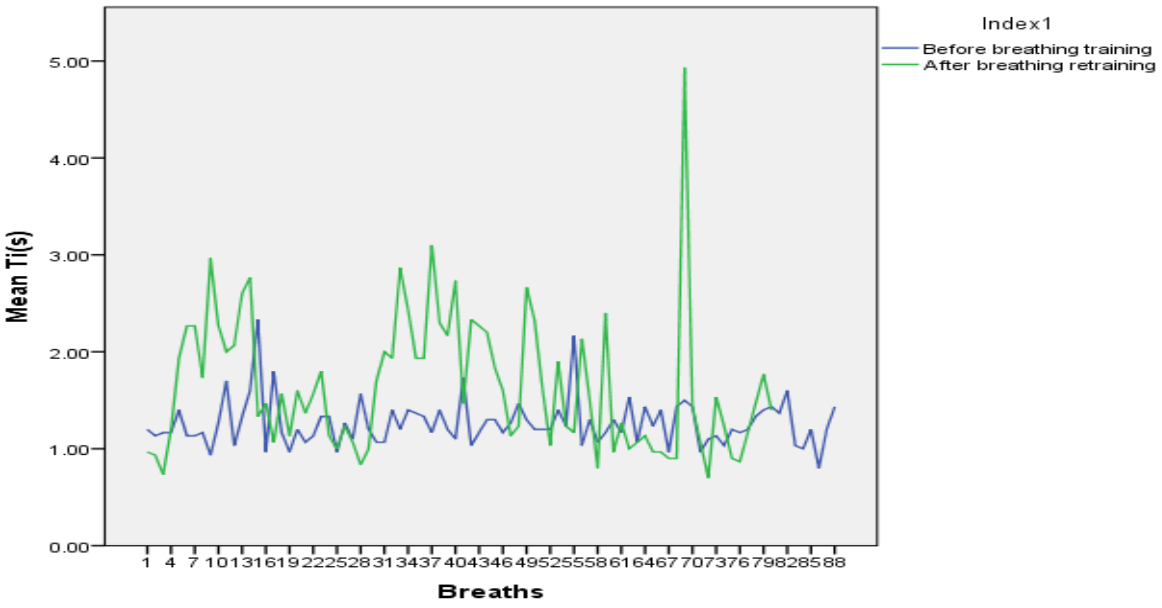
Table 6 Reliability estimates of breathing parameters in the SUPINE position for self-reported asthma (n=4)

	Estimate	Within sessions		Between sessions 1&2
		Session 1	Session 2	
TI (seconds)	**ANOVA**	P=0.50, F=0.58	P=0.22, F=2.4	P=0.4, F=0.95
	ICC	0.758 (-1.42, 0.984)	0.451(-4.47, 0.964)	-2.35 (-11.32, 0.918)
	WSSD	0.40	0.08	0.89
	SRD	1.11	0.23	2.46
	Mean Difference	-0.23	-0.08	0.61
	Bland-Altman	-1.42, 0.96	-0.28, 0.12	-1.99,3.21
TE (seconds)	**ANOVA**	P=0.84, F=0.48	P=0.95, F=0.004	P=0.43, F=0.82
	ICC	-2.605(-3.4.97, 0.761)	0.925 (0.255, 0.995)	-1.497(-23.914, 0.835)
	WSSD	0.29	0.15	0.43
	SRD	0.81	0.42	1.18
	Mean Difference	-0.05	-0.01	0.28
	Bland-Altman	-1.01, 0.91	-0.51,0 .49	-0.96, 1.52
RR(breaths per minute)	**ANOVA**	P=0.53, F=0.49	P=0.63, F=0.28	P=0.41, F=0.93
	ICC	0.215(-6.837, 0.948)	0.873 (-0.269, 0.992)	-4.82(-57.099, 0.614)
	WSSD	5.04	1.08	4.03
	SRD	13.96	2.99	11.16
	Mean Difference	2.68	0.45	-2.77
	Bland-Altman	-12.58, 17.94	-2.91, 3.81	-14.25, 8.71
%RCExp (percentage)	**ANOVA**	P=0.377, F=1.07	P=0.31, F=1.51	P=0.32, F=1.39
	ICC	-1.278 (-21.74, 0.85)	0.875 (-0.294, 0.992)	0.884 (-0.154, 0.992)
	WSSD	20.57	5.41	5.59
	SRD	56.96	14.99	15.48
	Mean Difference	-14.91	4.43	-4.5
	Bland-Altman	-72.57, 42.75	-9.99, 18.84	-19.55, 10.65
%ABexp (percentage)	**ANOVA**	P=0.35, F=1.21	P=0.299, F=1.57	P=0.34, F=1.28
	ICC	0.627(-2.72, 0.975)	0.882 (-0.177, 0.992)	0.883(-0.168, 0.992)
	WSSD	11.41	5.25	5.61
	SRD	31.69	14.54	15.55
	Mean Difference	8.68	-4.35	4.34
	Bland-Altman	-22.86, 40.22	-18.23, 9.53	-11.02, 19.7

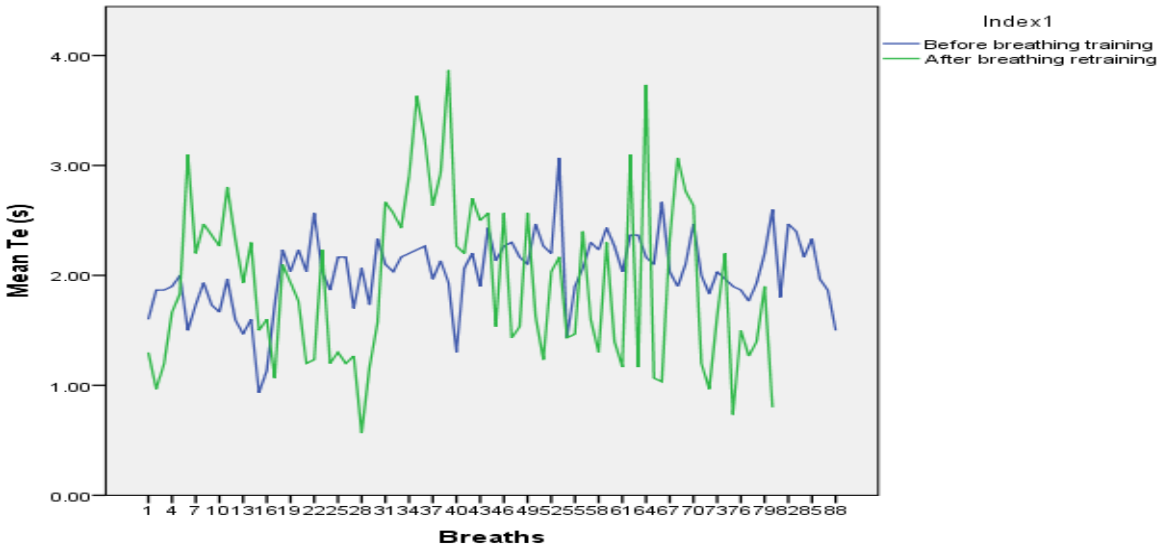
Appendix G The response of change occur in breathing pattern for each individuals after breathing retraining (third study)

G.1 Participant number 2

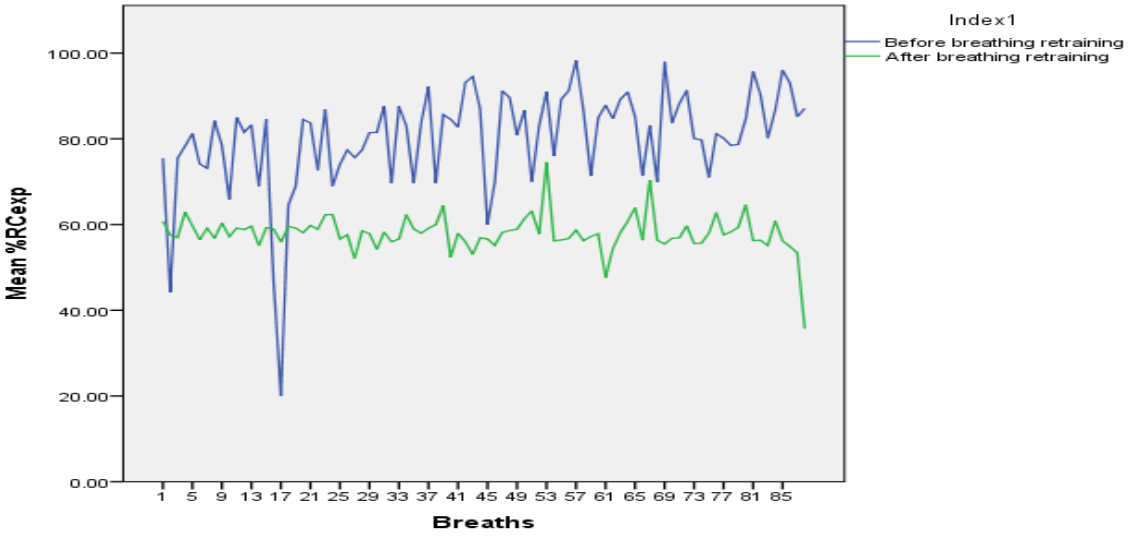
Graph 1: Breath-by-breath data for Inspiratory time (Ti) before & after breathing retraining (BR).



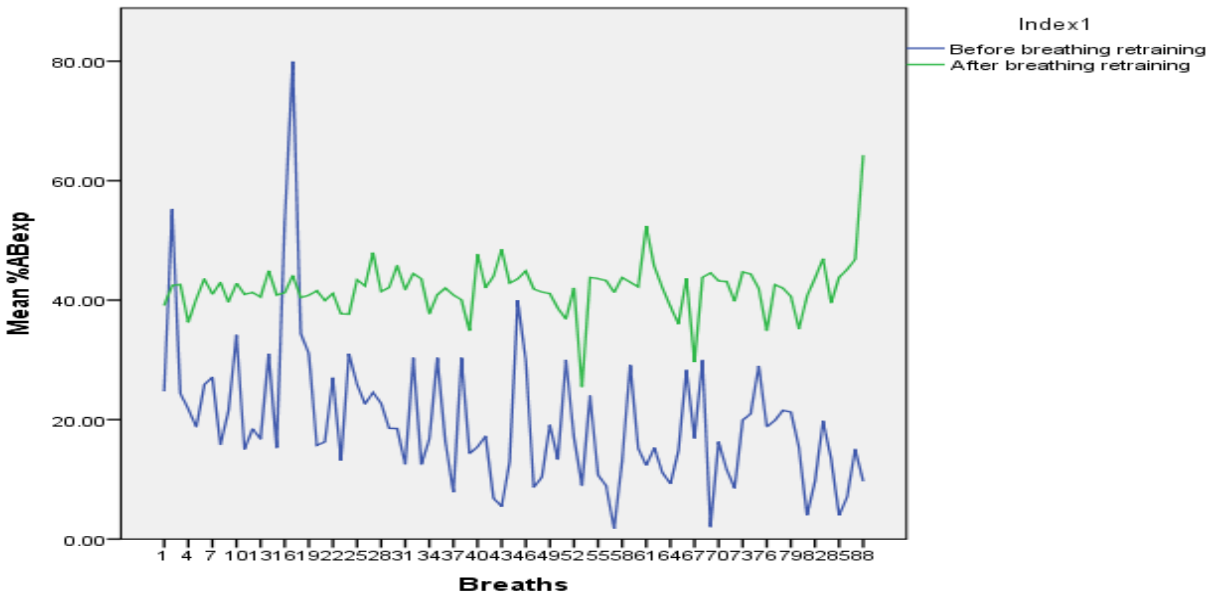
Graph 2: Breath-by-breath data for expiratory time (Te) before & after breathing retraining (BR).



Graph 3: Breath-by-breath data for RC_{exp} before & after breathing retraining (BR).

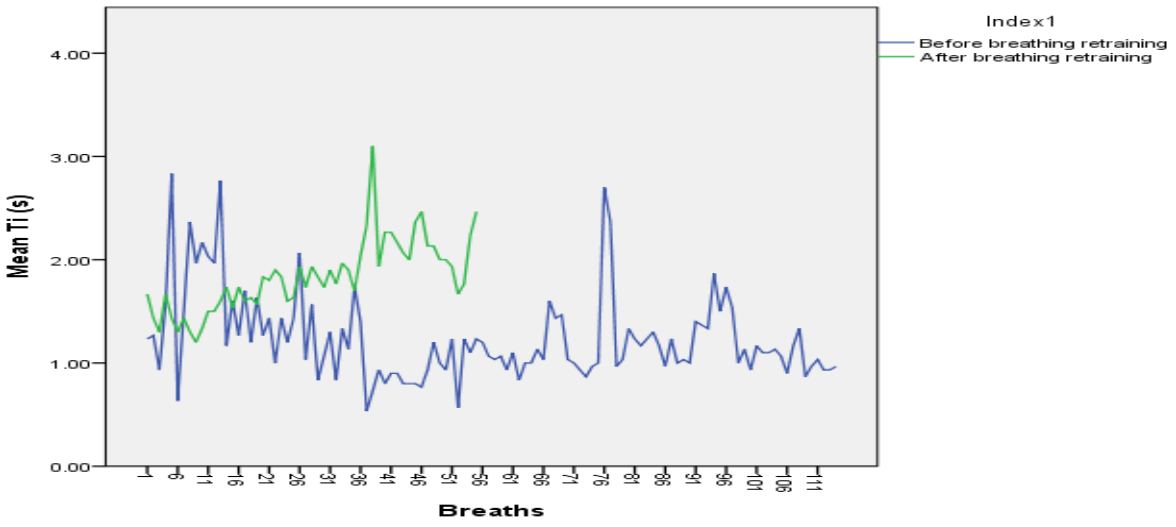


Graph 4: Breath-by-breath data for AB_{exp} before & after breathing retraining (BR).

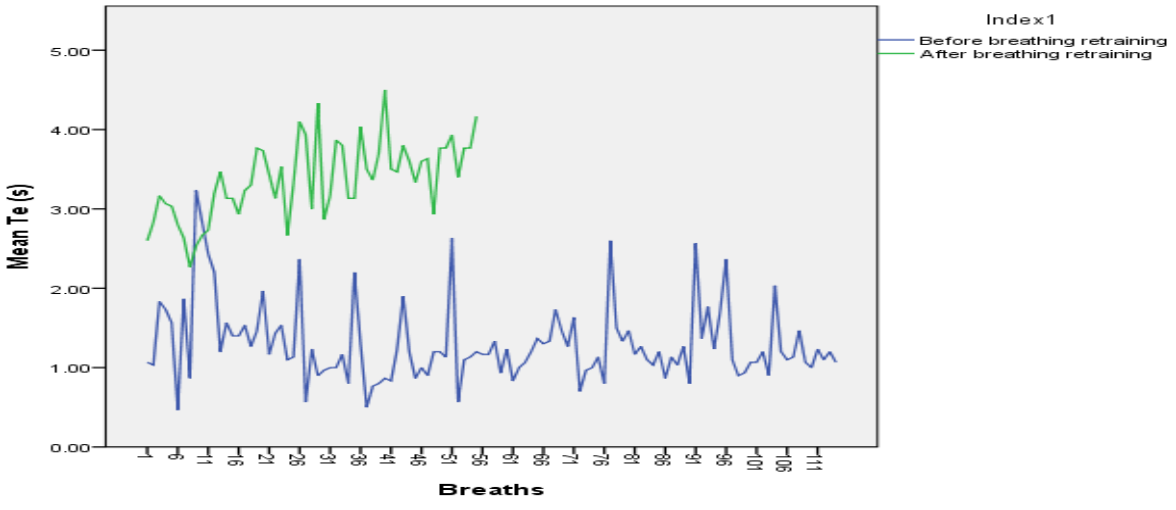


G.2 Participant number 3

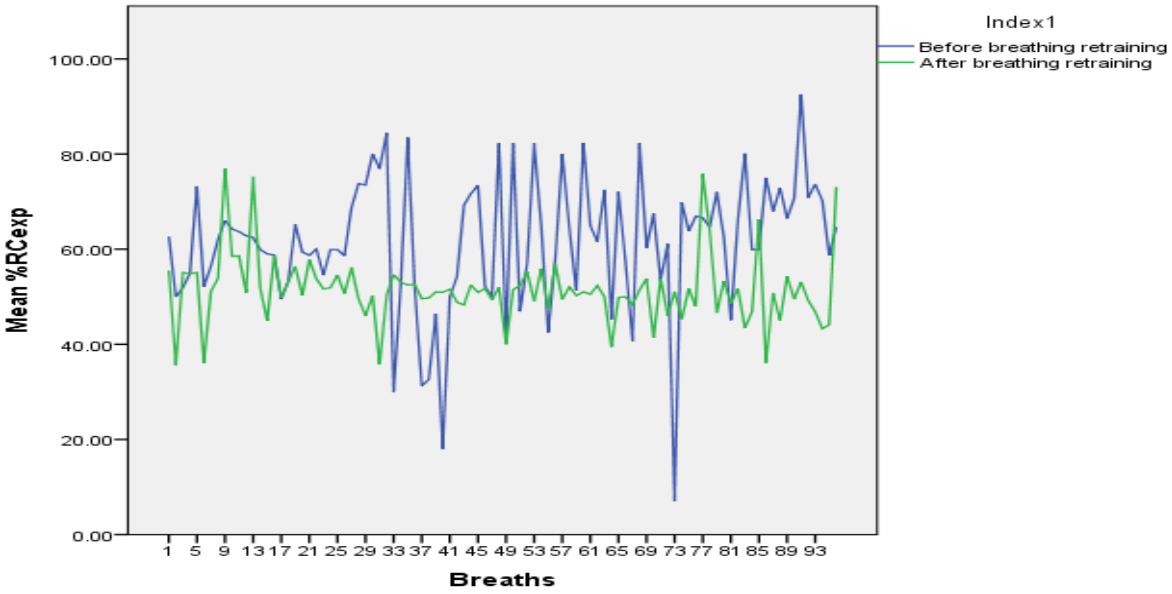
Graph 5: Breath-by-breath data for Inspiratory time (T_i) before & after breathing retraining (BR).



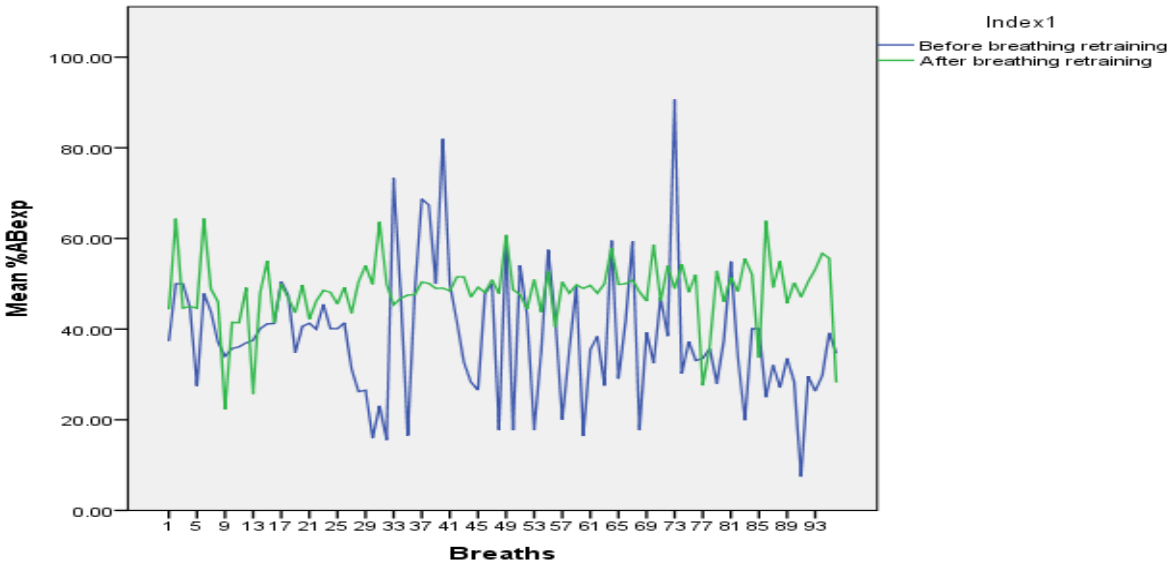
Graph 6: Breath-by-breath data for expiratory time (T_e) before & after breathing retraining (BR).



Graph 7: Breath-by-breath data for %RC$_{exp}$ before & after breathing retraining (BR).

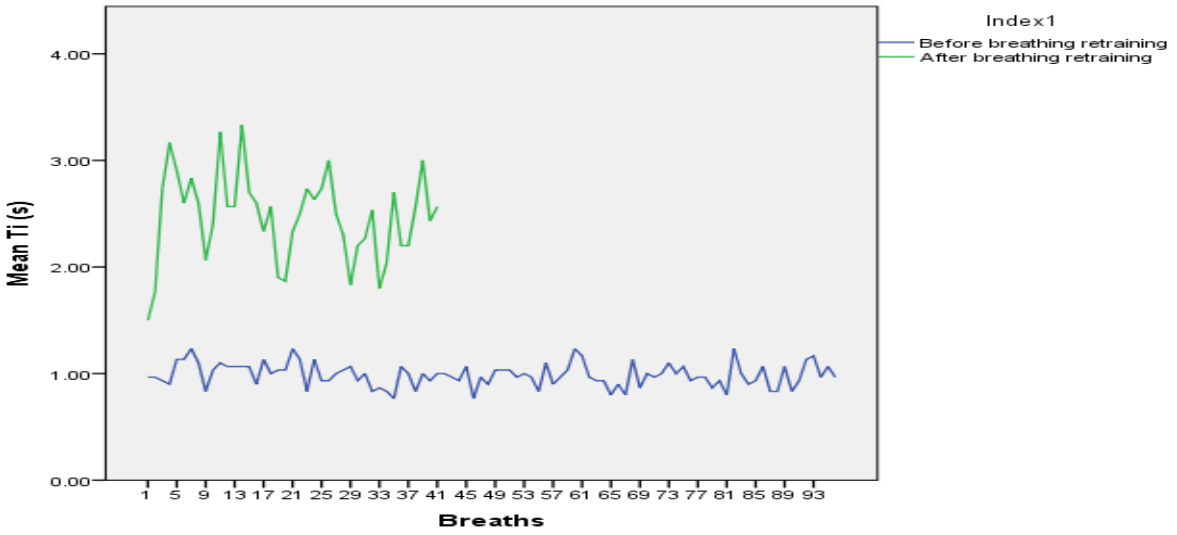


Graph 8: Breath-by-breath data for %AB$_{exp}$ before & after breathing retraining (BR).

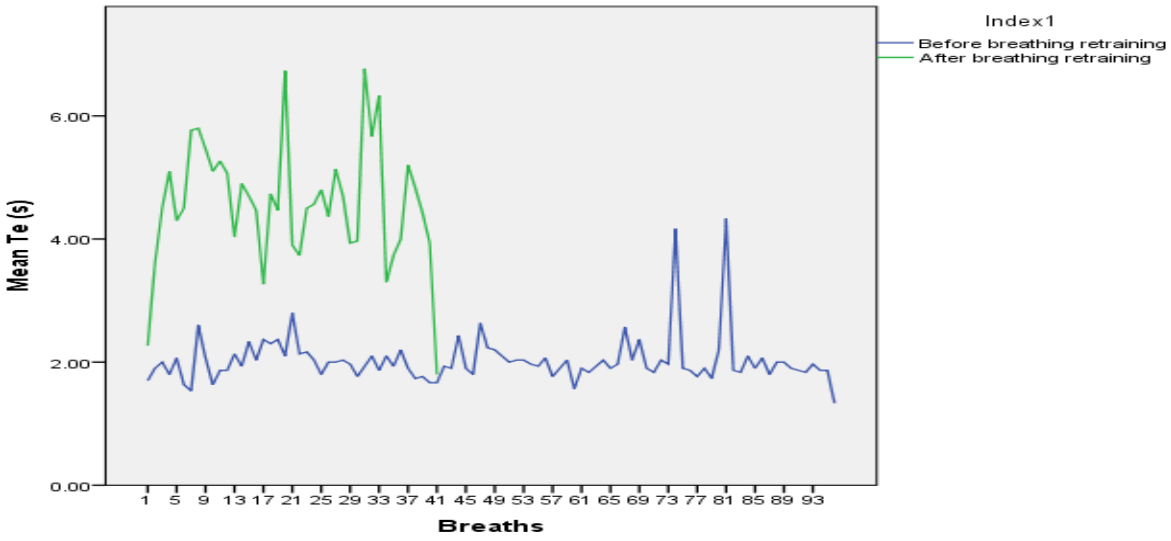


G.3 Participant number 4

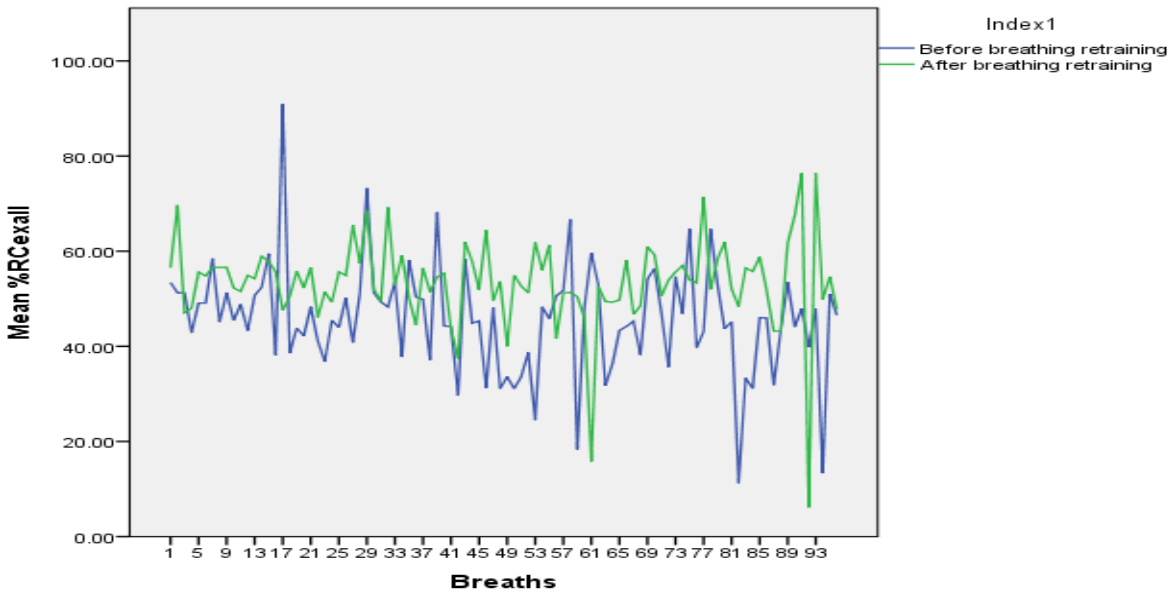
Graph 9: Breath-by-breath data for Inspiratory time (Ti) before & after breathing retraining (BR).



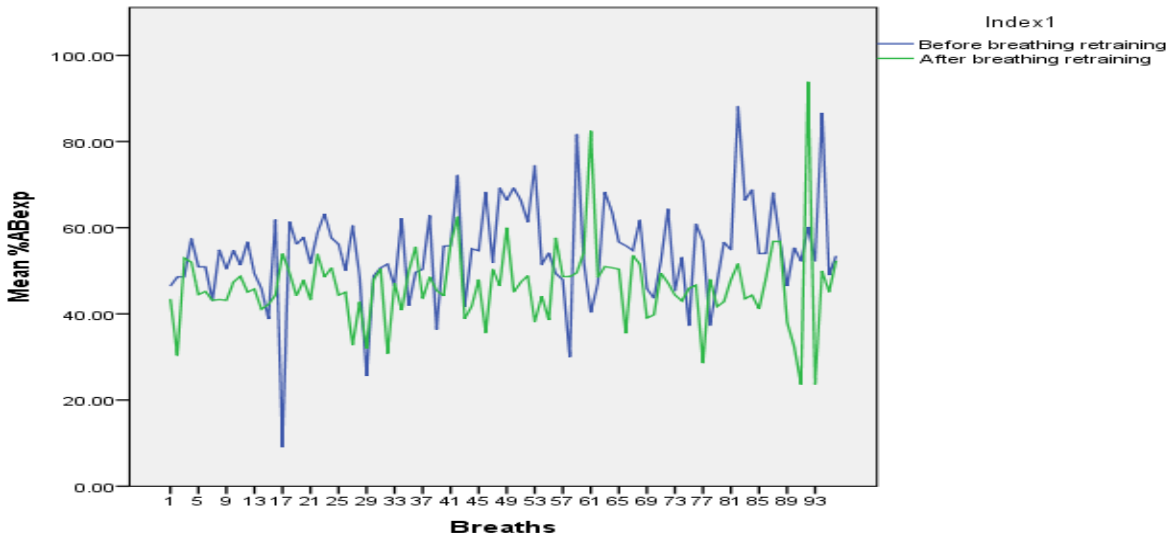
Graph 10: Breath-by-breath data for expiratory time (Te) before & after breathing retraining (BR).



Graph 11: Breath-by-breath data for %RCexp before & after breathing retraining (BR).

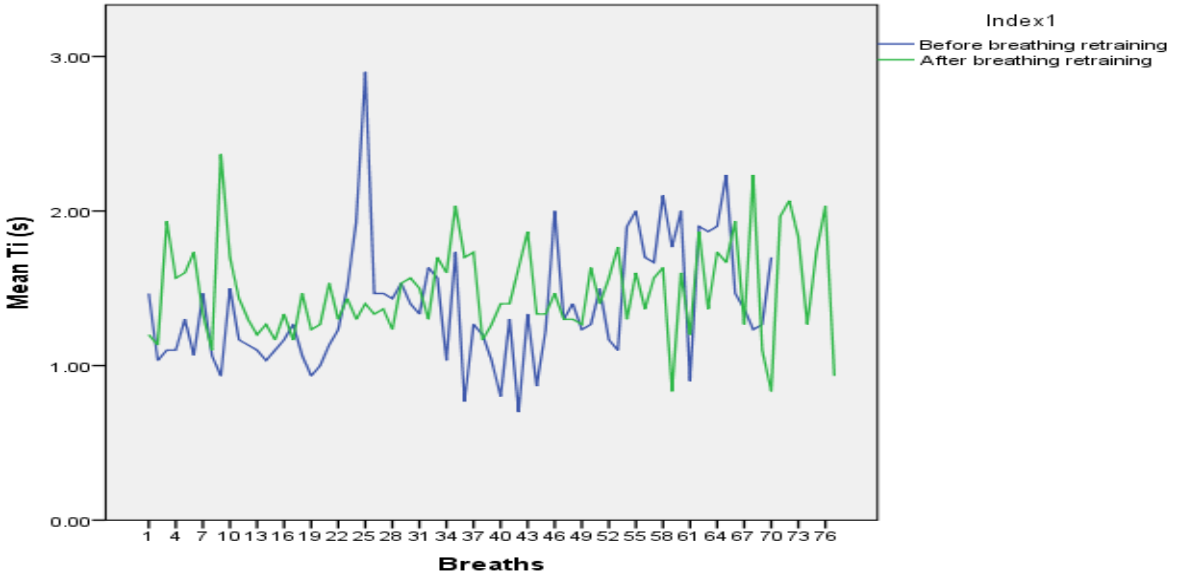


Graph 12: Breath-by-breath data for %ABexp before & after breathing retraining (BR).

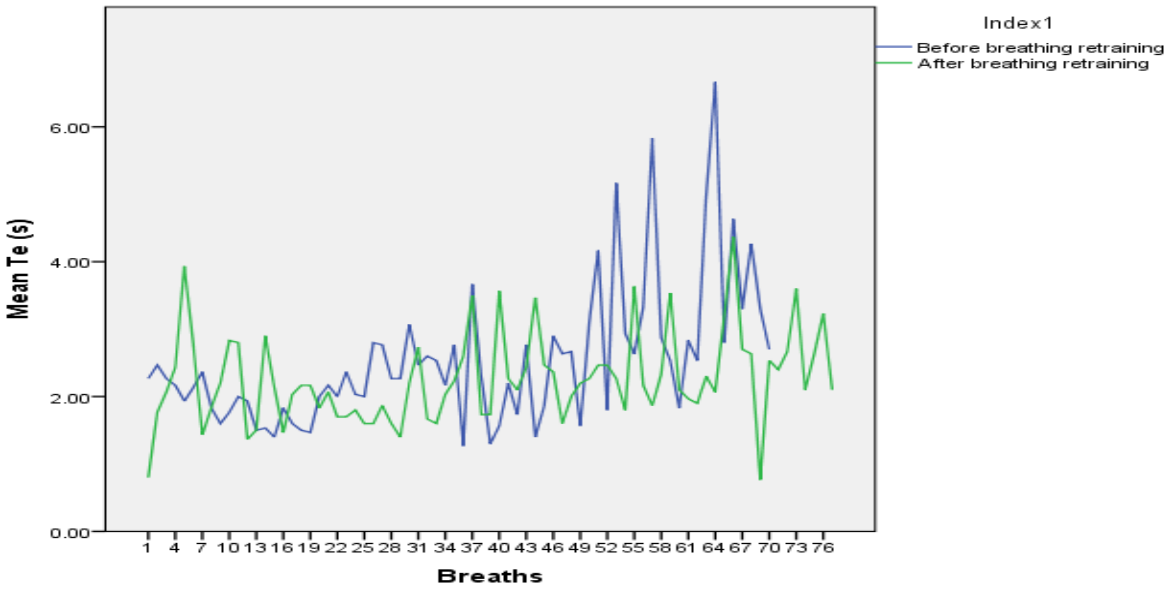


G.4 Participant number 5

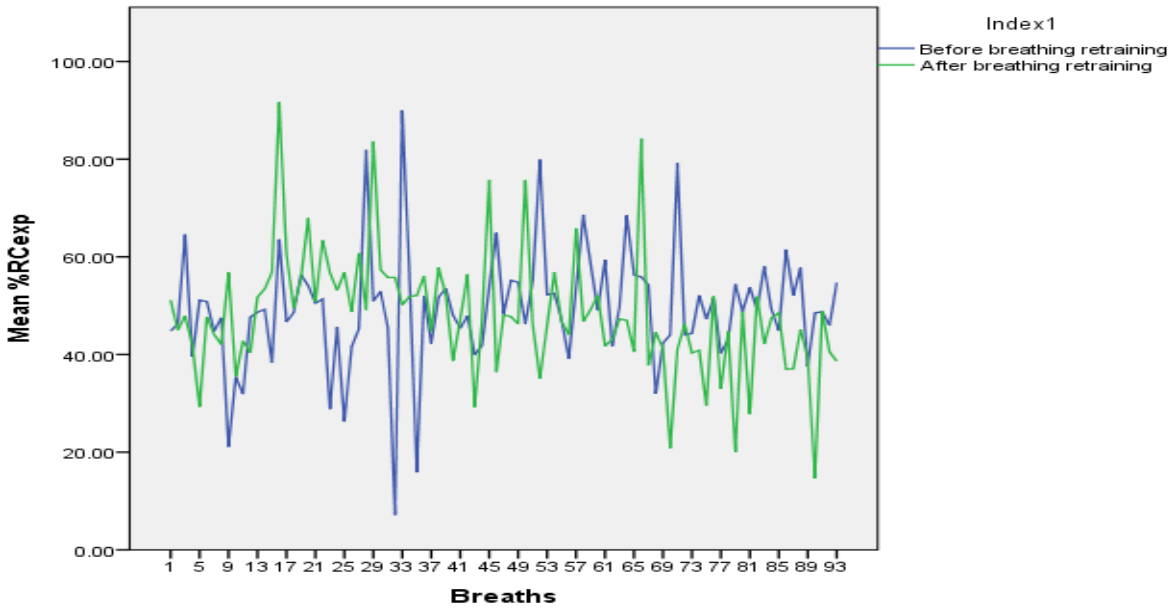
Graph 13: Breath-by-breath data for Inspiratory time (Ti) before & after breathing retraining (BR).



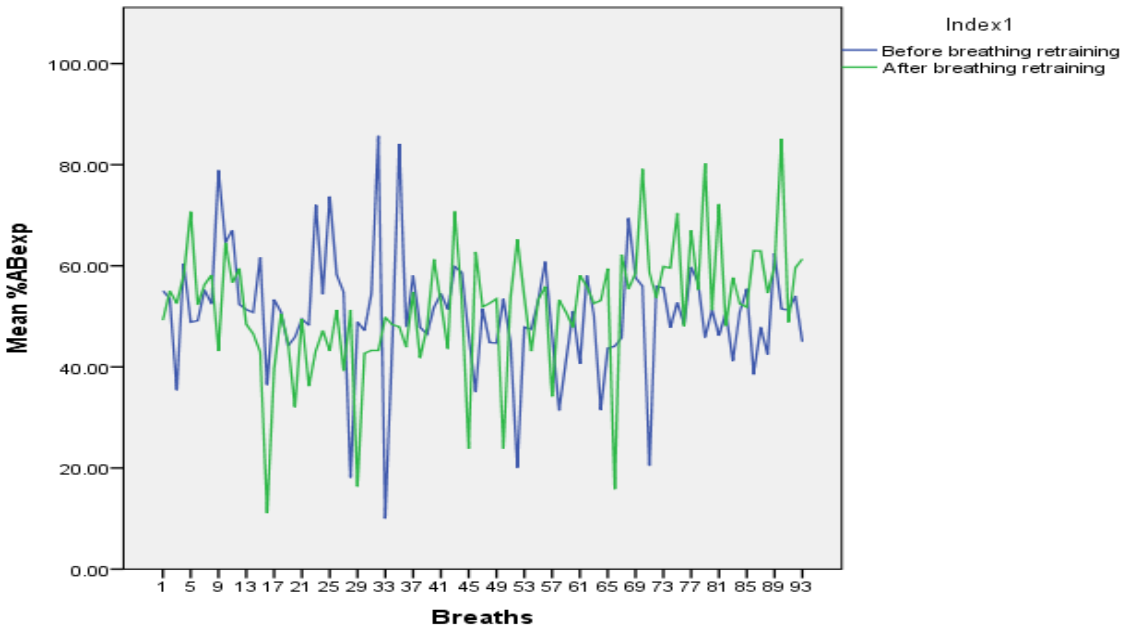
Graph 14: Breath-by-breath data for expiratory time (Te) before & after breathing retraining (BR).



Graph 15: Breath-by-breath data for %RCexp before & after breathing retraining (BR).



Graph 16: Breath-by-breath data for %ABexp before & after breathing retraining (BR).



Appendix H Demographic data for first and second study

Demographic data for the first study

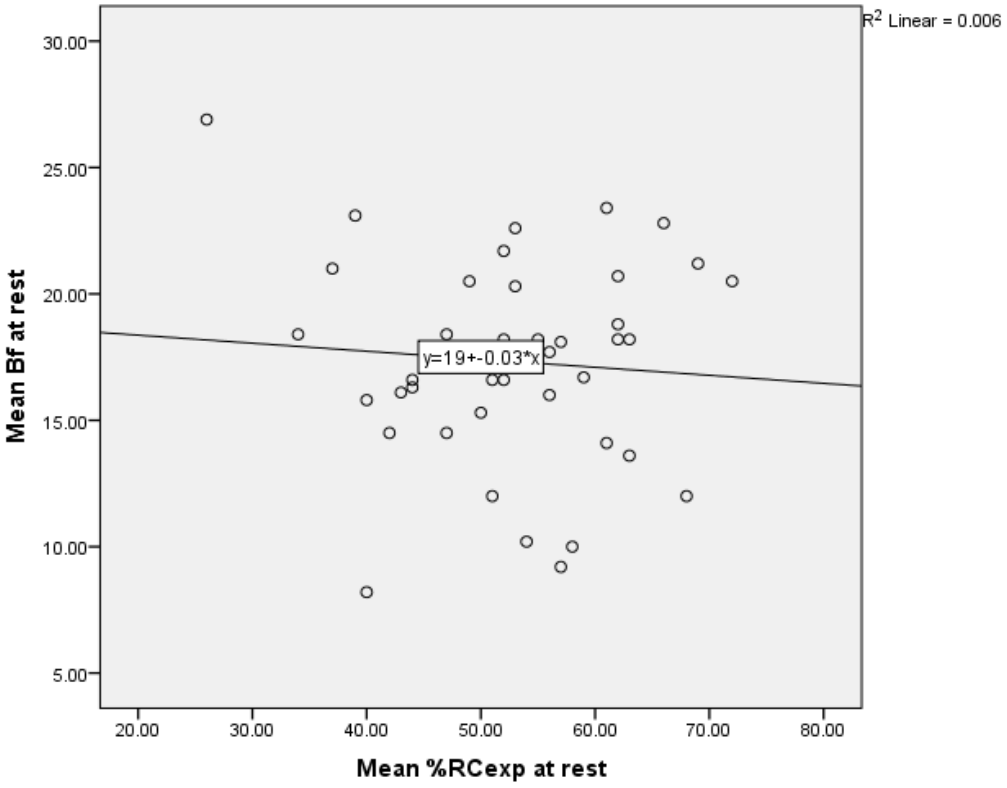
Participants	Gender	Age	BMI
1	Female	42	20.9
2	Male	28	33
3	Male	30	23.4
4	Male	25	21.2
5	Female	27	27.6
6	Female	20	20.3
7	Male	21	23.1
8	Female	31	31.2
9	Male	29	27.3
10	Female	27	23
11	Female	38	34.7
12	Female	34	44.1
13	Female	31	20
14	Female	34	18.8
15	Male	35	28.4
16	Male	30	26.2
17	Female	36	27
18	Female	36	21
19	Female	35	20
20	Female	43	26
21	Male	43	25.8
22	Female	34	29.5
23	Female	33	21.5
24	Female	30	24.7
25	Female	27	21.5
26	Female	24	16.5
27	Female	30	32.9
28	Female	37	23.1
29	Female	34	35.2
30	Female	22	20.4
31	Female	22	17.7
32	Female	19	26.4
33	Male	19	27.1
34	Female	26	25.4
35	Male	52	25.1
36	Female	37	20.2
37	Female	37	26.9
38	Female	29	19.4
39	Female	38	25.7
40	Female	32	23.1
41	Female	36	30.4
42	Female	28	18.1
43	Female	32	28
44	Female	29	21.7
45	Female	26	24.9
46	Male	36	31.2
47	Female	27	25.5
48	Male	25	26.4
49	Female	20	23.4
50	Female	34	23.8
51	Female	33	30.8

Demographic data for the second study

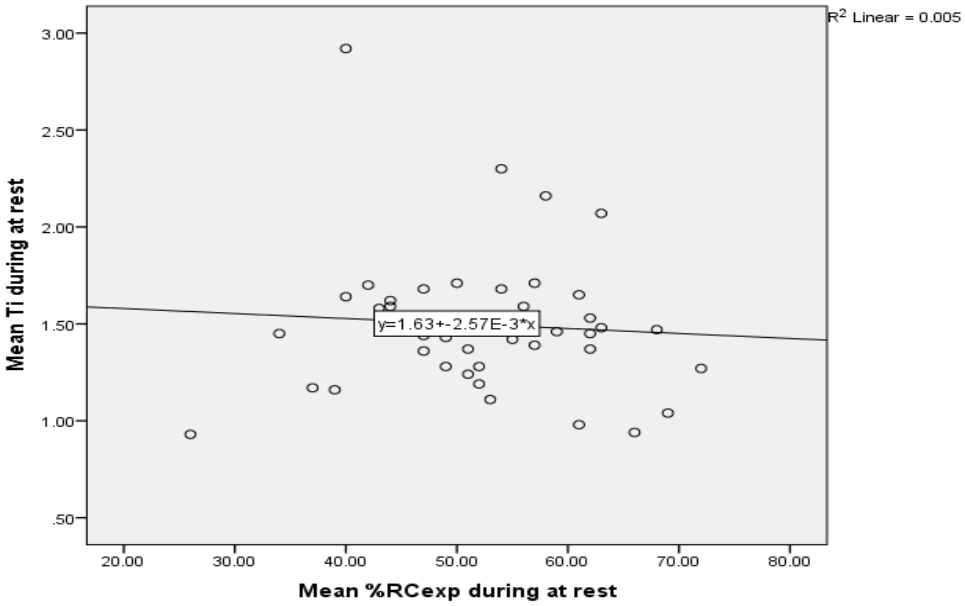
Participants	Gender	Age	BMI
1	Male	39	23.8
2	Female	38	21.36
3	Male	28	26.06
4	Male	39	23.74
5	Male	48	24.91
6	Male	39	22.6
7	Male	34	27.61
8	Female	34	28.08
9	Female	23	27.24
10	Male	39	25.38
11	Male	31	27.76
12	Male	39	26.79
13	Male	30	23.81
14	Female	35	22.67
15	Female	39	25.71
16	Female	35	23.03
17	Male	41	27.58
18	Female	32	23.73
19	Male	36	26.23
20	Male	45	22.92
21	Female	34	29.00
22	Female	34	22.31
23	Female	26	23.56
24	Female	25	23.81
25	Female	26	20.58
26	Female	30	21.39
27	Female	29	24.75
28	Male	62	29.00
29	Male	29	20.9
30	Male	39	20.02
31	Female	24	27.89
32	Male	40	20.2
33	Female	29	27.76
34	Male	36	19.71
35	Female	27	25.15
36	Female	26	20.28
37	Female	34	29.38
38	Female	23	18.36
39	Male	19	23.27
40	Male	19	23.94
41	Female	39	27.06
42	Male	27	20.7
43	Male	38	24.4

Appendix I Pearson's scatterplot for the second study

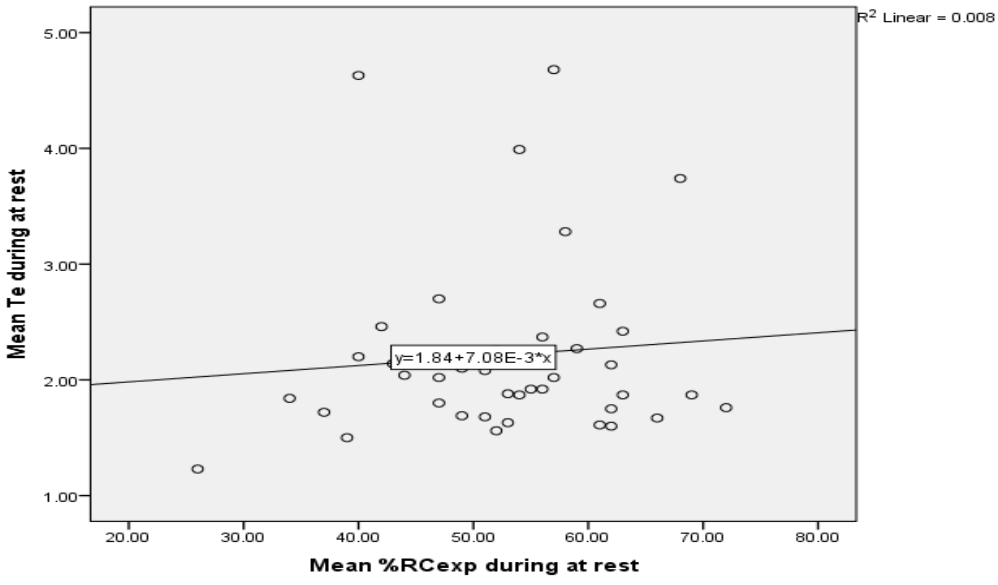
The relationship between cohort thoracoabdominal motion and the cohort timing components at rest



Graph 1: Scatterplot for the relationship between cohort mean %RCexp and cohort mean Bf at rest.

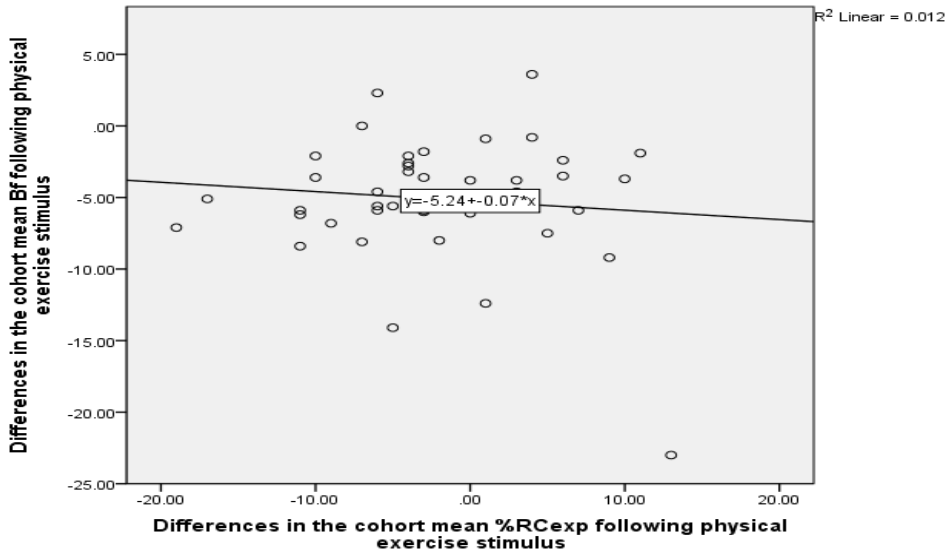


Graph 2: Scatterplot for the relationship between cohort mean %RCexp and cohort mean Ti at rest.

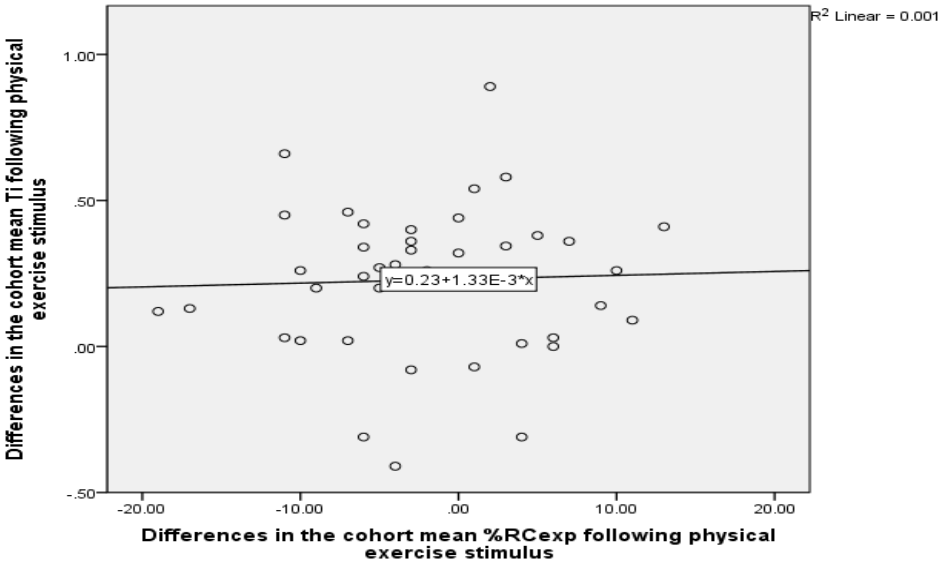


Graph 3: Scatterplot for the relationship between cohort mean %RCexp and cohort mean Te at rest.

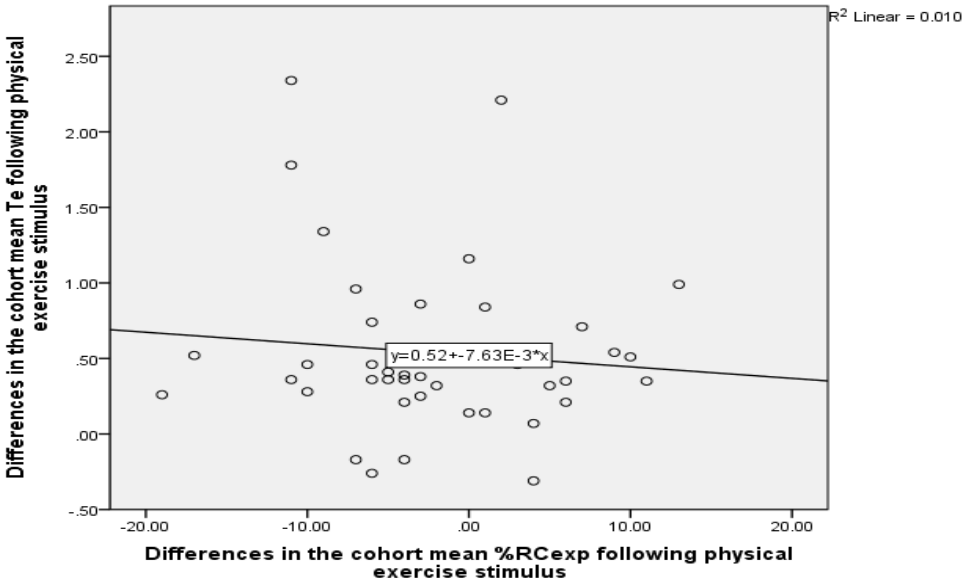
<u>The relationship between the differences in cohort thoracoabdominal motion and the differences in cohort timing components during recovery from physical exercise</u>



Graph 4: Scatterplot for the relationship between the change in cohort mean %RCexp and the change in cohort Bf during recovery from physical exercise

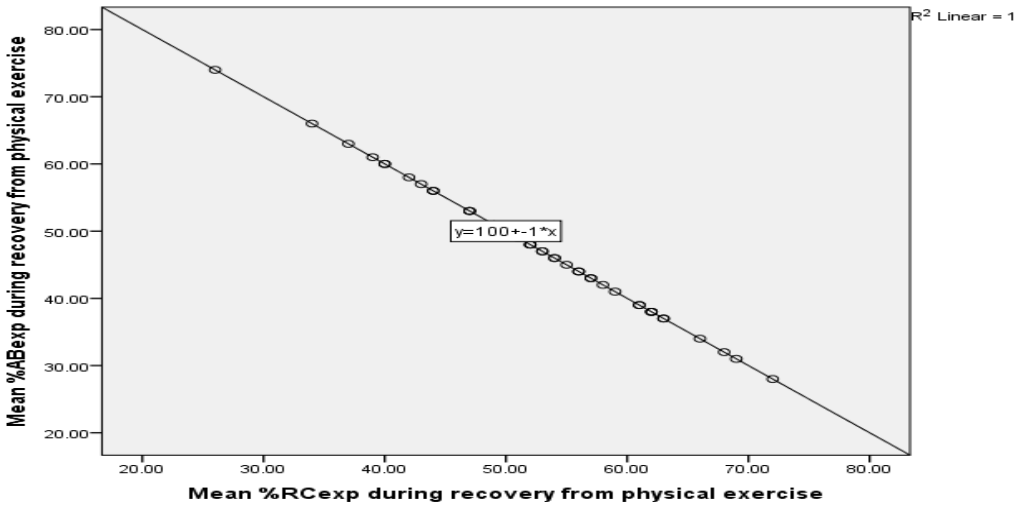


Graph 5: Scatterplot for the relationship between the change in cohort mean %RCexp and the change in cohort Ti during recovery from physical exercise

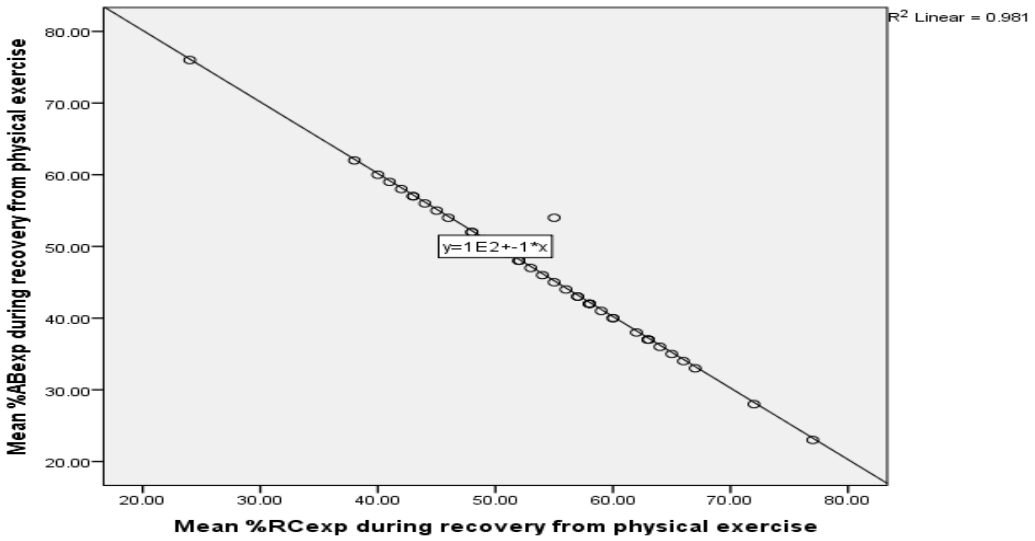


Graph 6: Scatterplot for the relationship between the change in cohort mean %RCexp and the change in cohort Te during recovery from physical exercise.

The relationship between thoracoabdominal motion at rest and during recovery from physical exercise

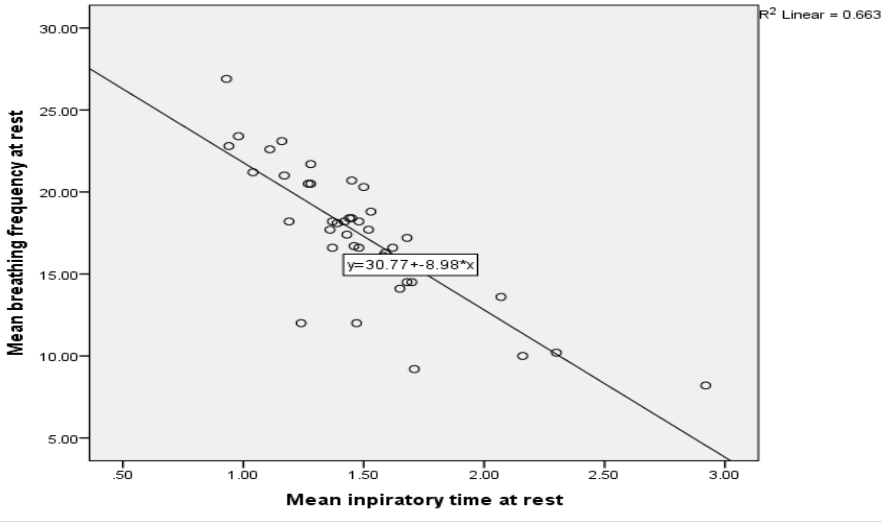


Graph 7: Scatterplot for the relationship between cohort mean %RCexp and cohort mean %ABexp at rest.

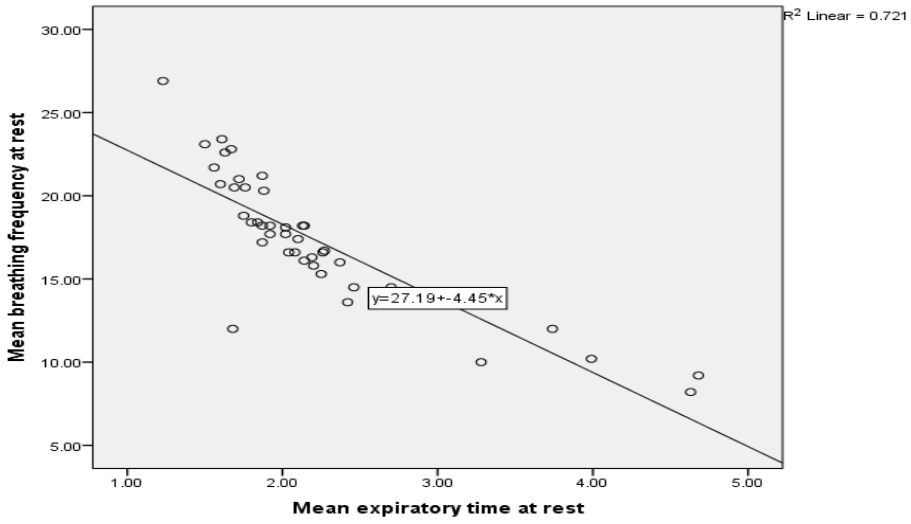


Graph 8: Scatterplot for the relationship between - cohort mean %RCexp and cohort mean %ABexp recovery from physical exercise.

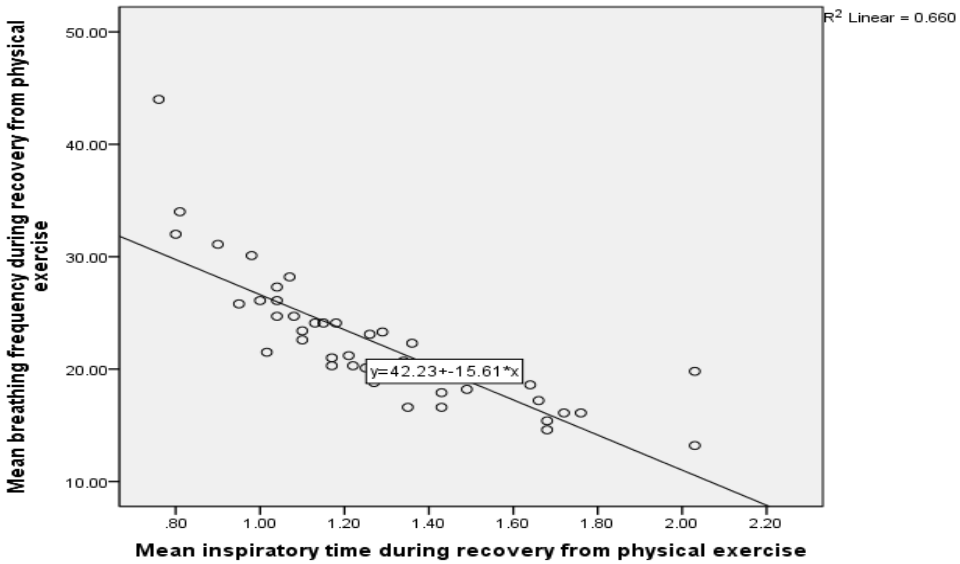
The relationship between timing components at rest and during recovery from physical exercise



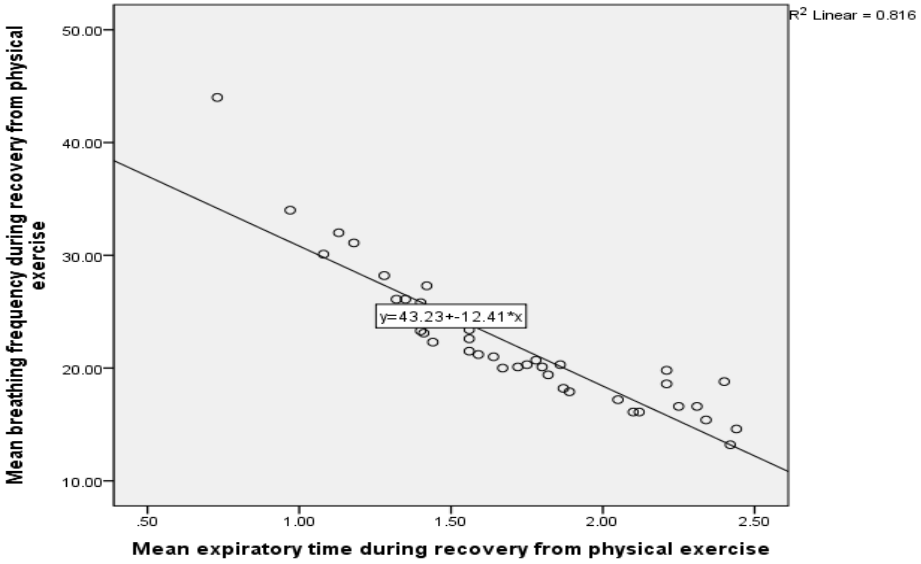
Graph 9: Scatterplot for the relationship between cohort mean T_i and cohort mean Bf at rest.



Graph 10: Scatterplot for the relationship between cohort mean T_e and cohort mean Bf at rest.



Graph 11: Scatterplot for the relationship between cohort mean Ti and cohort mean Bf recovery from physical exercise.



Graph 12: Scatterplot for the relationship between cohort mean Te and cohort mean Bf recovery from physical exercise.

Appendix J Asthma

J.1 Introduction

Asthma is a chronic condition that results in a reduced expiratory airflow, within susceptible individuals, that is reversible with appropriate therapy or spontaneously (Blumenthal 2012; WHO 2017) . According to recent European Respiratory Society (2015) statistics, over 5 million people in UK have been diagnosed with asthma and respiratory diseases are stated to be the third largest cause of death in the UK (after circulatory diseases and cancer) (NHS 2012). The UK's 2010 Health survey for respiratory health, stated that 16% of men and 17% of women have been diagnosed with asthma, which can inflict a huge burden on the sufferer and can severely impact their quality of life. In addition, the cost of controlling and treating respiratory diseases can be significant to many economies; asthma costs the NHS around £1.1 billion a year (Mukherjee et al. 2016). The prevalence of respiratory disease across the world is overwhelming. In short, asthma causes a significant burden in patient quality of life and health care cost. However, there is still a major shortfall in the understanding and management of asthma, with controversy over the etiology, pathophysiological processes and effective alternative treatment for asthma (Holgate 2008).

J.2 Pathology of asthma

Asthma is a chronic inflammatory disorder characterized by variable and repeated episodes of dyspnea, wheezing, chest tightness and coughing. It is a complex disorder that results from the complex interactions between host and environmental factors. Risk factors associated with asthma included genetic, environmental, viruses, occupational and physical exercise (Melen & Pershagen 2012). However, the precise cause of asthma is not known, but

most asthma is associated with atopy, which is the inherited predisposition to generate immunoglobulin E (IgE) against common environmental allergens. This has led asthma to be regarded largely as an allergic disorder along with other atopic diseases (Holgate & Douglass 2010).

Asthma symptoms occur as a consequence of a reversible and variable degree of airway inflammation, airway hyper responsiveness, and is sometimes associated with airway-wall remodelling. Understanding how these abnormalities interact and produce the clinical manifestations of asthma is not fully understood (Loxham et al. 2014; Perez-Zoghbi & Castro-Piedras 2015; Qi et al. 2016). At microscopic levels, asthmatics' airways display epithelial damage and an inability to heal, and there is an overproduction of growth factors, mucus and pro inflammatory cytokines (Ordoñez et al. 2001; Grainge et al. 2011). This is likely to have important clinical implications, since chronic mucus hypersecretion is an indicator of reduced forced expiratory volume in one second (FEV_1) in patients with asthma (Lange et al. 1998; de Marco et al. 2006; Thomson et al. 2013).

The inflammatory activity in asthma is a multicellular/mediator process involving the infiltration of various cell types associated with inflammation, including: eosinophils, neutrophils, lymphocytes, macrophages and activated mast cells (Holgate et al. 2001; Holgate & Polosa 2006; Holgate 2008). Increased eosinophils cell population and eosinophilic infiltration have been identified as a key contributor in allergic asthma. This is due to the increased numbers of eosinophils associated with disease severity (Jeffery 2001; Holgate 2007; Galli & Tsai 2012) and the dramatic decrease in sputum and eosinophils on treatment with inhaled or oral glucocorticoids in the majority of, but not all, asthma patients (Djukanović et al. 1992; Jatakanon et al.

2000). Hence, it has been suggested that increased eosinophils is a major contributing factor to airway dysfunction in asthma; however, it is not the only primary effector cell, but it likely has a distinct role in different phases of the disease (Education et al. 2007).

Eosinophils and multiple inflammatory cells continually interact with structural tissue of the airways and can cause direct damage to the epithelial layer, sub-basement thickening, smooth muscle hyperplasia and an increase in the number of nerves and blood vessels (Olin & Wechsler 2014). This chronic inflammation of the airway may alter the structure of the airway to an extent where airway remodelling occurs (Grainge et al. 2011; Doeing & Solway 2013) These changes are not fully reversible and contribute to airflow obstruction (Niimi et al. 2000a). The severity of airway remodelling can be clinically detected by measuring non-reversible airflow obstruction FEV_1 following bronchodilator treatment (Chetta et al. 1997).

J.3 Diagnosis of asthma

The diagnosis of asthma is primarily based on the evaluation of patients' medical and family history by a health professional (NICE 2015). Respiratory symptoms indicative of asthma include a combination of an expiratory polyphonic wheeze, dyspnea, chest tightness and cough (BTS/SIGA 2014; NICE 2015). One of the methods of objectively evaluating airways to determine the likelihood of asthma includes measuring the presence and severity of airflow obstruction using spirometry. During the spirometry test in asthma diagnosis, airflow and volume are measured during a forced expiratory manoeuvre using a spirometer device (see section 3.4.2 for a description of a spirometer), this facilitates the assessment of the forced expiratory volume in one second (FEV_1) and forced vital capacity (FVC). The

subsequent improvement in FEV_1 after inhaling a short-acting bronchodilator, or following a more effective controller treatment such as glucocorticoids enables the reversibility to be assessed. An improvement of >15% (or > 200 ml) in FEV_1 measured at least 15 minutes post bronchodilator therapy is accepted as reversible airflow obstruction and therefore indicative of the presence of asthma (Pellegrino et al. 2005; GINA 2010).

Spirometry can also be used to measure airway responsiveness to a direct challenge, such as inhaled histamine and methacholine (Cockcroft 2010), and indirect challenges, such as inhaled mannitol (Anderson et al. 2009), or as a response to exercise (Stensrud et al. 2007). This process can be used to confirm a diagnosis in patients with normal lung function, but experiencing asthma symptoms (GINA 2010). Methacholine for use in a non-specific bronchial provocation challenge can be used to diagnose airway hyper responsiveness as it induces a 20% decrease in the force expiratory volume (FEV_1) in people with asthma (O'byrne et al. 2009). In healthy subjects, PC20 (the concentration of methacholine to cause a response) is about 100 mg/ml of methacholine, whereas in mild and severe asthma typical PC20 values are 4 and 1 mg/ml of methacholine, respectively (O'Byrne & Inman 2003).

Other methods for diagnosing asthma include blood or pin prick tests, which enable the detection of allergic reactions to aeroallergens, exercise tests to detect bronchoconstriction and measuring chest wall motion using body plethysmography to analyse ventilation to demonstrate airway obstruction. However, as NICE (2015) assert, there is no clear consensus regarding which method, or combination of methods, is most effective in accurately diagnosing asthma. Therefore, it is recognised that in reality, asthma is still commonly diagnosed on the basis of symptoms alone (Holgate & Polosa,

2006) and due to the lack of a gold standard test that enables the objective diagnosis of asthma, it has been suggested that 30% of asthma population in the UK do not have clear evidence of asthma (NICE 2015) and may have been given an incorrect diagnosis. Due to the potential irreversible damage that can be caused to the airway as a result of chronic inflammation it is essential that patients receive accurate diagnosis of asthma in order to receive appropriate therapy that will avoid or prevent airway remodelling.

J.4 Asthma management

Asthma has been associated with increased morbidity (Mukherjee et. al 2014) and it has been suggested that much of this morbidity is related to the poor management of asthma symptoms and particularly the under use of preventative medicine (Bruton &Thomas 2014). It has also been established that asthma alters breathing pattern, which is likely to impair an individuals' ability to control asthma symptoms (Thomas et al. 2001). Today there is no available therapy to cure asthma; therefore, the main aim of asthma management is to reduce and gain control of asthma associated symptoms. In 2012, the British Thoracic Society (BTS) and Scottish Intercollegiate Guidelines Network (SIGN) introduced comprehensive guidelines outlining how asthma should be managed and treated in the general population. This guideline was produced following rigorous scrutiny of research to justify health care decision making processes, and provide uniformity of asthma care across the UK. BTS/SIGN (2014) recommended 3 main steps to control asthma symptoms: 1) self-management, education and asthma action plans (AAP), 2) pharmacological treatment and 3) non-pharmacological treatment. These are discussed in the following sections.

J.4.1 Self-management/asthma action plans (AAP)

One recommendation is to produce an individualised written AAP, which is tailored to the patient's underlying asthma severity and treatment. AAPs have become a core component of asthma management with best practice guidelines and help the patient or carer recognise worsening asthma. The idea of a written action plan is that the patient is given a set of rules by which to alter therapy, dependent on either PEF monitoring or symptom levels. The implication is that an appropriate, early response to deterioration will prevent dangerous exacerbations and will generally improve health-related quality of life. AAPs contain four essential components that work effectively together:

- Instructions on when to increase treatment;
- How to increase treatment;
- The duration of the treatment increase; and
- When to cease self-management and seek medical help.

It has been shown that increasing patients' participation in their own care is associated with improved asthma management, regardless of asthma symptoms (Adams et al. 2005). Moreover, a systematic review by Gibson and Powell (2004) of thirty-six trials compared the use of written AAPs and self-management education with usual care. Using weighted mean difference (WMD) analyses (which is the difference in means) it was found that health outcomes in patients with AAPs were improved. Self-management education was found to significantly reduce hospitalisations, emergency departments visits, unscheduled visits to the doctor, days off work or school and significantly improve QOL scores. In another study, written action plans including the adaptation of breathing behaviour, were used in a randomised control trial by Grammatopoulou et al. (2011) examining the effect of breathing retraining in asthma patients (n=20). The findings suggest that

using AAPs may have contributed complementarily to the reduction of breathlessness and the improvement of quality of life scores.

J.4.2 Pharmacological management

Asthma medication can be divided into two groups. Firstly, ‘Controllers’ are taken daily on a long-term basis to get and keep persistent asthma under control, and include: leukotriene modifiers, combinations between inhaled corticosteroids and long-acting beta agonists (LABA), theophylline, cromones, anti-IgE, and other systemic steroid-sparing therapies). Secondly, ‘Relievers’ act quickly to relieve bronchoconstriction and its accompanying acute symptoms, such as: coughing, chest tightness and wheezing, which can also be used on an as needed basis, i.e. as rescue medication (Rabe & Schmidt 2001) and are referred to as Short acting β2 agonists.

The BTS/SIGN 2003 guidelines conclude, "Inhaled steroids are the most effective preventer drug for adults and children for achieving overall treatment goals". However, despite major improvements in modern medicine regarding the increasingly effective pharmacological treatment of asthma using beta Agonist and inhaled corticosteroid, asthma is still one of the most common, long-term, incurable health conditions in UK (Asthma UK 2014). Hospitalisation and morbidity rates for asthma also remain high and the treatment of asthma continues to be a significant economic burden on NHS services in the UK (Mukherjee et al. 2014). Therefore, the need for alternative, non-pharmacological treatment is increasingly pressing in order to assist individuals with asthma to reduce the impact of asthma on their lives. The following section outlines the existing non-pharmacological treatments for asthma.

J.4.3 Non-pharmacological treatment

Although research has indicated that pharmacotherapy is an effective method of asthma control in most cases (Bateman et al. 2004), there is evidence suggesting that individuals are becoming increasingly interested in non-pharmacological treatment (Bruton & Holgate 2005b). Barnes and Woolcock (1998) also highlighted the need for alternative, therapeutic therapies in the finding that 5% of people with asthma are unable to control or stabilise asthma symptoms with pharmacological treatment.

There are a number of methods to control asthma symptoms that do not involve the use of drugs, including dietary adjustments, avoiding triggers and allergens, weight reduction, avoiding smoking and air pollutants, Chinese or herbal medicine, education, physical exercise and breathing exercise. This section focuses specifically on breathing exercises as a method of controlling asthma symptoms, since it is widely used within clinical practice (Bruton 2014) as well as by individuals (Ernst et al. 1999). Breathing exercises are becoming part of mainstream asthma management with a strong evidence base and is recommended within the BTS/SIGN guidelines (2016).

J.5 Breathing exercises

Correction of abnormal breathing patterns through breathing exercises is a therapeutic method of controlling asthma symptoms. The use of breathing exercises as a complementary therapy to pharmacological treatment has been widely used across the globe for people with asthma (Freitas et al. 2013). It is also frequently used in relaxation and anxiety reduction therapies as a way of reducing stress and anxiety and particularly in the management of hyperventilation (Wollburg et al. 2011). Breathing exercise is an evidence based, multicomponent, behavioural change intervention for the care of

patients with asthma (BTS/SIGN 2016) and other respiratory diseases (Han et al. 1996). It aims to modify breathing pattern by slowing breathing frequency and reducing hyperventilation and comprises a variety of techniques; including the Papworth method, Buteyko breathing technique, yoga or any other similar physiotherapy intervention that involves the manipulation of breathing pattern (Ernst 1998; Ernst 2000; Ram et al. 2003). The majority of the evidence for its effectiveness comes from studies of patients with psychological disorder, asthma and/or COPD (Ritz & Roth 2003; Thomas et al. 2009; Borge et al. 2014a). Randomised control trials have repeatedly shown that breathing exercises have a favourable effect on asthma symptoms, improve QOL scores, reduce the use of bronchodilators and have some effect in improving lung function when compared with control groups (Bowler et al. 1998; Slader et al. 2006; Thomas et al. 2009; Grammatopoulou et al. 2011). These observations highlight the importance and potential usefulness of breathing exercises in the care of patients with asthma, as poor control of asthma symptoms and the level of disease burden remains significant (BTS/SIGN 2016).

Consequently, breathing exercises are routinely used by physiotherapists and other professionals to assist with the control and management of asthma symptoms (Bruton & Lewith 2005). Thomas & Bruton (2014) explain that breathing exercises can be largely divided into three categories. One category focuses on strengthening respiratory muscles and is referred to as respiratory muscle training. The other category aims to increase the flexibility of the thoracic cage and improving posture, which is referred to as musculoskeletal training. The third category focuses on the manipulation of breathing pattern and is referred to as breathing retraining. It can be delivered via face to face session in small group or one to one intervention (Thomas et al. 2009), or via

a videotaped instruction programme (Slader et al. 2006). The type of breathing exercise used in the third study is face to face, breathing retraining, since this has the strongest evidence base within the literature and is widely used in asthma management, which is discussed in the following section.

J.6 Content of effective breathing retraining program

At present, there is considerable variation in the description and delivery of breathing retraining interventions and a lack of clear definition of terminology used in the RCT that have examined the efficacy of this intervention (Bruton et al. 2011). Nevertheless, comprehensive, evidence based guidelines agree that all breathing retraining programmes should include an instructional phase by a qualified therapist, which comprises demonstrations of breathing manipulation techniques. It should also include an education phase and guidance encouraging relaxation (Bott et al. 2009; BTS/SIGN 2016).

J.6.1 Behavioural / and self-management

Instructional physiotherapy breathing manipulation

Breathing manipulation is the cornerstone of any breathing retraining program and involves reducing dyspnoea through increasing diaphragmatic excursions and simultaneously reducing accessory muscle use (which contributes greatly to work of breathing) and correcting abnormal chest wall movement (Cahalin et al. 2002; Fernandes et al. 2011; Yamaguti et al. 2012). It also aims to reduce and eliminate anxiety, which is associated with hyperventilation syndrome (Cahalin et al. 2002; Wollburg et al. 2011). Also,

breathing retraining focuses on slowing breathing frequency, modifying depth of breathing and airflow velocity, varying the duration of inspiratory and expiratory phases. It can also place emphasis on encouraging nasal breathing and expiratory breath holding techniques. The duration and the number of sessions to be effective is not known. However, Thomas & Bruton (2014) suggest that three to four sessions over a period of approximately six weeks may provide positive effects, while the BTS/SIGN (2016) guidelines mention that programmes consisting of five hours or more are more likely to be effective.

The effects of breathing manipulation have been examined within the literature; however, the consistent combination of breathing modification techniques with other therapies (education and relaxation) make it difficult to separate the individual effects of the breathing modification techniques. In addition, no data has been reported regarding the improvement that occurs in breathing pattern components (timing and thoracoabdominal motion) following these interventions, making it difficult to confirm its efficacy in modifying breathing pattern in patients with asthma. However, it is evident that breathing manipulation can improve patient's QOL, reduce asthma symptoms and decrease medication use (Thomas et al. 2009; Cowie et al. 2009; Grammatopoulou et al. 2011; Burgess et al. 2014)

Education and home advice

Education and home-advice is another important component of the breathing retaining package and involves providing detailed information regarding the correct and effective self-administration of the breathing retraining programme. Also, patients are encouraged to make healthy lifestyle choices that would improve their asthma symptoms and QOL and the rationale behind those choices, including cessation of smoking (Tomlinson et al. 2005) and

increasing regular physical exercise(Ram et al. 2005). Although, education is important, a control group that only received an education and home advice programme did not demonstrate any significant improvements in asthma symptoms, this indicates that an educational programme alone is not sufficient, but rather should be used in conjunction with a comprehensive breathing retraining package (Thomas et al. 2009).

Relaxation training

Asthma patients have increased likelihood of depression, panic attacks and anxiety disorder; this is highly associated with an increase of asthma symptoms. Hence, relaxation techniques are frequently integrated into the breathing retraining package for asthma management (Lehrer et al. 2002). According to evidence based guidelines (BTS/SIGN 2016), relaxation techniques are suggested as a secondary, non-pharmacological prevention therapy to assist in the control of asthma. In a systematic review by Huntley et al. (2002) including 15 RCTs (5 used progressive muscle relaxation techniques, 1 used mental and muscular relaxation, 3 examined the function of hypnotherapy and self-hypnosis, 3 used autogenic training, 2 used biofeedback techniques, and 1 investigated transcendental meditation). No therapeutic effects were found in all except 2 of the studies, which showed the significant effects of progressive muscle relaxation techniques on lung function in comparison to control groups. Perhaps the most notable finding was the lack of methodological quality of the studies, with 9 failing to meet the criteria necessary to statistically compare a treatment group with a control group. This highlights the need for more rigorous, well- designed RCT in this area. Similar improvements in lung function were noted in asthma patients performing yoga based relaxation techniques (Burgess et al. 2011). It

is apparent that relaxation therapy is an important part of a retraining package and may benefit lung function in patients with asthma.

J.7 Theoretical mechanism behind breathing retraining

Although breathing retraining programmes have been shown to benefit QOL, asthma symptoms and some physiological outcomes ($ETCO_2$), the underlying mechanism as to how they work is not fully understood (Jerath et al. 2006). However, there are a number of psychological and physiological theories as to how and why the goals of breathing retraining are achieved (Bruton &Thomas 2011; Bailey et al. 2016).

Regarding the ***psychological theory*****,** it has been hypothesised that improvements in QOL and asthma symptoms may be related to a decrease in anxiety and an increase in patients' awareness using mindfulness training (Pbert et al. 2012; Bailey et al. 2016). Although thought to have origins within Buddhist practices, a structured 'Mindfulness' programme was first developed by Kabat-Zinn et al. (1985). The Mindfulness intervention is taught through a variety of meditation exercises, involving directing attention to the sensations associated with breathing (Baer 2003), a behavioral framework to explain the positive effects of mindfulness, interceptive exposure and increasing patients' awareness of their breathing in order to adjust it to match metabolic requirements (Ritz & Roth 2003). Individuals practicing mindfulness techniques learn to understand the sensations associated with shortness of breath. Therefore, 'mindfulness' focuses individuals to psychologically come to terms with and, consequently, *feel* more in control their asthma symptoms, which reduces the anxiety surrounding asthma symptoms and sensations of dyspnea (Delgado et al. 2010; Bailey et al. 2016).

RCTs examining the effects of breathing retraining by Bowler et al. (1998), Holloway et al. (2007), Thomas et al. (2009) and Grammatopoulou et al. (2011) have shown significant improvements in QOL and reductions in anxiety and depression in comparison with control groups. However, it is unknown if this improvement in anxiety and depression scores can improve asthma control. A randomised controlled trial by Brown et al. (2005) involving 90 participants with asthma and current major depressive disorder demonstrated that a reduction in depressive symptoms was associated with improvement in asthma symptom severity as determined by self-reported Asthma Control Questionnaire scores. A systematic review of 14 RCTs, involving a total of 617 adults, was carried out by Yorke et al. (2007) examining the effects of psychological interventions (including cognitive behavioural therapy, relaxation therapy and counselling) in improving health and behavioural outcomes for adults with asthma. The results noted a significant reduction in medication use and significant improvements in asthma QOL questionnaire scores. However, a lack of homogeneity and rigorous methodological protocol within the studies included in analysis, the authors were unable to draw firm conclusions regarding the efficacy of psychological interventions in asthma.

In addition, another RCT conducted by Pbert et al. (2012) examined the effectiveness of the Mindfulness based stress reduction techniques in improving asthma-related QOL and lung function in 42 patients with mild, moderate or severe persistent asthma in comparison to an educational control programme involving 41 participants (also with asthma). At a 12 month follow-up assessment, there were significant improvements in the asthma-related QOL questionnaire scores and the Perceived Stress Scale scores in comparison to the control group; 0.66 (95% CI 0.30 to 1.03;

p<0.001) and −4.5 (95% CI −7.1 to −1.9; p=0.001) respectively. However, there were no significant differences between the two groups in lung function. Bailey et al. (2016) argues that there are many similarities between mindfulness and breathing retraining techniques and that the success of breathing retraining is largely due to the features found within mindfulness techniques. Although Bailey et al. (2016) are clearly proponents of mindfulness techniques, it is important to mention that a number of studies examining breathing retraining have found not only improvements in QOL scores, but also improvements in lung function, reductions in medication use and improvements in asthma symptoms.

It appears that the main issue relates to a lack of homogeneity between the studies, which makes meta-analysis regarding these particular outcomes difficult or impossible (Freitas et al. 2012; O'Conner et al. 2013); nevertheless, improvements in lung function as a result of breathing retraining are clearly reported within the literature (Leher et al. 2000; Sodhi et al. 2009; Grammatopoulou et al. 2011). Hence, there have been calls for increased homogeneity and standardised research protocols for studies examining the effect of breathing retraining in asthma in order to improve the evidence base (Rams et al. 2003; Yorke et al. 2007; Burgess et al. 2011; Bruton et al. 2011; Freitas et al. 2012; O'Conner et al. 2013). Moreover, it can be suggested that a physiological outcome is necessary to be measured in conjunction with psychological outcomes in order to monitor the improvement of asthma control in a comprehensive manner.

Relating to the ***physiological theory,*** it has been hypothesised that encouraging hypoventilation by increasing carbon dioxide levels stimulates dilation of the smooth muscles in the bronchi, bronchial and alveolar ducts

(Prem et al. 2013). Treating hyperventilation, according to Buteyko practitioners, can be achieved by reducing and slowing ventilation, encouraging nasal breathing and prolonged expiratory breath holding. This theory has been examined by McFadden et al. (1977), Van den Elshout et al. (1991), and Osborne et al. (2000) who found that decreasing the alveolar carbon dioxide level can lead to an increase in respiratory muscle resistance, while increasing CO_2 level decreased bronchospasm. However, in studies by Bowler et al. (1998), Slader et al. (2006) and Thomas et al. (2009) examining Buteyko and physiotherapy breathing retraining techniques in asthma patients, no significant changes were found in CO_2 levels when measured following the intervention. On the other hand, Meuret et al. (2007) and Grammatopoulou et al. (2011) found that $ETCO_2$ significantly increased at 8 weeks and 6 months following breathing retraining programmes. A review by Bruton & Holgate (2005) found lower levels of CO_2 in individuals with asthma; however, in direct contradiction to Buteyko's claims, Courtney and Cohen (2008) found a negative correlation between breath holding time and $ETCO_2$ levels. These contradictory results within the literature make it difficult to draw any firm conclusion regarding the role of CO_2 levels in bronchoconstriction and there is a need for further, well-designed clinical trials to full understand the role of $C0_2$ levels, and its manipulation using breathing retraining, in asthma patients.

Although there are a number of psychological and physiological theories underpinning breathing retraining techniques, the underlying mechanism is not fully understood or explained within the literature. Despite this, there is a strong evidence base within the literature that breathing retraining programmes benefit QOL, asthma symptoms and some physiological outcomes ($ETCO_2$), which is discussed in more detail in the following section.

J.8 Scientific evidence for the effectiveness of breathing retraining

The wide-spread and increasing use of breathing retraining as an adjunct treatment for people with asthma has inevitably generated considerable interest among researchers to develop studies that examine the effectiveness of breathing retraining in the management of asthma (Freitas et al. 2013). Indeed, the efficacy of breathing retraining in people with asthma has been suggested within the literature in asthma management (Freitas et al. 2013; O'Connor et al. 2012; Burgess et al. 2011; Ram et al. 2003 and Ernst 2000). However, there are inconsistencies within the literature regarding the effects of breathing retraining and a clear lack of homogeneity. O'Connor et al. (2012) and Freitas et al. (2013) conducted the two most recent published systematic reviews assessing the effectiveness of breathing exercise in the management of asthma.

Freitas et al. (2013) evaluated the evidence for the effectiveness of breathing exercises in the management of patients with asthma. 13 RCTs were included involving a total of 906 participants. Although, the various differences and heterogeneity between the studies (relating to the type of breathing exercise, number of participants, number and duration of sessions, outcomes measured and statistical analysis), limited the meta-analysis to two outcomes; namely, QOL and improvement in asthma symptoms. The findings revealed that all 8 studies that examined QOL found improvements in this outcome and 6 of 7 studies that examined asthma symptoms found significant improvements following breathing exercise. Five of the eleven studies that examined the effects on lung function did not note any differences, although the remaining 6 found significant improvements. This may be related to the

different age groups included in the studies or the participants' familiarity with the spirometer test.

O'Conner et al. (2012) also conducted a systematic review of the literature examining the evidence regarding the efficacy of breathing exercises and retraining techniques in improving in asthma symptoms, reducing asthma medication use, improving QOL and improving pulmonary function in asthma patients. The inclusion criteria included English-language trials of breathing retraining techniques that reported asthma symptoms at 4 weeks post-baseline or later, usage of asthma medication, QOL and pulmonary function. Also, all trials included a control or comparison group. Twenty-two trials were included in the final review; all were RCTs except one randomised crossover trial.

The results showed that the most robust body of evidence supported the use of hyperventilation reduction breathing techniques for improving asthma symptoms and reducing reliever medication use by approximately 1.5 to 2.5 puffs per day, it was the only large-scale trial with 600 participants (aged 14+). However, no improvement in pulmonary function was found. Regarding the yoga breathing technique, four of the five trials reported improvements in asthma symptoms and others reported a favourable effect on QOL, medication relief and improvements in lung function. However, all the studies involving yoga breathing techniques were conducted primarily in India and possessed a variety of methodological and reporting weaknesses and inconsistencies. Hence, the heterogeneity, the lack of applicability to the United States and other protocol weaknesses reduce the strength of the body of evidence regarding yoga breathing techniques greatly.

Both Freitas et al. (2013) and O'Conner et al. (2012) explain that the lack of homogeneity between the studies has resulted in difficulties in drawing firm conclusions regarding the effectiveness of breathing exercises in the treatment of adults with asthma, although it is worth noting that all individual trials reported some positive effects on various different outcomes. Consequently, both authors call for a standardisation of asthma related terms, particularly when characterising breathing retraining, as also recommended by Bruton et al. (2011). Also, there are calls for greater homogeneity regarding methodological protocol and reporting in order to assist future meta-analysis and further improve understanding. Nevertheless, the importance of breathing retraining as an adjuvant to pharmacological treatment in the control of asthma is apparent. This is evidenced by the literature and also recent guidelines produced by the Global Initiative for Asthma (GINA 2014 and BTS/SIGN 2014) Guideline recommend breathing exercise programmes (including physiotherapist-taught methods) to improve QOL and reduce symptoms for people with asthma (Bott et al. 2009).

J.9 Summary

Asthma is an increasingly prevalent and common condition across the globe, which increases the likelihood of hospitalisation, increasing morbidity and has a significantly negative impact on the sufferers' quality of life. Asthma symptoms can be controlled in pharmacological and non-pharmacological ways, and breathing exercise has been shown to be an effective method of asthma control, although theoretical underpinning regarding its efficacy is not fully known. More research is, therefore, essential in this field. What is clear is that there is a lack of heterogeneity within the evidence base regarding the efficacy of therapeutic interventions involving breathing exercises. As part of the aims of this study, it is hoped to establish the

usefulness of breathing pattern as an outcome measure, which may be used in future research.

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