Biomechanical Assessment of Sports Bra Performance

A doctoral thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

By

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Summary

Biomechanical testing has been the cornerstone of sports bra research to date and the quantification of breast kinematics during exercise has received increasing interest. However, comparatively little research has been published regarding the development of biomechanical testing methodology and how this testing may inform the development of sports bra design. Thus, the overall research aim was the 'Development and application of methods used in the biomechanical assessment of sports bra performance with the end goal of better biomechanical tools for use in the sports bra design process'.

Breast kinematics are typically measured relative to the torso, therefore, it is necessary to track both torso and breast motion. The absence of a universally accepted torso tracking model, and information regarding the sensitivity of breast kinematics to the selected torso model were identified as limitations to the existing research. The seven marker torso tracking model presented is the first to be specifically developed for analysing relative breast motion during activities such as treadmill running and is recommended to be implemented in future sports bra research.

The torso segment used to calculate relative breast kinematics is assumed to be rigid, however, breast movement resulting from respiration has been reported for a static condition. The effect of breathing on breast kinematics during treadmill running was investigated. Significant differences were observed in the breast kinematics between breathing and non-breathing conditions, notably in the superior-inferior direction; however, they could not definitively be directly linked to breathing since significant differences in running gait were also observed. The results do suggest that increasing the number of gait cycles analysed may reduce any effects of breathing on breast kinematics due to phase-locking, the synchronisation of breathing with running locomotion. Analysing breast kinematics over 30 gait cycles may help minimise any potential effects of phase-locking across all commonly used phase-locking ratios.

Further understanding of breast motion and whether markers placed on the bra represent the underlying breast were identified as pertinent to advancing biomechanical assessment of sports bra performance. Motion between the breast and bra (either during

an initial bedding in phase or steady state running) has yet to be explored within the existing literature and is assumed to be negligible for a correctly fitted bra. A settling in period of ~30 seconds between the breast and bra was found to occur during the initial phase of treadmill running. Whilst the study is recognised to be exploratory in nature, the findings suggest future breast kinematic study should consider the possibility of a settling in effect. Therefore, experimental protocols may benefit from including a short period of activity after the subject has changed into the bra to help eliminate any settling in effect prior to data capture or application of over bra markers. The results also suggest that motion occurs between the breast and bra irrespective of bra size and that over bra markers underestimate superior-inferior (S-I) breast displacement and anterior-posterior (A-P) displacement at the upper breast. Markers positioned over the bra were found to be less sensitive to variation in A-P and S-I displacement in different regions of the breast. However, use of under bra markers is limited by current motion capture technology and until advances in technology are made the use of over bra markers remains current best practice. Future studies are recommended to state whether breast markers were located over or under the bra and recognise that over bra markers represent bra motion.

Bra strap stiffness was identified as a potentially important factor in sports bra performance. The effect was investigated using a modified bra with removable strap sections of three differing stiffness. Bra strap mechanical properties were characterised using a specifically developed tensile testing protocol. Sports bra performance during treadmill running was assessed using biomechanical and perceptual measures. Increasing bra strap stiffness was found to improve sports bra performance with respect to bra kinematics (primarily in the superior-interior direction) and subjective perception ratings (in particular the perception of support), suggesting strap stiffness may have an important role to play in bra design.

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Publications

FORRESTER, S., AND WHITTINGHAM, L., 2015, Effect of bra strap stiffness on breast kinematics and perceived bra performance during treadmill running, *Proceedings of the XXV Congress of the International Society of Biomechanics*, 12-16 July 2015 Glasgow.

WHITTINGHAM, L., ROBERTS, B., WEIR, R., CAINE, M.P. AND FORRESTER S.E., 2012, Determination of a Suitable Torso Marker Set to Measure Breast Kinematics during Running, *Proceedings of the Biomechanics Interest Group of the British Association of Sport and Exercise Sciences*, 4 April 2012 University of Ulster, Belfast.

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Nomenclature

3D	Three dimensional
a	Acceleration
A-P	Anterior-Posterior
ASIS	Anterior superior iliac crest
d	Cohen's d effect size
F	Force
FEA	Finite element analysis
g	Gravitational acceleration
GCS	Global Coordinate System
k	Stiffness
LCS	Local Coordinate System
m	Mass
M-L	Medial-Lateral
NRS	Numerical Rating Scale
p	Statistical significance
POSE	Position and Orientation
r	Effect size
RBS	Rigid body smoothing
ROM	Range of motion
S-I	Superior-Inferior
SD	Standard deviation
VAS	Visual Analogue Scale

Chapter 1

Introduction

1.1 Introduction

Breast discomfort during exercise has been reported to affect between 20% and 72% of women (Hunter and Torgan, 1982, Lorentzen and Lawson, 1987, Gehlsen and Albohm, 1980). The underlying cause of exercise induced breast discomfort is unknown, but is thought to result from the increased breast motion during exercise placing additional load on the breasts supporting structures (Mason et al., 1999). Exercise induced breast discomfort may be so severe that it restricts a woman's participation in exercise or reduce her enjoyment of exercising. A number of authors have voiced concerns over the implications to long term breast health, suggesting that the repeated loading of breast support structures may cause permanent damage leading to breast ptosis (sag) (Mason et al., 1999, Page and Steele, 1999). Additionally, embarrassment or self-consciousness due to excessive breast motion during exercise may act as a barrier to exercise participation. Sports bras may have an important role to play, particularly in larger breasted women, not only to reduce relative breast motion but also to improve posture and possibly prevent secondary musculoskeletal pain or injury (McGhee et al., 2013).

The primary function of a sports bra is to provide an external support structure to the breasts during exercise. The first sports bra is attributed to two American women, who in 1977 produced a prototype by stitching together two jock straps (Schuster, 1979, Pedersen, 2004). Designs have advanced since these early days particularly with the introduction of Lycra™ in the 1980's (Pedersen, 2004). Sports bra research is still a developing area and has received increased interest within the last decade (Zhou et al., 2011). Aspects contributing to this drive include exercise based health initiatives, a growing body of evidence that breast pain during exercise is a significant issue that may discourage women from exercising (Brown et al., 2013) and companies, in an increasing sports bra market, wanting to quantify the performance of their products. Whilst sports bras are widely acknowledged to reduce breast motion and exercise induced breast discomfort compared to an everyday bra, a substantial proportion of women remain dissatisfied with current sports bra designs, especially amongst larger breasted women (Brown et al., 2014).

1.1.1 Research Motivation

The overriding motivation for undertaking this research was to improve sports bra design by better informing the design process. Although sports bra research has recently received an increase in interest, dissatisfaction with current bra designs suggests there is more work to do. Improved sports bra design may benefit both the general population partaking in recreational activity and performance athletes.

1.1.2 Sports Bra Design - A complex problem

Sports bra design presents a complex problem, firstly, the breast which the bra is designed to support has many anatomic variations with respect to volume, shape and structure (Snell, 2004, Avsar et al., 2010). Secondly, breast structure, size and composition change during woman's life and are affected by factors including menstrual cycle, pregnancy, menopause and changes in body fat. Furthermore, whilst primary function of a sports bra is to support the breasts during exercise, many other aspects must be considered in the design process of sports bra including; durability, washablity, commercial viability of manufacture, wide ranging aspects of comfort plus fashion as an important driver of design decisions.

1.1.3 Overview of Current Sports Bra Research

Sports bra research is a developing area which has received increased interest in recent years. The research community is relatively small with the three main active research groups based at University of Portsmouth, Hong Kong Polytechnic University and University of Wollongong. As the research area is still relatively young and developing there are a number of areas which remain poorly understood and limitations in how research can be applied to the sports bra design process and development of bra design. The research has been directed by the interlinking factors of comfort, injury and performance. Human, mechanical and virtual test modalities have been utilised, however, the greatest focus on upon human based biomechanical and perceptual studies.

Biomechanical testing has been the cornerstone of sports bra research to date and the quantification of breast kinematics during exercise has received increasing interest. Breast kinematics are typically measured relative to the torso, therefore, it is necessary to track both torso and breast motion. This is most commonly performed using opto-electronic motion capture systems and has focused on treadmill walking and running. The majority of studies use a single marker at the nipple to represent breast motion which is placed on the exterior of the bra if one is worn. Four different torso tracking marker sets have been proposed in the literature, however, they generally provide little evidence of how they were developed or how well they are able to track torso movement (Scurr et al., 2009, Scurr et al., 2010b, Zhou, 2011, McGhee and Steele, 2010a). Furthermore, there is a lack of consensus over the method used to calculate relative breast motion (either with or without rigid body assumption). At present there is no standard protocol for measuring relative breast kinematics making it difficult to compare studies. A substantial focus has been placed upon understanding of bare breast biomechanics and the effect of breast support on breast motion during treadmill running and walking. The effect of activity type, running speed, breast size and breast kinematics on body motion have also been investigated. Relative breast displacement, velocity, acceleration have been studied although displacement is most commonly reported and perhaps best understood (Zhou et al., 2011). However, comparatively little research has been published regarding the development of sports bra testing methodology.

Perception data is often collected in conjunction with kinematic data and has typically focused upon exercise induced breast discomfort. The source of exercise induced breast discomfort and whether it is an indicator of breast injury remains to be understood. At present, sports bra perception is a relatively unexplored area, with much scope to investigate the important perceptual variables, terminology and data collection protocols White (2013).

Sport bra performance is typically assessed using breast kinematics and subject perception of the bra during treadmill running (Zhou et al., 2011). It is widely acknowledged that exercise induced breast discomfort and relative breast displacement are reduced by wearing a bra, and that a sports bra is more effecting at reducing discomfort and displacement than an everyday bra. Breast displacement and exercise induced breast discomfort are typically higher in larger breast sizes (Lorentzen and Lawson, 1987). Whilst sports bras are widely acknowledged to be effective at reducing breast motion and reducing breast discomfort during exercise, the relationship between biomechanical measures and breast discomfort remains unclear. However, studies are typically limited to a small number of very different bras, therefore, experimental variables (bra structure and mechanical properties) have been poorly controlled making it difficult to infer any relationships. Therefore, there is relatively little understanding of how a specific sports bra design affects bra performance.

Mechanical testing within the sports bra literature is extremely limited, and focused upon the characterisation of mechanical properties through tensile testing (Zhou, 2011). Zhou's findings suggest that increasing strap modulus may reduce S-I breast displacement which may have implications for sports bra design. However, it is highly likely that manufacturers conduct extensive and unreported in house mechanical testing.

A small number of studies have used virtual models to investigate breast or breast-bra behaviour ranging from simple mass-spring models to finite element analysis (Zhou and Yu 2013, Li et al., 2003, Cai et al., 2014). However, to apply these research methods within the design process will require extensive work to validate model results with human testing.

1.2 Research Aim

The overall research aim was the 'Development and application of methods used in the biomechanical assessment of sports bra performance with the end goal of better biomechanical tools for use in the sports bra design process.'

This research has focused upon biomechanical testing as it has been the cornerstone of sports bra research to date. Despite the prominent role of biomechanical testing in assessing sports bra performance, comparatively little research has been published regarding the development of biomechanical testing methodology and how this testing may inform the sports bra design process. Furthermore, mechanical and virtual test modalities also offer exciting opportunities for future advances in the sports bra design process, however, such development tools rely upon extensive validation using human biomechanical testing. Therefore, this research focused upon the development and application of methods used in the biomechanical assessment of sports bra performance.

1.3 Research Design

A systems approach was taken to the planning of the research programme, systems thinking has been applied across variety of fields including research and engineering design (Reynolds and Holwell, 2010, Misra, 2008). A system is frequently defined as 'a set of interrelated components working together toward some common objective' (Kossiakoff et al., 2011). A system is composed a number of interacting elements or subsystems (Kossiakoff et al., 2011), in this case the system is considered to be composed of three subsystems; the torso, the breast and the sports bra (Figure 1.1). The breast is attached to the torso, the sports bra encompasses both the breast and the torso.

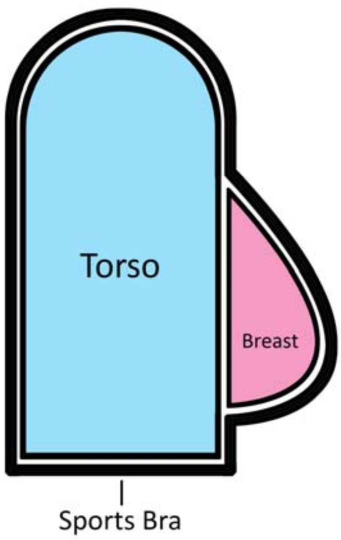


Figure 1.1 - Schematic of the breast - torso - sports bra system

The initial research focus was the torso, as it is commonly used as the reference frame from which breast motion is measured. After reviewing the literature, it was found that a standard method of tracking the torso and calculating relative breast motion was lacking (Scurr et al., 2009, Scurr et al., 2010b, Zhou, 2011, McGhee and Steele, 2010a). Therefore, the development of a torso marker set specifically for measuring breast kinematics and investigation into the effect of calculation method were identified as a key elements to advance the biomechanical assessment of sports bra performance. This lead to Research Question 1 being proposed.

The torso underlying the breasts forms the reference frame from which relative breast motion is measured. Within this process the torso is assumed to be rigid, however, the ribcage expands and contracts during respiration. Respiration is known to result in breast motion in a static situation (Chopra et al., 2006), however, whether respiration affects relative breast kinematic measurements during a dynamic situation is yet to be considered. Research Question 2 was proposed to address this gap in knowledge.

After developing a specific torso marker set and investigating the effect of breathing on relative breast kinematic measures, the research focus was placed upon tracking breast motion. The breast is a non-rigid body which varies in size, shape and tissue composition, however, breast motion is typically represented by a single breast marker (Lorentzen and Lawson, 1987, Starr et al., 2005, Campbell et al., 2007, McGhee et al., 2013, McGhee and Steele, 2010a, Scurr et al., 2009, White et al., 2009b, Scurr et al., 2010b, White et al., 2010). A small number of studies have utilised breast marker arrays, with variation in motion observed across the breast, however, the trends are currently unclear (Mason et al., 1999, Zhou et al., 2009, Zhou et al., 2012, Zhou et al., 2013). As Zhou et al. (2012) suggest, utilising multiple breast markers may provide additional information about breast motion to better assist bra design, and warrants further exploration. Wearing of a sports bra covers the breast surface making it difficult to track the breast directly using motion analysis markers. Markers placed over the bra are assumed to represent the underlying breast motion and that the breast does not move inside the bra if the bra is correctly fitted (Scurr et al., 2010a). These assumptions are yet to be explored within the literature and appear pertinent to progress within breast kinematic research. These observations lead to the proposal of Research Question 3.

The final research focus was to apply the processes developed through Research Questions 1-3 to assess sports bra performance, with a view to informing the sports bra design process. The literature review identified that sports bra studies have typically been limited to small number of very different bras (Lawson and Lorentzen, 1990, Starr et al., 2005, Zhou et al., 2009, Zhou et al., 2013). Therefore, the experimental variables of bra structure and mechanical properties were poorly controlled making it difficult to infer any relationships. A number of studies identify a strong positive relationship between decreased vertical breast displacement and reduced breast discomfort (Gehlsen and Albohm, 1980, Lorentzen and Lawson, 1987, Mason et al., 1999, McGhee et al., 2007, Starr et al., 2005, White et al., 2009b). Bra straps are thought to play an important role in limiting superior-inferior motion of the breast during running (Zhou and Yu 2013), however, experimental studies exploring this relationship have been very limited (Zhou et al., 2013). Research Question 4 was proposed in response.

1.4 Research Questions

In order to meet the research aim four research questions were proposed.

Q1. What does a torso marker set specifically developed for measuring breast kinematics look like and how does this compare to existing models?

Breast kinematics are typically measured relative to the torso. It is, therefore, necessary to track both torso and breast motion. Four different torso marker sets have been proposed within the literature, often with little evidence of their development or ability to track torso motion. There is also a lack of consensus over the method used to calculate relative breast motion. Therefore, the development of a torso marker set specifically for breast kinematics and investigation into the effect of calculation method on breast kinematics appear important to advance knowledge within this area.

Q2. Does breathing affect breast kinematic measurement during running?

The torso segment used to calculate relative breast kinematics is assumed to be rigid, however, as the ribcage expands and contracts during respiration some torso markers are likely to move, particularly those positioned over the ribcage. Respiration has been found to result in breast movement whilst static, however, the effect of breathing is yet to be considered when studying breast kinematics during dynamic activities (Chopra et al., 2006).

Q3. How does motion vary across the breast and do markers placed on the bra represent the underlying breast?

Tracking breast motion poses a number of challenges. Notably, the breast is a non-rigid body which varies in size, shape and tissue composition; whilst wearing of a sports bra covers the breast surface making it difficult to track the breast directly using motion analysis markers. However, breast motion is typically represented by a single breast marker and that marker is often placed over the bra if one is worn. Further understanding of breast motion and whether markers placed on the bra represent the underlying breast appear pertinent to advancing biomechanical assessment of sports bra performance.

Q4. How do mechanical properties of bra straps affect sports bra performance during running?

Sports bras are widely acknowledged to be more effective at limiting breast motion and reducing breast pain during exercise compared to an everyday bra (Mason et al., 1999). However, there is relatively little understanding of how specific aspects of sports bra design (structure and material properties) influence the mechanical properties of the bra and thereby its performance. Although a number of studies have sought to explore the relationship between biomechanical and perception data, this has typically been undertaken using very different bras, often with poor control of experimental variables (bra structure and mechanical properties) making it difficult to infer any relationships. Although the exact nature of the relationship is unclear a number of studies have identified a strong positive relationship between decreased superior-inferior breast displacement and decreased breast discomfort (Gehlsen and Albohm, 1980, Lorentzen and Lawson, 1987, Mason et al., 1999, McGhee et al., 2007, Starr et al., 2005, White et al., 2009b). Bra straps are thought to play an important role in limiting superior-inferior breast motion. Therefore, the relationship between the mechanical properties of sports bra straps and sports bra performance (breast kinematics and perceived support, comfort and fit) was investigated.

1.5 Overview of Chapters

This thesis contains eight chapters. This section includes an overview of chapters two to eight followed by a schematic of the thesis structure (Figure 1.2).

Chapter 2 - Literature review

This chapter presents a review of current sports bra and breast literature relevant to this thesis. Initially, the research contexts of the breast and sports bra are outlined. The factors driving sports bra research are then explored, focusing upon the three interlinking areas of comfort, injury and performance. Sports bra research is reviewed and covers human, mechanical and virtual testing modalities with focus placed upon human biomechanical testing. The chapter concludes with a summary of key outcomes; concentrating upon where current research has focused and where the gaps in the knowledge remain.

Chapter 3 - Human testing methods

The data collection and analysis methods used within human testing included within this thesis are presented. Breast and body kinematics were collected using a CODA motion analysis system. Details of the experimental set up, subject preparation, marker locations, descriptions of the test movements performed, selection of the sports bra tested and sports bra fitting protocol are included. The data analysis process is outlined for each study activity undertaken.

Chapter 4 - Development of a torso tracking model to measure relative breast kinematics

The absence of a universally accepted torso marker set for sports bra research, and information on the sensitivity of the breast kinematics to the selected torso model was identified as a limitation to current research. Therefore, a marker set was developed specifically to track the rigid body motion of the torso for the analysis of breast kinematics. Secondly, the sensitivity of breast kinematics to this torso tracking model was evaluated by comparing the present model with existing models from the literature. A new torso tracking marker set is recommended and implemented throughout the subsequent chapters of this thesis. This chapter addresses Research Question 1.

Chapter 5 - Does breathing affect breast kinematic measurements during treadmill running?

Breast kinematics are typically measured relative to a 'rigid' torso segment, however, this 'rigid' segment encompasses the ribcage which expands and contracts during respiration. There is evidence that breasts move during respiration whilst static in a supine position. However, the effect of breathing on breast motion during exercise is yet to be investigated. This chapter evaluates whether breathing affects relative breast kinematics measured during treadmill running and, if so, how this can be accounted for in the measurement process. Based on the findings a minimum number of gait cycles are suggested for analysis of breast kinematics during running. This is applied within all subsequent chapters. This chapter addresses Research Question 2.

Chapter 6 - The effect of breast marker position on relative breast kinematics

The breast is a complex structure varying in size, shape and composition, however, breast motion is typically represented by a single marker which is often placed over the bra if one is worn. Therefore, further understanding of breast motion and whether markers placed on the bra represent the underlying breast was identified as pertinent to developing the biomechanical assessment of sports bra performance. This chapter compares relative breast displacement measured using markers placed under bra versus over the bra, for different marker locations over the breast. The effect of bra fit on these findings was investigated using three differently sized bras; a well fitting bra, a size too small and a size too large. This chapter addresses Research Question 3.

Chapter 7 - The effect of bra strap stiffness on bra kinematics and perception measures during treadmill running

Although sports bras are widely acknowledged to reduce breast motion and discomfort during exercise, there is relatively little understanding of how a specific sports bra design (structure and material properties) affects performance. This chapter investigates the relationship between the mechanical properties of sports bra straps and sports bra performance (bra kinematics and perceived support, comfort and fit) during treadmill running. This chapter addresses Research Question 4.

Chapter 8 - Conclusions

This chapter presents a summary of the research outcomes, the novelty and implications of the work are identified. Future directions within sports bra research are suggested.

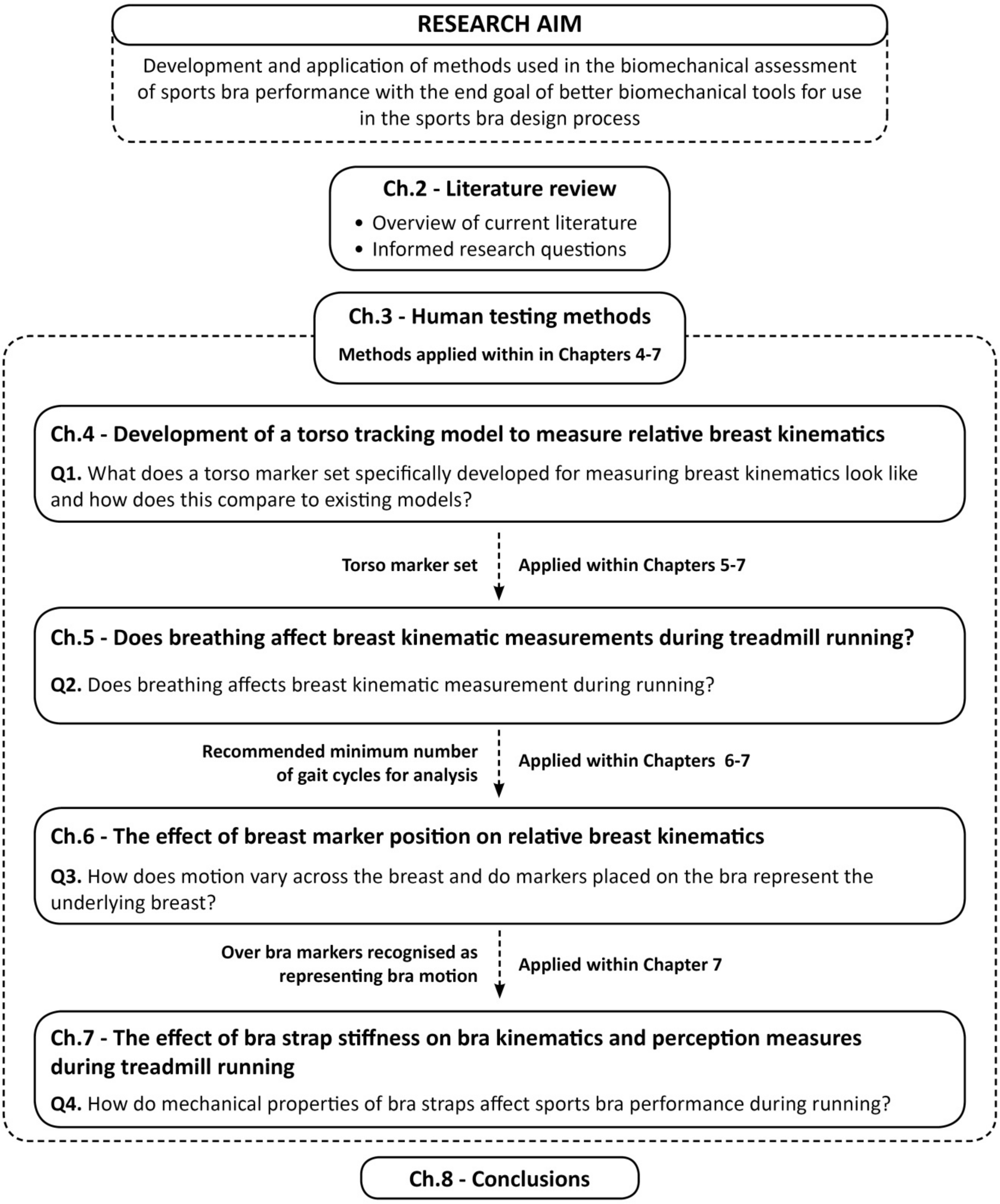


Figure 1.2 - Overview of thesis structure

Chapter 2

Literature Review

2.1 Introduction

This chapter aims to provide a review of the current sports bra and breast literature relevant to this thesis. Initially, the breast structure, physical properties and mastalgia (breast pain) are outlined. A brief overview of the torso underlying the breast and effect of respiration are provided, this is followed by an outline of sports bra design, components and sizing to give an understanding of the research context. The factors driving sports bra research are then explored, focusing upon the interlinking concerns of comfort, injury and performance. Sports bra research is reviewed and covers human, mechanical and virtual testing modalities. Finally, a summary of key outcomes is presented; concentrating on where current research has focused and where the current gaps in the knowledge remain. The literature review structure is illustrated below (Figure 2.1).

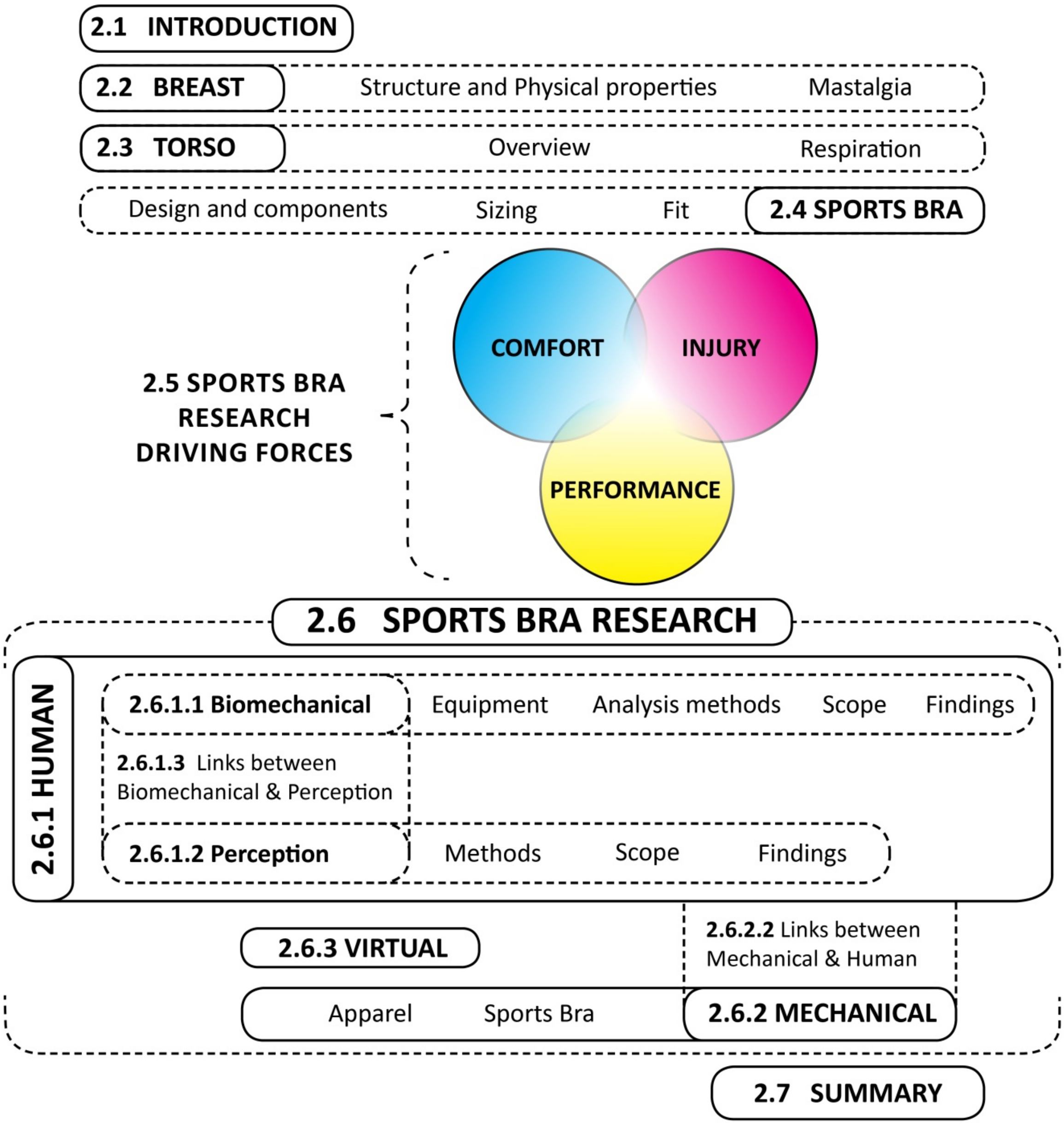


Figure 2.1 - Schematic of literature review structure

2.2 Breast

This section provides an overview of the breast structure, physical properties and mastalgia (breast pain).

2.2.1 Structure and Physical Properties

The mature female breast base extends from the 2nd to the 6th rib and from the midauxillary line to the sternum (Snell, 2004) (Figure 2.2). The breast has many anatomic variations with respect to volume, shape, width, length and projection, with a degree of asymmetry common between the two breasts (Snell, 2004, Avsar et al., 2010). Average breast volume have been reported between 325 cm^3 and 582 cm^3, however, the findings may be dependent on measurement method used and limited to a specific population studied (Qiao et al., 1997, Avsar et al., 2010, Kovacs et al., 2007, Hussain et al., 1999, Loughry et al., 1987).

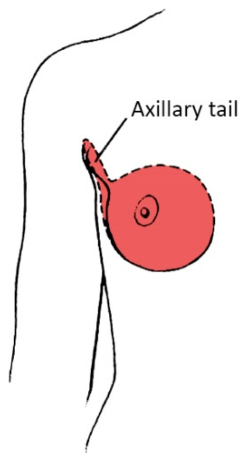


Figure 2.2 - Extent of breast tissue in a mature female (adapted from Snell (2004))

The breast contains 15 to 20 lobes (milk producing glands) connected to the nipple through a series of ducts. These lobes are surrounded by adipose tissue and it is estimated that 3.5% total weight of body fat and 12% of sex specific body fat are found in the breast (Katch et al., 1980). The breast tissue is enveloped between two layers of superficial fascia, known as the superficial and deep layers of the superficial fascia (Figure 2.3). The superficial layer runs along the anterior breast surface and is covered by a layer of fat (5 to 25 mm thick) and skin (Gefen and Dilmoney, 2007, Riggio et al., 2000, Mugea, 2009).

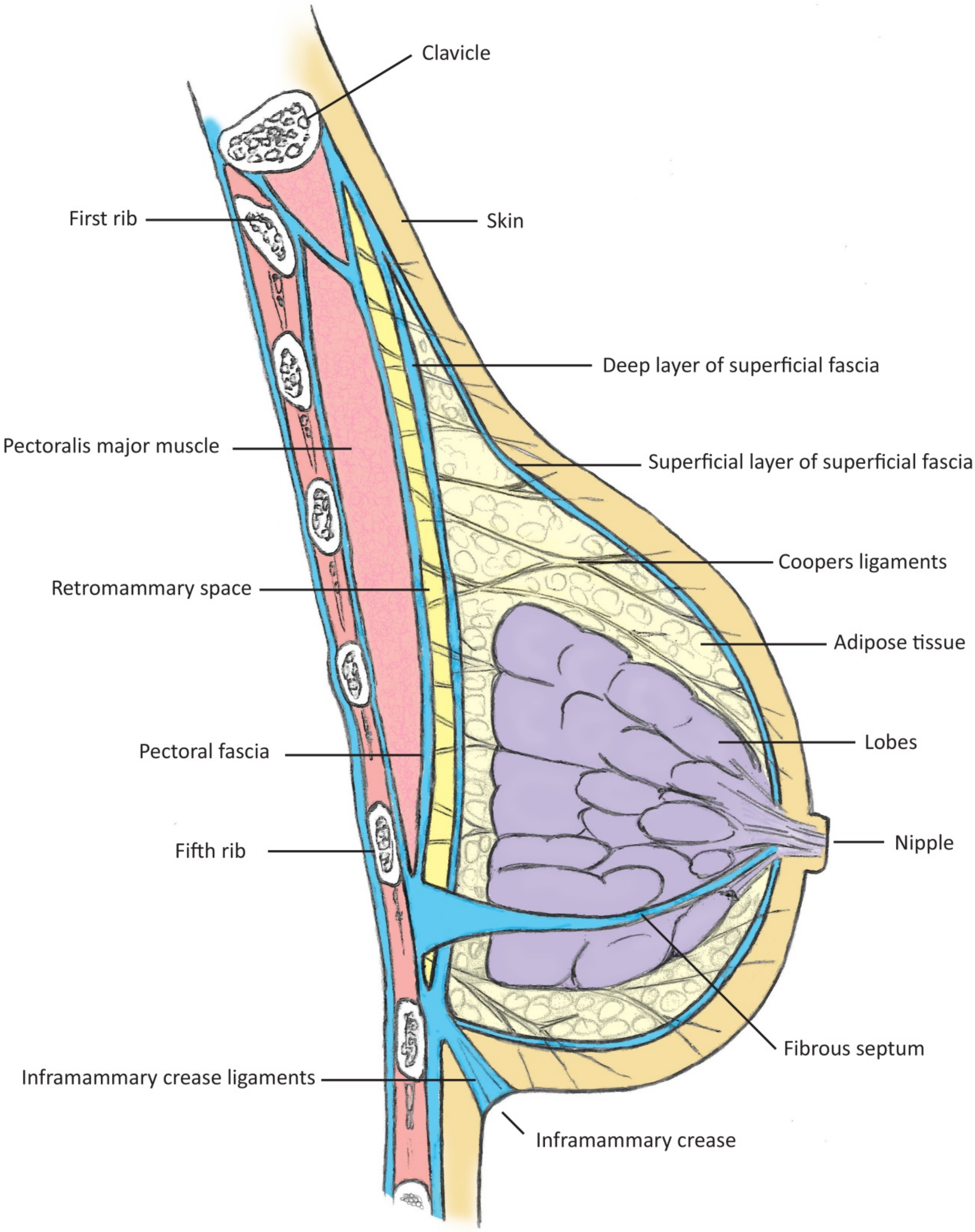


Figure 2.3 - Sagittal section of the breast (after Nahai (2010), Mugea (2009) and Riggio et al. (2000))

Whilst some debate remains over breast structure, studies have demonstrated the superficial fascia attaches to the musculature and skeletal structure at a number of different locations. Superior to the breast the two superficial fascia layers merge with the pectoral muscle fascia and attach to the clavicle (Figure 2.3) (Mugea, 2009). Medially both layers of superficial fascia attach to the sternum (Riggio et al., 2000). Posterior to the breast the deep superficial fascia is separated from the pectoral muscle fascia by the retromammary space, a loose areolar layer which allows the breast to glide over the chest (Ellis and Mahadevan, 2013). The Coopers ligaments run from the pectoral fascia through the retromammary space and breast tissue to the skin dermis connecting both layers of superficial fascia. The pectoral fascia firmly connects to the underlying pectoralis major muscle by numerous intramuscular septa, indicating a chain of attachment between the breast and skeletal structure (Stecco et al., 2009). The Coopers ligaments separate the lobes into compartments and are more developed in the upper breast, their connection through the retromammary space is not tight and therefore allows breast mobility (Mugea, 2009, Snell, 2004, Round, 2006, Gefen and Dilmoney, 2007). The superficial fascia layers join below the breast close to the inframammary crease, some studies have observed a connection (inframammary crease ligament) between the skin and the pectoral fascia in this area (Riggio et al., 2000, Jinde et al., 2006, Nahai, 2010).

A horizontal septum of thin connective tissue runs from the pectoral fascia attached to the fifth rib (costal origin of the pectoralis major) through the breast to the nipple (Figure 2.4) (Mugea, 2009, Jinde et al., 2006, Hamdi et al., 2005). The septum curves upward at its medial and lateral boarders to form vertical ligaments, creating a sling of dense connective tissue which attaches the breast to the thoracic wall (Hamdi et al., 2005, Würinger et al., 1998). The medial and lateral ligaments have been found to merge into the superficial fascia and Coopers ligaments, along with deep attachments medially at the sternum and laterally to the axillary fascia (Mugea, 2009, Hamdi et al., 2005). Superficial ligament attachments to the skin have been found medial, caudal and lateral to the breast. Mugea (2009) demonstrated that due the connection of suspensory ligaments raising the arms overhead causes the breasts to lift and nipple position to raise.

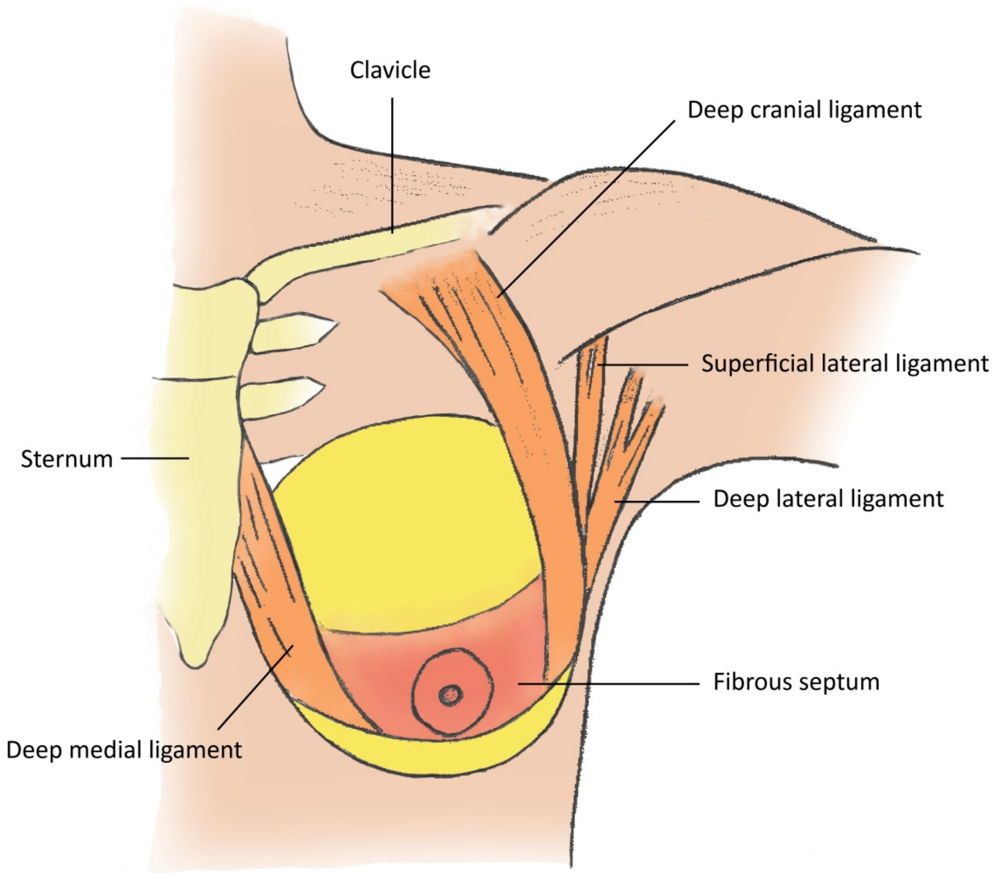


Figure 2.4 - Ligamentous suspension of the breast (after Mugea (2009) and Würinger et al. (1998))

Breast structure, size and composition change during the course of a woman's life. A reduction in the proportion of connective tissue and relative increase in adipose tissue with increasing age leads to breast sag (ptosis) (Round, 2006). Post menopause reduced levels of progesterone and oestrogen cause the lobes to atrophy, leaving adipose tissue and a reduced level of connective tissue (Shah et al., 2001, Snell, 2004). Therefore, participant age, menopause status and degree of breast ptosis may be relevant when designing experiments. During pregnancy breast size increases as the duct system lengthens and branches (Snell, 2004). Breast size also fluctuates during the course of the menstrual cycle, breast volume is smallest mid-cycle which is reported to increase by up to 40% in the week prior to menstruation, when progesterone levels are highest (Milligan et al., 1975, Hussain et al., 1999). The pattern of breast volume change can be altered by oral contraceptive use. Additionally, as the breast is a store of body fat changes in body fat levels can influence breast size. This highlights a number of considerations for sport bra research, for example scheduling test sessions consecutives days to minimise changes or at same point in the menstrual cycle.

2.2.2 Mastalgia

Mastalgia is a commonly occurring breast disorder classified into three forms; cyclical mastalgia, non-cyclical mastalgia and extramammary (non breast) pain. Cyclical mastalgia is breast pain clearly related to the menstrual cycle, normally it commences during the luteal phase (days 14 to 28) of the menstrual cycle and increases until the onset of menses (Smith et al., 2004, Mansel, 1994, Jernstrom and Olsson, 1997). Non-cyclical mastalgia is intermittent or constant breast pain not associated with the menstrual cycle and typically localised within a quadrant of the breast (Mansel, 1994, Harrison and Halliday, 2010). Extramammary pain may be due to a variety of conditions, commonly costochondritis (inflammation of joints between ribs and sternum) (Smith et al., 2004). The presence of mastalgia should be also be considered within sports bra research particularly if multiple test sessions are planned.

2.2.3 Summary of Breast

The breast is a complex structure containing milk producing glands, adipose tissue and connective tissues. The breast tissue is enveloped between two layers of superficial fascia which attach to skeletal structure at the clavicle and sternum. Coopers ligaments run from the pectoral muscle fascia through the breast to the superficial fascia separating glands into compartments. A horizontal septum also connects from pectoral fascia attached to 5th rib through the breast, this septum curves upward at the medial and lateral edges to form a ligamentous supportive sling. These suspensory ligaments have many attachments including at the sternum, axillary fascia, superficial fascia, coopers ligaments and skin. Breast structure, size and composition change during woman’s life and are affected by factors including menstrual cycle, pregnancy, menopause and changes in body fat. Mastalgia is a commonly occurring disorder relating to breast pain and occurs in three forms; cyclical mastalgia (related to menstrual cycle), non-cyclical (unrelated to menstrual cycle) and extra mammary pain.

2.3 Torso

This section provides an overview of the torso underlying the breast and the effect of respiration.

2.3.1 Torso Overview

The breasts are positioned on the torso, extending from the 2nd to the 6th rib and from the midauxillary line to the sternum (Snell, 2004) (Figure 2.2). The breast tissue connects to the torso skeletal structure through a series of fascial and ligamentous attachments outlined within §2.2.1 (Hamdi et al., 2005, Jinde et al., 2006, Mugea, 2009, Würinger et al., 1998).

Breast kinematics are typically measured relative to the torso, therefore, to investigate breast motion, it is necessary to track this torso motion using an appropriate marker set. This poses a number of challenges including the typically substantial amount of soft tissue in the torso region (Sohlstroem et al., 1993) and the wearing of a sports bra may limit marker position options. Movement of the torso is very complex as motion occurs at numerous small joints, and tracking single bones such as ribs, scapula or vertebrae in 3D is difficult, therefore, the torso is frequently assumed to be a single rigid body (Leardini et al., 2009, Konz et al., 2006). Methods of measuring relative breast motion and existing torso marker sets are discussed in greater detail within §2.6.1.1 and Table 2.3.

2.3.2 Respiration

The ribcage expands and contracts during respiration. The effect of breathing on breast motion has been studied in a static situation, in relation to medical imaging. Chopra et al. (2006) found during supine lying a maximum breast marker movement of 1, 2 and 2 mm occurred during normal breathing (medial-lateral, superior-inferior and anterior-posterior directions respectively), this increased to 2, 6 and 5 mm during deep breathing. However, the effect of breathing on the relative breast kinematics is yet to be considered.

2.3.3 Summary of Torso

The breasts are positioned on the torso, with a series of fascial and ligamentous attachments connecting the breast tissue to underlying skeletal structure. Breast kinematics are typically measured relative to the torso, therefore, torso motion to be tracked. This presents a number of challenges including high levels of soft tissue and presence of a sports bra obscuring the skin. The ribcage expands and contracts during respiration. Respiration has been reported to result in breast movement during a static situation (Chopra et al., 2006)., however, the effect of respiration on breast kinematic measurement during activity is yet to be considered

2.4 Sports Bra

This section provides an overview of sports bras including design, typical components and common bra sizing systems used.

2.4.1 Design and Components

The first sports bra is attributed to two American women, who in 1977 produced a prototype by stitching together two jock straps, a further advance was made with the introduction of Lycra ™ in the 1980's (Schuster, 1979, Pedersen, 2004). Sports bras have been typically been classified into either compression type where the breasts are flattened close to the chest, or encapsulation type where the breasts are individually supported (Page and Steele, 1999). However, many sports bras combine both compression and encapsulation. Typical bra components are illustrated in Figure 2.5. Research relating to the contribution of individual bra components has primarily focused upon the strap. Mechanical testing of bra straps is included in §2.6.2.1 and a virtual study of bra straps in §2.6.3.1. The effect of other components has been considered but as discussed in §2.6.1.1 experimental variables such as bra structure and mechanical properties were generally poorly controlled making it difficult to infer any relationships.

The primary function of a sports bra is to support the breasts during exercise. However, many other aspects must be considered in sports bra design; durability, washablity, commercial viability of manufacture, thermal and sensorial comfort plus fashion as an important driver of design decisions. Comfort is discussed in greater detail in §2.5.1.2.

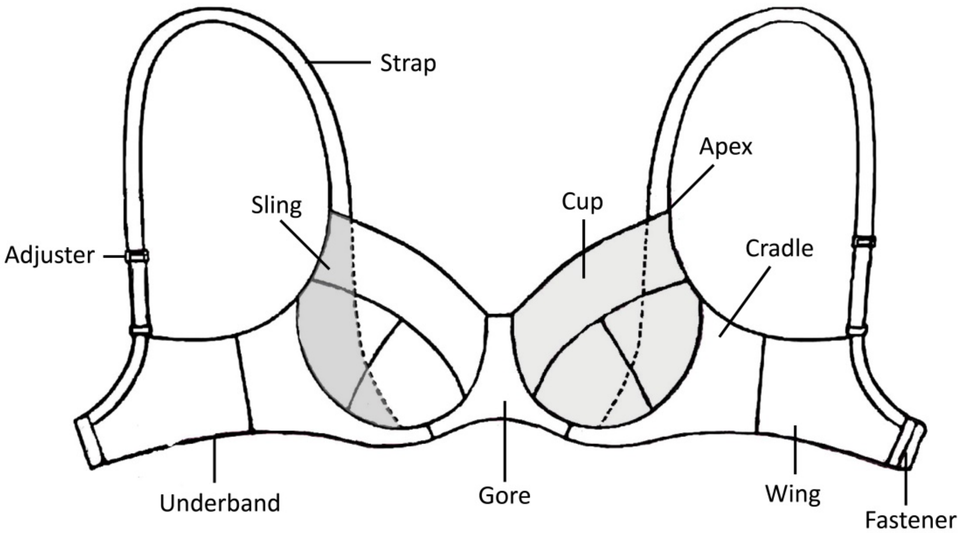


Figure 2.5 - Typical bra components

2.4.2 Sizing

The imperial bra sizing system, which specifies bras by underband and cup size, is widely used in the UK (Yu et al., 2006). The traditional method of bra sizing uses the under breast chest circumference measured in inches plus either four inches for an even number or five inches for an odd number to obtain the underband size. For example, under breast chest circumference measurements of 29” or 30” give an underband size of 34 (Yu et al., 2006). The over bust circumference, measured at the fullest part of the breasts is then subtracted from the underband size to determine the cup size (Table 2.1).

Table 2.1 - Imperial cup sizing system

Cup Size	AA	A	B	C	D	DD	E	F
Overbust measurement - Underband size (Inches)	-1	0	1	2	3	4	5	6

A number of difficulties have been identified with this sizing method; firstly the over bust circumference is likely to underestimate cup size for women with larger, more ptotic breasts (Pechter, 1999, Greenbaum et al., 2003). Secondly, respiratory state is not standardised; McGhee *et al* (2006) found that changing from voluntary expiration to voluntary inspiration resulted in an average error of one band size and one cup size. Several other methods have been developed with a view to improving the bra sizing system (Pechter, 1998, Zheng et al., 2007). However, both high street bra fitters and sports bra research have moved away from bra sizing through tape measurements towards visual inspection process to ensure the bra fits (discussed further in §2.5.1.2) (Bowles, 2012, McGhee and Steele, 2010b).

2.4.3 Summary of Sports Bra

The primary function of a sports bra is to support the breasts during exercise. Sports bras are commonly sized using the imperial system which specifies bras by cup and under band size. Traditionally bra size has been determined by tape measurements, however, sports bra research has tended to move away from this method towards a visual inspection process to ensure good bra fit.

2.5 Sports Bra Research Driving Forces

This section explores the forces driving sports bra research, a developing area which has received increased interest in recent years. Aspects contributing to this drive include exercise based health initiatives, a growing body of evidence that breast pain during exercise is a significant issue that may discourage women from exercising (Brown et al., 2013) and companies, in an increasing sports bra market, wanting to quantify the performance of their products.

Sports bra research undertaken has been directed by three interlinking factors; comfort, injury and performance (Figure 2.6). Comfort is a broad and multifaceted area which includes exercise induced breast discomfort, fit, thermal comfort, sensorial comfort (feel) and aesthetic appeal. Injury can relate to both direct breast tissue damage as a result of exercise and indirect injury resulting from inappropriate breast support worn. Performance incorporates the role of breast support on sporting performance and in removing barriers to exercise participation.

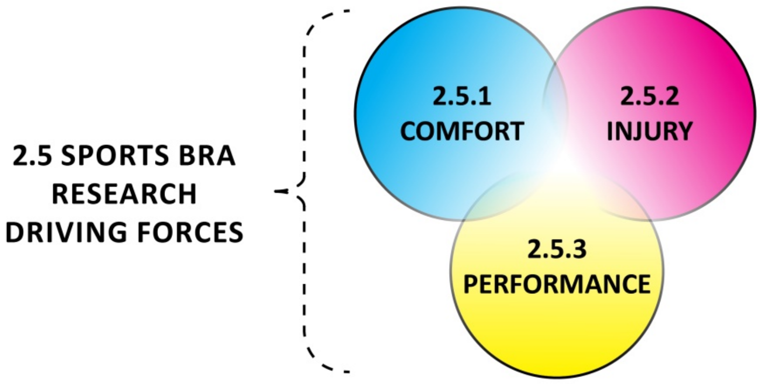


Figure 2.6 - Driving forces of sports bra research

2.5.1 Comfort

The concept of comfort will be discussed within the wider context of garments before focusing upon sports bras specific comfort.

2.5.1.1 Garment Comfort

Early comfort models suggest there are three main components that influence feelings of comfort: the individual, the environment and garment, and their interaction (Fourt and Hollies, 1970). This model has been refined through further development stages to represent greater interaction between the different elements and include physical, social and psychological aspects. Based upon conceptual models and focus groups both Schutz et al. (2005) and Webster (2010) identify four main aspects of comfort; Thermal comfort, Sensorial comfort (feel), Body movement comfort (fit and freedom of movement) and aesthetic appeal (appearance).

Within sports technology, Webster (2010) developed specific comfort models for personal protective equipment (cricket leg guards and taekwondo chest guards), which were subsequently used to inform the development of test protocols and produce a design specification. Factors contributing to player comfort were elicited using individual interviews, focus groups and co-discovery sessions. The data was analysed using an inductive process similar to that used by Roberts (2002) to explore player perception of golf clubs and Scanlan et al. (1989a, 1989b) to produce comfort models. The relative importance of each main factor was determined using an analytical hierarchy process.

The outcome of this process was to establish the key aspects which affect comfort and the language used to describe them which can then be used to implement quantitative testing.

2.5.1.2 Sports Bra

The four aspects of comfort outlined by Webster (2010) and Schutz et al. (2005); thermal comfort, sensorial comfort (feel), body movement comfort (fit and freedom of movement) and aesthetic appeal (appearance) have been touched upon within sports bra literature, however, a comprehensive exploration of sports bra comfort is lacking. This section focuses primarily upon the aspects of comfort considered, the methodology used to assess comfort within sports bra studies is covered in §2.6.1.2.

Thermal Comfort

The role of thermal comfort in sports bra comfort is acknowledged by a number of authors (Krenzer et al., 2005, Page and Steele, 1999, Starr et al., 2005). Thermal comfort has been the focus of two sport bra studies to date, both compared skin temperature and perceptual measures of thermal comfort between two sports bra material conditions (Ayres et al., 2013, Lin et al., 2015).

Sensorial Comfort (Feel)

The bra is an intimate garment worn next to the skin therefore sensorial comfort must be carefully considered, 'non-irritating' fabrics and careful positioning of seams, fasteners and underwire have been recommended (Page and Steele, 1999, Starr et al., 2005, Lorentzen and Lawson, 1987). A study of 1285 female marathon runners found 28% frequently experienced problems with sports bras rubbing or chaffing (Brown et al., 2013). This outlines the importance of sensorial comfort which if ignored may lead to minor injuries.

Body Movement Comfort

Within the context of sports bras body movement comfort can be considered to relate to bra fit, freedom of body movement and exercise induced breast discomfort. Bra fit and exercise induced breast discomfort have been more widely discussed in the literature.

A large percentage (66 – 100%) of women are reported to wear the incorrect bra size, with a negative correlation between increasing breast size and bra fit (Greenbaum et al., 2003, McGhee and Steele, 2006, Page and Steele, 1999, Wood et al., 2008, Spencer and Briffa, 2013). These findings are unsurprising given the complexity and limitations of the current sizing system, additionally bra fit can vary between different styles of bra even within the same brand (Greenbaum et al., 2003). These statistics should be viewed with some caution due to confusion over how bra size should be measured.

To date, studies have focused primarily upon assessing static rather than dynamic bra fit. Three bra fitting guidelines have been published for use in sports bra research; McGhee and Steele (2010b), White (2013) and Zhou et al. (2013). All are based upon the systematic visual inspection of key bra areas and are similar in content. The majority of recent publications by the three main sports bra research group implement their own fitting guidelines (Milligan et al., 2014a, Ayres et al., 2013, Mills et al., 2015b, McGhee et al., 2013, Zhou et al., 2013). Dynamic sports bra fit has been less widely considered within the literature. A number of studies have highlighted common problems relating to dynamic fit including; straps slipping off the shoulders, straps cutting into the shoulder and the under band 'creeping up' during activity (Bowles et al., 2008, Bowles et al., 2012, Boschma, 1994, Starr et al., 2005). Brown et al. (2013) found 75% of female runners surveyed prior to London marathon reported bra fit issues with problems more prevalent in larger bra sizes.

Exercise-induced breast discomfort has been a primary concern for sports bra research and has been reported to affect between 20% and 72% of women (Hunter and Torgan, 1982, Lorentzen and Lawson, 1987, Gehlsen and Albohm, 1980). At present the underlying cause of exercise induced breast discomfort is unknown, Gehlsen and Albohm (1980) cite three theories relating to muscle damage or spasm, whereas, Mason et al. (1999) suggest it results from stretching of the breasts anatomical structures (skin and coopers ligaments) (Figure 2.3). It is unknown whether exercise-induced breast discomfort is an indicator of injury to the breast.

It has been postulated that poor bra fit may reduce the ability of a sports bra to limit breast motion, and result in increased levels of breast discomfort (Page and Steele, 1999, Mason et al., 1999, White et al., 2009b). However, the relationship between bra fit and relative breast motion is yet to be explored. Within a clinical setting, improving bra fit has been found to help relieve mastalgia (Greenbaum et al., 2003, Hadi, 2000). Poor bra fit has been found to contribute to poor posture and injury including upper body musculoskeletal and nerve problems, presenting an important link between comfort and injury (Greenbaum et al., 2003, de Silva, 1986). Whilst the sports bra must restrict breast motion, it should not restrict the range of body motion or respiration as this may negatively impact sporting performance. Bra fit plays a key role in comfort, the possibility of injury and may potentially influence performance.

Aesthetic Appeal (Appearance)

Fashion is likely to be a major driver in sports bra design decisions. In addition to garment appearance, aspects such breast shape/lift given, the silhouette and appearance under clothes and visual effect on breast motion have been highlighted as significant considerations in bra selection (Lorentzen and Lawson, 1987, Krenzer et al., 2005, Risius et al., 2014).

2.5.2 Injury

This section will focus upon injury to the breast as a result of the sports bra and breast motion rather than contact injuries such as lacerations or contusions as documented by Haycock (1987).

2.5.2.1 Damage to Breast Tissue due to Exercise

It has been speculated that repeated loading of the breast support structures (such as skin and coopers ligaments) through excessive breast motion may cause permanent damage to these tissues and lead to breast ptosis (sag) (Mason et al., 1999, Page and Steele, 1999) (Figure 2.3). The wearing of sports bras during exercise has been promoted to prevent such injury, although the effect of breast support during exercise on breast structure has yet been studied. Many questions remain about the effect of breast motion on both short and long term breast structure and whether exercise-induced breast discomfort is an indicator of injury.

2.5.2.2 Role of Sports Bras in Injury

Sports bras have a potential role in both causing and helping prevent injury. Poor bra fit can lead to injury, for example, costoclavicular syndrome caused by excessively tight straps digging into the soft tissue of the shoulder leading to nerve damage, neck and back pain (de Silva, 1986). A study of pressure beneath sport bra shoulder straps during running reports that mean (0.52 – 1.06 N/cm^2) and maximal pressures (0.83 – 2.67 N/cm^2) exceed the threshold at which blood flow to skin can be occluded (0.4 N/cm^2) and in some cases 1.4 N/cm^2 which has been recommended as maximum continuous pressure to avoid tissue damage carrying a backpack (Bowles and Steele, 2013).

Poor bra fit has been found to contribute to poor posture and secondary musculoskeletal pain (Greenbaum et al., 2003). Women with large breasts are more likely to report thoracic pain; Spencer and Briffa (2013) found breast size was significantly positively associated with thoracic pain ($p = 0.002$). McGhee et al. (2013) suggest that sports bras may help larger breasted women achieve good posture and help prevent musculoskeletal pain. Sports bras may have an important role to play in improving posture and possibly preventing secondary musculoskeletal pain or injury. It is possible that improved posture may also transfer to a performance benefit.

2.5.3 Performance

The potential for sports bra design to affect sporting performance is currently an underexplored area within sports bra research. Poor breast support may negatively impact on sporting performance through pain inhibiting activity, breast movement influencing biomechanics and energy expenditure.

A small number of studies have considered the effect of breast support on aspects which may affect running performance including; kinematics, ground reaction force and upper body muscle activity. Boschma (1994) found vertical torso displacement decreased with decreased breast support in 9 of 15 subjects, and that this change was more apparent in C and D cup subject compared to smaller breasted subjects. However, for similar studies Milligan et al. (2015a) reported marginal differences in torso, pelvis and arm kinematics between breast support conditions and White et al. (2015) found no significant effect of breast support on torso kinematics. Studies also suggest increased breast support may increase peak vertical ground reaction force during running (Shivitz, 2001, White et al., 2009b). The effect of breast support on upper body muscle activity has been explored using surface EMG sensors and identified reductions in pectoralis major, anterior and medial deltoid activity with high breast support (Milligan et al., 2014a).

Bowles et al. (2005) investigated the common perception that sports bras are too tight and restrict breathing thus negatively affecting performance. However, VO_{2peak} measures during maximal exercise tests on cycle ergometer were not found to significantly differ between no bra and sports bra conditions. Similarly, no significant differences were observed between no bra, everyday bra or sports bra conditions for spirometry measures during submaximal treadmill running. The authors conclude that a correctly fitted sports bra has no negative effect on respiration.

Exercise induced breast discomfort and embarrassment due to excessive breast motion may be barriers to exercise participation or may reduce the enjoyment of exercise (Lorentzen and Lawson, 1987, Shivitz, 2001, Bowles et al., 2008, Yu et al., 2006). A survey of London Marathon participants found that 17% of women who suffered from mastalgia had missed an exercise session or had to adjust their training because of breast pain (Brown et al., 2013). Appropriate breast support may help women feel more physically and emotionally comfortable when exercising, therefore, reducing potential barriers to exercise participation.

2.5.4 Summary of Sports Bra Research Driving Forces

Sport bra research is a developing area which has received increased interest linked to health based initiatives and commercial research. The interlinking factors of comfort, injury and performance have driven research undertaken. The four aspects of garment comfort identified by Schutz et al. (2005) have been touched upon within sports bra literature although a comprehensive exploration of sports bra comfort is lacking. Body movement comfort has been most widely discussed and can be considered to relate to bra fit, freedom of body movement and exercise induced breast discomfort.

It has been widely speculated that repeated loading of breast support structures through excessive breast motion may lead to damage of the support tissues and cause breast ptosis. It is unknown whether exercise induced breast discomfort is an indicator of breast damage. The close connection between comfort and injury is demonstrated by examples of poor bra fit such as excessively tight shoulder straps leading to nerve damage. Conversely, sports bras may have a role in improving posture and help to prevent secondary musculoskeletal injuries. Improved posture and reduced exercise induced breast pain may mean also confer a role for sports bras in improving sporting performance.

2.6 Sports Bra Research

Sports bra research has included human, mechanical and virtual testing modalities, although the focus has primarily been upon human testing (Figure 2.7). The research methods, scope of studies and main findings are outlined for each test modality.

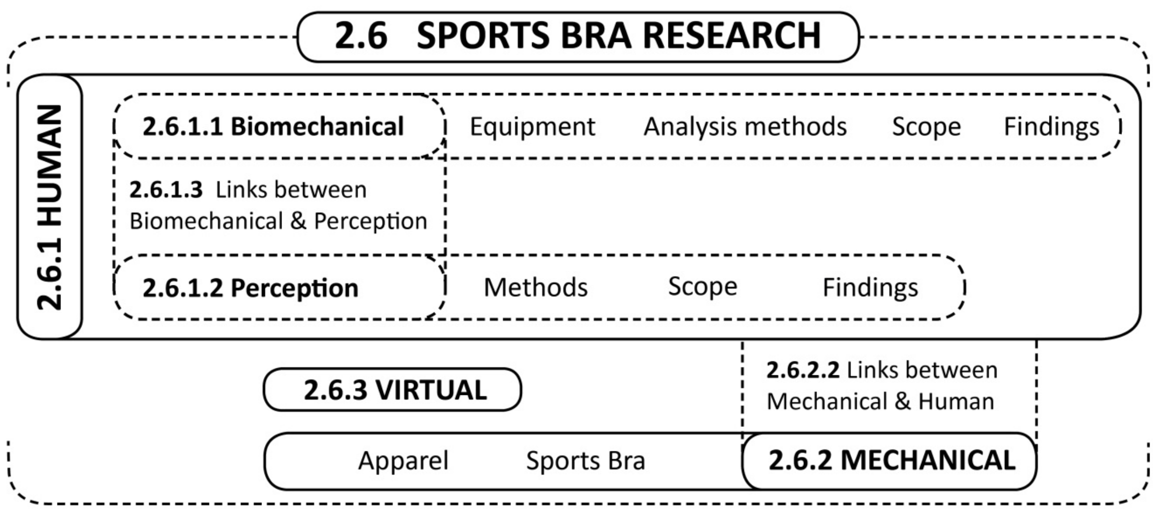


Figure 2.7 - Schematic of sports bra research

2.6.1 Human Studies

Sports bra research has primarily utilised human testing and can divided into two areas; biomechanical and perception testing.

2.6.1.1 Biomechanical

This section is presented in four sections, equipment, analysis methods, scope of studies and main findings.

Equipment

Within the existing literature four different types of equipment have been used to study breast biomechanics, however almost 80% of studies reviewed utilised opto-electronic motion analysis systems. These systems are categorised as passive or active systems depending upon the type of markers used. Other equipment used includes accelerometers, high speed video analysis and strain sensors. A summary of the equipment operation, previous applications, advantages and disadvantages is presented in Table 2.2.

Table 2.2 - Equipment types used within breast biomechanics studies - a summary of operation, previous applications, advantages and disadvantages

Method	Opto-electronic motion analysis systems		High Speed Video	Accelerometers	Strain sensors
	Passive	Active			
Operation	The retro-reflective markers reflect light back to the cameras to calculate 3D position of markers.	Markers emit an infra-red signal which is captured by the cameras to calculate the 3D position of markers.	Footage from high speed camera or multiple cameras synchronised to capture 3D motion. Footage must be digitized after data capture.	Accelerometers are sensors which generate an electrical signal in response to acceleration applied along the sensitive axis.	Strain sensors are most commonly based on piezoresistive or optical designs where a change in strain alters the output signal.
Previous applications	Widely used within breast kinematic and sports bra research, around 60% of studies reviewed utilise these systems (e.g. Scurr et al. (2010b), White et al. (2009b), Zhou et al. (2013)).	Primarily used by the Australian based research group, commonly used within the wider field of biomechanics (e.g. McGhee and Steele (2010a), Bowles and Steele (2013)).	High speed video has primarily been used within the early breast kinematic studies including (Gehlsen and Albohm, 1980, Boschma, 1994, Lorentzen and Lawson, 1987) and more recently for studies of water based activities (McGhee et al., 2007, Mills et al., 2014a).	Of the reviewed literature only Himmelsbach et al. (1992) use uni-directional accelerometers to measure breast acceleration. However, accelerometers are used within the wider field of biomechanics particularly to study impacts.	Within sports bra research Campbell et al. (2007) used polymer coated fabric strain sensors attached to the bra fabric. The integration of strain sensors within textiles is a developing area with potential applications within sports bra research.
Advantages	The small, low mass hemi-spherical markers minimise disruption to the subjects natural movement. The application of markers is relatively quick as markers are identified after data capture.	The markers signal travels through thin fabric therefore can be placed beneath some bras. Markers are relatively small and low mass.	High speed video can be used in a wide range of environments. It also allows visual inspection of how the breasts, bra and subject are moving.	May provide interesting information of soft tissue vibration of breasts	There is potential for fabric sensors to be integrated within the bra construction to create an instrumented bra that could be worn in a wide variety of test environments e.g In the field of play.
Disadvantages	Markers must be in view of the camera to collect data. Markers require labelling following data collection, which can be time consuming. Attaching markers with adhesive tape may locally affect material properties.	Markers are wired and have a small power box, therefore, may disturb the subjects natural movement. Markers must be in view of the cameras to record data. Attaching markers with adhesive tape may locally affect material properties.	Digitisation of footage can be very time consuming	Orientation of axes change with changes in torso or breast orientation. Attaching accelerometers with adhesive tape may locally affect material properties.	Campbell et al. (2007) found limitations of fabric sensor calibration need to be overcome and that the sensor was affected by environmental changes. The addition of fabric sensors to the bra may alter the bra material properties.

Analysis Methods

Breast kinematic studies to date have primarily focused upon treadmill running and have included speeds ranging between 3 km/h (walking) and 14 km/h (fast running), however, a variety of other activities have been studied including multi-directional running, jumping and water based activities. This section focuses upon analysis methods related to running, as the most commonly investigated movement, its popularity and relevance across a range of sports (Sport England, 2015).

Breast biomechanics are most usually studied by measuring breast motion relative to the torso, therefore, it is necessary to track the motion of both the breast and torso. Breast motion is typically tracked using a single marker most commonly at the nipple. Mason et al. (1999) recommended the nipple to be a good indicator of breast motion, based on their findings that greatest displacement occurred at the nipple and inferior breast during bare breast running. These findings were supported by Eden et al. (1992) and Zhou et al. (2009) for markers located on the exterior of a sports bra. However, the methods used within these studies did not track the six degrees of freedom motion of the torso as only one or two torso tracking markers were used. Zhou et al. (2013) and (2012) questioned the validity of a single marker to represent whole breast movement and suggested that information pertinent to bra design could be gained by using an array of breast markers.

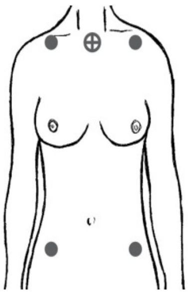
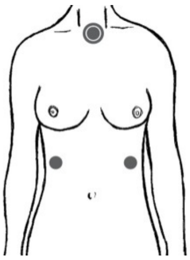
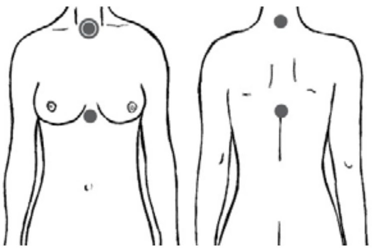
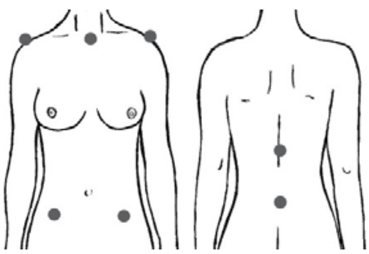
The majority of studies reviewed utilised markers attached onto the bra exterior rather than on the breast surface under the bra. This may be necessitated by the equipment used, for example, retro-reflective markers used within passive motion capture systems will not work if obscured beneath a bra. Presently, markers placed over the bra are assumed to represent the underlying breast motion and that movement of the breast inside the bra should not occur if the bra is well fitted (Scurr et al., 2010a). However, the studies of Shivitz (2001) and Zhou et al. (2013) suggest this is an area that warrants further investigation. Shivitz (2001) observed for running in a low support bra that in a number of larger breasted subjects the breast appeared to move around within the bra. The biomechanical data for these subjects showed less breast displacement in low support compared to medium support bra, a finding which conflicted with the results of other subjects. The author attributed the surprising result to fact that the breast marker was attached over the bra and, therefore, less breast displacement was measured due to relative movement between breast and bra. Zhou et al. (2013) compared breast displacement at six locations during running for bare breasted (using markers located on the skin) and for a sports bra condition (using markers over the bra). They found motion of the over bra markers was reduced in comparison to the bare breast condition, but observed markers at the upper breast reduced by a lower percentage compared to other areas of the breast. The authors suggested this may have resulted from the breast and upper cup separating as the body moved upwards during running. Within related literature, Mills et al. (2011) used markers both under and over compression shorts to measure soft tissue movement during a drop landing. Markers were placed in pairs (one marker attached to skin the other over the garment) with 3 cm superior-inferior (S-I) separation at five anatomical locations. The maximum change in separation between markers averaged across the five anatomical locations were (mean, SD); no compression (3.3 ± 0.6 mm), medium (4.4 ± 1.5 mm) and high (2.6 ± 0.6 mm). The maximum change in separation was significantly reduced from no compression to high compression and medium to high compression, leading the authors to recommend the method is sufficiently sensitive to monitor soft tissue movement under compression shorts. However, no significant difference was observed between medium and no compression conditions. The authors suggest the greater standard deviation observed in medium compression may be due to independent movement or sliding of garment over skin but do not comment upon the increased change in separation.

In order to measure relative breast motion the torso motion must also be tracked. Early breast biomechanics studies typically used a single torso tracking marker, however, it is common practice to track the torso segment using multiple markers to allow its six degrees of movement to be quantified. Four different torso marker sets have been proposed in the existing literature for quantifying relative breast motion (Table 2.3) (Scurr et al., 2009, Scurr et al., 2010b, McGhee and Steele, 2010a, Zhou, 2011). Interestingly, they generally provide little evidence for how they were developed and how well they are able to track the torso movement. The main exception to this is the marker set proposed by Zhou (2011) which is based on the International Society of Biomechanics standard (Wu et al., 2005). However, this recommendation was based on the work of van der Helm

(1997) to measure shoulder motion not specifically breast motion. It may be inappropriate for this purpose as the xiphoid process marker is likely to be occluded by bra particularly in women with large ptotic breasts. The Portsmouth based research group initially used the Scurr et al. (2009) torso model, which comprises of the clavicles superior to the nipple and midpoint between ASIS markers (Scurr et al., 2009). As discussed in §2.2.1, the breast tissue is enveloped by two layers of superficial fascia, these layers merge with the pectoral fascia close to its attachment to the clavicle (Figure 2.3). This suggests the clavicle may be an appropriate anatomical position to track relative breast motion. However, the ASIS markers represent the pelvis segment rather than torso segment underlying the breasts, and are likely to misrepresent the ribcage if the spine is arched forwards or backwards. This may have led the Portsmouth research group to change to the Scurr et al. (2010b) model to better represent the torso segment underlying the breasts. The suprasternal notch and anterior inferior aspects of the 10th ribs, appear to be practical marker locations as the superficial fascia which envelopes the breast attaches to the sternum and breast overlies the rib cage (Figures 2.3 and 2.4). However, a limitation of this model is that it only uses three markers, therefore, if any marker is obstructed the local coordinate system (LCS) cannot be calculated. The torso tracking model of McGhee and Steele (2010a) is quite heavily dependent upon markers placed on the on pelvis (ASIS and sacrum) and lower back (L5) which may poorly represent torso segment under lying breasts.

Within the wider field of biomechanics, relatively little attention has been given to the development of protocols to measure trunk kinematics within standard gait analysis (Leardini et al., 2009). To date, torso tracking models have largely been associated with specific clinical problems (Ferrarin et al., 2002, Bartonek et al., 2002, Leardini et al., 2009). Leardini et al. (2009) analysed eight different models taken from the literature or personal communications which included Davis III (2005), Fantozzi et al. (2003), Ferrarin et al. (2002), Ferrarin et al. (2004), Nguyen and Baker (2004), Wu et al. (2005) and Baker (2006). Markers from these models were applied as a single marker set and trunk kinematics for each model. Unsurprisingly, trunk motion measured using the different models was found to be very dissimilar, large differences in range of motion and different patterns of motion were observed.

Table 2.3 - Summary of torso tracking models previously used to assess breast kinematics during running

Author	Diagram	Marker locations, LCS and Method
Scurr et al. (2009)		**Marker locations** - Clavicles superior to the nipple and the midpoint between anterior superior iliac crests (ASIS). **LCS** – Origin at midpoint between clavicle markers. Clavicle markers create medial-lateral (M-L) axis. Frontal plane defined by clavicle markers and midpoint of ASIS markers. Anterior-posterior (A-P) axis perpendicular to frontal plane, superior-inferior (S-I) axis perpendicular to M-L and A-P axes. **Method** – Direct POSE estimation
Scurr et al. (2010b)		**Marker locations** - Suprasternal notch and the anterior inferior aspects of the 10th ribs. **LCS** – Origin at suprasternal notch. M-L axis created between rib markers. Frontal plane created by all three markers. A-P axis perpendicular to frontal plane, S-I axis perpendicular M-L and A-P. **Method** – Direct POSE estimation
Zhou (2011)		**Marker locations** - Incisura jugularis (IJ), xiphoid process, C7 and T8 vertebrae. **LCS** – Origin at IJ. S-I axis is aligned parallel to a line (Y_t) between midpoint of IJ and C7 and midpoint of xiphiod process and T8. A sagittal plane was created using line Y_t and IJ, the M-L axis was aligned perpendicular to this plane. A-P axis was aligned perpendicular to S-I and M-L. **Method** – Segment optimisation POSE estimation
McGhee and Steele (2010a)		**Marker locations** - Suprasternal notch, acromion processes, iliac crests (ASIS), T12 and L5 vertebrae. **LCS** – No details of the LCS were provided. **Method** - Segment optimisation POSE estimation

Relative breast motion has been calculated using three different methods to measure relative breast displacement; global separation, direct POSE estimation (direct) and segment optimisation POSE estimation (optimised) (Table 2.4). The first method, primarily used within early studies, provides the position of the breast marker relative to a single torso marker within the global coordinate system and cannot account for torso rotation. The direct method recalculates the position and orientation of the torso LCS for each frame, whereas segment optimisation POSE estimation method assumes the torso to be a rigid segment.

Mills et al. (2014c) found that for running the segment optimised POSE method produced lower values of breast displacement compared to the direct method, the greatest difference (11 mm) occurred in the superior-inferior (S-I) direction during bare breasted running. Using the direct method torso markers were found to move relative to each other and torso length changed by up to 34 mm. The direction in which greatest displacement occurred was also observed to differ depending upon method used; for the bare breasted and everyday bra conditions displacement was greatest in the medial-lateral (M-L) direction using segment optimisation method but greatest in the S-I direction for the direct method. The authors advised using the segment optimised method to minimise differences in relative breast motion due to changes in torso segment deformation particularly between different activities. Although torso length defined using the direct method changed during running, torso length was not found to be significantly affected by breast support condition. Therefore, the authors suggest this method may be suitable when comparing breast motion between different bra conditions.

The LCS of the trunk segment has been defined using two main methods; using either the medial-lateral (Scurr et al., 2010a) or superior-inferior axis (Zhou et al., 2013) as primary reference axis. When comparing the two methods Mills et al. (2014b) found the definition used significantly affected the S-I breast displacement recorded and altered the direction in which the greatest breast displacement was observed. In accordance with Kontaxis et al. (2009) the authors suggest the 'stable' longitudinal axis should be defined as the first rotational axis. Calculation and LCS definition methods used to measure relative breast motion have been found to affect both the magnitude and direction of breast displacement reported, therefore, caution should be exercised when comparing data from studies which use different methods.

To date, the effect of breathing on relative breast motion has not been considered. However, the effect of breathing on breast motion in a static condition has been more widely studied in relation to imaging and radiotherapy treatment of breast cancer (Price et al., 2009, Chopra et al., 2006). During supine lying Chopra et al. (2006) found maximum breast marker movements of 1, 2 and 2 mm during normal breathing (medial-lateral, superior-inferior and anterior-posterior directions respectively) increasing to 2, 6 and 5 mm during deep breathing.

Typically the range of motion / peak breast displacement, velocity and acceleration are determined on a per gait cycle basis and then averaged over several gait cycles (Scurr et al., 2010a, McGhee and Steele, 2010a). However, the number of gait cycles analysed varies considerably between studies and as present there is no published research to establish a minimum sample length (Table 2.4).

Breast biomechanics studies have typically been conducted over relatively short periods of running (up to 5 minutes) with around 2 minutes being usual. Interestingly, Bowles (2003), reports that S-I separation between torso marker and breast significantly increased following 5 minutes of bare breasted running. This is supported by Milligan et al. (2015b) who found a significant increase in multiplanar breast kinematics for both sports bra and everyday bra conditions over the course of a 5 km run. The greatest increase in breast motion occurred between 2 minutes (322 m) and 1 km (~7 minutes) with most measures plateauing after 2 km (~13 minutes), therefore, Milligan et al. recommend trials include at least 7 minutes (~1 km) of running. The authors suggest these changes may be due to a small degree of tissue strain resulting from repeated loading or changes in tissue properties associated with increased in temperature. Increased temperature and sweat absorption may also have influenced the bra mechanical properties. However, it should be noted that gait variables or torso kinematics were not measured during either study, therefore, changes in breast kinematics may have resulted from altered body position or movements as the subject warmed up or fatigued.

Relatively few breast biomechanics studies report gait variables during the sample period (Table 2.5). As high levels of exercise-induced breast pain are frequently reported in bare breasted or low breast support conditions, subjects may modify their running style to reduce their discomfort thus affecting the breast biomechanics measures recorded. Including measures of gait variables may help identify such cases.

Table 2.4 - Summary of methods used within biomechanical sports bra studies

Study	Activity	Breast marker Location and attachment (Under/ Over bra)		Torso marker	Method	Filter	Sample analysed	Gait variables		
Boschma (1994)	10.3 km/h Treadmill running	Nipple	O	Sternum	GS	2-9 Hz	5 Gait cycles	Yes	p	F
Boschma et al. (1994),	10.3 km/h Treadmill running	n/s	O	n/s	n/s	n/s	5 Gait cycles	Yes		F
Bowles (2003)	Treadmill running	Nipple	n/s	Sternal notch	GS	n/s	15 s	n/s	p	
Bowles and Steele (2013)	Treadmill running - self selected pace (6.3 - 8.5 km/h)	Nipple	U	Sternal notch	GS	n/s	5 Gait cycles	n/s	p	
Bridgeman et al. (2010)	2 Step star jumps	Nipple	O	Scurr et al. (2009)	D	n/s	n/a	n/s	p	
Campbell et al. (2007)	7 km/h Treadmill walking 10 km/h Treadmill running	Nipple	U	Sternal notch	GS	n/s	10 s	Yes		
Eden et al. (1992)	9.6 km/h Treadmill running – stride rate self selected (X=85) and fixed 96	5 Markers	O	Sternal notch and proximal clavicle	n/s	n/s	n/s	n/s		F
Gehlsen and Albohm (1980)	10.3 km/h Treadmill running	Breast centre	O	Centre of left clavicle	GS	n/s	1 Gait cycle	Yes		
Gho et al. (2011)	Treadmill running – self selected pace	Nipple	U	Sternal notch	GS	n/s	5 Gait cycles	n/s		
Haake and Scurr (2010)	10 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	D	10 Hz	30 s	Yes		
Haake and Scurr (2011)	Static drop of breast 4 km/h Treadmill walking 7 km/h Treadmill walking 10 km/h Treadmill running 14 km/h Treadmill running	Nipple	O	Sternal notch	GS	n/s	n/s	n/s	p	
Haake et al. (2012)	Static drop of breast 10 km/h Treadmill running 14 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	D	10 Hz	10 Gait cycles	n/s	p	
Himmelsbach et al. (1992)	9.6 km/h Treadmill running	Medial nipple	O	Proximal sternum, sternum	GS	7 Hz	n/s	n/s		F
Knight et al. (2014)	10.1 km/h Treadmill running Static breast drop Counter movement jump	Nipple	O	Scurr et al. (2010b)	GS	7-10 Hz	n/s	n/s	p	
Lawson and Lorentzen (1990)	10.1 km/h Treadmill running	Nipple	O	Sternum	GS	n/s	3 Gait cycles	n/s	p	
Lorentzen and Lawson (1987)	10.3 km/h Treadmill running	Nipple	O	Sternum	GS	n/s	1 Gait cycle	n/s	p	
Mason et al. (1999)	7 km/h Treadmill walking 10 km/h Treadmill jogging 13 km/h Treadmill running Aerobics march	5 Markers	O	Sternal notch	GS	4 Hz	2 Gait cycles	n/s	p	F
McGhee et al. (2007)	Treadmill running - self-selected pace Aquajogging	Superior breast (4-5th rib)	U	Sternum (3rd rib)	GS	n/s	7.5 Gait cycles	Yes	p	
McGhee et al. (2010)	Treadmill running	n/s		n/s	n/s	n/s	n/s	n/s	p	
McGhee and Steele (2010a)	Treadmill running - self selected pace (mean 8.3±1.3 km/h)	Nipple	U	McGhee and Steele (2010a)	S	10 Hz	≥ 30 Gait cycles	Yes	p	
McGhee et al. (2013)	8-9 km/h Treadmill running	Nipple	U	Sternal notch	GS	10 Hz	30 breast cycles	n/s	p	
Milligan et al. (2014b)	Treadmill running – self selected pace (mean 9 km/h)	Nipple	O	Scurr et al. (2010b)	S	13 Hz	5 Gait cycles	n/s		

n/s = Not stated N/A = Not applicable O = Attached over bra U = Attached to skin under bra GS = Global separation D = Direct POSE estimation S =Segment optimisation POSE estimation p = Perception data also collected F= Funded by commercial partner

Table 2.4 (Continued) - Summary of methods used within biomechanical sports bra studies

Study	Activity	**Breast marker** Location and attachment (Under/ Over bra)		Torso marker	Method	Filter	Sample analysed	Gait variables		
Milligan et al. (2015a)	Treadmill running – self selected pace (mean 9 km/h)	Nipple	O	Scurr et al. (2010b)	S	8 Hz	5 Gait cycles	Yes	p	
Milligan et al. (2015b)	Treadmill running - self selected pace (mean 9 km/h)	Nipple	O	Scurr et al. (2010b)	S	13 Hz	5 Gait cycles	n/s		
Mills et al. (2014a)	Swimming (front crawl and breaststroke)	Nipple	O	Scurr et al. (2010b)	D	8 Hz	2 Stroke cycles	N/A		F
Mills et al. (2014b)	10.1 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	D	13 Hz	5 Gait cycles	n/s		F
Mills et al. (2014c)	10.1 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	S & D	13 Hz	5 Gait cycles	n/s		F
Mills et al. (2015b)	10 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	D	13 Hz	5 Gait cycles	n/s	p	
Mills et al. (2015a)	Continuous vertical jumps with arms overhead – land based and water based	Nipple	U	Scurr et al. (2010b)	D	8 Hz	3 jumps	Yes	p	
Risius et al. (2014)	10 km/h Treadmill running Counter movement jump Agility T-test (3 x 3 m)	Nipple	O	Scurr et al. (2010b)	S	13 Hz	5 Gait cycles	n/s		F
Scurr et al. (2007b)	Treadmill running - 5 km/h increased by 1 km/h until stop	Nipple	O	Scurr et al. (2009)	n/s	n/s	5 Gait cycles	Y		
Scurr et al. (2008)	10.1 km/h treadmill running	Nipple	O	Origin at right clavicle	n/s	n/s	5 Gait cycles	n/s		
Scurr et al. (2009)	5 km/h Treadmill walking 10 km/h Treadmill running	Nipple	O	Scurr et al. (2009)	D	n/s	6 Gait cycles	Yes		
Scurr et al. (2010a)	10.1 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	D	10 Hz	10 Gait cycles	Yes	p	
Scurr et al. (2010b)	Treadmill running - 5 km/h increased by 1 km/h until stop	Nipple	O	Scurr et al. (2010b)	D	10 Hz	5 Gait cycles	Yes		
Shivitz (2001)	10.3 km/h Treadmill running	Nipple	O	Sternum	GS	60 Hz (force plate)	45 Gait cycles	Yes		
Starr et al. (2005)	Treadmill running (speed n/s)	Bust points	O	Acromion processes, sternal angle	GS	n/s	3 Gait cycles	n/s		
White et al. (2009a)	10.8 km/h Overground running	Nipple	O	Scurr et al. (2009)	D	n/s	2 Gait cycles	n/s	p	
White et al. (2010)	Counter movement jumps Agility T- test (3 x 3 m)	Nipple	O	Scurr et al. (2010b)	n/s	n/s	n/a	n/s	p	
White et al. (2011)	11.2 km/h Treadmill running 11.2 km/h Over ground running	Nipple	O	Scurr et al. (2009)	D	n/s	5 Gait cycles 1 Gait cycle	Yes	p	
White et al. (2015)	9.3 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	D	13 Hz	5 Gait cycles	Yes	p	
Wood et al. (2012)	10.1 km/h Treadmill running	Nipple	O	Scurr et al. (2010b)	D	10 Hz	5-10 Gait cycles	n/s		
Zhou et al. (2009)	Treadmill walking - self selected pace Treadmill running - self selected pace Step ups (24 cm box)	6 Markers	O	Sternal notch	GS	n/s	n/s	n/s		
Zhou et al. (2013)	3 km/h Treadmill walking 7 km/h Treadmill jogging Step ups (24 cm box)	6 Markers	O	Zhou (2011)	S	8 Hz	10 Gait cycles	n/s		
Zhou et al. (2012)	7 km/h Treadmill jogging	6 Markers	O	Zhou (2011)	S	8 Hz	≥ 15 Gait cycles	n/s		

n/s = Not stated N/A = Not applicable O = Attached over bra U = Attached to skin under bra GS = Global separation D = Direct POSE estimation S =Segment optimisation POSE estimation p = Perception data also collected F= Funded by commercial partner

Table 2.5 - Gait variables reported within breast biomechanics studies

	Gait		Torso		Pelvis	Upper arm
Study	**Cadence**	**Stride length**	**S-I displacement**	**Anterior-posterior lean, lateral bend and axial rotation**	**ROM**	**ROM**
Boschma (1994)	x	x	x			x
Campbell et al. (2007)			x			
Gehlsen and Albohm (1980)			x			
Haake and Scurr (2010)			x			
McGhee et al. (2007)	x					
McGhee and Steele (2010a)	x					
White et al. (2011)	x	x				
Milligan et al. (2015a)			x	x	x	x
Mills et al. (2015a)			x			
Scurr et al. (2007b)	x		x	x		
Scurr et al. (2009)	x			x		
Scurr et al. (2010a)			x			
Scurr et al. (2010b)			x			
White et al. (2015)	x		x	x		x

Scope of Biomechanical Studies

This section provides an overview of the scope of biomechanical sports bra studies to date. Of the studies reviewed nine were commercially funded, therefore, the direction may have been somewhat driven by commercial interest. Comparatively little research has been published regarding the development of sports bra testing methodology.

A substantial focus has been placed upon understanding of bare breast biomechanics and the effect of breast support on breast motion. This drive may be linked with commercial partners seeking product validation or data for marketing material. The studies have generally been limited to a small number of very different bras with experimental variables such as bra structure and material properties poorly controlled making it difficult to infer any relationship between bra design and breast motion. A smaller number have studied the effect of breast support on body motion including ground reaction force and limb kinematics during running (Shivitz, 2001, White et al., 2015, Milligan et al., 2015a).

Although emphasis has been placed upon breast biomechanics during running, activity type in addition to running speed and duration have also been investigated as a study variables (Scurr et al., 2010b, Milligan et al., 2014b, Risius et al., 2014). The scope of these studies has been varied and included: understanding breast motion during multidirectional movement used within sport; the exploring activity specific breast support; and the development of test protocols for laboratory research and within the confines of a changing room.

The effect of breast size is often included as a study variable with subjects commonly grouped as 'small' or 'large' breasted by cup size with 'large' defined as either ≥ C cup (McGhee et al., 2007, McGhee and Steele, 2010a) or ≥ D cup (Lorentzen and Lawson, 1987, Scurr et al., 2010a).

Findings

This section summarises the main findings of biomechanical studies. As previously discussed, a number of different analysis methods have been used within the literature, therefore, it is difficult to compare the absolute magnitudes of breast biomechanics measures reported between studies. Thus, this section focuses upon the more general findings and trends reported.

Displacement

Relative breast displacement is the most commonly reported parameter and the sole focus of early breast kinematic studies. Breast motion has been described over one gait cycle (period of locomotion from one foot contacting the ground to the same foot contacting the ground again), with a double peak in the S-I direction and single peaks occurring in anterior-posterior (A-P) and M-L directions (Figure 2.8a) (Scurr et al., 2009, Scurr et al., 2010a). Medial-lateral and anterior-posterior breast motion has been found to be asymmetrical with single peaks in lateral and posterior displacement occurring following same side foot contact as the breast studied (i.e. right foot and right breast) (Scurr et al., 2009). Similarly, S-I displacement has been found to differ between same side foot contact and collateral foot contact (Boschma, 1994, Mason et al., 1999).

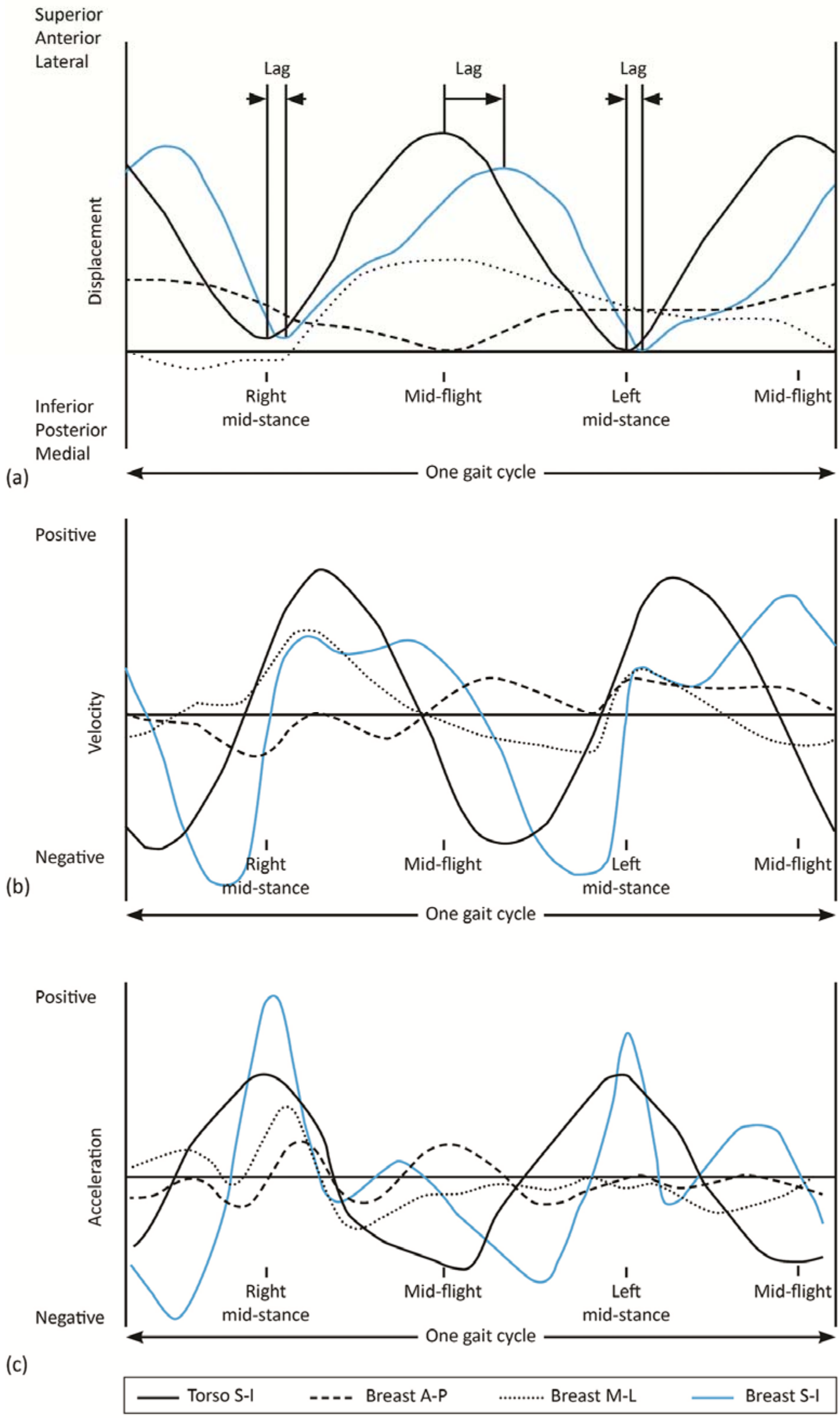


Figure 2.8 - Schematic of typical right breast relative kinematics during one gait cycle of bare breast running (a) Displacement (b) Velocity (c) Acceleration (adapted from Scurr et al. (2010a) and Scurr et al. (2009))

It is widely acknowledged that wearing of a bra reduces breast displacement compared to bare breasted condition and that sports bras reduce displacement to a greater extent compared to an everyday bra. This change in breast support has been reported to primarily affect displacement in the superior-inferior direction (Haake and Scurr, 2010, Scurr, 2007, White et al., 2009a, Mason et al., 1999, Boschma, 1994, Shivitz, 2001, Scurr et al., 2010a, White et al., 2011, Gho et al., 2011, White et al., 2015). However, significant reductions have also been reported in the anterior-posterior direction (White et al., 2009a, Scurr et al., 2010a, White et al., 2011, White et al., 2015) and the medial-lateral direction (White et al., 2009a, White et al., 2011, White et al., 2015). The percentage reduction in breast displacement between no bra and a test bra condition has been commonly used as in indicator of a sports bra performance (Zhou et al., 2009).

Studies utilising an array of breast markers have found breast displacement differs across the breast, however, the trend in displacements across the breast remains unclear. Greatest displacement has been reported at the nipple and inferior breast during bare breast running (Mason et al., 1999, Zhou et al., 2012) and for markers located on the exterior of a sports bra (Eden et al., 1992, Zhou et al., 2009). Whereas for a sports bra condition Zhou et al. (2012) found markers over the bra experienced greatest displacement at the upper breast.

A time lag can be observed between peaks in S-I torso and S-I breast motion during running, it is most prominent at mid-flight and lesser at mid-stance (Figure 2.8a). The duration of this lag has been found to reduce with increased breast support from no bra to everyday bra to negligible lag for the sports bra condition (Haake and Scurr, 2010, Scurr et al., 2010a, Scurr et al., 2008).

Breast displacement has been found to increase with locomotion velocity, with a marked increase observed following the transition from walking to running (Scurr, 2007, Mason et al., 1999, Scurr et al., 2007b, Campbell et al., 2007). However, Scurr et al. (2010b) observed that breast displacement plateaued at 10 km/h with no significant changes in amplitude or direction beyond that point. Subjects have been found to land more flat footed during treadmill running than over ground running (Nigg et al., 1995), however, the only study to compare breast kinematics between the two running modalities reported no significant difference in breast displacement (White et al., 2011). Although it should be noted that breast kinematics were obtained from five gait cycles for treadmill and only a single gait cycle for over ground running. Jumping activities have been found to cause greater vertical displacement than running (Risius et al., 2014).

Breast displacement has been commonly reported to increase with increasing breast size, particularly in the superior-inferior direction (White et al., 2010, Lorentzen and Lawson, 1987, Bridgeman et al., 2010, Wood et al., 2012). However, high variation in displacement within cup size groups has been observed, which may result from differences in running technique, breast size (due to cross grading size system) or breast structure (Scurr et al., 2010b). As a small degree of breast size asymmetry is common it is unsurprising that breast motion asymmetry as also been observed within subjects (Mills et al., 2015b, Snell, 2004).

Strain

A small number of studies have expressed superior-inferior breast displacement in terms of strain. Typically strain is expressed relative to the neutral breast position (determined as the point were measured acceleration equals -g during free vibration of the breast) (Haake and Scurr, 2011, Haake et al., 2012). Using this method the breasts natural frequency has been used estimated to be 5.9 Hz (Haake and Scurr, 2011). Static strain was found to increase significantly with breast size when no bra was worn, presumably due to greater breast ptosis in larger breasted women, however, this relationship was removed by wearing a bra. Strain was found to be non-linear during downward phase and was up to 70% greater than static value during no bra running condition (Haake and Scurr, 2011). Wearing of a bra is suggested to reduce strain by lifting the breast towards its neutral position (Haake and Scurr, 2011, Haake et al., 2012).

Velocity

A number of studies have also reported relative breast velocity during running. Scurr et al. (2010a) observed that superior-inferior breast velocity peaked when velocity of torso in that direction was zero (measured at the sternal notch) (Figure 2.8b). Peak magnitude of superior-inferior breast velocity has been consistently observed during the downward movement of the breast (McGhee et al., 2007, Shivitz, 2001, Scurr et al., 2010a). Similar trends in S-I breast velocity across a gait cycle have been observed for no bra, everyday bra and sports bra conditions. Both Scurr et al. (2010a) and White et al. (2015) found peak superior-inferior and anterior-posterior breast velocity reduced with wearing of a bra and from everyday bra to sports bra condition. They observed no effect in the medial-lateral direction. Resultant breast velocity has been reported to increase with increased breast size during running (Wood et al., 2012) and two step star jump (Bridgeman et al., 2010).

Acceleration

Peak magnitude of S-I acceleration has been found to occur around mid-stance as the breast moves downward below the static equilibrium position; this trend was observed across different breast support conditions (Scurr et al., 2010a, McGhee et al., 2013) (Figure 2.8c). Peak positive S-I acceleration has been found to reduce from a no bra condition with wearing a bra and from an everyday bra to sports bra condition (Mason et al., 1999, White et al., 2015, McGhee et al., 2010, Himmelsbach et al., 1992, Haake et al., 2012, McGhee et al., 2013). As for displacement and velocity, relative breast acceleration has been found to increase with increasing breast size (Wood et al., 2012).

Force

Force acting upon the breast-bra system has been estimated using measures of breast mass and acceleration at the nipple (using $F = m.a$ and assuming mass acts at the nipple) (McGhee et al., 2013). Using a similar method, Zhou et al. (2014) calculated that the force acting on the breast during running without a bra during downward motion was almost double that in upward direction. Breast-bra force during running was on average significantly less for a sports bra compared to an everyday bra (McGhee et al., 2013).

2.6.1.2 Perception

Perception testing is presented in three sections; the methods, scope of perception studies and findings reported within the current literature.

Methods

An overview of sports bra perception studies is given in Table 2.6 and summarises the perceptual variables, measurement methodology and timing of data collection used. Studies have focused upon comfort related variables which have been considered as breast, bra or overall comfort rather than the four main comfort factors discussed in §2.5.1.2.

Studies have focused upon exercise-related breast discomfort (differentiating it from breast pain due to cyclical or non-cyclical mastalgia as detailed in §2.2.2) which has been described using a variety of terms including 'breast pain', 'breast discomfort', 'breast comfort', 'overall breast discomfort', 'exercise induced breast pain' and 'exercise induced breast discomfort'. Perceived breast motion and supportiveness (a combination of breast motion and exercise-related breast discomfort) have been studied. These variables have typically been measured using a numerical rating scale based upon that of Mason et al. (1999) or a visual analogue scale. The terms comfort and pain are often combined on the same scale, which, as White (2013) observes may confuse subjects or question the factor being measured. A small number of studies including Boschma (1994), have implemented a Likert scale. An adapted version of the McGill pain questionnaire (used to assess clinical breast pain) has also been implemented to explore the influence of breast pain on activity (Burnett et al., 2015). It includes 15 descriptor scales to describe the discomfort and provides an indication of its location. This method has not been utilised to assess specific sports bras, whilst it provides a greater level of information it may be too time consuming for multiple collections within a test session.

Bra related perception has been assessed using a single broad measure of 'bra comfort' or 'bra fit' and multiple measures associated with specific bra features such as the strap, cup, band or material comfort. Again, either a 10 cm visual analogue scale or 0-10 numerical rating scale have been most commonly used. Bra perception is closely interrelated with comfort, a very multi-factorial concept, therefore, a subject's interpretation of 'comfort' may vary greatly. The concept of comfort was discussed in greater depth within §2.5.1.

Perception of the overall breast-bra system has been assessed using a single measure of ‘overall comfort’ or by ranking the bras in order of preference (Haake and Scurr, 2011, McGhee and Steele, 2010a, Scurr et al., 2010a). Whilst providing a quick snapshot measurement, the factors influencing the subjects decision may vary greatly (for example exercise-induced breast discomfort, appearance, fit) and provides little information to assist bra design. Performance related variables such as exertion or ability to perform an activity have also been recorded in a small number of studies (White, 2013).

Sports bra perception studies have been performed in two main ways; ‘specific studies’ where data collection is performed for specific breast support or activity conditions and ‘standalone studies’ which consider a subjects more general experience. Standalone studies are typically administered in a questionnaire format to a much larger sample size than specific studies to provide broad overview of sports bra perception. Specific perception studies are largely performed in a controlled laboratory setting and often incorporate biomechanical data collection, a number of studies explore the relationship between biomechanical and perceptual variables (discussed in §2.6.1.3). However, the study periods are often relatively short, therefore not representative of ‘real’ activity situations and may be insufficient for factors such as rubbing or chaffing to be perceived. Only Lawson and Lorentzen (1990) have reported field testing of bras, whilst this method affords less control over the experimental conditions it provides the subject with a broader experience of the bra that may allow a greater depth of feedback. Perception data is most commonly recorded following each study condition or trial. Chen et al. (2015) use both static and dynamic data collections, this may enable the factors affecting static and dynamic perception to be differentiated. Perception is currently an underexplored area of research which is likely to be pertinent to developing sports bra designs.

Table 2.6 - Summary of perception variables and methods included within sports bra studies

	Measures	Method	Timing	Study
Comfort – Breast related	Breast pain	Visual Analogue Scale (VAS)	After trial	Bowles (2003)
	Breast pain	Breast Pain Questionnaire - Adapted from McGill pain questionnaire	Survey	Burnett et al. (2015),
	Breast pain	100 mm VAS (0 = No pain, 100 = Worst pain possible)	After trial	Bowles and Steele (2013)
	Breast pain	Numerical rating scale (NRS) 0-10 (0 = No pain, 5 = Moderate pain, 10 = Excruciating pain)	During and after trial	Milligan et al. (2014a)
	Breast pain	0-10 Likert Scale (0 = No pain, 5 = Uncomfortable, 10 = Painful) based on White et al. (2009a)	During and after trial	Milligan et al. (2015a)
	Breast pain	Modified version of McGill Pain Questionnaire	Survey	Scurr et al. (2014)
	Breast pain	NRS 0-10 (0 = no pain, 5 = uncomfortable, 10 = painful) based on Mason et al. (1999)	After trial	White et al. (2015)
	Mastalgia,	Adapted McGill pain questionnaire	Survey	Brown et al. (2013)
	Breast discomfort	10 cm VAS (0 = No discomfort, 10 = Worst possible discomfort) Reasons for discomfort noted	Before and after trial	Chen et al. (2015)
	Breast discomfort	NRS 0-10 (0 = Comfort, 10 = Discomfort) based on Mason et al. (1999)	After trial	Haake et al. (2012)
	Breast discomfort	10 cm VAS (0 = Comfort, 10 = Discomfort)	Before and after trial	Knight et al. (2014)
	Breast discomfort	10 cm VAS (0 = No discomfort, 10 = Extreme discomfort)	Before and after trial	McGhee and Steele (2010a)
	Breast discomfort	10 cm VAS – breast pain also collected so this assumed to related to other comfort aspects	After trial	McGhee et al. (2007)
	Overall breast discomfort	NRS 0-10 (0 = Comfortable, 5 = Uncomfortable, 10 = Painful) based on Mason et al. (1999)	After each condition	Bridgeman et al. (2010)
	Breast comfort	10 cm VAS (0= Very comfortable, 10 = Very uncomfortable)	After trial	White et al. (2010)
	Breast comfort	NRS 0-10 (0 = Comfortable, 5 = Uncomfortable, 10 = Painful) based on Mason et al. (1999)	After each trial	White (2013)
	Each subject asked '"thinking specifically about the breast area which sensation most closely reflects your present breast sensation?"	7 Point Likert scale (1= Comfortable, 3 = Slightly uncomfortable, 5 = Uncomfortable, 7 = Very uncomfortable)	During and after trial	Boschma (1994)
	Exercise-induced breast pain	10cm VAS	After trial	McGhee et al. (2007)
	Exercise induced breast pain	NRS 0-10 (0 = No pain, 10 = Painful) based on Mason et al. (1999)	After trial	Mills et al. (2015b)
	Exercise-induced breast pain	NRS (0 = No pain, 10 = Painful) based on Mason et al. (1999)	After trial	Mills et al. (2015a)
	Pain felt in breast region during exercise	NRS (0 = Comfortable, 5 = Uncomfortable, 10 = Painful)	After trial	Mason et al. (1999)
	Sports related breast pain (discomfort)	Questionnaire	Survey	Lorentzen and Lawson (1987)
	Do your breasts ever hurt during participation in your sport?	Included in questionnaire Yes / No response	Survey	Hunter and Torgan (1982)
	Exercise induced breast discomfort	Not stated (abstract only)	n/s	McGhee et al. (2010)
	Exercise-induced breast discomfort	10 cm VAS (0 = No discomfort, 10 = Extreme discomfort)	After trial	McGhee et al. (2013)
	Breast discomfort (related to breast movement)	NRS 0-10 (0= Comfortable, 5 =Uncomfortable, 10 = Painful) from Mason et al. (1999)	After each condition	White et al. (2011)
	Perceived breast movement	10 cm VAS (0 = No movement, 10= Extreme movement)	Before and after trial	Chen et al. (2015)
	Perceived breast movement	10 cm VAS (0 = No movement, 10 = Extreme movement)	Before and after trial	McGhee and Steele (2010a)
Comfort – Bra	Bra comfort	10 cm VAS (0 = Very uncomfortable, 10 = Very comfortable)	After trial	Ayres et al. (2013)
	Bra comfort (i.e.rubbing/chaffing)	NRS 0-10 (0 = Very comfortable (would wear), 5 = Uncomfortable, 10 = Very uncomfortable) from Mason et al. (1999)	After each trial	White (2013)
	Overall bra comfort	Qualitative questions	After all trials	Bowles and Steele (2013)

VAS = Visual Analogue Scale , NRS = Numerical Rating Scale

Continued overleaf

Table 2.6 (continued) - Summary of perception variables and methods included within sports bra studies

		Measures	Method	Timing	Study
Comfort		Comfort 'perceived freedom from dermatological / physical distress caused by the sports bras rigid fasteners, irritating seams or trim, stiff of itchy fabric, confining cut, strap configuration & hot or bulky fabric	Questionnaire 15 items mostly scored on 1-5 scale	After vigorous exercise session of participants choice (not supervised)	Lawson and Lorentzen (1990)
	Bra related	Shoulder comfort	100 mm VAS (0 = Most comfortable possible, 100 = Least comfort possible)	After all trials	Bowles and Steele (2013)
		Strap discomfort* (* = summed to give bra discomfort)	10 cm VAS (0 = No discomfort, 10 = Worst possible discomfort)	Before and after trial	Chen et al. (2015)
		Cup discomfort *	10 cm VAS (0 = No discomfort, 10 = Worst possible discomfort)	Before and after trial	Chen et al. (2015)
		Band discomfort*	10 cm VAS (0 = No discomfort, 10 = Worst possible discomfort)	Before and after trial	Chen et al. (2015)
		Material discomfort*	10 cm VAS (0 = No discomfort, 10 = Worst possible discomfort)	Before and after trial	Chen et al. (2015)
		Bra fit comfort	Not stated (abstract only)	n/s	McGhee et al. (2010)
		Bra fit comfort	10 cm VAS (0 = No discomfort, 10 = Extreme discomfort)	Before and after trial	McGhee and Steele (2010a)
		Bra fit	10 cm VAS (0 = Poor fit , 10 = Good fit)	After trial	Ayres et al. (2013)
		Bra fit (used place of 'bra comfort' to avoid confusion with breast comfort)	NRS 0-10 (0 = Very poor fit 5 = Moderately good fit, 10 = Very good fit) based on Mason et al. (1999)	After all trials	White (2013)
		Preferred strap configuration	Qualitative questions	After all trials	Bowles and Steele (2013)
		Support - defined as perceived ability of sports bra to restrict breast motion during exercise and to prevent soreness and distress that can be caused by excessive breast motion	Questionnaire - 10 items related to nature and extent of perceived breast motion restriction and sports induced motion. Mostly scored on 1-5 scale	After vigorous exercise session of participants choice (not supervised)	Lawson and Lorentzen (1990)
		Bra supportiveness	NRS 0-10 (0 = Very unsupportive 5 = Moderately supportive, 10 = Very supportive)	After all trials	White (2013)
	Overall	Thermal comfort	10 cm VAS (0 = Cool, 10 = Hot)	After trial	Ayres et al. (2013)
		Comfort/Perceived pain	Likert scale 1 -10 (1 = Comfortable, 5 = Uncomfortable, 10 = Painful)	After each condition	White et al. (2009a)
		Overall comfort	NRS 0-10 (0 = Comfort, 10 = Extreme discomfort) from Mason et al. (1999)	After each condition	Haake and Scurr (2011)
		Overall breast comfort	NRS 0-10 (0 = Comfortable, 5 = Uncomfortable, 10 = Painful) from Mason et al. (1999)	After each test condition	Scurr et al. (2010a)
		Rank bras in order of preference to wear during running, considering breast and bra discomfort and perceived breast movement	Bras ranked 1–3 (1 =Most preferred, 3= Least preferred). If preferential ranking same for two bras same, the marks split between two bras.	After all trials	McGhee and Steele (2010a)
Performance		Rating of perceived exertion	Borg Scale (6 = No exertion at all, 20 = Maximal exertion)	After trial	Chen et al. (2015)
		Rating of perceived exertion	Borg scale (6-20)	After trial	McGhee et al. (2007)
		Rating of perceived exertion	Borg scale (6-20)	After trial	McGhee and Steele (2010a)
		Rating of perceived exertion	Borg scale (6-20)	After trial	McGhee et al. (2013)
		Rating of perceived exertion	Borg scale (6-20)	After trial (not jumping)	White (2013)
		Did support impact on jump performance and landing strategy	Multiple choice (Yes/No/Indifferent) with option of extended response	After all trials	White (2013)

VAS = Visual Analogue Scale , NRS = Numerical Rating Scale

Scope of Perception Studies

Sports bra perception studies have been performed as 'specific studies' where data collection is associated with a test condition and 'standalone studies' which consider the subjects more general experience. Specific perception studies are often conducted alongside biomechanical data collection, and as for biomechanical studies the scope of perception studies may be influenced by commercially driven research. A number of studies have sought to better understand the relationship between breast biomechanics and exercise induced discomfort. Studies have explored the effect of breast support, activity and breast size on perceptual variables with a focus primarily upon exercise induced breast discomfort. As discussed in §2.5.1.2 aspects contributing to sports bra comfort have been little explored, thus the scope of perception studies has been limited. Additionally, the breast support conditions studied have generally been limited to a small number of very different bras with experimental variables such as bra structure and material properties poorly controlled making it difficult to identify any relationships between bra design and perceptual variables. Standalone studies have sought to gauge the prevalence of exercise-induced breast discomfort, whether breast concerns affect participation in exercise and identify key aspects of sports bra design.

Findings

It is well established that exercise-induced breast discomfort is reduced by wearing a bra compared to no bra and that a sports bra is more effective at reducing discomfort than an everyday bra (White et al., 2009a, Mason et al., 1999, Boschma, 1994, McGhee et al., 2010, Haake and Scurr, 2011, Haake et al., 2012, White et al., 2011, White et al., 2015, Scurr et al., 2010a, McGhee et al., 2013, Milligan et al., 2014a, Mills et al., 2015b, Milligan et al., 2015a). Exercise induced breast discomfort has been consistently reported to be high during activity in a bare breasted condition, with subjects only able to withstand running for a limited duration (Knight et al., 2014, White et al., 2010).

Exercise induced breast discomfort has been found to increase with locomotion speed (Haake and Scurr, 2011), but not found to differ between treadmill or over ground running modalities (White et al., 2011). Chen et al. (2015) found that breast support condition only affected perceived breast discomfort during jogging (7.5 km/h) and running (10 km/h) but not during walking activities. The duration of run has also been reported to affect exercise-induced breast discomfort, with lower discomfort reported after 5 km compared to 2 minute point for a low support bra, no difference was observed found for a high support bra (Milligan et al., 2014a, Milligan et al., 2015a). Gait parameters were not measured within this study, therefore, subjects may have adapted their running style to minimise discomfort. Alternatively, subjects may have become habituated to the discomfort.

Whilst exercise-induced breast discomfort has been reported across different breast size groups, a number of studies have reported discomfort to increase with breast or bra cup size (Bridgeman et al., 2010, Haake and Scurr, 2011, Haake et al., 2012, Lorentzen and Lawson, 1987, White et al., 2009a). Lawson and Lorentzen (1990) observed that larger breasted women were more likely to associate exercise-induced breast discomfort with excessive breast movement and smaller breasted women with premenstrual syndrome. Study results have suggested that larger breasted subjects may be more sensitive to changes in breast support condition (Boschma, 1994, Lawson and Lorentzen, 1990). Lawson and Lorentzen (1990) found that larger breasted subjects reported differences in perceived support (ability to reduce pain and breast motion) between seven test bras whereas smaller breasted subject did not.

2.6.1.3 Links between Biomechanical and Perception Studies

A number of studies have explored the connection between breast biomechanics and perception of exercise-induced breast discomfort. However the relationship remains unclear, a summary of the main findings follows and relates to displacement, velocity, acceleration and parameters accounting for breast mass. Breast support condition is typically used as a controlled study variable, however, a small number have also used activity type (Mills et al., 2015a, McGhee et al., 2007). The relationship between exercise induced breast discomfort and body kinematics outcome variables has also been explored by a small number of studies (included in §2.5.3).

Displacement

A strong relationship between reduced breast discomfort and decreased S-I breast displacement has been found by a number of studies (Gehlsen and Albohm, 1980, Lorentzen and Lawson, 1987, Mason et al., 1999, McGhee et al., 2007, Starr et al., 2005, White et al., 2009b, Bowles and Steele, 2013, Scurr et al., 2010a, Bowles, 2003, Bridgeman et al., 2010). Other studies have reported correlations with A-P displacement (White et al., 2015), resultant displacement (White et al., 2011) or displacement in all directions (Mills et al., 2015b). However, when investigating a prototype bra combining compression and elevation McGhee and Steele (2010a) found that differences in breast discomfort and perceived breast movement were not associated with S-I displacement range. The authors speculate that although the breast moved through similar range elevating the breast resulted in less stretching of breast support tissues. Lawson and Lorentzen (1990) also report weak correlations between perceived support and vertical displacement, however, perception and kinematics measures were recorded at different times.

Interestingly, White et al. (2011) reports a stronger correlation between breast displacement and discomfort during treadmill running compared to over ground running. The authors suggest this may have resulted from the subjects being more able to focus on comfort levels during the controlled activity of treadmill running compared to a short duration over ground run.

Velocity

A number of studies have found exercise induced breast discomfort to positively correlate with peak relative breast velocity during running (Scurr et al., 2010a, White et al., 2015) and a two step star jump (Bridgeman et al., 2010). However, differences in breast discomfort between jumping activities on land and in water were not associated with changes in breast velocity (Mills et al., 2015a). In this scenario, forces on the breast changed between conditions, therefore, it is not possible to draw conclusions on velocity alone.

Interestingly, a comparison of 20 women, 10 who had never experienced exercise induced breast discomfort and 10 who had, found no significant difference in peak S-I breast displacement or velocity between groups (Gehlsen and Albohm, 1980). But the women who experienced breast discomfort had a significantly higher breast momentum (breast mass x velocity).

Acceleration

The role of acceleration in exercise induced breast discomfort is also unclear as both Mason et al. (1999) and Scurr et al. (2010a) found no correlation to breast acceleration during running for B to C cup and D cup subjects respectively. Whereas a study of larger breasted women (D and E cup) found breast discomfort during running had a significant positive correlation with acceleration (White et al., 2015). Other studies have found breast force (breast mass x acceleration), to have a significant correlation to discomfort, with discomfort increasing with increased breast force (McGhee et al., 2010, McGhee et al., 2013).

Interestingly, Haake et al. (2012) developed a model to predict exercise induced breast discomfort using a plot of acceleration against strain. Using a straight line boundary on this plot the authors were able to correctly predict 77% of cases whether discomfort rating (from 0 - 10) was in the comfort (0 - 5 rating) or discomfort range (6 - 10 rating).

2.6.1.4 Summary of Human Studies

Sports bra research has focused on human testing and studies often collect both biomechanical and perception data. Breast kinematics are typically measured relative to the torso, it is therefore necessary to track both breast and torso motion. This is most commonly performed using opto-electronic motion capture systems and has focused on treadmill walking and running. The majority of studies use a single marker at the nipple to represent breast motion which is placed on the exterior of the bra if one is worn. Four different torso tracking marker sets have been proposed in the literature however, with the exception of Zhou (2011), they generally provide little evidence of how they were developed or how well they are able to track torso movement (Table 2.3). Furthermore, two different methods have been proposed to calculate relative breast motion, the POSE

Method (which assumes the torso to be a rigid segment) and Non-POSE method (which has no rigid body assumption). At present the effect of breathing on breast kinematics have not been considered, despite respiration being reported to result in breast movement in a static condition (Chopra et al., 2006). Studies have analysed between 1 and 45 gait cycles, with peaks or range of motion identified and averaged over the gait cycles analysed.

The scope of sports bra biomechanical studies has included understanding bare breast motion and effect of bras on breast motion, typically an everyday bra and sports bra have been utilised. Other study variables have included activity type, running speed or duration and breast size.

Relative breast displacement, velocity, acceleration have been studied although displacement is most commonly reported and perhaps best understood. It has been widely reported that relative breast displacement reduces with wearing of a bra and between everyday bra and sports bra conditions, studies also found reductions in peak velocity and acceleration. During bare breast running a lag between torso and breast motion can be observed in S-I direction most obviously at mid-flight, this is also reduced with bra use. Breast displacement increases with locomotion speed with marked change observed following the walk-run transition, further increases appear to plateau around 10 km/h. Unsurprisingly, breast displacement has been found to increase with increased breast size. Breast velocity is thought to peak during the downward phase of breast motion and peak acceleration around mid-stance as the breast moved below its static position.

Perception studies are often conducted in conjunction with biomechanical data collection. The scope of perception studies has included the effect of bra, often between very different bras, to explore the relationship between biomechanical and perception data. Studies have used a wide variety of terminology to describe the perceptual variables measured, which is often confusing. However, most focus has been placed on assessing exercise induced breast discomfort. Data is most commonly collected following completion of a trial using a visual analogue scale or numerical rating scale. Typically trials are conducted in a laboratory setting and are of short duration, which allows greater control over variables and multiple conditions to be tested. Although it may be insufficient duration to represent real activity conditions and assess all aspects of comfort.

It is well established that exercise induced breast discomfort is reduced by wearing a bra, and that a sports bra is more effecting at reducing discomfort than an everyday bra. Exercise induced breast discomfort is typically higher in larger breast sizes and increases with locomotion speed. At present the relationship between biomechanical and perception measures is unclear.

2.6.2 Mechanical Studies

The mechanical testing of sports bras and links to human studies are discussed followed by an overview mechanical tests used within the wider field of apparel.

2.6.2.1 Sports Bra

Mechanical testing of sports bras encompasses two aspects: characterisation of bra mechanical properties using methods such as tensile testing; and mechanical testing of bra performance. The scope of mechanical testing within the sports bra literature is limited, however, it is highly likely that manufacturers conduct extensive and unreported in house mechanical testing. Zhou (2011) analysed ten bra strap fabric samples using ASTM Standard D 4964-96 tensile testing method, which uses a constant extension rate (30 cm/min) up to 50% extension (ASTM, 1996). The author also reported strap modulus at 25% extension (3.18 - 15.85 MPa). Zhou et al. (2013) performed very crude tensile tests of commercial sports bras by manually stretching bra components and measuring maximum extension using a rule.

There is much scope to further develop mechanical testing of sports bras, to quantify bra mechanical properties and investigate the relationship between mechanical properties and human testing. The possibility of developing a mechanical test dummy is yet to be explored. Developing an actuated torso and breast model to mimic motion during different activities could provide a very convenient and repeatable test method. It would enable more frequent and much longer test durations than human testing to study aspects such as change in bra performance over time or with washing. However, validation of material properties, form and motion with human testing would be required to ensure the test results were meaningful.

2.6.2.2 Links between Mechanical and Human Studies

Only Zhou (2011) has explored the link between mechanical properties of the bra and biomechanical performance, investigating the effect of strap modulus on S-I breast displacement during treadmill jogging (7 km/h). The author reported no effect for smaller breasted participants but suggested an inverse relationship between modulus and vertical breast displacement occurred in larger breasted subjects. However, no statistical analysis of the data was provided and on visual inspection the trend appears somewhat unclear suggesting further investigation is warranted.

2.6.2.3 Apparel

Within the wider field of apparel two common methods for testing fabrics are the Kawabata Evaluation System (KES-F) and Fabric Assurance by Simple Test (FAST). The KES measures 16 characteristics to quantify fabric properties which can be related to different subjective measures of fabric hand (feel on the skin) (Kawabata et al., 2002). Using this system a standards have been produced for specific clothing types (e.g. men's winter suiting). The FAST system objectively measures fabric mechanical properties which affect garment manufacture and handle (Ciesielska-Wrobel and Van Langenhove, 2012).

2.6.2.4 Summary of Mechanical Studies

The scope of previous mechanical sports bra testing is very limited and focuses on tensile testing of bra components. Only Zhou (2011) has explored links between mechanical properties and biomechanical performance, the findings suggest increasing strap modulus may reduce S-I breast displacement which may have implications for sports bra design.

2.6.3 Virtual Studies

Virtual testing has formed a relatively small part of sports bra research to date. Virtual models studying the bra and or breast during activity are reviewed, and followed by an overview of breast modelling within wider medical context.

2.6.3.1 Sports Bra

A small number of studies use virtual models to investigate bra and or breast behaviour during activity. The scope of studies to date has ranged from simple mass-spring models to finite element analysis (FEA) simulations. Zhou and Yu (2013) investigate the effect of bra strap configuration and position by modelling bra straps as Hookean springs (where extension = force / spring constant). Assuming that spring constant increases proportionally with increasing strap width they concluded that wider straps were more effective at reducing breast displacement. Zhou et al. (2014) modelled the breast as a Kelvin-Voigt mass-spring-damper system, the breast damping co-efficient was measured by studying the decay in vibration amplitude (logarithmic decrement) after free vibration of the breast, a method also used by Haake and Scurr (2010).

Li et al. (2003) and Cai et al. (2014) use finite element analysis to model the interaction between breast and bra and Chen et al. (2013) to study bare breast deformation. The Li et al. (2003) model of breast and bra deformation during walking included only three elements (breast, bra and torso) with an assumption that bra-breast fit is perfect and frictionless. Simulations showed that during downward motion of the breasts pressure on the bra was greatest over the lower breast and stress on the breast was greatest on the upper breast superior to the nipple. Interestingly, the model predicted highest stress on the upper and medial breast during upward motion of the breast. However, there are a number of limitations including that the model gave poor correspondence to experimental pressure data used for validation, rotation of the torso during walking was omitted, the torso was modelled as solid bone and the breast assumed to be a homogenous mass. The method of Cai et al. (2014) was more complex using 3D scanning to create the mesh geometry, incorporating three skin layers over breast tissue and multiple bra components into the model. The results showed increased contact pressure along the underwire and upper edges of the cups with greater levels of deformation in these areas. However, very little detail was provided about model validation. It is also unclear how the results presented relate to the gait cycle.

The Chen et al. (2013) model used to predict breast deformation was similar to that of Cai et al. (2014), however, breast damping properties were obtained using a Voigt model (considering the breast as a mass spring damper system) and analysis of free vibration of the breast. A number of images of breast deformation during activity were presented, whilst the shapes presented look realistic a comparison to the images of the subject would have been useful. The kinematic data used to validate the model utilised only one torso reference marker therefore does not account for torso rotation.

Modelling the breast presents a number of challenges; it is difficult to know how ex-vivo testing of breast tissue relates to in-vivo behaviour, breast size and shape varies, breast structure is likely to vary between subjects and also changes with age. Model validation should be performed using 3D relative breast kinematics obtained using a torso marker set rather than a single torso marker, to account for torso rotation. At present it is difficult to translate modelling results into improvements in sports bra design. Further development of breast-bra models may eventually enable the virtual development and testing of bra design prior to human testing. However, to achieve this much work must be undertaken to validate model results with human testing.

2.6.3.2 Breast

Within the wider medical field modelling breast deformation has received much interest, with numerous applications in surgery, imaging and biopsy (Arnab, 2009, Azar et al., 2001, Ozan, 2008, Ruiter et al., 2003, Samani et al., 2001). For example, predicting the position of a breast tumour when the patient is in a supine position from mammogram images for which the breast has been vertically compressed. However, these models are also limited by validity of the breast tissue material data available, the relative simplicity of breast models compared to breast structure and typically model static rather than dynamic deformations.

2.6.3.3 Summary of Virtual Studies

A small number of studies have used virtual models to investigate breast or breast-bra behaviour ranging from simple mass-spring models to finite element analysis. However, to translate these results into sports bra design development will require extensive work to validate results with human testing.

2.7 Summary

This chapter has presented an overview of sports bra literature in addition to relevant breast and torso literature. Sports bra research is a developing area which has received increased interest in recent years, and the research undertaken driven by the interlinking factors of comfort, injury and performance. Human, mechanical and virtual test modalities have been utilised, however, the greatest focus in upon human based biomechanical and perceptual studies. As the research area is still relatively young and developing there are a number of areas which remain poorly understood and limitations in how research can be applied to the development of bra design.

Sport bra performance is typically assessed using breast kinematics and subject perception of the bra during treadmill running. Whilst questions remain over the applicability of this activity to a wider sporting context, further development of test methodologies may be more pertinent to advance research within this area.

Biomechanical testing has been the cornerstone of sports bra research to date and the quantification of breast kinematics during exercise has received increasing interest. At present there is no standard protocol for measuring relative breast kinematics making it difficult to compare studies. The breast is a complex structure varying in shape, size and composition, however, breast motion is typically represented by a single breast marker and that marker is often placed over the bra if one is worn. Further understanding of breast motion and whether markers placed on the bra represent the underlying breast appear pertinent to the development of sports bra design. Breast kinematics are typically measured relative to the torso. To date, four different torso marker sets have been proposed, although often with little evidence of their development or ability to track torso motion. Additionally, there is a lack of consensus over the method used to calculate relative breast motion (either with or without rigid body assumption). Therefore, the development of a torso marker set specifically for breast kinematics and investigation into the effect of calculation method on breast kinematics appear important to advancement within this area. Breast motion resulting from respiration has been reported for a static condition, however, the effect of respiration on breast kinematics during exercise has yet to be considered. Therefore, it should be investigated whether breathing affects breast kinematic measurements.

Perception data is often collected alongside kinematic data with a focus on exercise induced breast discomfort. The source of exercise induced breast discomfort and whether it is an indicator of breast injury remains to be understood. A better understanding of these questions is likely to require extensive breast imaging e.g. MRI scans and therefore beyond the scope of this thesis. A more extensive exploration of aspects contributing to sports bra comfort and the terminology used to describe it is likely to help advance perception testing. Although beyond the scope of this study, factors involved in sports bra comfort could be more fully explored by implementing methods similar to Roberts (2002) and Webster (2010) which identified key words within the field of sports equipment perception. Establishing the key factors and terminology used to describe sports bra comfort may assist the development of a more sophisticated tool to assess sports bra comfort and further design development. Alongside this, further work to explore the methodology used and timing of data collection may help develop test protocols which can better inform sports bra design.

Whilst sports bras are widely acknowledged to be effective at reducing breast motion and reducing breast discomfort during exercise, the relationship between biomechanical measures and breast discomfort remains unclear. However, studies are typically limited to a small number of very different bras, therefore, experimental variables of (bra structure and mechanical properties) have been poorly controlled making it difficult to infer any relationships. Therefore, there is relatively little understanding of how a specific sports bra design affects bra performance.

Mechanical testing of sports bras is limited within the existing literature. However, the findings of Zhou (2011) that increasing strap modulus may reduce S-I breast displacement is of particular interest, as a number of studies have identified a strong positive relationship between decreased S-I breast displacement and breast discomfort (Gehlsen and Albohm, 1980, Lorentzen and Lawson, 1987, Mason et al., 1999, McGhee et al., 2007, Starr et al., 2005, White et al., 2009b). The role of bra strap mechanical properties in sports bra performance appears to be an interesting avenue for further investigation.

Bare breasted running is commonly used as a control or 'worst case' condition, however, it is unrepresentative of typical exercise conditions and may deter subject participation.

Other exciting areas for future development include the use of virtual testing and mechanical test dummies to help develop sports bra designs. However, such development tools rely upon extensive validation using human testing, therefore, this thesis will focus primarily upon the development of biomechanical testing methods.

Chapter 3

Human Testing Methods

3.1 Introduction

This chapter presents the data collection and analysis methods used within the human testing conducted. Breast and body kinematics were collected using a CODA motion analysis system (Charnwood Dynamics Ltd; Leicestershire, UK) and analysed in a two stage process using Visual 3D (Version 4.96.9, C-Motion Incorporated, Germantown, MD, USA) and Matlab software (Version R2010a, MathWorks Incorporated, Natick, Massachusetts, USA). The data collection section also includes details of the experimental set up, subject preparation, marker locations, descriptions of the test movements performed, selection of the sports bra tested and sports bra fitting protocol. The data processing section includes details of torso segment definition, filter selection and methods used to analyse static, drop landing and running trials.

3.2 Data Collection

This section details the testing equipment, experimental set up and subject preparation used to collect breast kinematic data.

3.2.1 CODA Motion Analysis System

CODA CX1 (Charnwood Dynamics Ltd; Leicestershire, UK) is an active marker system where by infra-red emitting markers are attached to specific anatomical locations and each marker has its own identity. Signals from the markers are recorded by the CODA heads, three masked linear arrays in each CODA head combine to give the X, Y, Z coordinates of each marker in 3D space. The global coordinate system (GCS) was set and calibration performed using three markers, one to denote the GCS origin and two positioned at right angles to the origin marker to define the medial-lateral and anterior-posterior axes. The GCS origin was located on the treadmill belt with X positive in the direction of running, Y positive in the horizontal plane to right of the run direction and Z vertical (positive upwards) (Figure 3.1).

The CODA system was set up to sample data at 200 Hz (as CODA can capture up to 28 markers at 200 Hz) with out of view interpolation on. The out of view interpolation function uses a cubic curve between in-view values to fill out of view markers, the first two samples either side of the gap are ignored to achieve a more reliable interpolation (Ward, 2012). The cameras have a horizontal and vertical resolution of 0.05 mm and distance resolution of 0.3 mm at 3 m displacement.

3.2.2 Experimental Set Up

Testing took place within a privacy enabled laboratory as illustrated below (Figure 3.1). A four-head CODA motion analysis system was set up around the treadmill (H-P Cosmos Mercury Med., H/P/Cosmos Sports & Medical GmbH, Nussdorf, Germany) and a 35 cm high aerobics step.

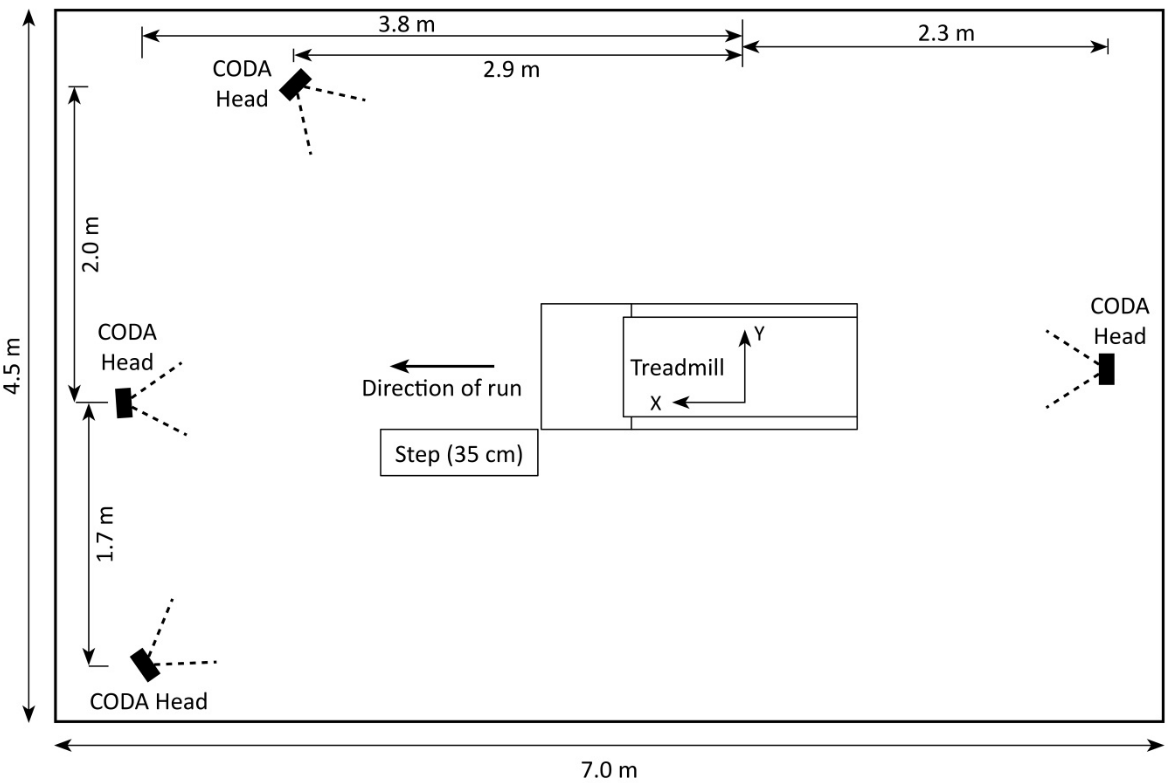


Figure 3.1 - Schematic of experimental set up

3.2.3 Subject Preparation

The research within this thesis is focused upon larger breasted subjects (≥ D cup size). Breast displacement and exercise induced breast discomfort have been found to increase with breast size, suggesting adequate breast support during exercise is particularly important for larger breasted women. 'Larger' breasted has been defined as either ≥ C cup size (McGhee et al., 2007, McGhee and Steele, 2010a) or ≥ D cup size (Lorentzen and Lawson, 1987, Scurr et al., 2010a). However the UK average breast size in 2010 was reported to be 36D, an increase from 34C in 2003, therefore, for the purpose of this thesis larger breasted women will be classed as D cup size and above (Fisher, 2010).

All subjects gave written voluntary informed consent to participate in the study following ethical approval gained from the institution.

Before attaching the markers a small dot was placed on all anatomical landmarks so that any dislodged markers could be replaced in the same location. The markers, marker boxes and wires were secured in place using medical tape. Care was taken to ensure that wires were not obstructing markers or disturbing the subjects normal movement. Prior to recording the first trial the subject was asked to stand within the test area to ensure all markers were visible throughout the test area.

3.2.4 Marker Locations

A diagram and description of marker locations used during the course of this thesis are provided in Figure 3.2 and Table 3.1. Not all marker locations were used in all studies. The specific marker locations used in each study are indicated in Table 3.1 and are presented in the relevant chapter.

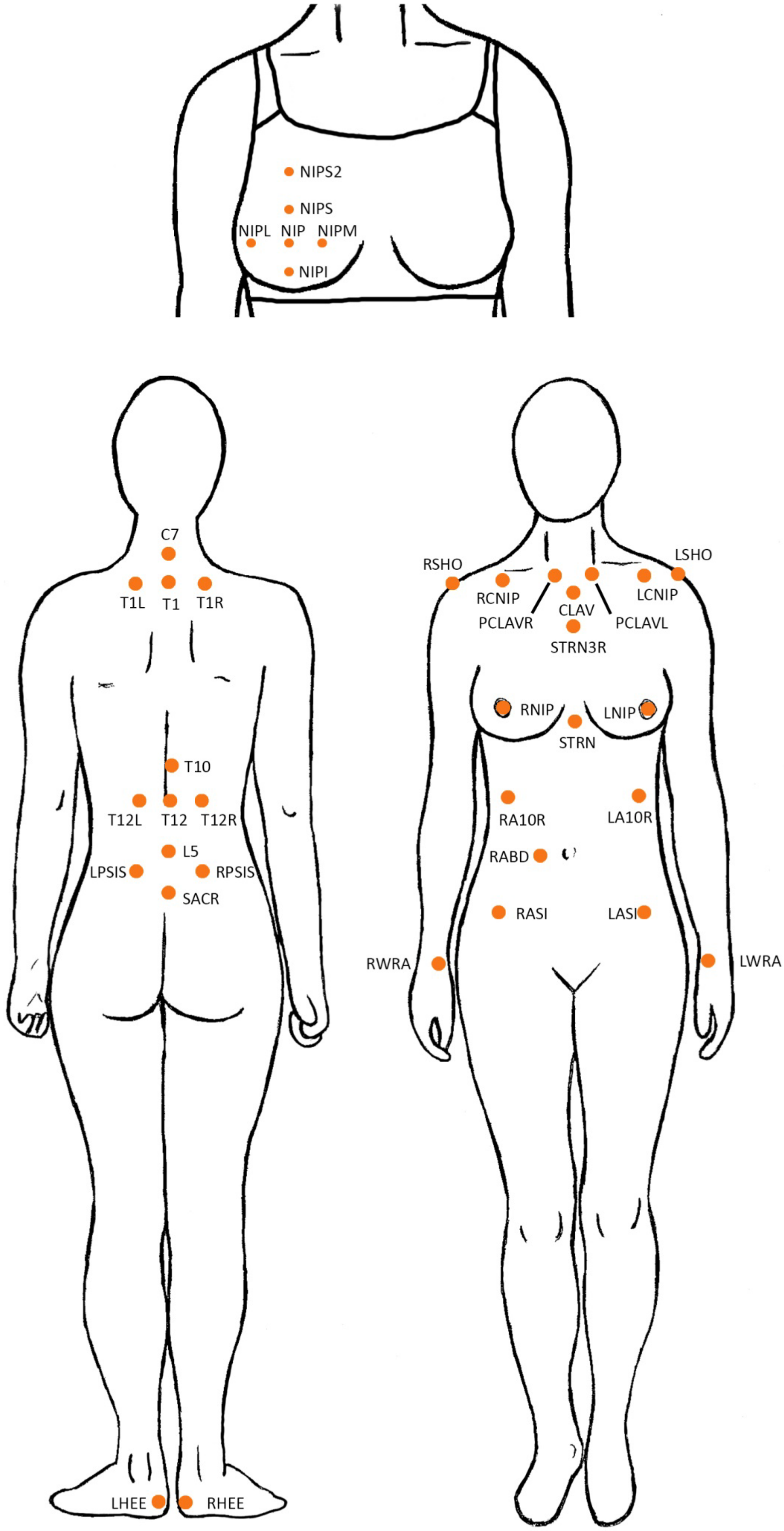


Figure 3.2 - Locations of breast and body markers used within this thesis

Table 3.1 - Marker locations and descriptions

Marker	Location description	Chapter and Study No.						
		C4			C5	C6	C7	
		A1	A2	B			Pre.	Main
Torso								
CLAV	Suprasternal notch	x	x	x	x	x		x
PCLAVR	Proximal clavicle right	x	x					
PCLAVL	Proximal clavicle left	x	x					
RCNIP	Right clavicle directly above nipple	x	x	x	x	x		x
LCNIP	Left clavicle directly above nipple	x	x	x	x	x		x
LSHO	Left shoulder - over acromio-clavicular joint	x						
RSHO	Right shoulder - over acromio-clavicular joint	x						
STRN3R	Sternum level with articulation of 3rd rib	x						
STRN	Xiphoid process of the sternum	x						
RA10R	Right inferior anterior aspect of 10th rib	x	x	x	x	x		x
LA10R	Left inferior anterior aspect of 10th rib	x	x	x	x	x		x
C7	Directly over C7	x						
T1	Directly over T1	x	x	x	x	x		x
T1R	Level with T1 over right shoulder	x						
T1L	Level with T1 over left shoulder	x						
T10	Directly over T10	x	x	x	x	x		x
T12	Directly over T12	x						
T12R	Level with T12 over angles of ribs	x						
T12L	Level with T12 over angles of ribs	x						
RABD	3 cm right of belly button over fullest part of abdomen	x						
Lower torso / Pelvis								
L5	Directly over L5	x						
SACR	Sacrum - central	x						
RPSIS	Right PSIS	x						
LPSIS	Left PSIS	x						
RASI	Right ASIS	x						
LASI	Left ASIS	x						
Breast								
RNIP	Right nipple	x	x	x	x	x		
LNIP	Left nipple	x	x	x	x	x	x	x
NIPI	4 cm inferior of nipple						x	x
NIPL	4 cm lateral of nipple						x	x
NIPM	4 cm medial of nipple						x	x
NIPS	4 cm superior of nipple						x	x
NIPS2	8 cm superior of nipple						x	x
Arm								
LWRA	Left wrist radial side	x						
RWRA	Right wrist radial side	x						
Leg								
LHEE	Left calcaneous at same height as toe marker	x	x	x	x	x		x
RHEE	Right calcaneous at same height as toe marker	x	x	x	x	x		x

3.2.5 Test Movements

The test movements performed during the course of this thesis are detailed within this section and categorised as stationary, treadmill running or drop landing.

3.2.5.1 Stationary

Eight different stationary trials were performed during the course of this thesis (Table 3.2). The activity was demonstrated and explained to the subject prior to commencing that trial. Each activity began with subject standing in the anatomical position and finished in the same position. The subject was instructed to perform the movements in a slow controlled manner, maintaining the same body posture and position throughout the activity. The subject was breathing normally during all stationary activities.

Table 3.2 - Stationary trials

				Chapter and Study No.						
No.	**Description**	**Sample Time**	**Purpose**	**C4**			**C5**	**C6**	**C7**	
				A1	**A2**	**B**			**Pr.**	**M**
S1	Standing still	10 s	Static trial required to calibrate segment in Visual 3D analysis	x	x	x	x	x	x	x
S2	Abduct arms to above head (thumbs to ceiling)	~ 6 s	Study torso marker displacement resulting from upper body movement - may be more applicable to non running activities	x						
S3	Raise arms in front of body to above head (thumbs to ceiling)	~ 6 s	Study torso marker displacement resulting from upper body movement - may be more applicable to non running activities	x						
S4	Lift both arms behind back to end of range	~ 6 s	Study torso marker displacement resulting from upper body movement - may be more applicable to non running activities	x						
S5	One cycle of the arm action during running (Humerus at ~ 45°)	~ 8 s	Study torso marker displacement resulting from upper body movement - mimics running arm action	x						
S6	Shrug shoulders towards ears	~ 6 s	Study torso marker displacement resulting from upper body movement - mimics extreme posture sometimes seen during running	x						
S7	Round shoulders forwards	~ 6 s	Study torso marker displacement resulting from upper body movement - mimics extreme posture sometimes seen during running	x						
S8	Pull shoulder blades back together	~ 6 s	Study torso marker displacement resulting from upper body movement - mimics extreme posture sometimes seen during running	x						

3.2.5.2 Treadmill Running

Following a three minute warm up and familiarisation period the subjects ran on a treadmill with zero incline for 90 seconds (Table 3.3). Data was collected between 30 and 90 seconds.

Table 3.3 - Treadmill running trials

				Chapter and Study No.						
				C4			C5	C6	C7	
No.	Description	Sample time	Purpose	A1	A2	B			Pr.	M
R1	Running at 10 km/h	90 s at speed	Most commonly used running speed in bra studies.	x	x	x	x	x		
R2	Running at 8 km/h	30 s at speed	Comfortable jogging speed						x	x
R3	Running at 12 km/h	90 s at speed	Faster pace than standard as test subject was particularly tall							x
R4	Hold breath during running at 10 km/h	90 s at speed	Determine whether the breathing effect needs to be accounted for sports bra testing during treadmill running. This removes any breathing effect from running data.				x			

3.2.5.3 Drop Landing

The subject was instructed how to perform a two footed drop landing from a 35 cm high aerobics step by stepping off the box and landing with relatively stiff legs (Table 3.4). The subject was instructed to 'land flat footed and stop themselves as quickly as possible'. The activity commenced standing in the anatomical position and the subject was instructed to keep their arms by their sides during the movement (this was to prevent the arms obstructing markers). The subject practiced until they could perform the activity satisfactorily.

Table 3.4 - Drop landing trial

				Chapter and Study No.						
				C4			C5	C6	C7	
No.	Description	Sample time	Purpose	A1	A2	B			Pr.	M
D1	Drop landing from 35 cm step	~ 8 s	Study marker displacement due to soft tissue movement	x						

3.2.6 Selection of Test Sports Bra

The sports bra selected for this thesis was the ShockAbsorber High Exertion N109, a non-underwired ‘high impact’ sports bra with adjustable underband and straps (Figure 3.3). The bra fabric consisted of 50% polyamide, 47% polyester and 3% elastane. The N109 was one of the most widely available and popular sports bras (Saxby, 2011). The bra is specifically targeted at larger breasted women and is available in sizes: 30-40 D, DD, E, F, FF, G and 32-38 GG, H. It has adjustable underband and straps to enable a more uniform fit across subjects. Additionally, this design of bra allowed the strap section to be easily modified (§7.2.2).

Figure 3.3 - ShockAbsorber N109 sports bra (a) Front (b) Back (c) Side view

3.2.7 Sports Bra Fitting Protocol

Before a test session subjects were asked to provide their bra size, this size was used as a starting point for the bra fitting procedure. The subject changed into the test bra and the bra fit checked according to the bra fitting criteria outlined by McGhee and Steele (2010b) (Table 3.5). Size adjustments were made as necessary; for example, if the cups were loose fitting the next cup size down was used or if breast tissue was bulging from the bra a larger cup size bra was used. This was continued until all criteria were satisfied.

Table 3.5 - Bra fitting criteria of McGhee and Steele (2010b)

Band	Too tight: flesh bulging over top of band; subjective discomfort 'feels too tight'
	Too loose: band lifts when arms are moved above head, posterior band not level with inframammary fold
Cup	Too big: wrinkles in cup fabric
	Too small: breast tissue bulging above, below or at the sides
Underwire	Incorrect shape: underwire sitting on breast tissue laterally (under armpit) or anterior midline; subjective complaint of discomfort
Straps	Too tight: digging in; subjective complaint of discomfort; carrying too much of the weight of the breasts
	Too loose: sliding down off shoulder with no ability to adjust the length
Front band	Not all in contact with the sternum
Rating of bra	Pass: no errors or if hooks or straps can be adjusted to allow correct fit
	Fail: any other ticks

3.2.8 Perception Data Collection

Three aspects of bra perception (comfort, fit and breast support) were assessed using the Roberts bra scale, a commercially used bra perception questionnaire (Progressive Sports Technology, 2011). Immediately following the running trials for each strap condition, subjects answered three questions using a seven point Likert scale (Table 3.6).

Table 3.6 - Roberts bra perception questionnaire using seven point Likert scale (Progressive Sports Technology, 2011)

How comfortable is the bra?						
Extremely comfortable	Very comfortable	Quite comfortable	Neither comfortable nor uncomfortable	Quite uncomfortable	Very uncomfortable	Extremely uncomfortable
Score = 3	2	1	0	-1	-2	-3
How well does the bra fit?						
Extremely well	Very well	Quite well	Neither well nor badly	Quite badly	Very badly	Extremely badly
Score = 3	2	1	0	-1	-2	-3
How supportive is the bra?						
Extremely supportive	Very supportive	Quite supportive	Neither supportive nor unsupportive	Quite unsupportive	Very unsupportive	Extremely unsupportive
Score = 3	2	1	0	-1	-2	-3

3.3 Data Processing

This section details the data processing methods used within this thesis and includes torso segment definition, selection of filter frequency and analysis of stationary, drop landing and running trials.

Data for all trials was collected using the CODA motion analysis system. The running trials were processed in a two stages; firstly Visual 3D software was used to define the torso local coordinate system, filter the marker positions and calculate relative breast kinematics; secondly Matlab software was used to identify the individual gait cycles then analyse this data on a gait cycle by gait cycle basis including peak finding (Figure 3.4). The drop landing and stationary trials were processed in one stage using Matlab software.

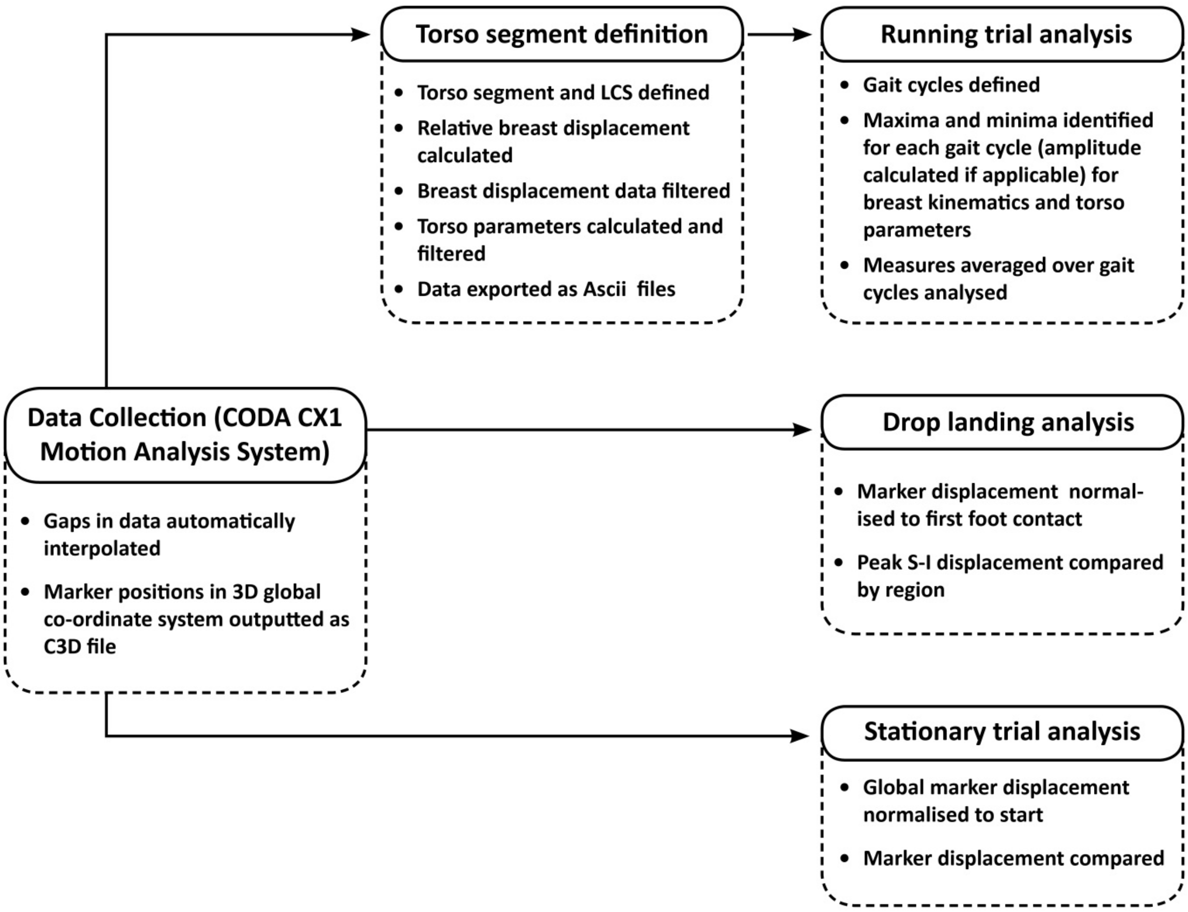


Figure 3.4 - Schematic of data processing procedures

3.3.1 Torso Segment Definition

Visual3D Standard software (Version 4.96.9, C-Motion Incorporated, Germantown, MD, USA) was used to model the torso segment and calculate relative breast motion. Torso kinematics were determined using the POSE estimation method, whereby the torso segment was assumed to be rigid and the torso markers used to determine the position and orientation of the segment based on a least squares fitting method to their POSE in the static trial (Spoor and Veldpaus, 1980).

Using Visual 3D segment endpoints can be defined using two to four marker points (referred to as defining markers). To measure six degrees of freedom segment motion three or more non-colinear markers (tracking markers) must be fixed to the segment, this can include some or all of the defining markers. The segment is calibrated (i.e. the rigid segment POSE defined) using a static trial, the marker positions are averaged over the range of frames selected. A ten second static trial over two complete breathing cycles was used. The local co-ordinate system (LCS) origin and orientation was defined using segment defining markers. Relative breast displacement was then calculated using the instantaneous local co-ordinate system of the torso. Relative breast displacement data was filtered using a 4th order zero-lag low pass Butterworth filter at 15 Hz (filter frequency selection detailed in §3.3.2). In order to monitor any changes in running gait between conditions torso vertical displacement, anterior-posterior lean, lateral bend and axial rotation ranges plus the average torso anterior-posterior lean angle were measured in the global coordinate system and also filtered at 15 Hz. These parameters along with breast kinematic data were outputted as Ascii files for further analysis in Matlab software (§3.3.3).

3.3.2 Filter Frequency Selection

Within the literature the most common filter applied is low pass filter with a cut off frequency between 4 and 13 Hz (Himmelsbach et al., 1992, Zhou et al., 2012, Scurr et al., 2010a, Mason et al., 1999, White, 2013). In order to select a suitable filter frequency residual analysis was performed on all markers for number of different subjects and trials, the range of frequencies used was 5 to 30 Hz (Winter, 1990). The cut off frequencies for the various markers ranged from 9 to 13 Hz, therefore, a cut off frequency of 15 Hz was selected (Figure 3.5).

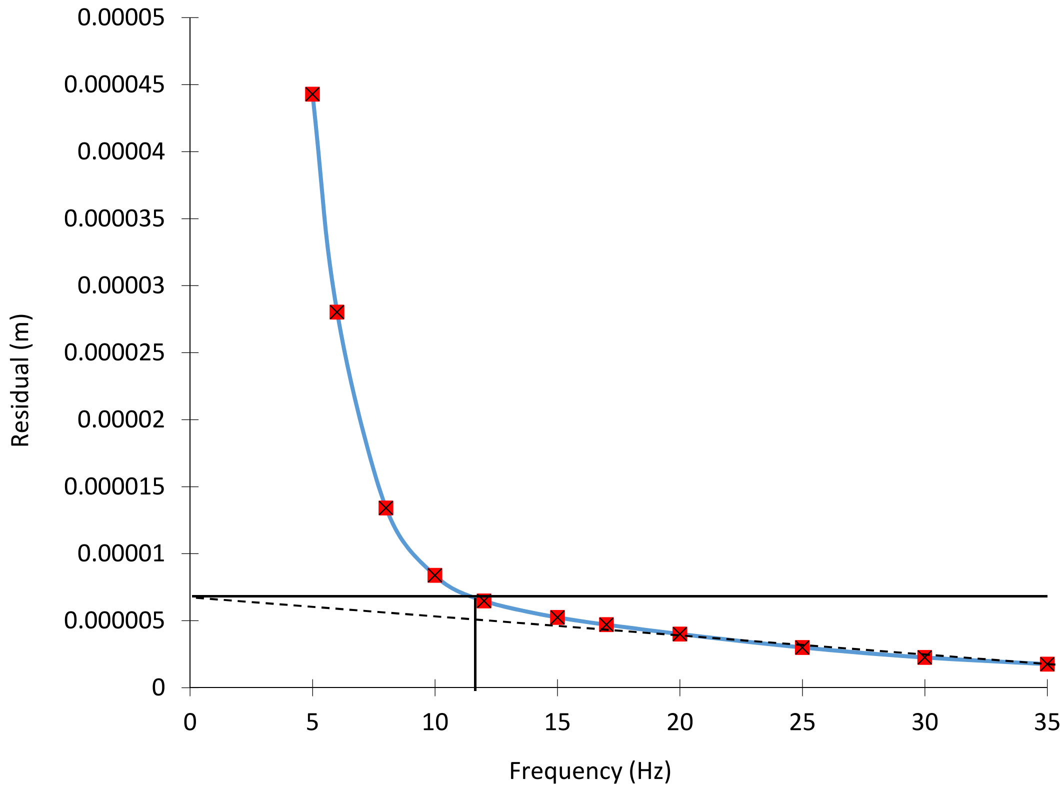


Figure 3.5 - Example of residual analysis performed to select suitable filter frequency (Winter, 1990)

3.3.3 Analysis of Running Trials

Breast and torso data outputted from Visual 3D was further analysed using Matlab (Version R2010a, MathWorks Incorporated, Natick, Massachusetts, USA). The start and end of each gait cycle were defined by the point at which the global anterior-posterior velocity of the right heel marker changed from positive to negative (Zeni et al., 2008). This occurred with the right foot in the most anterior position and typically represents immediately prior to right foot touch down. Breast velocities and accelerations were obtained by numerical differentiation of the breast displacement data using the central difference method. The data for each gait cycle was analysed to identify the maxima and minima data points using the '*max*' function this was performed for medial-lateral (M-L), anterior-posterior (A-P) and superior-inferior (S-I) directions (Figure 3.6).

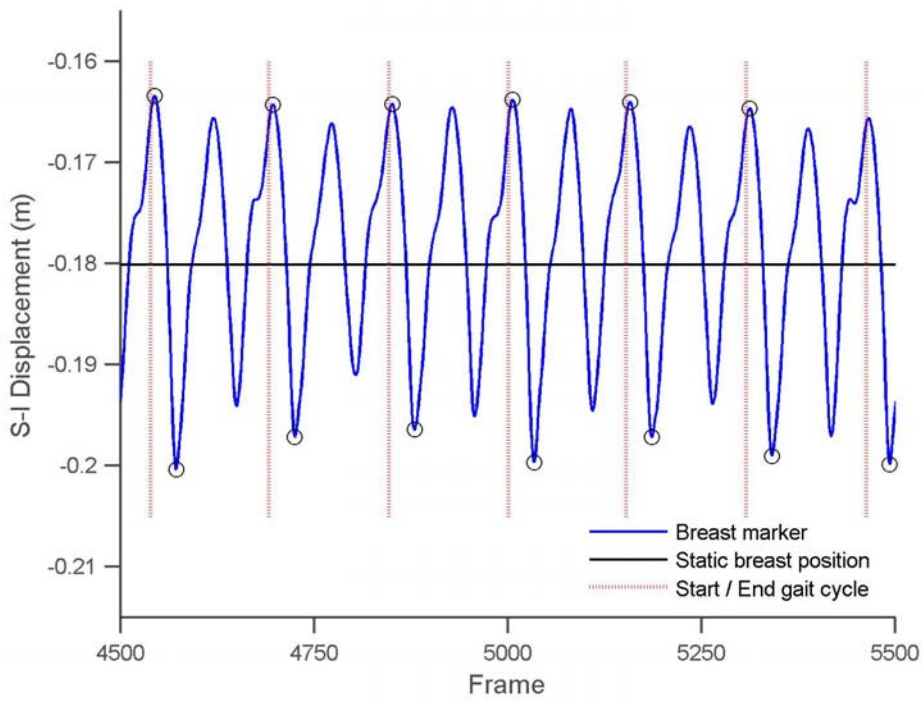


Figure 3.6 - Superior-inferior displacement of right nipple marker from torso origin during 10km/h treadmill running. Maxima and minima are identified for each gait cycle (Subject 1)

Displacement ranges, minimum and maximum velocities and accelerations were determined for each gait cycle and averaged over the number of gait cycles analysed. Displacement range was obtained by subtracting minima value from maxima. Maximum and minimum displacement were calculated relative to the static breast position and again these were determined for each gait cycle then averaged over the gait cycles analysed.

3.3.4 Analysis of Drop Landings Trials

Drop landing trials were used to investigate soft tissue artefact as part of the torso marker set development process (Chapter 4). Global vertical displacement of markers was normalised to initial ground contact (i.e. initial ground contact was taken as zero displacement for all markers) and plotted for the proceeding one second (Figure 3.7). The displacement minima point was identified using Matlab *'min'* function.

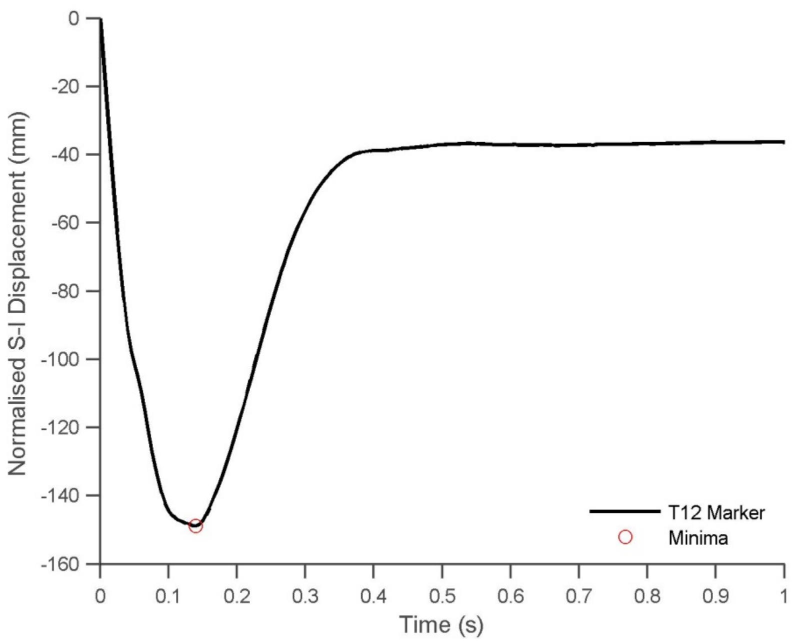


Figure 3.7 - Superior-inferior torso marker displacement normalised to first foot contact following drop landing

3.3.5 Analysis of Stationary Trials

Stationary trials (S2-8, Table 3.2) were used as part of the torso marker set development process (Chapter 4) to investigate whether a marker represented the 'rigid' torso body underlying the breasts. Marker displacement relative to the global origin was plotted normalised to the start position of each marker using Matlab software. Resultant, 3D displacement was plotted and compared for markers in each region (Figure 3.8). The resultant displacement was calculated from the x, y and z amplitudes using Equation 1.

Equation 1

$$\textbf{Resultant displacement} = \sqrt{(\textbf{X amplitude}^{\,2}) + (\textbf{Y amplitude}^{\,2}) + (\textbf{Z amplitude}^{\,2})}$$

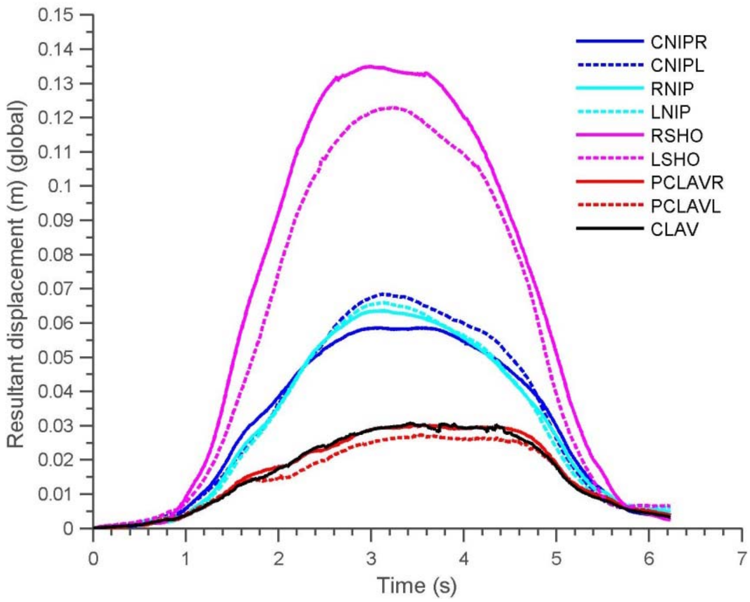


Figure 3.8 - Torso and breast marker displacement during stationary trial S2 (abduct arms)

3.3.6 Statistical Analysis

The statistical analysis included within this thesis was performed using IBM SPSS Statistics software (version 22, Armonk, NY, USA). Details of the statistical analysis methods used were predominantly study specific and are therefore included within the relevant chapters.

3.4 Conclusion

This chapter presented the data collection and analysis methods used within human testing included within this thesis. This general methodology is referred to throughout the thesis, any additions to these methods are outlined in the relevant chapter.

Chapter 4

Development of a torso tracking model to measure relative breast kinematics

4.1 Introduction

The quantification of breast kinematics during exercise has received increased interest in recent years. Factors contributing to this drive include exercise based health initiatives, a growing body of evidence that breast pain during exercise is a significant issue that may discourage women from exercising (Brown et al., 2013) and companies, in an increasing sports bra market, wanting to quantify the performance of their products.

Breast kinematics are typically measured relative to the underlying torso segment. Therefore, to investigate breast motion, it is necessary to track this rigid torso segment motion using an appropriate marker set. This poses a number of challenges including the typically substantial amount of soft tissue in the torso region (Sohlstroem et al., 1993) and the wearing of a sports bra may limit marker position options. The connection between breast tissue and skeletal structure through fascial and ligamentous attachments outlined within §2.2.1 should be a significant consideration when measuring relative breast motion. Four different torso marker sets have been proposed in the existing literature for quantifying relative breast motion (Table 2.3 in §2.6.1.1) (Scurr et al., 2009, Scurr et al., 2010b, Zhou, 2011, McGhee and Steele, 2010a). Interestingly, they generally provide little evidence for how they were developed and how well they are able to track the torso movement. The main exception to this is the marker set proposed by Zhou (2011) which is based on the International Society of Biomechanics standard (Wu et al., 2005). However, this recommendation was based on the work of van der Helm (1997) to measure shoulder motion not specifically breast motion. Marker sets used within the wider field of biomechanics have largely been associated with specific clinical problems (Leardini et al., 2009).

The lack of a universally accepted torso tracking model, and information on the sensitivity of the breast kinematics to the selected torso model, appear to be limitations of the existing breast biomechanics research. Hence the objectives of this study were: firstly to develop a marker set to track the rigid body motion of the torso for the analysis of breast kinematics; and secondly to evaluate the sensitivity of breast kinematics to the torso tracking model used by comparing the present model with existing models from the literature. It was hypothesized that a model specifically developed to track the rigid body motion of the torso for studying breast kinematics would lead to significant differences in breast kinematics compared to the existing literature models.

4.2 Methods

Ten recreationally active female subjects (mean ± SD; age 25.9 ± 5.5 years; height 1.65 ± 0.09 m; mass 67.0 ± 9.6 kg) with large breasts (underband size range 32 – 36 and cup size range D – F) gave voluntary informed consent to participate in the study following ethical approval gained from the institution.

The investigation was carried out in two parts reflecting the two objectives detailed above. Furthermore, Part A (torso tracking model development) was carried out in two stages (Studies 1 and 2), the first (Study 1) examined the markers on an individual position basis and the second (Study 2) considered their performance within torso tracking models. The overall structure of the chapter is summarised in Table 4.1

Table 4.1 - Summary of the work undertaken for torso tracking model development and evaluation

Part	**A. Torso tracking model development**		**B. Torso tracking model evaluation**
Stage	**Study 1**	**Study 2**	**Study 3**
Purpose	Initial screening of the individual torso markers (single subject)	Secondary screening of the torso tracking models (all ten subjects)	Evaluation of the final torso tracking model against those previously used in bra studies (all ten subjects)
Input	All potential torso marker locations (from previous literature)	Reduced marker set	Final torso tracking model Literature torso tracking models
Analysis	Basic screening of individual markers (torso representation, soft tissue artefact, ease of placement and occlusion)	Rigidity of torso tracking model during running. 3D breast kinematics	3D breast kinematics
Output	Reduced marker set	Final torso tracking model	Comparison of the torso tracking models in terms of relative breast kinematics

4.2.1 Part A (Study 1) - Initial screening of markers for torso marker development

The initial screening of markers was performed using one of the ten subjects (age 25, height 1.52 m, body mass 54 kg, bra size 32F). The subject performed the entire test protocol wearing their own sports bra.

4.2.1.1 Part A (Study 1) - Data collection

Twenty five infra-red emitting markers were placed on the torso representing the full range of positions used in previous torso tracking studies (Figure 4.1) (Bowles, 2003, Mason et al., 1999, Himmelsbach et al., 1992, McGhee and Steele, 2010a, Campbell et al., 2007, Eden et al., 1992, Scurr et al., 2008, McGhee et al., 2007, Scurr et al., 2010a, Scurr et al., 2010b, Scurr et al., 2009, Scurr et al., 2007b, Scurr et al., 2007a, Leardini et al., 2009, Sartor et al., 1999, Crosbie et al., 1997, Wu et al., 2005, Nguyen and Baker, 2004, Haake and Scurr, 2010, White et al., 2009b, Fantozzi et al., 2003, Ferrarin et al., 2002, Ferrarin et al., 2004, Bridgeman et al., 2010). A preliminary screening of markers used in previous torso tracking studies was performed to eliminate almost duplicate marker positions or those occluded by a bra. Twenty five markers were taken forward to this initial stage from a possible 33 detailed in Appendix A. One marker was placed on the fullest part of the abdomen (an area with substantial subcutaneous fat) to use as a comparison to more bony landmarks and two markers were placed on the sports bra one on each nipple. Additional markers were placed on the wrists to track arm motion and heels for gait cycle determination. Body kinematics were collected using 10 infra-red emitting markers and a four-head CODA motion system (Charnwood Dynamics Ltd; Leicestershire, UK; 200 Hz) (detailed in §3.2).

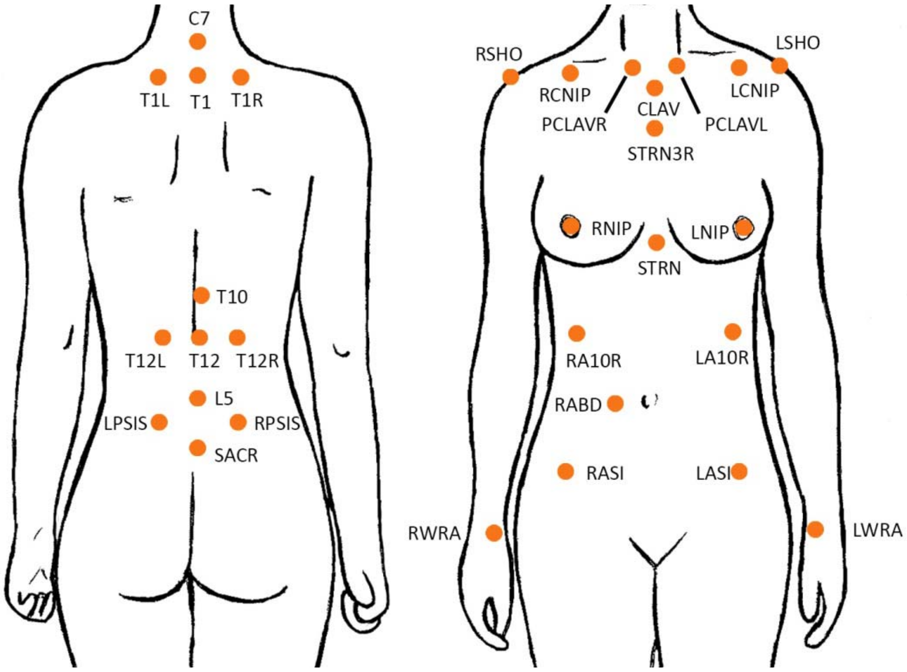


Figure 4.1 - Torso, breast and wrist marker locations used in torso tracking model development

The subject performed a 10 second static trial (S1 in Table 3.2), followed by a series of arm and shoulder movements (S2-S8 in Table 3.2, running arm movement, abduct arms, raise arms in front, raise arms behind, shrug shoulders, round shoulders, pull shoulder blades together). Following a three minute warm up and familiarisation period on the treadmill, the subjects performed three running trials (R1 in Table 3.3, 90 seconds at 10 km/h) and three drop landings (D1 in Table 3.4). Data was collected after 30 seconds at speed. A minimum of two minutes rest was given between running trials.

4.2.1.2 Part A (Study 1) - Data analysis

Prior to the analysis, the 25 torso markers were divided into six groups corresponding to regions of the torso (Table 4.2). This was done to ensure that as markers were eliminated a sufficient marker distribution over the torso remained. If tracking targets are almost in a straight line, or closely positioned, small differences in marker placement and/or soft tissue artefact can produce large differences in local coordinate system alignment. Four factors were assessed: whether a marker represented the ‘rigid’ torso body underlying the breasts; soft tissue artefact; ease of marker positioning; and occlusion of the marker during test activities. Markers which poorly represented the ‘rigid’ torso body underlying the breasts were eliminated, e.g. those that moved excessively during the arm and shoulder movements. Soft tissue artefact was quantified by measuring the vertical displacement of markers following ground contact of the drop landings. Global vertical displacement of markers was normalised to initial ground contact and plotted for the proceeding one second (further detailed in §3.3.4). Peak vertical displacement was compared for markers on a regional basis as markers in the same region are likely to follow the same pattern of movement. Comparisons were made visually and statistically using one-way repeated measures ANOVA with pairwise comparisons that included a Bonferroni correction (significance set at $p < 0.05$). Markers with significantly higher displacement than other markers in that region were eliminated as suffering excessive soft tissue artefact. Ease of marker placement was subjectively assessed during marker application, while marker occlusion was similarly assessed during all the movement trials. Markers that performed poorly in any of these assessments were identified and removed provided this did not compromise the overall marker distribution.

4.2.2 Part A (Study 2) - Secondary screening of torso tracking models for torso marker development

The second study within Part A included all ten of the subjects. The subjects wore a Shock Absorber N109 sports bra (detailed in §3.2.6) which was fitted following the criteria outlined in §3.2.7.

4.2.2.1 Part A (Study 2) - Data collection

Markers were placed on all remaining torso landmarks following Part A (Study 1), together with one on the sports bra over each nipple and one on the right heel for gait cycle identification. As before the markers were tracked using a four head CODA motion analysis system (Charnwood Dynamics Ltd, Leicestershire, UK; 200 Hz). The subjects completed a 10 second static trial followed by a minimum two minute warm up and familiarisation period on the treadmill. The subjects then completed three 90 second running trials at 10 km/h (R1 in Table 3.3) with data collected after 30 seconds at speed. A minimum of 2 minutes rest was given between trials.

4.2.2.2 Part A (Study 2) - Data analysis

This stage of analysis investigated the impact of each marker (or marker pair) in turn on the rigidity of a torso tracking model comprising all markers. Torso models were created using all the markers, and with each marker (or marker pair) excluded in turn. Marker positional data was filtered using a 4th order Butterworth filter at 15 Hz and torso segments then created in Visual3D Standard (Version 4.96.9, C-Motion Incorporated, Germantown, MD, USA). The local co-ordinate system (LCS) and segment pose (obtained from the static trial) remained fixed throughout and only the tracking markers changed. The same LCS was used throughout to better isolate the effects of marker location on resulting kinematics. The torso local co-ordinate system was defined using markers at CLAV, RA10R and LA10R as in in Scurr et al. (2010b). The LCS was defined with the origin at CLAV, the superior-inferior (S-I) axis was from the midpoint of the ribs markers (RA10R and LA10R) to the CLAV, the frontal plane was defined by CLAV, RA10R and LA10R, the anterior-posterior (A-P) axis was projected perpendicular to this frontal plane in the anterior direction, and finally the medial-lateral (M-L) axis was calculated as perpendicular to the S-I and A-P axes (Figure 4.2). In accordance with the recommendation of Mills et al. (2014b) (as discussed in §2.6.1.1) the more ‘stable’ longitudinal axis was defined as the first rotational axis.

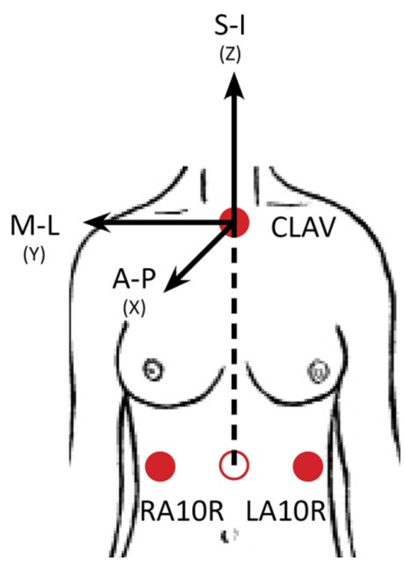


Figure 4.2 - Torso local co-ordinate system

The segment residuals and relative breast displacement data were obtained for all the treadmill running trials and exported to Matlab (Version R2010a, MathWorks Incorporated, Natick, Massachusetts, USA) for gait cycle analysis. The start and end of each gait cycle were defined by the point at which the global A-P velocity of the right heel marker changed from positive to negative (Zeni et al., 2008). The maximum, minimum and range of relative breast displacement for each co-ordinate direction and each gait cycle was calculated and then averaged over the first 30 gait cycles. Similarly, the mean segment residual for each gait cycle was determined and then averaged over the same 30 gait cycles. The torso tracking model which included all the torso markers was used as the standard (the Inclusive model) to which the remainder were compared.

4.2.2.3 Part A (Study 2) - Statistical analysis

Significant differences between the torso tracking models in each of the breast kinematic variables were tested using a one-way repeated measures ANOVA with pairwise comparisons that included a Bonferroni correction (significance set at $p < 0.05$). Torso tracking models that were most different to the Inclusive model were investigated and the markers which led to this difference identified and considered for removal (again provided this did not compromise the overall marker distribution).

4.2.3 Part B - Torso tracking model evaluation

This second part of this investigation evaluated the final torso tracking model that emerged from Part A by comparing the performance against two of the existing torso tracking models used to quantify breast kinematics, i.e. Scurr et al (2010b) and Zhou (2011). The comparison was based on relative breast displacements, peak velocities and peak accelerations during treadmill running. The Zhou (2011) model was as close as could be established based on the markers remaining in the current analysis (i.e. using the T1, T10, CLAV and midpoint of RA10R and LA10R from the current marker set). Since the Scurr et al (2010b) torso model did not include rigid body smoothing both variants of this model were included such that the effects of marker selection and rigid body smoothing on the resulting breast kinematics could be assessed independently. Hence a total of four torso tracking models were compared: this study, Zhou (2011), Scurr et al (2010b) both with and without rigid body smoothing.

4.2.3.1 Part B - Data collection

The second part used the same raw data as collected for Part A (Study 2) as detailed within §4.2.2.1.

4.2.3.2 Part B - Data Processing

The data processing was similar to Part A (Study 2) except for the different torso tracking model definitions. In addition to the relative breast displacements, breast velocities and accelerations were obtained by numerical differentiation using the central difference method. Displacement ranges, minimum and maximum velocities and accelerations were determined for each gait cycle and then averaged across the 30 gait cycles on a per subject basis.

4.2.3.3 Part B - Statistical analysis

Significant differences between the four torso tracking models in each of the breast kinematic variables were tested using a one-way repeated measures ANOVA with pairwise comparisons that included a Bonferroni correction (significance set at $p < 0.05$).

4.3 Results

4.3.1 Part A - Development of the torso tracking model

The first part of this investigation involved the development of the torso tracking model. A summary of all markers initially considered for the torso tracking model and which were eliminated at each stage, including the reasoning, is given in Table 4.2. Of the 25 markers originally included, 16 were eliminated in Study A; 8 were removed as not representing the torso and 8 as suffering from at least one of excessive soft tissue artefact, occlusion and difficulty in locating. In addition, the ribs markers (RA10R and

LA10R) were identified as having high soft tissue artefact but were kept in to maintain the marker distribution over the torso.

Table 4.2 - Summary of the outcomes from Part A (Studies 1 and 2) representing the development of the torso tracking model

Region	Marker	Position	Part A - Study 1 outcome	Part A - Study 2 outcome
Upper Back	C7	C7	Remove - soft tissue artefact & occlusion	
	T1	**T1**	**Take forward - lower soft tissue artefact and less chance of occlusion**	**Final marker set**
	T1R	5 cm right of T1	Remove - position not easily defined	
	T1L	5 cm left of T1	Remove - position not easily defined	
Mid Back	**T10**	**T10**	**Take forward - lower soft tissue artefact than T12**	**Final marker set**
	T12	T12	Remove - soft tissue artefact	
	T12R	5cm right of T12	Remove - poorly defined & soft tissue artefact	
	T12L	5cm left of T12	Remove - poorly defined & soft tissue artefact artefact	
Lower Back	L5	L5	Remove - does not represent torso segment	
	SACR	Sacrum	Remove - does not represent torso segment	
	RPSIS	Right PSIS	Remove - does not represent torso segment	
	LPSIS	Left PSIS	Remove - does not represent torso segment	
Upper Front Medial	**CLAV**	**Suprasternal notch**	**Take forward - Possible occlusion by PCLAVR / PCLAVL**	**Final marker set**
	PCLAVR	Proximal clavicle right	Take forward	Remove – too close to CLAV
	PCLAVL	Proximal clavicle left	Take forward	Remove – too close to CLAV
	STRN3R	Sternum level with 3rd rib	Remove - difficult to locate, occluded by bra, soft tissue artefact	
Upper Front Lateral	**RCNIP**	**Right clavicle above nipple**	**Take forward - may be useful in trials which involve arm raising**	**Final marker set**
	RSHO	Right acromion process	Remove - does not represent torso segment	
	LCNIP	**Left clavicle above nipple**	**Take forward - may be useful in trials which involve arm raising**	**Final marker set**
	LSHO	Left acromion process	Remove - does not represent torso segment	
Lower Front	STRN	Xiphoid process	Remove - occluded by bra	
	RA10R	**Right anterior aspect of 10th rib**	**Take forwards - Although higher soft tissue displacement, provides marker distribution**	**Final marker set**
	RASI	Right ASIS	Remove - does not represent torso segment	
	LA10R	**Left anterior aspect of 10th rib**	**Take forwards - Although higher soft tissue displacement, provides marker distribution**	**Final marker set**
	LASI	Left ASIS	Remove - does not represent torso segment	

In Part A Study 2, seven torso tracking models were assessed using the nine markers taken forward from Study 1 (Table 4.3). A number of statistically significant differences in the segment residual and breast displacements were found between the torso tracking models and the Inclusive (all markers) tracking model (Figure 4.3). The torso tracking model Norib, which excluded the rib markers, exhibited a different pattern of results to the other models; both M-L and A-P displacement were lower compared to the Inclusive model whereas all other models were higher. Also, standard deviations were larger for the Norib torso tracking model than other models. Despite these results, the rib markers were retained as they provided good marker distribution over the torso segment. The close proximity of the CLAV and two PCLAV markers caused issues in consistently and accurately identifying these markers during the running trials. Since the CLAV marker was easier to consistently locate and was used to define the torso model LCS, this marker was retained and the two PCLAV markers removed. Thus, the final torso tracking model comprised of seven markers (T1, CLAV, RCNIP, LCNIP, RA10R, LA10R and T10; Figure 4.4).

Table 4.3 - Torso tracking models used in Part A (Study 2)

Name	**Tracking markers**
Inclusive (all)	T1, CLAV, PCLAVR, PCLAVL, RCNIP, LCNIP, RA10R, LA10R, T10
Noclav	T1, PCLAVR, PCLAVL, RCNIP, LCNIP, RA10R, LA10R, T10
Nocnip	T1, CLAV, PCLAVR, PCLAVL, RA10R, LA10R, T10
Nopclav	T1, CLAV, RCNIP, LCNIP, RA10R, LA10R, T10
Norib	T1, CLAV, PCLAVR, PCLAVL, RCNIP, LCNIP, T10
Not10	T1, CLAV, PCLAVR, PCLAVL, RCNIP, LCNIP, RA10R, LA10R
Not1	CLAV, PCLAVR, PCLAVL, RCNIP, LCNIP, RA10R, LA10R, T10

Note - All torso tracking models used the same local co-ordinate system.

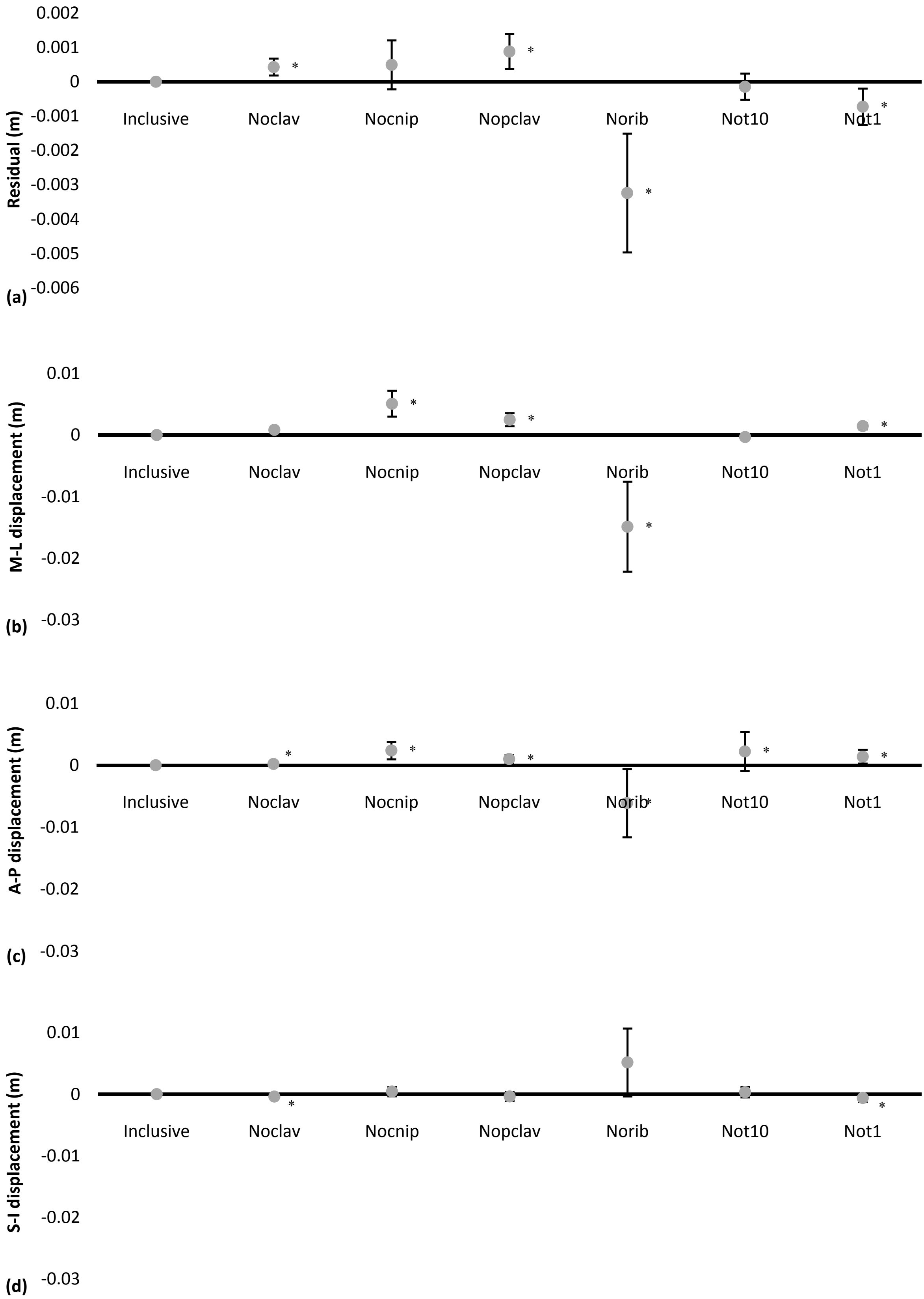


Figure 4.3 - Torso tracking model residual and relative left breast displacement results normalised to the Inclusive torso tracking model (Part A - Study 2) (a) Residual (b) M-L displacement (c) A-P displacement (d) S-I displacement. (* Indicates statistically significant difference between the model and Inclusive (all) model p < 0.05)

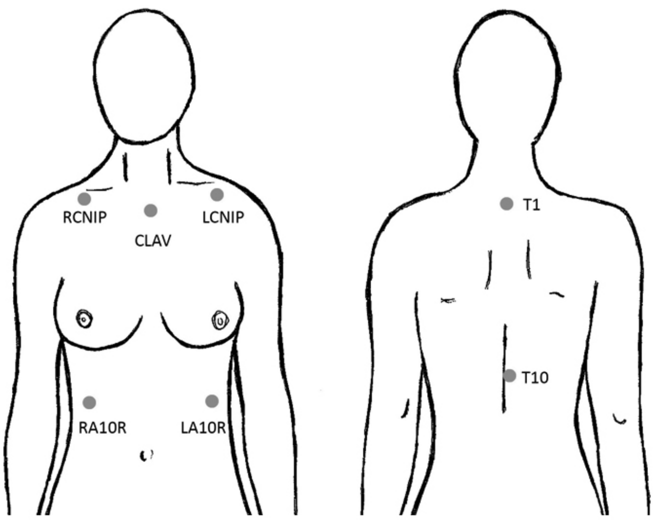


Figure 4.4 - Marker locations used in the current torso tracking model

4.3.2 Part B - Evaluation of torso tracking model

The second part of this chapter evaluated this final torso tracking model by comparing it to the previously defined torso tracking models of Scurr et al (2010b) (with and without RBS) and Zhou (2011) (modified based on the remaining markers used here), in terms of breast kinematics. Statistically significant differences were found between models in the majority of kinematic measures (Figure 4.5). The current torso model was most dissimilar to Scurr-RBS and Scurr-NoRBS models. The general trend in the results was for the current and Zhou models to give smaller displacements (by ~ 7 - 11 mm), peak velocities (by ~ 0.1 - 0.2 $m.s^{-1}$) and peak accelerations (by ~ 8 - 12 $m.s^{-2}$) in M-L and A-P directions compared to the Scurr models. The only significant differences between the current and Zhou models were in the S-I direction; however, the four models were generally more similar in the S-I direction. Examining the effects of rigid body smoothing by comparing the two Scurr models, statistically significant differences were observed in S-I displacement ($p = .002$); the Scurr-NoRBS displacements were on average 8 mm larger. Statistically significant differences were also observed in M-L displacement ($p = 0.035$) and peak positive velocity ($p = 0.034$); the Scurr-RBS model gave slightly larger values by 1 mm and 0.01 $m.s^{-1}$ respectively.

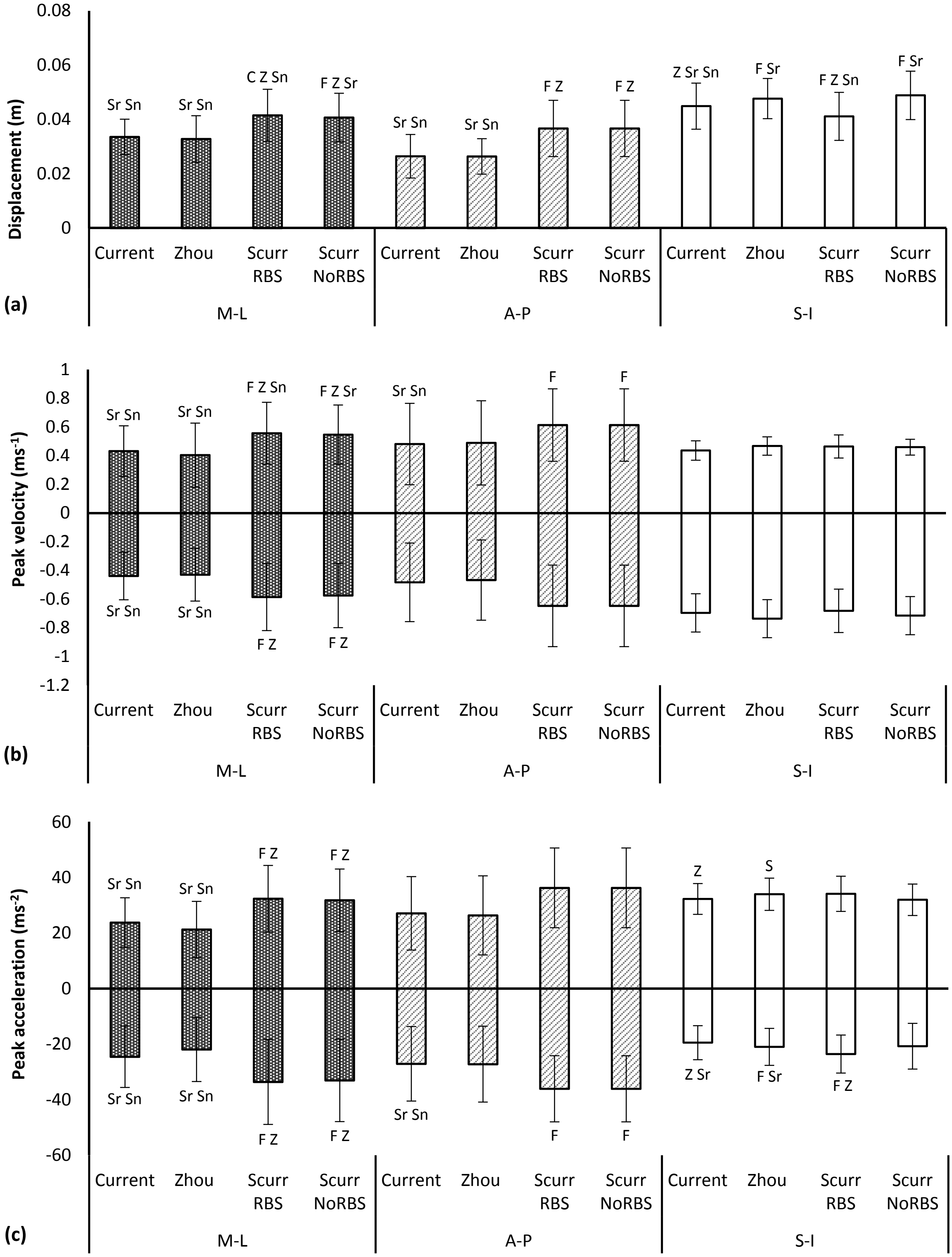


Figure 4.5 - Relative left breast kinematics obtained from the four torso tracking models (a) Displacement (b) Peak positive and negative velocity (c) Peak positive and negative acceleration. (Significant differences between models are denoted by C =significant difference to the Current model, Z = significant difference to the Zhou model, Sr = significant difference to the Scurr-RBS model and Sn = significant difference to the Scurr-NoRBS model)

4.4 Discussion

Four different torso tracking models have been used to quantify relative breast motion in the existing literature. However, little evidence has been provided about their development or their ability to track torso movement. Therefore, the two objectives of this study were: firstly to develop a model to track the rigid body motion of the torso for the analysis of breast kinematics; and secondly to evaluate the sensitivity of breast kinematics to the torso tracking model used. The first objective was addressed in two stages, the first evaluated all possible marker locations on an individual basis, based on considerations such as occlusion and soft tissue artefact. Of the original 25 torso marker locations, 16 were eliminated in this stage. The second stage examined the 9 remaining markers in terms of their contribution to the performance of the torso tracking model. This stage resulted in the removal of a further two markers leaving a final torso tracking model consisting of seven markers (CLAV, RCNIP, LCNIP, T1, T10, RA10R and LA10R; Figure 4.4).

Perhaps of greatest debate regarding the final seven marker selection surrounded the rib markers (RA10R and LA10R). These were highlighted as experiencing significant soft tissue artefact and having the most significant effect on the torso segment residual and the relative breast displacements. A reduction in residual when removing the rib markers suggested they were less rigid than the other markers considered (Figure 4.3). This is likely the result of higher levels of soft tissue in this area (Sohlstroem et al., 1993) as well as the expansion of the ribcage during breathing. It is also worth noting that the rib markers were quite far from other markers; therefore, some reduction in residual may be due to removing more distant markers. Whilst it is acknowledged that the rib markers were comparatively less rigid than other markers they provide important marker distribution over the torso segment. Furthermore, it is known that some breast movement occurs due to ribcage movement during breathing (Chopra et al., 2006); the rib markers may play a role in accounting for that movement. At present the effect of breathing on breast kinematics is unexplored and is a relevant area for future research.

The second objective was to evaluate the sensitivity of breast kinematics to the torso model used by comparing the current torso tracking model with existing models from the literature. The results indicated numerous significant differences in the relative breast kinematic variables between the four torso tracking models, thus supporting the original hypothesis. Medio-lateral breast kinematics obtained using the current model were significantly lower than Scurr-RBS, the same trend was observed for A-P displacement, positive velocity and negative acceleration. The Scurr-RBS model comprised of only three markers, two of which were the ribs (RA10R and RA10L), identified above as experiencing greater soft tissue artefact than the remaining torso markers. Hence, the range of significant differences between the current and Scurr-RBS models is perhaps unsurprising. Whilst only three tracking markers are required to calculate the local co-ordinate system of a rigid body, increasing the number of markers has been shown to improve accuracy and give more repeatable orientation (Challis, 1995, Della-Croce et al., 2003). This was demonstrated by Roosen et al. (2013) who report increased precision of hip joint centre by using more than three markers. However, a torso tracking marker protocol must also be practical within the time constraints of a data collection which often includes multiple bra or activity conditions.

Fewer differences were observed between the current and Zhou torso tracking models. However, as a number of the marker locations used in the original Zhou marker set were eliminated earlier in the selection process, the closest remaining markers were used for this comparison. The Zhou model used five of the seven markers from the current model. In particular, the two ribs markers were combined to form a virtual mid-ribs marker to replace the xiphoid process which was eliminated in Part A (Study 1) as being easily occluded by the bra. It is anticipated that more differences would have been observed had the exact Zhou model been replicated. The main limitation of the Zhou model is that all markers are positioned in a single (sagittal) plane; therefore, small differences in marker placement or soft tissue artefact have the potential to result in large changes in LCS alignment. Additionally, the xiphoid process marker was found to be obscured by wearing a bra.

Scurr et al. (2009) and McGhee and Steele (2010a) torso tracking models were not included in Part B of the study. Both models utilise markers which do not represent the underlying rigid body of the torso as, shown in Part A (Study 1) and therefore were rejected early (ASIS markers in Scurr et al. (2009) and both ASIS and acromion markers in McGhee and Steele (2010a)).

The markers used for the torso model generally had a greater effect on the relative breast kinematics than the use of rigid body smoothing. Significant differences between Scurr-RBS and Scurr-NoRBS were only observed for M-L displacement, velocity and S-I displacement. The most marked effect of rigid body smoothing was observed in S-I breast displacement. Scurr-RBS gave the lowest overall displacement (41 mm), whereas Scurr-NoRBS gave the highest overall displacement (49 mm) (Figure 4.4). As noted above, both Scurr models utilised only three markers, the minimum possible. Therefore, all markers must be in view and any problematic markers will directly impact the LCS alignment. Furthermore, two of the three markers were positioned on the ribs (RA10R and LA10R) which, as noted above, were subject to more soft tissue artefact than the other markers used in the torso tracking models. Thus, the inclusion of rigid body smoothing in this situation is likely to have a marked effect on the orientation of the LCS and; therefore, also on the relative breast kinematic measures. These results perhaps highlight the shortcomings of a torso model utilising a high proportion of markers susceptible to soft tissue artefact. The results for the Scurr-RBS and Scurr-NoRBS models were identical in the A-P direction; as these models comprised only three markers, all markers lie in the same frontal plane and rigid body smoothing has no effect on measures perpendicular to this plane.

The local coordinate system and segment POSE obtained from the static trial remained the same for the four torso models, only the tracking markers changed. The LCS was defined as detailed in §4.2.2.2 and Figure 4.2, in accordance with the recommendation of Mills et al. (2014b) the 'stable' longitudinal axis superior-inferior axis was used as the primary reference axis. However, within the literature the Scurr et al (2010b) model defines the first axis of rotation along the medial-lateral axis, whereas the Zhou (2011) and Current models utilise the superior-inferior axis. Mills et al. (2014b) calculated relative breast displacement using the same torso markers but with either the M-L or S-I axis as the first rotational axis. The authors found the direction in which greatest displacement occurred differed between the two conditions and that the magnitude of superior-inferior breast displacement was significantly altered. This suggests greater differences in relative breast kinematics may occur between the Scurr et al (2010b) model using the original LCS definition method and both the Zhou and Current models.

A number of limitations within this study are acknowledged. The torso is modelled as a single rigid body segment, whereas in reality it is a complex structure containing many small bones and joints within the spine and ribcage. There is no gold standard measure of torso rigid body motion to use as a comparison; therefore, it has been assumed that a marker set specifically developed to measure relative breast kinematics is a step forwards. It was not possible to fully replicate the Zhou model as some markers used were eliminated during torso model development and, therefore, not included in the final marker set. However, the limitations outlined are unlikely to have influenced the main outcomes of the study.

4.5 Conclusion

The current seven marker torso tracking model is the first to be specifically developed for analysing relative breast motion during activities such as treadmill running. Whilst the results indicated that the two ribs markers (RA10R and LA10R) were less rigid in their tracking of the torso than the other markers, they were retained for the final model to ensure a good marker distribution over the torso. The torso tracking model used was shown to have a significant effect on the calculated relative breast kinematics. As the torso tracking model developed herein is the first specifically designed to quantify relative breast kinematics it is recommended that this model is implemented in future research in this area.

Chapter 5

Does breathing affect breast kinematic measurements during treadmill running?

5.1 Introduction

Treadmill running is a commonly used exercise to assess sports bra performance (Bowles, 2012). Typically breast displacement, velocity and acceleration are measured (relative to the underlying torso) and the range of motion / peaks of these determined on a per gait cycle basis and then averaged over several gait cycles (Scurr et al., 2010a, McGhee and Steele, 2010a). Since breast kinematics are measured relative to the torso segment, it is necessary to track the motion of this segment using an appropriate marker set; with the spinal processes, 10th ribs, clavicles, suprasternal notch and sternum representing common marker locations (Chapter 4). Within this process the torso is typically assumed to be rigid; however, as the ribcage expands and contracts during respiration some torso markers are likely to move, particularly those positioned over the ribcage. There is also evidence that the breasts move during respiration; for supine lying maximum breast marker movements of 1, 2 and 2 mm during normal breathing (medial-lateral, superior-inferior and anterior-posterior directions respectively) increasing to 2, 6 and 5 mm during deep breathing have been reported (Chopra et al., 2006). The effect of breathing on the relative breast kinematics measured during treadmill running is currently unknown.

Respiration and running locomotion are synchronised or phase-locked. Humans are known to use several different phase locking patterns including 4:1 (strides : breaths), 3:1, 2:1, 1:1, 5:2, and 3:2 (Bramble and Carrier, 1983, McDermott et al., 2003). The most dominant pattern is 2:1, a 4:1 pattern is typically only used in slow sustained running, while a 1:1 pattern is rarely employed except during uphill running (Bramble and Carrier, 1983). During short duration treadmill locomotion McDermott et al. (2003) found no statistically significant difference in phase locking frequency between runners and non-runners. However, large inter-individual differences were reported within the range given above. If breathing is observed to affect breast kinematics during treadmill running, then phase-locking patterns are likely to be relevant in understanding how many gait cycles are necessary to average out breathing effects for an individual or group of subjects.

The objective of this chapter was to evaluate whether breathing affected relative breast kinematics measured during treadmill running, and if so, how this can be accounted for in the measurement process. It was hypothesized that breathing would not affect the mean values of the breast kinematic variables but that the standard deviations measured across multiple gait cycles would be greater in the presence of breathing.

5.2 Methods

The subjects included within this study are presented first, followed by three sub-sections detailing the data collection, data processing and statistical analysis methods used.

5.2.1 Subjects

Nine recreationally active female subjects (mean ± SD; age 26.3 ± 5.6 years; height 1.66 ± 0.09 m; mass 68.2 ± 9.4 kg) with large breasts (underband size range 32 – 36 and cup size range D – F) gave voluntary informed consent to participate in the study following ethical approval gained from the institution. All were familiar with treadmill running. The subjects performed all trials wearing the test bra (Shock Absorber High Exertion N109 detailed in §3.2.6). The bra was fitted following the criteria outlined in §3.2.7.

5.2.2 Data Collection

Body kinematics were collected using 10 infra-red emitting markers and a four-head CODA motion system (Charnwood Dynamics Ltd; Leicestershire, UK; 200 Hz) (detailed in §3.2). The torso segment was defined using the marker set previously developed for measuring breast kinematics (Chapter 4), this comprised markers on the spinal processes (T1, T10), sternal notch (CLAV), clavicles directly above the nipple (RCNIP and LCNIP) and the anterior inferior aspect of the 10^{th} ribs (RA10R and LA10R) (Figure 5.1). The torso segment local coordinate system (LCS) was defined as detailed in §4.2.2.2 and Figure 4.2. Markers were also placed on the sports bra directly over the nipples and one on the right heel for gait cycle determination.

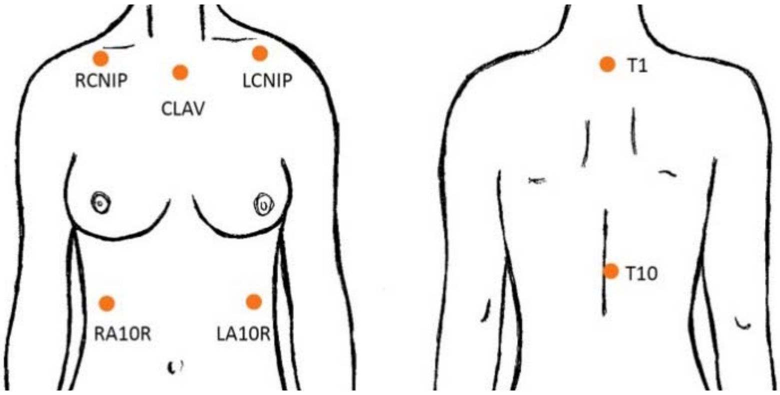


Figure 5.1 - Marker locations used to define the torso segment

Subjects initially performed a 10 second static trial over two complete breathing cycles (S1 - in Table 3.2). Following a three minute warm up and familiarisation period on the treadmill, the subjects performed six running trials (90 seconds at 10 km/h). Three running trials involved breathing normally (R1 - in Table 3.3) and three where at the halfway point subjects were instructed to take a deep breath in, exhale and hold the out breath as long as was comfortable, typically this period lasted around five seconds (R4 in Table 3.3). Data was collected after 30 seconds at speed and a minimum of two minutes rest was given between trials. A preliminary study identified that subjects found it easier to hold their breath after exhalation rather than inhalation. During the preliminary study subjects also reported being conscious of their breathing following the no breathing trials, therefore, the no breathing trials were performed subsequently to the normal breathing trials to avoid any psychological effects.

5.2.3 Data Processing

The running trials were processed following the procedure outlined in §3.3. The torso segment was modelled and relative breast motion calculated using Visual3D then filtered at 15 Hz (v4, C-Motion Incorporated, Germantown, MD, USA). Further analysis of the kinematic data was completed in Matlab (R2010a, MathWorks Incorporated, Natick, Massachusetts, USA). Displacement ranges, minimum and maximum velocities and accelerations were determined for each gait cycle and then averaged over five gait cycles and three trials for each condition (normal breathing and no breathing) to give the mean and standard deviation on a per condition and subject basis.

In order to monitor any changes in running gait between conditions torso vertical displacement, anterior-posterior lean, lateral bend and axial rotation ranges plus the mean torso anterior-posterior lean angle were measured in the global coordinate system. These parameters, along with running cadence and torso segment residual, were determined for each analysed gait cycle and the mean values determined similarly to the breast kinematics detailed above.

For the no breathing trials, the period of no breathing was identified by examining the change in circumference of the triangle formed by the RA10R, LA10R and T10 markers, which was assumed to approximate the ribcage circumference. This method utilised the exiting markers torso, minimising disruption to the subject and was found to be effective at monitoring breathing frequency during the preliminary study. The data was filtered using a zero-lag 4th order Butterworth low pass filter at 1.3 Hz to better isolate breathing frequencies from step frequencies. The lowest known phase locking pattern is 1:1, however, a phase-locking pattern of 2:1 is reported to be most favoured (Bramble and Carrier, 1983). The average running cadence was 2.6 steps per second; therefore, the highest breathing frequency was estimated to be 1.3 Hz. The period of no breathing was then determined by plotting the ribcage circumference triangle (represented by markers RA10R, LA10R and T10) and visually identifying the flat section of this plot (Figure 5.2). The central five seconds of this period was selected for breast kinematics analysis and a similar five second period analysed in the normal breathing trials.

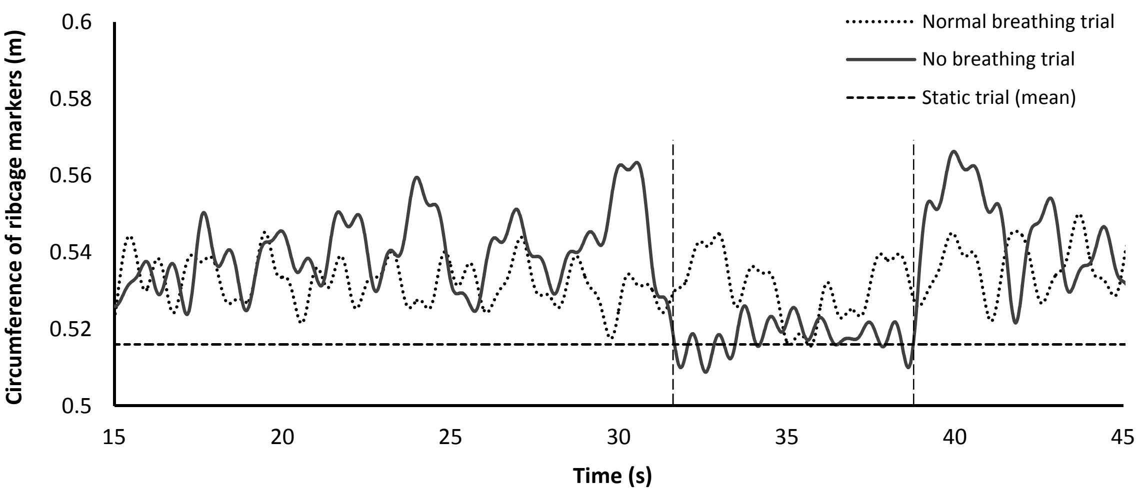


Figure 5.2 - An example ribcage triangle circumference during normal breathing and no breathing trials (filtered at 1.3 Hz). The period of no breathing is denoted by the dotted vertical lines. The horizontal dashed line indicates the mean ribcage triangle circumference in the static POSE trial (Subject 1, Run 2)

5.2.4 Statistical Analysis

Paired samples t-tests were used to test for significant differences between conditions (normal breathing and no breathing) in the means and standard deviations of each breast kinematic variable and the means of the torso variables. Significance was set at $p < 0.05$. The Cohen's d effect sizes were calculated and 0.2 considered a small effect, 0.5 medium and 0.8 large (Cohen, 1988).

5.3 Results

The nine subjects studied exhibited four different phase locking ratios, one subject used a 3:2 ratio, four a 2:1, three a 5:2 and one a 3:1 ratio (Figure 5.3).

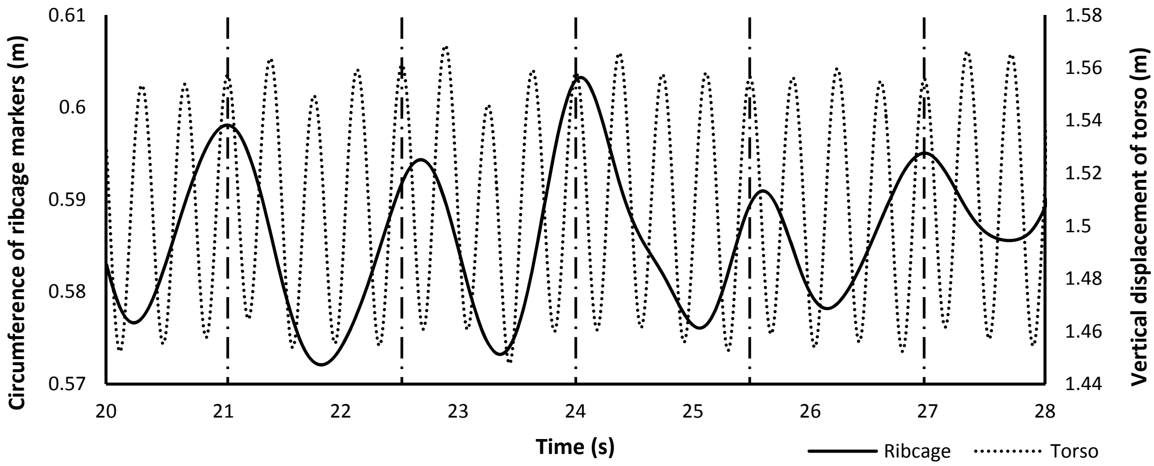


Figure 5.3 - Vertical torso displacement and ribcage triangle circumference during 10 km/h treadmill running for Subject 4 demonstrating a 2:1 phase locking pattern. The dashed vertical lines denote every two strides.

Statistically significant differences between the normal breathing and no breathing conditions were observed for breast displacement range, peak positive and peak negative breast velocities in the superior-inferior direction only (Figure 5.4). Relative breast displacement range was on average 2.3 mm lower in the normal breathing condition ($p = 0.007$) although the effect size was small ($d = 0.22$). Similarly peak velocities were lower in the normal breathing condition; by 0.03 $m.s^{-1}$ (positive; $p = 0.002$) and 0.04 $m.s^{-1}$ (negative; $p = 0.032$) although effect sizes were again small ($d = 0.25$ and 0.17 respectively).

Standard deviations for both medial-lateral and anterior-posterior breast displacements were significantly greater for the normal breathing condition compared to no breathing (p = 0.037 and 0.013 respectively) with medium effect sizes (d = 0.52 and 0.59 respectively). In the medial-lateral direction the standard deviation increased from 3.1 to 5.1 mm in the presence of breathing and in the anterior-posterior the increase was from 2.2 to 4.0 mm.

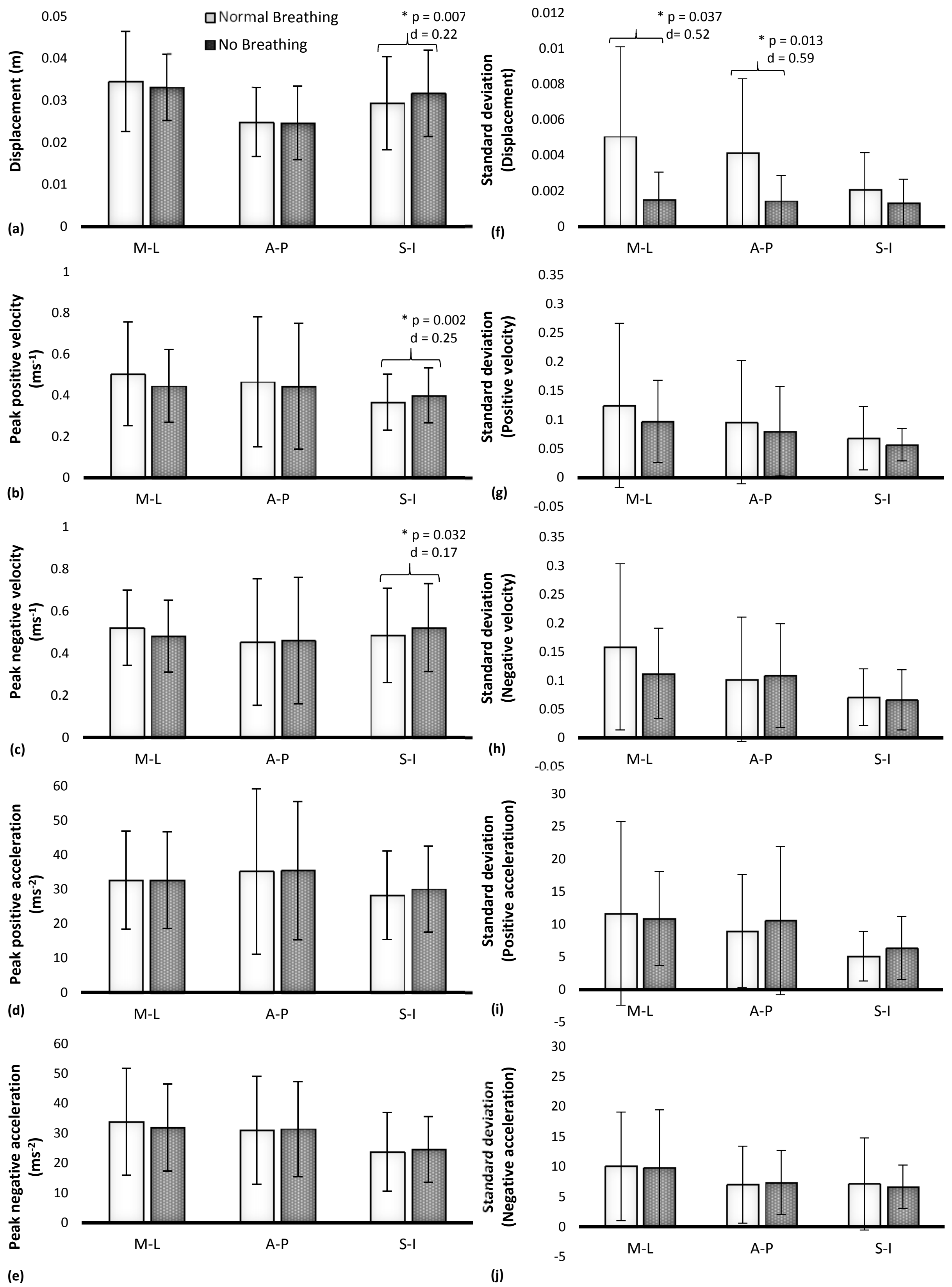


Figure 5.4 - Group mean ± standard deviation in: (a) Relative breast displacement (b) Peak positive breast velocity (c) Peak negative breast velocity (d) Peak positive breast acceleration (e) Peak negative breast acceleration. Mean ± standard deviation of the individual subject standard deviations in (f) Relative breast displacement (g) Peak positive breast velocity (h) Peak negative breast velocity (i) Peak positive breast acceleration (j) Peak negative breast acceleration. * Indicates statistically significant difference between conditions (p ≤ 0.05). d = Cohen's d effect size

Analysis of gait data revealed no significant differences between conditions in cadence, vertical torso displacement, torso lateral bend and axial rotation ranges (Table 5.1). However, statistically significant differences were observed between breathing conditions for both torso anterior-posterior lean range and mean angle. The results indicated that subjects ran with more anterior lean and less range of anterior-posterior motion during the no breathing condition compared to normal breathing, although in both cases it was by less than 1°.

Table 5.1 - Gait variables for both breathing conditions (Mean, SD)

		Normal (Mean ± SD)	No Breathing (Mean ± SD)	T-Test	Cohen's d effect size
	Cadence (strides/sec)	1.33 ± 0.03	1.34 ± 0.03	0.473	0.08
Torso	Vertical displacement (mm)	113 ± 9	112 ± 11	0.067	0.16
	Lateral bend range (°)	7.2 ± 2.2	7.5 ± 2.0	0.297	0.15
	Anterior-posterior lean range (°)	10.0 ± 3.04	9.4 ± 2.7	0.029*	0.23
	Mean anterior-posterior lean angle (°)	1.0 ± 4.2	1.7 ± 4.3	0.001**	0.17
	Axial rotation range (°)	28.6 ± 4.8	28.3 ± 4.6	0.580	0.06
	Segment residual (mm)	9.7 ± 2.6	9.1 ± 1.7	0.133	0.26
	Standard deviation of segment residual over a gait cycle (mm)	2.6 ± 1.0	2.4 ± 0.9	0.343	0.16

* indicates statistically significant difference ($p < 0.05$)
** indicates statistically significant difference ($p < 0.005$)

5.4 Discussion

This chapter aimed to determine whether breathing affected breast kinematics measured during treadmill running. If breathing was found to have an effect then this may have implications for designing experiments in order to minimise these effects and thereby maximise the validity of the breast kinematics measured. The results were in partial agreement with the hypotheses. No significant differences were observed between the breathing and no breathing conditions for the mean breast kinematics in the medial-lateral or anterior-posterior directions, while the standard deviations for breast displacement in these directions were significantly greater under the breathing condition. However, in contrast to the hypotheses, mean range of motion and peak velocities were significantly greater under the no breathing condition in the superior-inferior direction.

A number of factors could have contributed to these differences between the breathing and no breathing breast kinematics; notably, gait alterations, POSE estimation of the torso and phase-locking effects during breathing. Analysis of the gait data revealed subjects ran with significantly greater anterior torso lean and significantly less anterior-posterior lean range during the no breathing trials (by 0.7 ± 1.0° and 0.7 ± 1.5° respectively). However, this may be an artefact of the torso model used, as the no breathing condition was conducted whilst exhaled then the rib markers (RA10R and LA10R) were likely to be more posteriorly positioned compared to the breathing condition, thus leading to a more anterior lean in the torso segment and slightly less range of motion. Therefore, the difference in gait parameters between conditions may be potentially marginal.

At present few breast motion studies account for a possible variation in gait when reporting results. The current results highlight the need for such studies to include these measures, particularly when comparing different breast conditions. Within the current study, the observed changes in gait can be considered as a confounding factor, i.e. potentially causing a (systematic) change in breast kinematics in addition to any changes caused by the independent variable of interest (breathing).

The relationship between the raw torso marker positions and their rigid body POSE is likely to have changed between the breathing and no breathing conditions. Evidence of this can be seen in the ribcage triangle circumference data in Figure 5.2; the circumference was more consistent and remained closer to the static POSE value for the no breathing condition. In addition, the mean and standard deviation of the segment residual was lower for the no breathing condition (mean 9.1 mm versus 9.7 mm and standard deviation 2.4 mm versus 2.6 mm). This indicates that the static POSE estimation (obtained over two quiet standing breathing cycles) for the torso was closer to the fully exhaled position than to the average position during normal breathing running. The residual standard deviation was expected to be lower for the no breathing condition since torso dimensions are changing only due to soft tissue artefact and segment non-rigidity effects but not through breathing. Although these differences were not found to be statistically significant, the subject group was quite homogeneous, therefore, differences may be observed in a more varied sample. Regardless, differences in how the POSE estimation of the torso is achieved between the breathing and no breathing conditions may have contributed in the observed differences in breast kinematics.

The number of gait cycles (strides) analysed was limited to five by the duration that subjects could hold their breath. As the number of gait cycles analysed was small, phase-locking is more likely to have influenced the results. If the subject was utilising a 2:1 phase-locking pattern, as demonstrated by the subject in Figure 5.3, then two and a half breaths would occur during the analysis period, whilst a 5:2 ratio would result have resulted in two complete breaths and a 3:1 ratio would have resulted in one and two thirds of a breath. If breathing does affect breast kinematics, then averaging the breast kinematics over an incomplete number of breathing cycles would contribute a random difference between the breathing and no breathing conditions and increased variance in the measurements (as observed in the medial-lateral and anterior-posterior directions in this study; Figure 5.4). This effect would be greater for a lower numbers of gait cycles, i.e. where the incomplete breathing cycles contribute a greater proportion to the total number of breathing cycles analysed. An appropriate number of gait cycles required for breast kinematic analysis has yet to be established (§2.6.1.1), for example; Mason et al (1999) used only 2, White et al (2011) and Scurr et al (2009) used 5, Scurr et al (2010a) used 10, whereas McGhee and Steele (2010a) used 30. The current results suggest that breathing may directly affect breast kinematics during treadmill running and that the phase-locking pattern utilised may be a contributor to this effect. To counteract this, using a number of gait cycles that equates to a complete number of breathing cycles seems appropriate. In multi-subject studies a range of phase-locking ratios are likely to be present and whilst generally more gait cycles will help to minimise phase-locking pattern effects, interestingly 30 gait cycles (as used by McGhee and Steele (2010a)) represents the lowest number that equates to a complete number of breathing cycles for all commonly used phase-locking ratios (Bramble and Carrier, 1983).

Determining the effect of breathing on breast kinematics is a challenging problem. Although the method applied here could not provide definite answers, the outcome has allowed some recommendations to be presented. Of the three factors identified as possibly having affected the breast kinematics between breathing and no breathing conditions only the final one, i.e. phase-locking between stride and breathing frequencies is relevant. Both gait alterations and POSE estimation of the torso were specific to the breathing versus no breathing experimental comparison and would not be present under normal breathing conditions. In contrast, both intra and inter subject effects of phase-locking could be present under normal breathing conditions. Thus, although it cannot be firmly concluded that phase locking led to the significant differences between the breathing and no breathing conditions observed here, it can still be recommended that the number of gait cycles analysed is sufficient to ensure any potential phase locking effects are minimised.

5.5 Conclusion

This is the first study to have investigated the effect of breathing on breast kinematics during treadmill running. Significant differences were observed in the breast kinematics, notably in the superior-inferior direction; however, these cannot definitively be directly linked to breathing since significant differences in running gait were also observed. However, the results do suggest that increasing the number of gait cycles analysed can reduce any effects of breathing on breast kinematics due to phase-locking, with a recommended 30 gait cycles ensuring that this is the case across all commonly used phase-locking ratios.

Chapter 6

The effect of breast marker position on relative breast kinematics

6.1 Introduction

Sports bra performance is typically assessed using relative breast kinematics and measures of comfort. To investigate breast motion, it is necessary to track the rigid torso segment and the non-rigid body of the breast using appropriate marker sets. Chapter 4 detailed the development of a marker set specifically to track rigid body motion of the torso for studying breast kinematics. This chapter explores a number of factors relevant to tracking breast motion.

Tracking breast motion poses a number of challenges. Notably, the breast is a non-rigid body which varies in shape, size and tissue composition; whilst wearing of a sports bra covers the breast surface making it difficult to track the breast directly using motion analysis markers. Markers placed over the bra are assumed to represent the underlying breast motion and that movement of the breast inside the bra should not occur if the bra is well fitted (Scurr et al., 2010a). The use of thigh markers under and over compression shorts to measure soft tissue movement during a drop landing was investigated by Mills et al. (2011). Markers were placed in pairs (one marker attached to skin the other over the garment) with 3 cm superior-inferior (S-I) separation at five anatomical locations. The maximum change in separation between markers averaged across the five anatomical locations were (mean, SD); no compression (3.3 ± 0.6 mm), medium (4.4 ± 1.5 mm) and high (2.6 ± 0.6 mm). The variability in movement of markers placed under and over garments was 0.1 mm for both compression conditions. The maximum change in separation was significantly reduced from no compression to high compression and medium to high compression, leading the authors to recommend the method to be sufficiently sensitive to monitor soft tissue movement under compression shorts. Interestingly, the authors also suggested the greater standard deviation observed in medium compression may be due to independent movement or sliding of garment over skin but do not comment upon the increased change in separation. At present, under bra markers have primarily been utilised by the Australian based research group (McGhee and Steele, 2010a, McGhee et al., 2013). Whilst the use of under compared to over garment markers has been explored in compression shorts it is yet to be considered within sports bra research.

Breast displacement is known to differ across the breast (Mason et al., 1999, Zhou et al., 2012), however, most breast kinematic studies track breast motion using single marker at the nipple (Lorentzen and Lawson, 1987, Starr et al., 2005, Campbell et al., 2007, McGhee et al., 2013, McGhee and Steele, 2010a, Scurr et al., 2009, White et al., 2009b, Scurr et al., 2010b, White et al., 2010) or at the fullest point of the breast (Gehlsen and Albohm, 1980). Mason et al. (1999) recommended the nipple to be a good indicator of breast motion, based on their findings that greatest displacement occurred at the nipple and inferior breast during bare breast running. These findings are supported by Eden et al. (1992) and Zhou et al. (2009) for markers located on the exterior of a sports bra. However, the methods used within these studies do not track the six degrees of freedom motion of the torso as only one or two torso tracking markers were used. More recent studies by the Hong Kong based research group have used an array of 6 breast markers placed over the bra if worn (Zhou et al., 2009, Zhou et al., 2013, Zhou et al., 2012) (§2.6.1.1). The study by Zhou et al. (2012) of six breast markers (positioned at the nipple and 4 cm medial, lateral, inferior and superior plus 8 cm superior to the nipple) found breast displacement during bare breasted running to be highest at the nipple, inferior and lateral to the nipple (markers NIP, NIPI and NIPL in Figure 6.1 and Table 6.1). Interestingly, a different trend was observed when a sports bra was worn, using markers placed over the bra the highest breast displacement was found to occur at the upper breast (markers NIPS and NIPS2). The authors suggest the use of multiple breast markers may provide additional information about breast motion to better assist sports bra design.

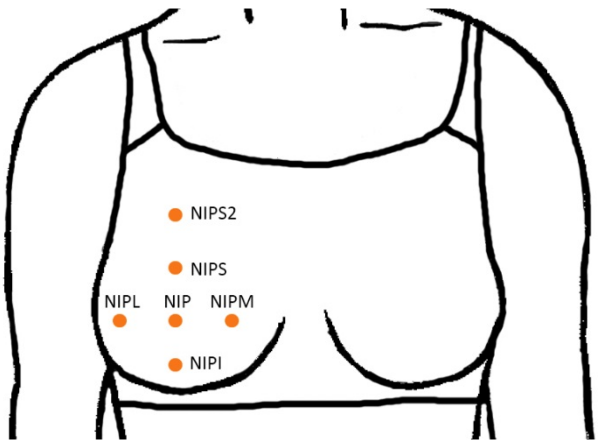


Figure 6.1 - Breast marker locations

Table 6.1 - Description of breast marker locations

Location	Description
NIP	Nipple
NIPL	4 cm lateral of nipple
NIPM	4 cm medial of nipple
NIPI	4 cm inferior of nipple
NIPS	4 cm superior of nipple
NIPS2	8 cm superior of nipple

The importance of wearing the correct bra size is widely advocated in the literature and it has been postulated that poor bra fit may reduce sports bras ability to limit breast motion, and result in increased levels of breast discomfort (Page and Steele, 1999, Mason et al., 1999, White et al., 2009b). Studies have reported that 66 - 100% of women wear the incorrect bra size, with a negative correlation between increasing breast size and bra fit (Greenbaum et al., 2003, McGhee and Steele, 2006, Page and Steele, 1999, Wood et al., 2008, Spencer and Briffa, 2013). Very poor bra fit has been found to contribute to poor posture, upper body musculoskeletal problems and nerve problems in the upper limb resulting from nerve compression beneath bra straps (Greenbaum et al., 2003, de Silva, 1986). However, the effect of bra fit on breast kinematics has yet to be investigated.

The principal aim of this study was to compare relative breast displacement measured using markers on the bra versus markers on the skin beneath the bra, for different marker locations over the breast. The secondary aim was to investigate the effect of bra fit on these displacements using a well fitting, a size too small and a size too large bra cup.

These aims were expressed as the following objectives.

1. To determine whether relative breast displacement differs when measured using markers placed under bra versus over the bra.
2. To determine how relative breast displacement varies over the breast and where it is highest.
3. To determine the effect of bra cup size on objectives 1 and 2.

To achieve these objectives it was necessary to conduct a preliminary study to assess how quickly the static breast bra position settles down following running. This would enable the equivalent positions on the bra versus on the skin under the bra to be identified.

6.2 Method

The preliminary and main study were performed both using single subjects; Preliminary subject (age 28, height 1.77 m, mass 75.1 kg, bra size 36D) and main subject (age 25, height 1.80 m, mass 73.0 kg, bra size 36E). Both subjects gave informed consent to participate and ethical approval was gained from the institution.

6.2.1 Preliminary Study

6.2.1.1 Preliminary Study - Data collection

The subject performed a warm up of 3 minutes treadmill running at 8 km/h wearing her own sports bra. The subject then changed into the test bra, a ShockAbsorber N109 (Figure 6.2) which was fitted as detailed in §3.2.7 and the six breast locations on each breast were identified on the outside of the bra with a small pen mark (Figure 6.1 and Table 6.1) (Zhou et al., 2012). A fine permanent marker pen was applied at the six locations to transfer a mark through the bra on to the breast. The subject completed a 15 second running trial at 8 km/h after which another permanent marker pen dot was placed on the same six locations in a different colour to mark the skin beneath. This process was continued until the pen dots on the skin beneath the bra remained in consistent positions. The study was repeated twice.

(a) (b)

Figure 6.2 - ShockAbsorber N109 test bra (a) Front and (b) Side views

6.2.1.2 Preliminary Study - Data processing

The position of the pen marks was measured relative to the initial mark at each of the six locations. The data was transferred to a graphical representation and was visually inspected to identify any trends in pen mark position with run time.

6.2.2 Main Study

6.2.2.1 Main Study - Data collection

Body kinematics were collected using 16 infra-red emitting markers and a four-head CODA motion analysis system (Charnwood Dynamics Ltd; Leicestershire, UK 200 Hz). The torso segment was defined using the marker set developed for measuring breast kinematics in Chapter 4, this comprised markers on the spinal processes (T1, T10), sternal notch (CLAV), clavicles directly above the nipple (RCNIP and LCNIP) and the anterior inferior aspect of the 10^{th} ribs (RA10R and LA10R) (Figure 6.3). The torso segment local coordinate system (LCS) was defined using CLAV, RA10R and LA10R as detailed in §4.2.2.2 and Figure 4.2. In each case, the segment pose was defined using the same static trial. In addition, a right heel marker was added for gait cycle determination.

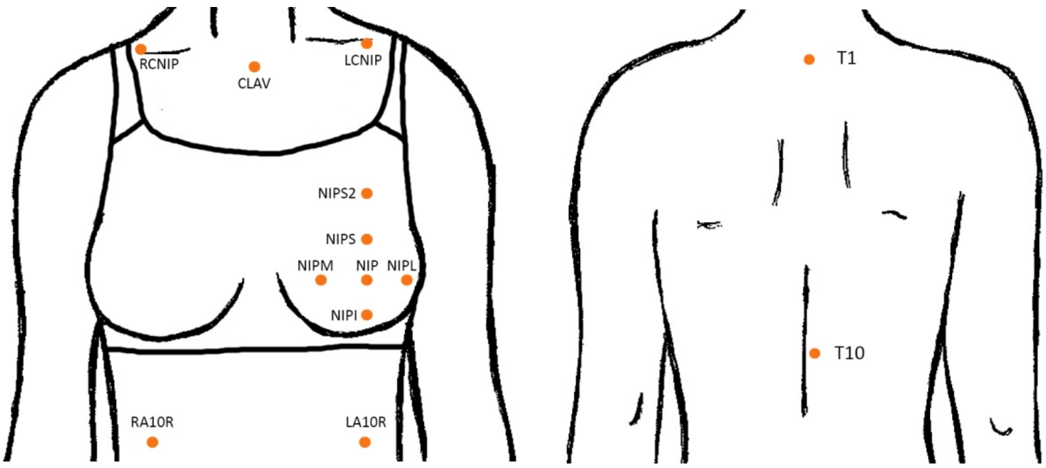


Figure 6.3 - Breast, bra and torso marker locations (Main study)

The subject wore a size 36E Shock Absorber N109 sports bra (Figure 6.2 and as detailed §3.2.6) which was fitted following the procedure outlined in §3.2.7. A three minute treadmill run at 12 km/h was performed as a warm up and to allow the breast to settle into the bra. The six breast locations were marked on the left bra cup using a fine permanent marker pen and transferred through the material to the underlying breast. Markers were applied at the six breast locations over the bra. The subject performed a 10 second static trial over two complete breathing cycles followed by a 90 second running trial at 12 km/h (Trials S1 - in Table 3.2 and R3 - in Table 3.3). Data was collected between 30 and 90 seconds of running. The six over bra markers on the cup were removed and two markers applied at the marked locations beneath the bra, disturbing the bra as little as possible. Markers were applied under the bra in pairs (NIPM and NIPL; NIPS and NIPI; NIPS2 and NIP) to minimise the change to bra fit. Based upon the findings of the preliminary study, a 30 second run at 8 km/h was performed for the breast to 'settle in' after applying the under bra markers. A static and running trial were then performed as before with a minimum of 2 minutes rest between running trials. These four static and running trials were then repeated for the cup size smaller and cup size larger bras (36DD and 36F).

6.2.2.2 Main Study - Data processing

The torso segment was modelled and relative breast motion calculated using Visual3D (v4, C-Motion Incorporated, Germantown, MD, USA) as detailed in §3.3. Relative breast marker displacement was filtered using a 4th order zero-lag low pass Butterworth filter at 15 Hz and further analysis of the kinematic data was completed in Matlab (R2010a, MathWorks Inc., Natick, Massachusetts, USA). Breast marker displacement from static position and displacement range were determined for each gait cycle and then averaged over 30 gait cycles (as recommended by the findings of Chapter 5).

In order to monitor any changes in running gait between conditions torso vertical displacement, anterior-posterior lean, lateral bend and axial rotation ranges plus the average torso anterior-posterior lean angle were measured in the global coordinate system. These parameters, along with running cadence, were determined for each analysed gait cycle and the mean values determined similarly to the breast kinematics detailed above.

6.2.2.3 Main Study - Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics software (version 22, Armonk, NY, USA). Mauchly's test indicated that the assumption of sphericity had not been violated for any of the gait variables studied ($p < 0.05$). Therefore, the gait variables were analysed using a two-way (trial and bra cup size) repeated measures ANOVA with post-hoc pairwise comparisons that included a Bonferroni correction (significance was set at $p < 0.05$).

6.3 Results

6.3.1 Preliminary Study - Running time for breast-bra positioning to settle

Initial settling in movement between the breast and bra during running was tracked by transferring pen marks through defined locations on the bra to the underlying breast. This process was done prior to running and during short breaks every 15 seconds until minimal change in breast markers occurred. The results show that movement between the breast and bra occurred primarily in the first 15 seconds with much smaller displacements during the subsequent 30 seconds, the test was stopped after 45 seconds of running (Figure 6.4). The trend observed in most locations was that the pen marks were inferior to the start position, with smaller amounts of medial or lateral displacement, no observable change in position occurred at the nipple or inferior breast (NIP and NIPI). These observations may be due to several effects; the breasts moving upward relative to the initial position within the bra, the bra moving downwards over the breasts or a combination of both effects. The direction of movement may be quite dependent on how the bra was put on, however 30-45 seconds of running appears to be sufficient to settle the bra-breast position. A similar outcome in terms of time scale was found on both occasions.

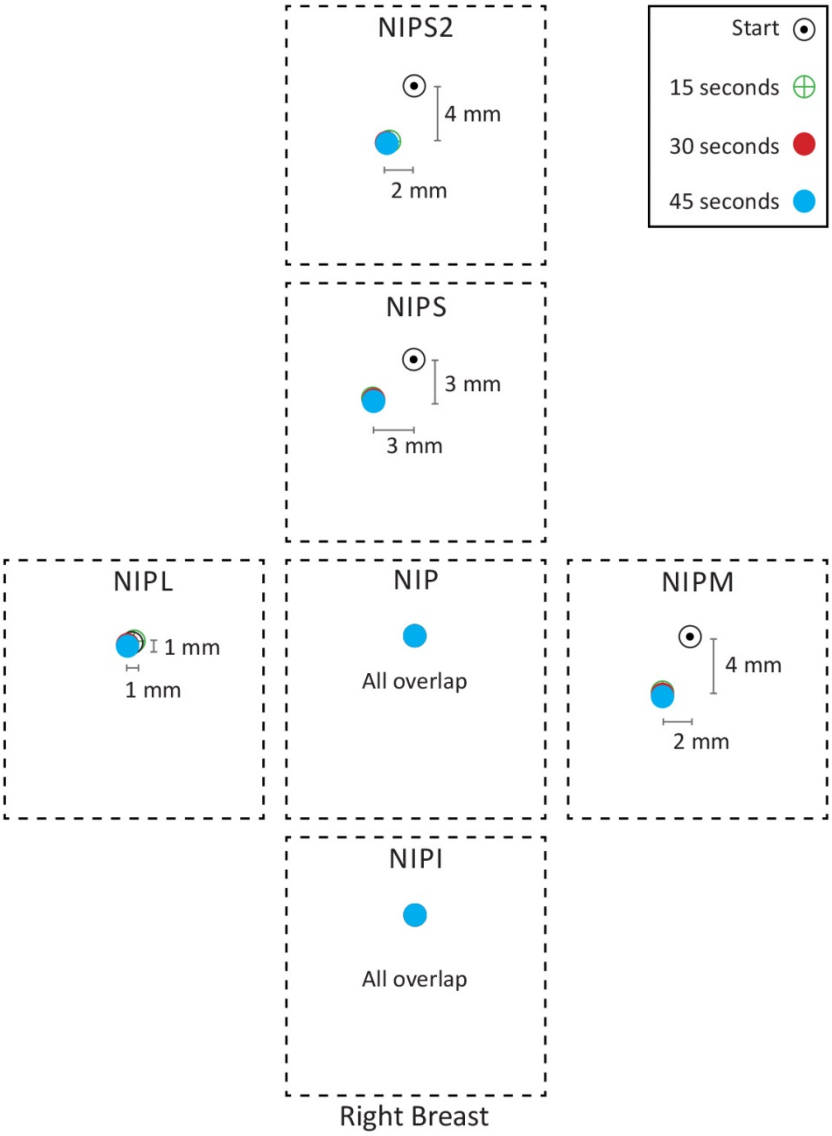


Figure 6.4 - Displacement of breast relative to bra during initial 45 seconds of 8 km/h running

6.3.2 Main Study

The objectives of the main study were;

1. To determine whether relative breast displacement differs when measured using markers placed under bra versus over the bra.
2. To determine how relative breast displacement varies over the breast and where it is highest.
3. To determine the effect of bra cup size on objectives 1 and 2.

In order to achieve these objectives relative breast displacement was assessed at six breast locations using markers under and over the bra for three different fitting bras, well fitting bra (36E), smaller fit (36DD) and larger fit (36F).

The results are presented in four sections: firstly those relating to objectives 1 and 2 are presented together and consider only the well fitting bra; followed by objective 3 which considers all bra fits; then the consistency in relative positioning of the markers; and finally the gait variables.

6.3.2.1 Objectives 1 and 2 - Over versus under the bra and the effect of marker location

Marker displacement data was visually examined and marker displacement relative to the static position was plotted over a typical gait cycle (Figure 6.5). Displacement was examined using markers positioned along the axis investigated, for example, medial-lateral displacement was examined using the markers NIPL, NIP and NIPM that were positioned in the M-L direction across the breast. A single peak in M-L displacement was observed during one gait cycle. The three markers move through very similar paths for both under and over bra conditions with exception of NIPL over bra, which exhibited greater medial and lateral displacement peaks. The breast markers typically exhibit greater medial displacement compared to lateral, particularly for the under bra condition (Figure 6.5b). Anterior-posterior displacements followed similar trends for both under and over bra conditions, however, there was greater variation between marker paths in the under bra condition. Interestingly, a distinct double peak in posterior displacement was observed for NIPS which tended to be more pronounced for the under bra condition. Whereas the other markers studied appear to undergo a single peak in posterior displacement. A clear double peak was observed in superior-inferior displacement for all markers in both under and over bra conditions (Figure 6.5 e-f). S-I displacement range was greater and marker displacement varied more across the breast for the under bra condition compared to over bra.

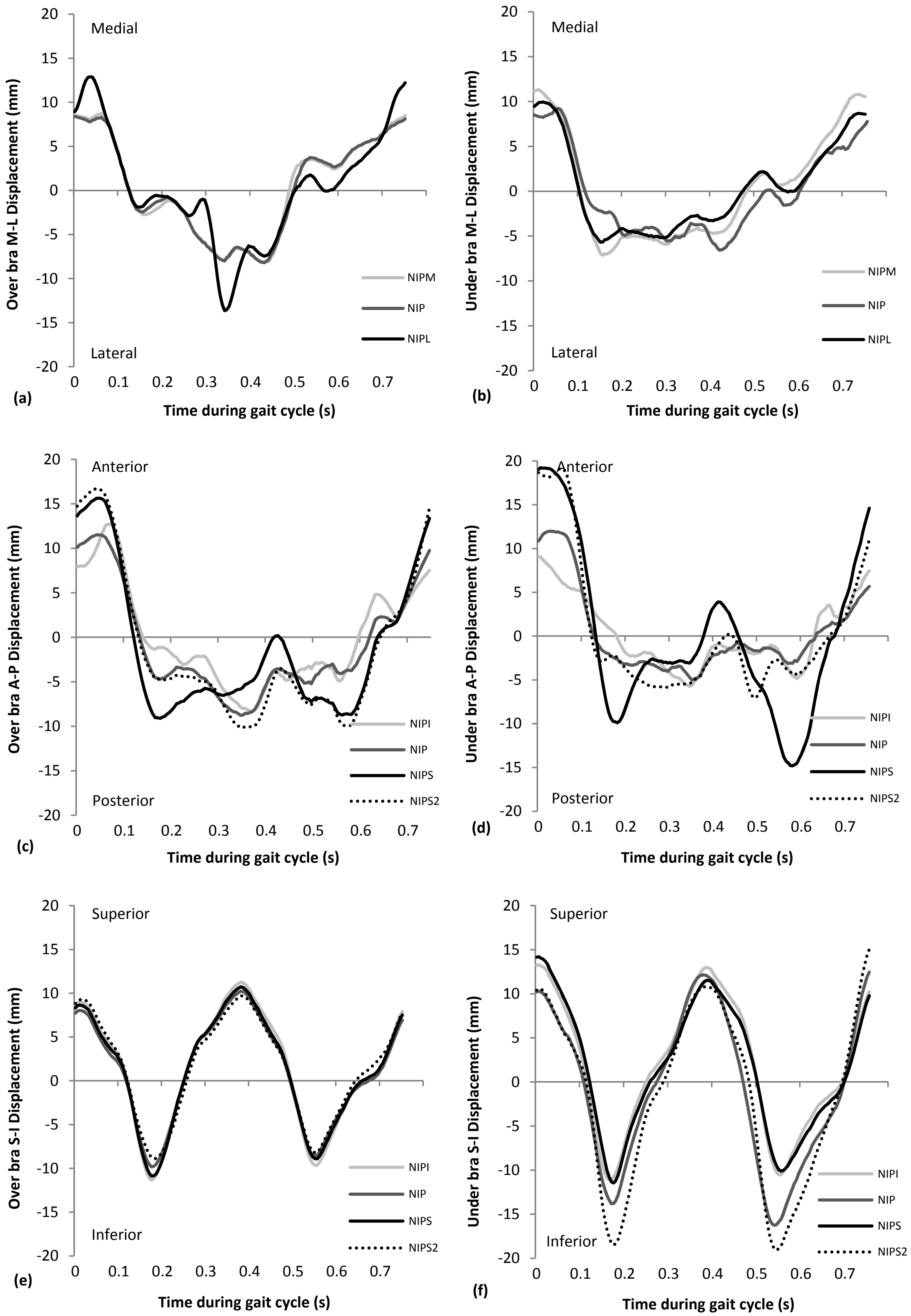


Figure 6.5 – Left breast marker displacements relative to the static position over a typical gait cycle (a) Over bra M-L direction (b) Under bra M-L direction (c) Over bra A-P direction (d) Under bra A-P direction (e) Over bra S-I direction (f) Under bra S-I direction. (Note - The gait cycle start and end point was as the right heel marker anterior-posterior velocity crossed zero in a downward direction (Zeni et al., 2008) i.e. Immediately prior to right foot touch down)

Peak displacements and displacement range were analysed over 30 gait cycles. Medial-lateral displacements were found to be similar in the over and under bra conditions except at marker NIPL, where mean M-L displacement range was 9 mm greater over bra compared to under bra (Figure 6.6 a-b). With the exception of NIPL over bra marker, little variation in M-L displacement was observed across the six breast locations. Interestingly, displacement was greater medially to the static breast position than laterally in all cases, with the exception of NIPS2 over bra which was almost identical (Figure 6.6a).

Small differences were observed in anterior displacement between the under and over bra markers with a more notable increase in over bra displacement observed at NIPL (Figure 6.6c). Mean posterior displacement and A-P displacement range at NIPS was greater under the bra compared to over the bra (by 6 mm and 8 mm respectively). A-P breast displacement varied more across the six locations, with greatest displacement at markers superior to the nipple (NIPS and NIPS2), the trend was more slightly pronounced in the under bra marker condition (Figure 6.6 c-d).

Superior and inferior displacements were greater under the bra at all breast locations, with the exception of superior displacement at NIPM which was almost identical (Figure 6.6e). The trend was slightly more pronounced in the inferior direction, a mean difference of 6 mm was found at the nipple (NIP) and 9 mm at NIPS2. Under bra S-I displacement range exceeded those measured over bra by 2-14 mm with the greatest disparity at NIPS2 (Figure 6.6f). Much less variation in S-I motion between the breast locations was observed in the over bra condition compared to under the bra. Mean S-I displacement ranged by 4.3 mm over the bra compared to 12.5 mm under the bra. In both under and over bra conditions the lowest level of S-I displacement occurred at NIPM (Figure 6.6 e-f).

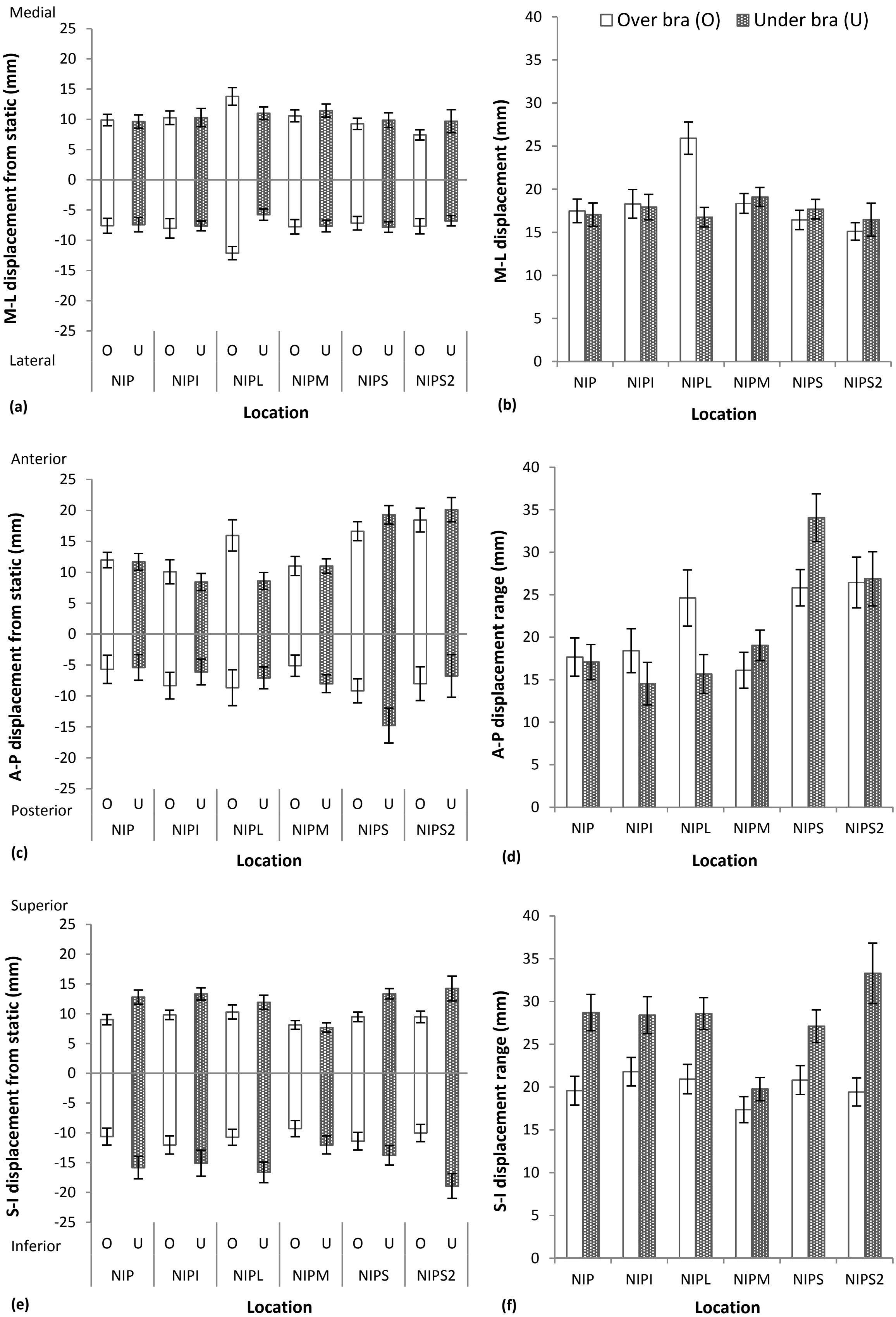


Figure 6.6 - Displacements relative to static position at six breast locations using over and under bra markers (a) Peak medial-lateral displacements (b) Medial-lateral displacement ranges (c) Peak anterior-posterior displacements (d) Anterior-posterior displacement ranges (e) Peak superior-inferior displacements (f) Superior-inferior displacement ranges (Mean, SD)(Bra = Well Fitting bra, Size 36E)

6.3.2.2 Objective 3 - Effect of bra cup size on relative breast displacement; over versus under the bra and the effect of marker location

The relationship between bra fit and breast displacement appears to be complex. Whilst there is a general trend of increasing M-L displacement with increasing cup size for under bra markers the trend is less clear for over bra markers (Figure 6.7 a-b). Anterior-posterior displacement tended to be highest in the largest cup size, although differences were small and the effect was not observed at the upper breast (Figure 6.7 c-d). In both M-L and A-P directions increase in displacement with cup size occurred at NIPL over bra. Cup size appeared to have little effect on over bra measures of S-I breast displacement (Figure 6.7 e-f). Interestingly, breast displacement tended to be slightly higher in the well fitting bra (36E) for the under bra condition and lowest in the largest cup size (36F). Greater variation in displacement between the breast locations was found using under bra markers in all cup sizes (Figure 6.7).

Medial-lateral displacement trends were similar in 36DD and 36E bras, with little difference between over and under bra measures (less than 3 mm difference in all locations except NIPL) and little variation in displacement between marker locations was observed in both cases (Figure 6.8 a-c). A similar trend was also observed in the larger cup size (36F) although under and over bra measures were slightly less similar. Medial displacement exceeded lateral displacement in all cup sizes studied. Greater M-L displacement over bra compared to under bra was observed at NIPL, the difference increased with increasing cup size (Figure 6.8c).

A similar trend of A-P displacement was observed in all cup sizes, displacement was greater at the upper breast (NIPS and NIPS2) and over bra motion was elevated at NIPL (Figure 6.7). The difference between over bra and under bra displacement at NIPL increased with increasing cup size (Figure 6.8 d and f). Differences between over and under bra motion followed similar trends in all cup sizes, as observed in A-P displacement range which was greater under bra at NIPS and NIPM but the reverse found at NIP and NIPI (Figure 6.8 d-f).

Superior-inferior displacement range was greater under bra than over bra in all cup sizes, with the most pronounced difference observed in inferior displacement (Figure 6.8 g-i).

Interestingly, only 36E exhibited increased under bra displacement in the superior direction and the greatest disparity between under and over bra S-I displacement (Figure 6.8g).

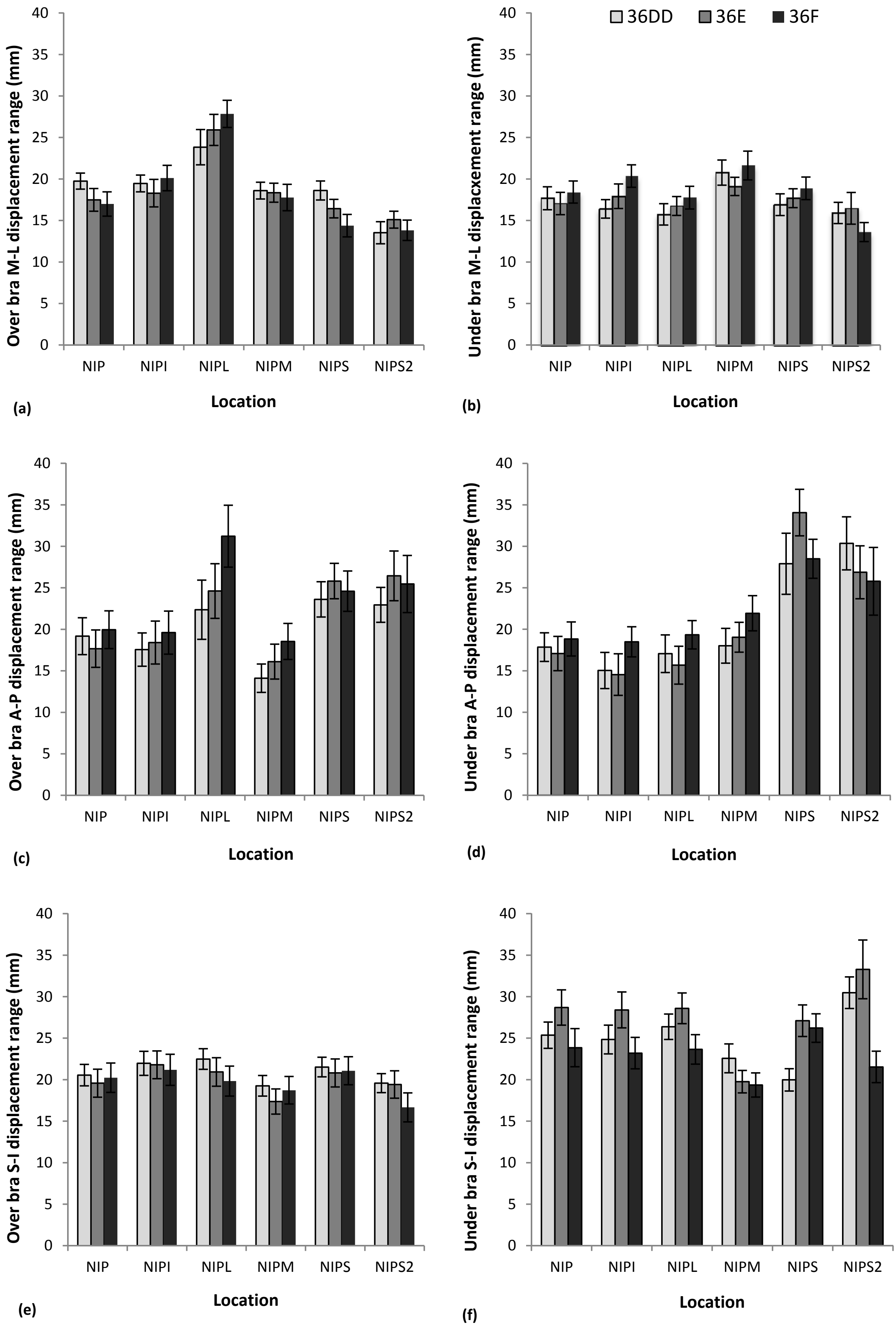


Figure 6.7 - Displacement range at six breast locations for three different bra cup sizes (a) M-L range for over bra markers (b) M-L range for under bra markers (c) A-P range for over bra markers (d) A-P range for under bra markers (e) S-I range for over bra markers (f) S-I range for under bra markers

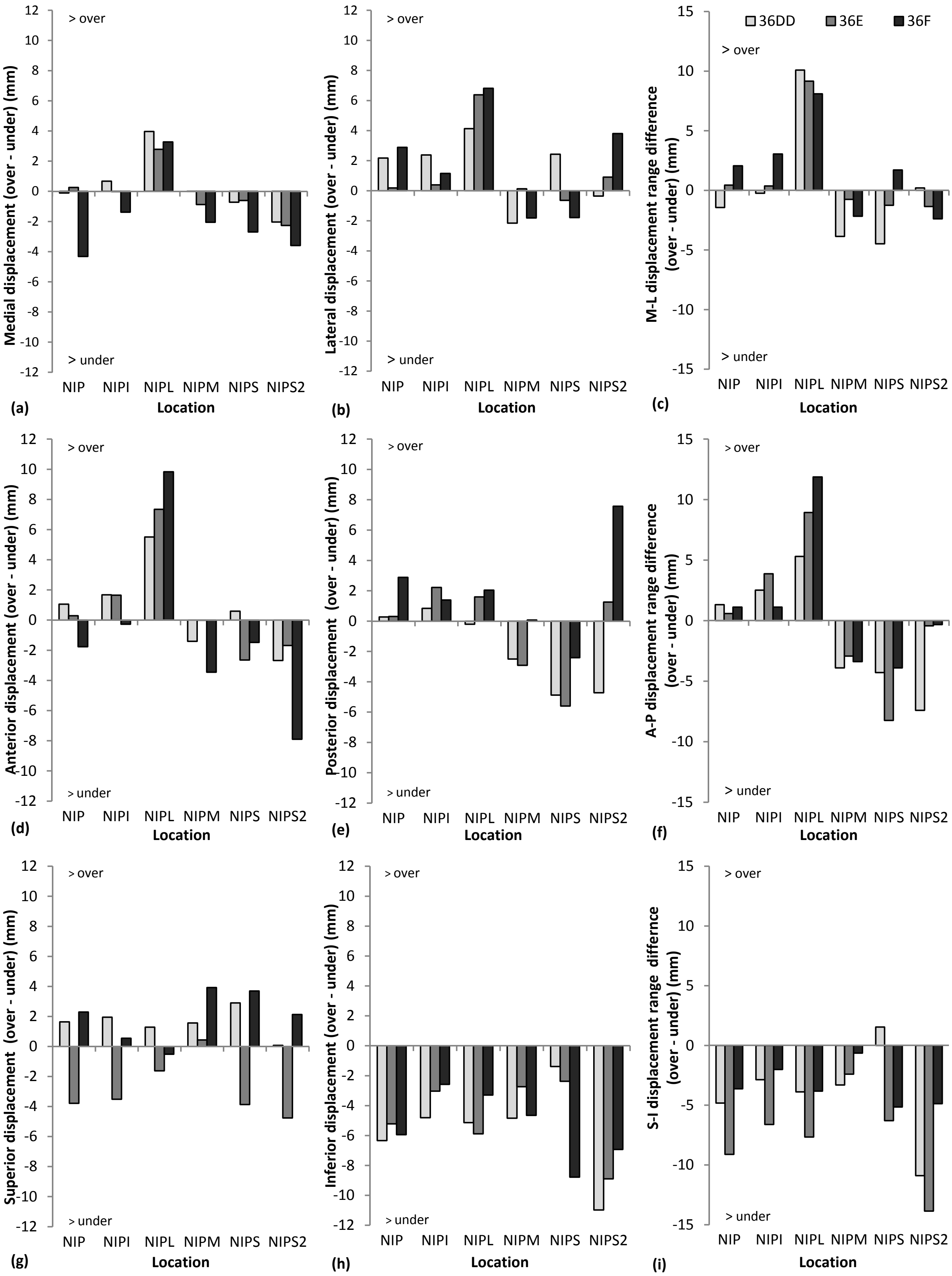


Figure 6.8 - Difference between breast displacements over and under the bra (over – under) at six breast locations for three different bra cup sizes (a) Medial displacement from static position (b) Lateral displacement from static position (c) M-L displacement range difference (d) Anterior displacement from static position (e) Posterior displacement from static position (f) A-P displacement range difference (g) Superior displacement from static position (h) Inferior displacement from static position (i) S-I displacement range difference

6.3.2.3 Consistency in the Relative Positioning of Markers between Over and Under Bra Trials

This study utilised markers attached over the bra and under the bra at six breast locations. Great care was taken in the experimental process to place the over and under bra markers in corresponding locations. To assess how well the markers corresponded the mean distance between over and under bra marker positions was calculated within the local (torso) coordinate system during the static trials (Table 6.2). Over and under bra marker positions differed by 3-13 mm with the exception of size 36F NIP. The 36F bra was a cup size larger than subject required, therefore, the cup was loose fitting in the nipple (NIP) area which may explain the increased distance between markers at this location. However, due to the experimental method used a small amount of systematic error was expected to account for the thickness of bra fabric and marker. The dimensions of the infra-red emitting markers were length 12 mm x breadth 8 mm x depth 6 mm. If the markers were placed in exactly corresponding locations above and below the bra the difference in relative position may be up to 7 mm (accounting for the thickness of the marker (6 mm) and bra fabric (~1 mm)). Therefore, the over and under bra markers can largely be considered to represent the same location. Any differences are likely to be small compared to the 40 mm separation between locations and represent different regions of the breast.

Table 6.2 - Three dimensional distance between over and under bra markers (mm)

Location	Bra size		
	36DD	36E	36F
NIP	6.5	13.3	25.8
NIPI	12.0	7.9	7.0
NIPL	6.7	11.0	2.8
NIPM	13.2	3.8	6.1
NIPS	8.8	5.0	4.1
NIPS2	5.2	10.1	7.0

6.3.2.4 Gait Variables

Gait variables were monitored as changes in running action may affect breast motion and therefore need to be considered when assessing breast kinematics. The bra, trial and bra*trial effects were statistically significant for all gait variables with the exceptions of bra on cadence and trial on anterior-posterior lean range (Table 6.3).

Table 6.3 - Gait variables for all running trials

			Over bra	Under bra				
			All (Mean ±SD)	NIPM & NIPL (Mean ±SD)	NIPS & NIPI (Mean ±SD)	NIPS2 & NIP (Mean ±SD)	Effect	ANOVA (F, p)
	Cadence (strides/sec)	36DD	1.33 ± 0.01	1.33 ± 0.02	1.33 ± 0.03	1.31 ± 0.01	**Bra**	(1.498, 0.232)
		36E	1.34 ± 0.01	1.34 ± 0.01	1.30 ±0.01	1.31 ± 0.01	**Trial**	(27.976, <0.001*)
		36F	1.30 ± 0.01	1.33 ± 0.01	1.33 ± 0.01	1.33 ± 0.01	**Bra* Trial**	(81.637, <0.001*)
Torso	Vertical displacement (mm)	36DD	110 ± 4	107 ± 4	109 ± 5	119 ± 6	**Bra**	(22.908, <0.001*)
		36E	110 ± 5	112 ± 4	118 ± 6	117 ± 5	**Trial**	(38.348, <0.001*)
		36F	116 ± 4	114 ± 5	119 ± 4	116 ± 5	**Bra* Trial**	(13.167, <0.001*)
	Lateral bend range (°)	36DD	7.0 ± 0.6	6.7 ± 0.8	6.7 ± 0.5	7.8 ± 0.7	**Bra**	(64.881, <0.001*)
		36E	7.8 ± 1.0	8.0 ± 0.7	7.9 ± 0.7	8.4 ± 0.8	**Trial**	(17.993, <0.001*)
		36F	8.1 ± 0.9	7.6 ± 0.7	7.6 ± 0.7	8.3 ± 0.8	**Bra* Trial**	(2.922, <0.010*)
	Anterior-posterior lean range (°)	36DD	7.5 ± 0.8	6.9 ± 0.8	7.0 ± 0.7	6.8 ± 0.7	**Bra**	(49.431, <0.001*)
		36E	7.0 ± 0.8	7.2 ± 0.8	7.9 ± 1.0	7.7 ± 1.0	**Trial**	(1.286, 0.286)
		36F	8.2 ± 0.7	8.1 ± 0.9	7.9 ± 0.8	8.1 ± 0.8	**Bra* Trial**	(5.951, <0.001*)
	Mean anterior lean angle (°)	36DD	-2.1 ± 0.1	-2.1 ± 0.4	-2.5 ± 0.3	-2.7 ± 0.5	**Bra**	(30.806, <0.001*)
		36E	-2.9 ± 0.6	-2.6 ± 0.6	-2.8 ± 0.6	-2.3 ± 0.6	**Trial**	(5.264, 0.002*)
		36F	-1.9 ± 0.5	-2.0 ± 0.6	-2.1 ± 0.6	-2.6 ± 0.6	**Bra* Trial**	(11.057, <0.001*)
	Axial rotation range (°)	36DD	27.5 ± 1.6	27.6 ± 1.2	27.5 ± 1.4	27.8 ± 1.5	**Bra**	(8.193, 0.001*)
		36E	27.0 ± 1.6	25.8 ± 1.5	26.8 ± 1.5	27.9 ± 1.4	**Trial**	(18.125, <0.001*)
		36F	26.6 ± 1.0	25.9 ± 1.4	26.2 ± 1.6	28.7 ± 1.9	**Bra* Trial**	(5.873, <0.001*)

* = Indicates statistically significant difference (p < 0.05)

The post-hoc pairwise comparisons of gait variable data revealed numerous statistically significant differences between bras and trials (Appendix B). Cadence differed by a maximum of 0.016 strides/s between runs and ranged by 0.04 strides/s across all trials. Mean vertical displacement was significantly lower in 36DD than 36E and 36F (by 3 mm and 4 mm respectively), the maximum difference between runs was 7 mm with a range of 12 mm across all trials. The trends illustrated in Figure 6.9 (c-f) suggest torso rotation was influenced by bra cup size to a greater extent than trial. Mean lateral bend range differed by less than 1 degree between bras and less than 0.8 degrees between trials. Anterior-posterior lean range differed by a maximum of 1 degree between bras with no significant effect of trial. Similarly, mean torso anterior-posterior lean angle differed by less than 0.5 degrees between bras and between trials. Axial rotation in 36DD was greater than other bras by an average of 0.7 degrees in both cases. Axial rotation differed by a maximum of 1.7 degrees between runs and ranged by 2.9 degrees across all trials.

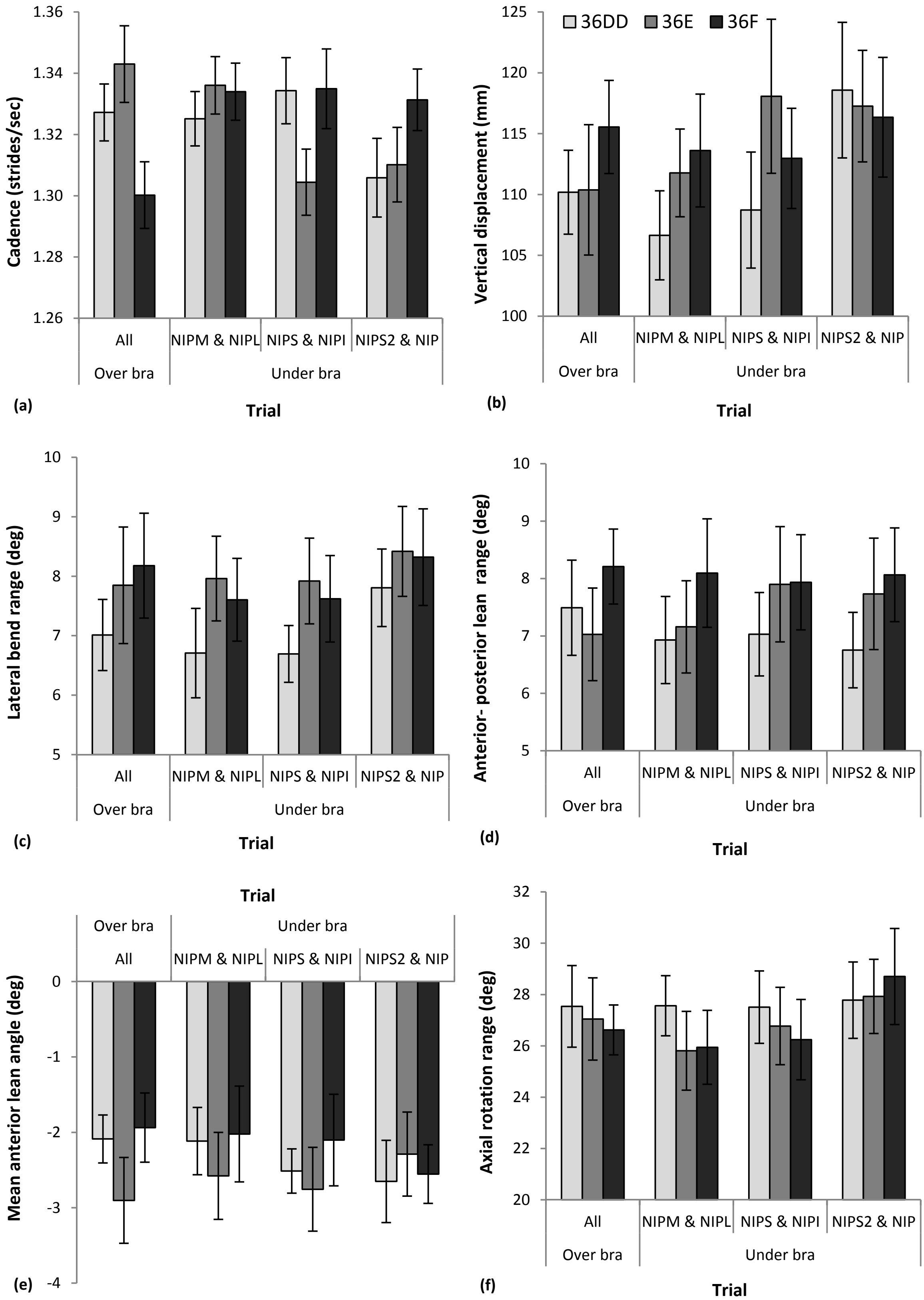


Figure 6.9 - Gait variables for the three bra cup sizes studied (4 trials each) (a) Cadence (b) Torso vertical displacement (c) Torso lateral bend (d) Torso anterior-posterior lean range (e) Mean torso anterior lean angle (f) Torso axial rotation range

6.3.2.5 Results Summary

The results of the main study are summarised in three tables, one for each bra cup size studied (36E, 36DD and 36F).

The results relating to objectives 1 and 2, which consider the displacement of markers over versus under bra and variation in displacement across the breast for a well fitting bra (36E) are summarised in Table 6.4. Trends observed in displacement range and marker movement from static position are noted with possible causes outlined.

Objective 3 considers the effect of bra cup size on (a) Displacement of markers over versus under bra (b) Variation in displacement across the breast. Results for the smaller (36DD) and larger fitting bra cups (36F) are summarised in a similar fashion in Tables 6.5 and 6.6. Observations about how results compare to those for the well fitting bra (36E) are included and possible causes for these findings outlined.

Table 6.4 - Summary of results for well fitting bra (36E)

36E Well fitting		Objective 1 Displacement using over bra and under bra markers		Objective 2 Variation in displacement across the breast	
		Observation	**Possible cause**	**Observation**	**Possible cause**
M-L	**M**	Displacement similar except at NIPL which was greater over bra and NIPS2 which was slightly lower over bra.	Little breast-bra motion. Arm movement causing increase in NIPL motion over bra.	More displacement medially than laterally. Little variation except NIPL greater over bra.	Medial bra cup not anchored to body along medial breast border, thus less effective at limiting breast motion.
	L	Displacement similar except at NIPL which was greater over bra.	Little breast-bra motion. Arm movement causing increase in NIPL motion over bra.	Less displacement laterally than medially. Little variation except NIPL greater over bra.	Lateral bra cup encapsulates whole of lateral breast border unlike the medial cup with greater tension in the fabric than medially, thus limiting breast motion more effectively.
	M-L range	Very similar results with the exception of NIPL (9 mm greater over bra)	Little breast-bra motion in the M-L direction. Arm movement causing increase in NIPL motion over bra.	Very similar across the breast with the exception of NIPL over bra higher	Similar amounts of M-L motion at locations tested. Arm movement causing increase in NIPL motion over bra.
A-P	**A**	Most markers similar in both conditions. Greater displacement over bra at NIPL.	Breast forced against bra fabric at anterior most point, therefore, few differences observed. Arm movement causing increase in NIPL motion over bra.	Highest displacement from static in upper breast NIPS and NIPS2	As breast mass rises upper breast markers projected more anteriorly.
	P	Under bra displacement 6 mm greater than over bra at NIPS.	Separation of upper breast from bra lead to greater displacement under bra compared to over bra.	Posterior displacement greatest at NIPS (under bra)	As breast mass descends, there is tension through the upper breast tissue, reducing breast projection in this area.
	A-P range	Similar in both conditions except NIPS is higher under bra and NIPL higher over bra.	Separation of breast from bra fabric likely at upper breast in posterior motion. Arm movement causing increase in NIPL anterior motion over bra.	Superior markers (NIPS and NIPS2) have highest displacement in both conditions.	As breast mass rises breast projected more anteriorly, as breast mass descends tissues under tension and less projection than static.
S-I	**S**	Under bra displacement higher in each location except NIPM which was almost identical.	Shearing motion of breast beneath bra likely to increase under bra displacement.	Displacement highest at upper breast area under bra.	As breast mass moved upward upper markers are pushed more superior.
	I	Mean displacement under bra between 2-9 mm higher than over bra across all marker locations.	Shearing motion of breast beneath bra. Separation of breast from bra may occur at upper breast (NIPS and NIPS2) during inferior breast motion.	Greatest displacement at NIPS2 under bra and NIPI over bra. Low displacement under bra at NIPM.	As breast mass moves downward, inferior marker pushed downward and superior breast (NIPS2) moved inferior under tension of breast mass.
	S-I range	S-I displacement greater in under bra condition at all marker positions. Largest difference at NIPS2 (14 mm) and 9 mm at NIP.	Shearing motion of breast sliding beneath the bra surface results in lower over bra displacement. Bra moves as one unit, therefore, less difference between marker displacement across the breast over bra	Variation in displacement across the breast much lower over bra. NIPM displacement lowest in both conditions.	Lowest displacement at NIPM likely to be due to reduced amount of breast tissue and not in vertical line of motion of main breast mass.

Table 6.5 - Summary of results for smaller fitting bra cup (36DD)

36DD Smaller cup		Objective 3 (a) Displacement using over bra and under bra markers		Objective 3 (b) Variation in displacement over the breast	
		Observation	**Possible cause**	**Observation**	**Possible cause**
M-L	**M**	Very similar trend to 36E observed. Displacement similar in both conditions except NIPL which was higher over bra and NIPS2 was slightly lower over bra.	Tight fitting bra cup, therefore, little breast-bra motion. Motion of arm causing movement of lateral bra cup.	As in 36E medial displacement greater than lateral displacement. Small variation in displacement across the breast	Medial bra cup not anchored to body along medial breast border, thus less effective at limiting breast motion.
	L	Over bra displacement greater than under the bra at NIP, NIPI, NIPL and NIPS. However, over bra displacement lower at NIPM.	Slightly unexpected. A small amount of M-L shearing motion may occur between breast and bra.	As in 36E less displacement laterally than medially. Displacement at NIPL similar to other markers. Under bra greatest displacement at NIPM.	Greater tension across bra as smaller size, less likely to be areas of loose fabric. As though to be at NIPL in 36E.
	M-L range	M-L displacement range similar under and over bra. Except over br a displacement greater at NIPL and NIPI to a lesser extent.	Tight fitting bra cup, therefore, minimal breast-bra motion. Possibly motion of arm causing movement of lateral bra cup.	Slightly greater variation in displacement across the breast than 36E in both under and over bra conditions.	With tighter bra cup a more uniform displacement was anticipated. However fit may not be consistent across breast leading to this variation.
A-P	**A**	Very similar trend to 36E observed. Greater displacement over bra at NIPL.	Tight fitting bra cup little separation between breast and bra. Motion of arm causing anterior movement of lateral bra cup over the breast.	Similar trend across breast to 36E. Superior markers highest displacement in both conditions except NIPL over bra.	As breast mass rises upper breast markers projected more anterior.
	P	As in 36E posterior displacement higher under breast at superior breast markers (NIPS and NIPS2).	Separation of upper breast from bra leads to greater displacement under bra compared to over bra.	Greater variation in displacement across the breast for under bra markers. Largest displacements under bra found at NIPS and NIPS2.	As breast mass descends, tension through the upper breast tissue, reduces breast projection in this area. The bra may move as one unit, therefore, more uniform displacement across the breast with over bra markers.
	A-P range	Broadly similar displacement in under and over bra marker conditions. Greatest difference at NIPS2 where under bra displacement was greater than over bra.	Although the bra cup was tighter fitting, separation of breast from bra fabric likely to have occurred at NIPS2 during downward breast motion increasing displacement.	As in 36E greatest A-P displacement range at upper breast (NIPS and NIPS2). Slightly less variation across breast than 36E.	Tighter bra cup, therefore, breast and bra more likely to move 'as one' leading to similar displacements across the breast. A-P motion occurred primarily at upper breast due compression and tension resulting from vertical breast mass motion.
S-I	**S**	Opposite trend to 36E, over bra displacements slightly higher than under bra.	Tighter bra cup likely to prevent sliding of breast beneath bra fabric as observed in 36E.	Similar displacement across breast in both conditions. Less variation in displacement across the breast compared to 36E.	Tighter bra, therefore, breast and bra likely to move more 'as one' leading to similar more displacements across the breast.
	I	Same trend as 36E. Inferior displacement greater in under bra condition at all marker locations. Largest difference at NIPS2 (9 mm).	Shearing motion of breast beneath bra as breast mass moves down and possible that upper breast (NIPS2) separated from overlying bra.	Similar trend to 36E, less variation in displacement across the breast over bra.	Tighter bra, therefore, breast and bra likely to move more 'as one' leading to similar more displacements across the breast.
	S-I range	S-I displacement range greater under bra compared to over bra at all marker locations except NIPS. Differences smaller than in 36E. Difference 11 mm at NIPS2 and 5 mm at NIP.	Tighter fit of bra cup reduced level of S-I shearing motion of breast beneath the bra compared to 36E. Majority of breast bra motion occurred inferior of static position.	Less variation in displacement across the breast over bra. Peak displacement range under bra at NIPS2.	Tighter bra, therefore, breast and bra likely to move more 'as one' leading to similar more displacements across the breast.

Table 6.6 - Summary of results for larger fitting bra cup (36F)

36F Larger cup		Objective 3 (a) Displacement using over bra and under bra markers		Objective 3 (b) Variation in displacement over the breast	
		Observation	**Possible cause**	**Observation**	**Possible cause**
M-L	**M**	Under bra measures greater at NIP, NIPM, NIPS and NIPS2. NIPL greater over bra.	Breast-bra motion is likely to have occurred. Breast may move beneath the bra, leading to greater under bra displacement. Motion of arm causing movement of lateral bra cup.	Greater variation in displacement over breast in larger bra compared to 36E. Greatest displacement at NIPL and least at NIPS2 in both marker conditions.	Looser fit of bra resulted in less uniform movement of the breast and over lying bra.
	L	Over bra displacement higher at NIP, NIPL and NIPS2	Bra cup larger, therefore, loose fabric at NIP, NIPL and NIPS2 may have resulting in greater over bra displacement.	As in 36E lateral displacement was lower than medial except NIPS2 over bra. Max over bra displacement at NIPS2. Under bra NIPM and NIPS highest.	Lateral bra cup encapsulates whole of lateral breast border unlike the medial cup with greater tension in the fabric than medially, thus limiting breast motion more effectively.
	M-L range	The similar trend observed to 36E with displacement at NIPL 8 mm greater over bra compared to under bra. Additionally, under bra displacement greater by 4 mm at NIPM and NIPS.	Motion between breast and bra is likely to have occurred, with some markers traveling through a similar overall range.	Greater variation in displacement across the breast than 36E in both under and over bra conditions.	Looser fit of bra resulted in less uniform movement of the breast and over lying bra.
A-P	**A**	As in 36E over bra displacement greater at NIPL. Under bra displacement greater at NIPS2.	Increase at NIPL likely to result from loose fabric or motion of arm resulting greater movement of lateral bra cup. Breast may slide beneath bra at NIPS2 as breast rises.	As in 36E greatest anterior displacement occurred under bra at the upper breast. NIPI least displacement as 36E.	As breast mass rises upper breast markers projected more anterior.
	P	Displacements generally similar under and over bra and generally small in magnitude except at NIPS2.	Looser bra fabric may have resulted in more similar displacements.	As in 36E under bra displacement highest at NIPS.	As breast mass descends, there is tension through the upper breast tissue, reducing breast projection in this area.
	A-P range	A-P range was similar in over and under bra condition as except NIPL. As in 36E over bra NIPL displacement greater than under bra (12 mm).	Looser bra fabric may have resulted in more similar displacements under and over the bra. Increase at NIPL may also result from motion of arm causing movement of lateral bra cup.	Less variation in displacement across the breast in the under bra condition. Markers at superior breast more similar to other markers than in 36E.	Larger bra may have more uniform loose fit, therefore A-P motion of the breast more similar.
S-I	**S**	Reverse trend to 36E as displacement greater over bra at 5 of 6 marker locations.	As the bra was looser the upper cup the bra may have separated from the under lying breast as the breast raised up leading to greater over bra displacement.	Less variation in displacement across breast in both under and over bra conditions compared to 36E.	Larger bra may have more uniform loose fit, therefore superior motion more similar across the breast.
	I	Same trend as 36E. Under bra displacement greater than over bra displacement. However inferior displacement was generally less than 36E.	Shearing motion of breast beneath bra as breast moves inferiorly. Subject may have made modifications to limit inferior breast motion.	As in 36E under bra displacement highest at NIPS. Over bra markers inferior displacement was small with negligible inferior displacement at NIPS2.	Subject may have made modifications to limit inferior breast motion.
	S-I range	S-I displacement range larger under bra compared to over bra. Differences smaller than in 36E, max difference 5 mm at NIPS and NIPS2.	Shearing motion of breast sliding beneath the bra surface and separation of bra.	Less variation across the breast compared to 36E particularly in under bra condition.	Larger bra may have more uniform loose fit, therefore S-I motion across the breast more similar.

6.4 Discussion

Relative breast kinematics are widely used as a measure of sports bra performance and as a tool to inform sports bra design. Breast motion is typically represented by a single marker placed on the bra over the nipple. However, it is unknown whether markers placed over the bra represent the breast beneath and if motion occurs between the breast and bra during running. The effect of marker location and bra fit on these factors is unclear. Therefore, the objectives of this study were:

1. To determine whether relative breast displacement differs when measured using markers placed under bra versus over the bra.
2. To determine how relative breast displacement varies over the breast and where it is highest.
3. To determine the effect of bra cup size on objectives 1 and 2.

To enable the equivalent positions on the bra versus on the skin under the bra to be identified it was also necessary to undertake a preliminary study to assess how quickly the static breast position within the bra settles down during running.

6.4.1 Preliminary Study - Settling in of bra

Motion between the breast and bra (either during an initial settling in phase or steady state running) has yet to be explored within the existing literature and is assumed to be negligible for a correctly fitted bra. The preliminary study explored whether a bedding in phase occurs. A shift in the relative position between the breast and bra was found primarily in the S-I direction and primarily during the first 15 seconds of running, with lower levels of movement in both medial and lateral directions. The position of the bra when first worn, bra design and breast geometry may also impact the direction and magnitude of breast-bra shift during the initial period of running. For example, if the bra is first worn skewed slightly to one side then the bra may move over the breasts to align more symmetrically during the bedding in phase. The findings of this study suggest a short period of activity should be performed prior to breast marker application in breast kinematic studies. This would allow the breast to 'settle in' to the bra, therefore, if markers are to be positioned over the bra they are likely to more closely represent the intended location on the breast.

6.4.2 Objective 1 - Over versus under bra marker displacement

Markers positioned over the bra are typically assumed to represent motion of the underlying breast (Scurr et al., 2010a). Objective 1 investigated whether relative breast displacement differs when measured using markers placed under bra versus over the bra. Medial-lateral displacement range was similar in under and over bra conditions at all locations except NIPL, this suggests that the breast locations studied move through a similar range with little relative motion between breast and bra in this direction. The increased M-L displacement observed at NIPL marker over bra (9 mm) was likely to result from the arm rubbing against the bra during the arm swing motion causing movement of the bra fabric and this effect was also observed in the A-P direction.

A-P displacement was greater for the under bra marker compared to over bra at NIPS on the upper breast. This suggests some separation of the breast from the bra may have occurred at the upper breast, leading to increased posterior displacement in the under bra condition.

The increased level of S-I displacement seen in under bra markers (by 2 - 14 mm) strongly suggests that the breast was moving relative to the overlying bra fabric in a vertical shearing motion. As the breast moved downward, the bra was anchored by straps but the breast may have continued to slide inside bra leading to a breast displacement greater than that of the bra. The upper breast surface may also have separated from the overlying bra during inferior breast motion as suggested by Zhou et al. (2012), leading to the greater difference observed at NIPS2 (Figure 6.6f).

6.4.3 Objective 2 - Variation in displacement at different breast locations

Breast kinematic studies commonly track breast motion using a single marker, however, Zhou et al. (2013) and (2012) have suggested information pertinent to bra design may be obtained using a marker array. Objective 2 investigated whether relative breast displacement varies over the breast and where it is highest.

A double peak in S-I displacement and single peaks in M-L and A-P displacement (with exception of a double peak A-P direction for in NIPS) were observed during a gait cycle (Figure 6.5). The findings largely support the trends reported by Scurr et al. (2009) and (2010a) (discussed in §2.6.1.1).

Little variation in medial-lateral displacement was observed across the breast (except NIPL over bra as previously discussed). Interestingly, at all breast locations greater displacement occurred in the medial direction relative to the static position compared to the lateral direction (Figure 6.6 a-b). This is likely a result of the bra construction (Figure 6.2), as the lateral bra cup encapsulates the breast more and under greater tension than the medial cup as it wraps around the side of the ribcage. Thus, it is likely to provide a firmer end point and more effectively limit breast motion in the lateral direction.

Anterior-posterior displacement range was found to be greatest for the upper breast. As the breast mass rises during the gait cycle, this may increase the tissue beneath the superior breast markers and lead to greater anterior projection of the upper breast. The most anterior point of the breast was most likely forced against the bra fabric. As the breast mass moves downward, the upper breast will be under tension resulting in less anterior projection of the upper breast compared to the static position. The double peak in A-P motion observed at NIPS (Figure 6.5 c-d) is likely to result from this effect, the breast mass moved inferiorly following each ground contact which in turn led to A-P breast motion. However, the effect of torso rotation is likely to have strongly influenced A-P breast motion, the breast moves anteriorly as the torso rotates forward and posteriorly at the torso rotates backward. Therefore, greater anterior breast displacement occurred at the beginning of the gait cycle when the opposing foot (right) contacted the ground. During same side foot contact, the backward torso rotation lead to posterior breast motion, therefore, posterior breast displacement (or reduced anterior displacement) was observed.

The least S-I motion was observed at the medial breast, this may be due to a reduced amount of breast tissue in the medial area, but more probably as the areas is not in a vertical line with the main breast mass, it is, therefore less influenced by vertical breast movement (unlike NIPS and NIPS2). Markers positioned over the bra were observed to move in a similar S-I motion at all breast locations, whereas, S-I motion was more varied across breast locations using under bra markers (Figure 6.5 e-f and Figure 6.6f). This suggests the bra moved as more rigid unit whilst the breast moved less uniformly. This further supports the breast sliding in a shearing motion beneath the bra and that the breast may separate from the overlying bra in the upper breast area.

Breast kinematic studies which utilise over bra markers risk underreporting S-I breast motion particularly at the upper breast, this risk is likely to be higher for very rigid or padded bra constructions. Over bra markers move in a more uniform S-I motion and may limit the additional information gained from using multiple breast markers. Markers positioned over the lateral aspect of the bra cup may be disturbed by the swinging action of the bra creating an artificial increased breast displacement within this area. The results demonstrated that displacement varies over the breast and supports Zhou et al. (2013) and (2012) in questioning the validity of a single marker to represent breast motion and that information pertinent to bra design could be gained by using an array of breast markers.

6.4.4 Objective 3 - Effect of bra fit

Breast displacement was hypothesised to increase with increasing bra cup size. Whilst this trend was observed in some instances the results suggest the relationship between bra fit and breast displacement is more complex. Although bra cup size was varied, the change in bra fit may not be uniform across the breast, thus the effect of cup size may differ with location. Additionally, the subject reported experiencing substantial breast discomfort during the 36F bra trials and therefore may have adapted her running style to minimise breast discomfort. This is supported by analysis which revealed a statistically significant effect of bra on five of six gait variables measured (all $p < 0.001$), however, the trends observed were mixed (Figure 6.9). Mean torso vertical displacement, lateral bending range and anterior-posterior lean range were slightly lower for 36DD compared to the other bras (greatest difference between means was 3 mm, 1° and 1° respectively). Mean anterior-posterior lean angle was slightly lower for 36E (by up to 0.5°) and axial rotation range 0.7° greater for 36DD when compared to the other bras. Whilst the magnitude of these differences was generally small, some may have had a meaningful impact upon breast kinematics. Torso segment residual was found to be slightly lower in 36F (mean ± SD) (6.1 ± 0.4 mm) compared to 36E (6.6 ± 0.7 mm) and 36DD (6.4 ± 0.5 mm). The larger fitting bra cup and resulting breast discomfort may have led the subject to 'tense up' in response to this discomfort or in an effort to reduce breast motion. Increasing muscle tension and more rigid torso segment may have led to a reduction in torso segment residual.

Objective 3 formed two parts, firstly it investigated the effect of bra fit on whether relative breast displacement differs when measured using markers placed under bra versus over the bra. Similar trends in M-L displacement were observed for 36E and 36DD with little difference found between under and over bra markers with the exception of NIPL. Over bra displacement exceeded under bra displacement at NIPL in both A-P and M-L directions, the effect increased with increasing cup size (Figure 6.8). This effect is likely to have resulted from the looser cup fabric of the larger size cup being moved through a greater motion by the swinging action of the arm. A looser and also less consistent fit of the larger cup (36F) is also likely to have allowed areas of the breast to move beneath the bra, leading to a slightly greater disparity between under and over bra measures. The increased level of inferior displacement observed beneath the bra for all cup sizes strongly suggests the breast surface slides beneath the bra as the breast mass descends and that this effect occurs irrespective of bra fit. Separation of the upper breast from the bra may also occur during this motion. The smaller tighter fitting bra cup was likely to have permitted less sliding of the breast beneath the bra, particularly in the superior direction where the force involved was less. The tighter cups compressed the breasts against the chest wall more strongly increasing the friction between breast and bra. Under and over bra S-I displacement in the larger bra may have been more similar due to the looser bra cup moving more similarly to the underlying breast.

The second part of Objective 3 investigated the effect of bra cup size on whether relative breast displacement varies over the breast and where it is highest. The trends observed in the smaller and larger fitting cups broadly agree with those observed in the well fitting bra and support the finding that breast displacement varied across the breast. A small variation in M-L displacement across breast displacement across the breast was observed for all cup sizes. Trends in A-P breast motion were similar across all cup sizes with greatest displacement occurring at the upper breast. Increased under bra A-P displacement at NIPS suggests the upper breast may have separated from overlying bra. Although the same trend was not seen at NIPS2 for all cup sizes this may have resulted from differences in fit, for example, the larger cup size was particularly loose fitting in this area and may not have been in contact with the breast in the static position; therefore, the over bra marker could move through a greater posterior range. Greater variation in S-I displacement across the breast locations was seen for under bra markers compared to over bra markers in all bra cup sizes studied. As noted previously, the bra is likely to move 'as one' giving a more uniform displacement across the breast.

The over bra results conflict with the findings of Eden et al. (1992) and Zhou et al. (2009) as breast displacement was not found to be greatest at the nipple in M-L, A-P or S-I directions in the three cup sizes tested (Figure 6.7). The results are partly in agreement with Zhou et al. (2012) as an elevated level of A-P displacement was observed at the upper breast. To date studies which utilise under bra markers have only included a single marker at the nipple, however, the increased A-P and S-I displacement observed under bra at the upper breast agrees with the findings of Zhou et al. (2012) for over bra markers. Furthermore, since breast shape, composition and nipple position are known to vary, particularly with breast ptosis (Avsar et al., 2010), the breast marker which experiences greatest displacement may depend on the individual subject, the design of the bra worn and activity undertaken. This questions the validity of using a single marker point to represent breast motion and highlights the need for a greater level of information.

6.4.5 Limitations

A number of limitations to the study are acknowledged. Due to the exploratory nature of this study, it was limited to a single subject and only one sports bra model, therefore, caution should be exercised when applying the findings more generally. However, the study highlights a number of considerations for future breast kinematic studies.

The preliminary study results suggest a settling in effect between breast and bra of 30-45 seconds. However, it was not possible to determine whether the breast moved upwards within the bra, the bra moved downwards or a combination of both effects. If the preliminary study were to be repeated inclusion of bra, breast and torso tracking markers (as in the main study) could provide further information about the motion occurring. A wider range of sports bras, more varied subject sample and repeated trials would help to clarify if the settling in effect is a more widely occurring phenomenon.

In the main study, the under and over bra markers could not be applied simultaneously in the same location because the under bra markers were occluded. Additionally, to minimise any change in bra fit the under bra markers were applied in pairs and three under bra trials performed for each bra. Bra and trial were found to have statistically significant effects on five of the six gait variables with a statistically significant bra*trial interaction effect for all gait variables. Whilst many statistically significant differences were observed the magnitude of these differences was generally small, however, in some cases the effects may be meaningful. Repeating the study with a larger sample size and randomising the order of trials would help to negate any familiarisation effect and increase robustness. Static over and under bra marker positions measured relative to the torso differed by up to 13 mm in bras 36DD and 36E and almost 26 mm at the nipple in 36F (Table 6.2). However, up to 7 mm could be attributed to placing the marker on different sides of the bra fabric. The increased difference in nipple marker position in the 36F bra may result from a much looser fit of the bra cup and slack fabric. The differences in under and over bra marker placement are small compared to the 40 mm separation between breast locations which represent different regions of the breast.

The wider use of under bra markers in breast kinematic studies is limited by the availability of a suitable motion capture system that can function through the test bra fabric, such as, active optical systems with infra-red emitting markers or electromagnetic systems. Additionally, placing markers under rather than over the bra is a more 'intrusive' method for the subject and depending upon the size and number of markers used may significantly affect bra fit, comfort and how the bra functions.

Despite the limitations outlined, this study is the first to consider whether markers placed over the bra represent the underlying breast and suggests that motion may occur between the breast and bra during running.

6.4.6 Implications

The study has a number of implications for future breast kinematic research. A period of activity immediately after the subject has put on the test bra, is recommended to help eliminate any settling in effect prior to over bra marker application or breast kinematics data collection. Future research should also consider that markers on the bra surface represent bra motion which may differ from that of the underlying breast and be less sensitive to variation in motion across the breast. The results suggest motion occurs between the breast and bra irrespective of bra cup size and that over bra markers underestimate S-I breast displacement and A-P displacement at the upper breast. However, the difference between under and over bra displacement is likely to be subject and bra dependant. The effect is likely to be greater in very stiff or padded bra cups, therefore, in these cases particular caution should be exercised if over bra markers are utilised. However, the use of under bra markers is currently limited by the motion capture technology available, as current systems may not function with all bra types and could significantly alter bra fit and comfort. Until advances in technology are made the use of over bra markers remains current best practice. Therefore, it is recommended that future studies state whether over or under bra markers were used and recognise that over bra markers represent bra motion.

Breast motion appears to be very 'non-rigid', therefore, the use of multiple breast markers appear necessary to provide more information and help better understand breast motion. Further research is required to better understand breast movement across a wider population before determining the most appropriate breast marker protocol. It would be interesting to explore the effect that systematic design changes have on breast motion and discomfort. For example, this study found greatest S-I and A-P motion in the upper breast area suggesting that the upper bra cup may be an area for design development. However, as discussed above technology is currently a limiting factor in tracking breast motion when a bra is worn. The motion of over bra markers was found to be much less varied between locations with the bra tending to 'move as one'. Whilst multiple bra markers provide more a complete picture of bra motion, a single marker approximation of bra motion as commonly used within the literature appears to be reasonable. However, further study of multiple bra markers is warranted to better understand the sensitivity to bra design and subject variation. The results agree with Zhou et al. (2012) and suggest that greatest breast and bra motion may not occur at the nipple. However, the nipple provides an easily identifiable landmark that can contribute to more consistent protocol when comparing bras rather than attempting to use the position of maximum displacement which is likely to be highly subject and bra dependant.

6.5 Conclusion

A settling in period of ~30 seconds between the breast and bra was found to occur during the initial phase treadmill running. Whilst the study is recognised to be exploratory in nature, the findings suggest future breast kinematic study should consider the possibility of a settling in effect. Therefore, experimental protocols may benefit from including a short period of activity after the subject has changed into the bra to help eliminate any settling in effect prior to data capture or application of over bra markers. Superior-inferior breast displacement was found to be considerably reduced using over bra markers compared to markers placed on the breast surface beneath the bra. Markers positioned over the bra were also found to be less sensitive to variation in A-P and S-I displacement in different regions of the breast. The difference between under and over bra displacement is likely to be subject and bra dependant. The effect is likely to be greater in very stiff or padded bra cups, therefore, in these cases particular caution should be exercised if over bra markers are utilised. However, until advances in technology are made the use of over bra markers remains current best practice. Future studies are recommended to state whether breast markers were located over or under the bra and recognise that over bra markers represent bra motion. The use of multiple breast markers enables a more comprehensive representation breast motion and provides a greater level of information to inform the development of sports bra design. Further study is recommended to better understand breast movement across a wider population before determining the most appropriate breast marker protocol. However, results showed the bra tended to 'move as one' with much less variation in motion between marker locations, therefore, a single marker appears to be a reasonable approximation of bra motion. Whilst maximum bra motion may not occur at the nipple, the nipple provides an easily identifiable landmark to ensure greater protocol consistency.

Chapter 7

The effect of bra strap stiffness on bra kinematics and perception measures during treadmill running

7.1 Introduction

Sports bras are widely acknowledged to be more effective at limiting breast motion and reducing breast pain during exercise compared to an everyday bra (Mason et al., 1999). However, there is relatively little understanding of how a specific sports bra design affects bra performance. Design describes the bra structure and material properties and thereby influences the mechanical properties of the bra and its performance, typically quantified through measures of relative breast kinematics and breast pain. A number of studies have sought to better understand this relationship by comparing breast kinematic and comfort perception results to the structure and materials used in a selection of sports bras (Lawson and Lorentzen, 1990, Starr et al., 2005, Zhou et al., 2009, Zhou et al., 2013). However, the findings have been limited by the small number of very different sports bras studied, therefore, the experimental variables (bra structure and material properties) which affect the bra mechanical properties have been poorly controlled making it difficult to infer any relationships. Other studies make design recommendations to reduce breast motion or breast discomfort but provide little supporting evidence (Stamford, 1996, Lawson and Lorentzen, 1990, Page and Steele, 1999). This has resulted in a variety of sometimes conflicting suggestions about the relationships between sports bra design, mechanical properties and breast motion and breast discomfort during exercise.

Sports bra performance is typically assessed using relative breast kinematics and subject perception of the bra during treadmill running. The relationship between increased breast motion and greater levels of breast discomfort is generally accepted. Although the exact nature of this relationship is unknown, vertical breast motion appears to play the most significant role in affecting breast discomfort. A number of studies identify a strong positive relationship between decreased vertical breast displacement and reduced breast discomfort (Gehlsen and Albohm, 1980, Lorentzen and Lawson, 1987, Mason et al., 1999, McGhee et al., 2007, Starr et al., 2005, White et al., 2009b). Peak vertical breast velocity (McGhee et al., 2007) and vertical breast force (breast mass x acceleration) have also been found to have a significant positive relationship with breast discomfort (McGhee et al., 2010).

Bra straps are thought to play an important role in limiting superior-inferior motion of the breast during running (Zhou and Yu 2013). A number of studies have reported 'stiff' or high modulus bra straps reducing vertical breast motion (Stamford, 1996, Lawson and Lorentzen, 1990, Page and Steele, 1999). This is somewhat supported by Zhou (2011) who investigating the effect of strap modulus on vertical breast displacement during treadmill jogging (7 km/h). Interestingly, the author reported no effect of strap modulus for smaller breasted participants but suggested an inverse relationship between modulus and vertical breast displacement occurred in larger breasted subjects. However, no statistical analysis of the data was provided and on visual inspection the trend appears somewhat unclear. In contrast, Zhou et al. (2013) suggested that less stiff straps maybe be more effective at reducing breast displacement. These authors argue that stiff straps lose tension when the breast moves upwards and the breast may separate from the bra, while less stiff straps maintain tension throughout the range of breast motion, keeping the bra in contact with the breast, thus better controlling breast motion. However, this study of seven commercially available bras used very rudimentary materials testing methods and did not control other bra design variables.

The objective of this study was to investigate the relationship between the mechanical properties of sports bra straps and sports bra performance (bra kinematics and perceived support, comfort and fit) during treadmill running. It was hypothesised that increasing bra strap stiffness would result in reduced vertical bra kinematics and increase support perception for the bra.

7.2 Method

The subjects and bra included within this study are presented first, followed by three sub-sections covering the mechanical testing of the bra, breast kinematics and bra perception. Each subsection details the data collection, data processing and statistical analysis method used.

7.2.1 Subjects

Ten recreationally active female subjects (mean ± SD; age 25.9 ± 5.5 years; height 1.65 ± 0.09 m; mass 67.0 ± 9.6 kg) with large breasts (underband size range 32 – 36 and cup size range D – F) gave voluntary informed consent to participate in the study following ethical approval gained from the institution. All were familiar with treadmill running. The subjects performed all trials wearing the same base bra, a modified Shock Absorber High Exertion N109 sports bra with three different strap sections inserted (single, double and triple thickness elastic tape). The subjects were not informed that the strap inserts used were of differing stiffness or which strap insert was fitted. The bra was fitted with the triple strap sections in place and followed the criteria outlined in §3.2.7. Subsequent testing of the three strap sections was conducted in a randomised order.

7.2.2 Bra

The base bra, a popular non-underwired 'high impact' sports bra with adjustable underband and straps (Shock Absorber High Exertion N109 detailed in §3.2.6) was modified by replacing a section of the existing shoulder straps with removable elastic strap sections (Figure 7.1). It was thought modifying the bras with a range of less stiff straps would have a more marked effect on the performance of a stiff cupped bra than a bra with very elastic cups. Three identical length strap sections were produced for each bra using 20 mm wide elastic tape (Korbond Elastic White 20 mm x 2 m, Korbond Industries Ltd., Grantham, UK). Steel hooks were added to allow straps to be easily interchanged without removing the bra. The three bra straps were;

Single - single thickness elastic tape

Double - double thickness elastic tape

Triple - triple thickness elastic tape

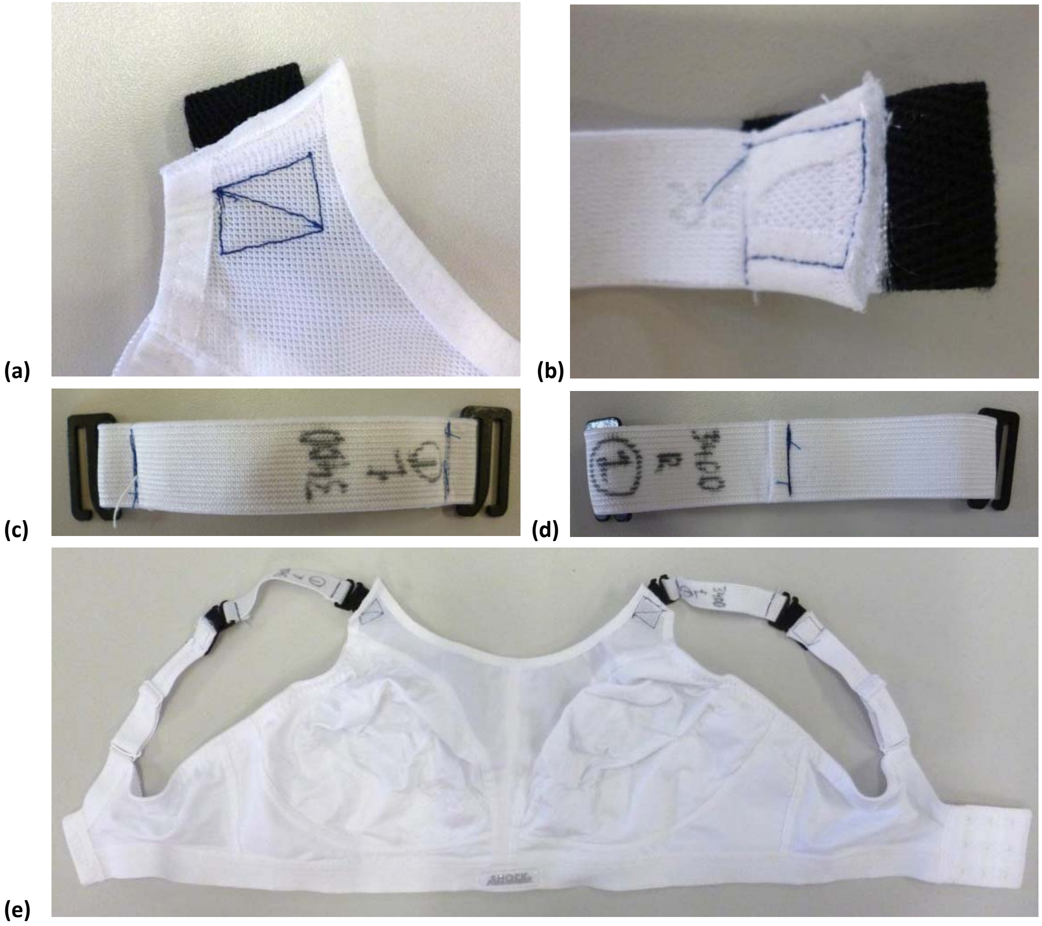


Figure 7.1 - Construction of the modified bras (a) Front strap attachment eyelet (b) Back strap attachment eyelet (c) Single strap (d) Double strap (e) Modified bra

7.2.3 Mechanical Testing

This section details the methods used to determine the mechanical testing protocol, data collection and data processing.

7.2.3.1 Data Collection

Cyclical tensile tests were performed on all elastic strap sections and the original strap using an Instron 5569 (Instron Corporation, Norwood, MA, USA). A cyclical loading protocol was used to most closely replicate the loading of bra straps during running and also allow time for the fabric to 'settle in'. The test parameters were selected based on the following calculations.

The Instron 5569 has a maximum extension speed of 500 mm/min (Instron Corporation, 2005). The duration over which bra strap extension occurs was estimated using the step frequency reported by Haake and Scurr (2010) of 2.7 Hz during 10 km/h treadmill running. The bra strap was estimated to extend by *X* mm following foot ground contact and it was assumed that extension occurred over half the step duration.

Time per step	1 / 2.7 = 0.37 s per step
Time of half step	0.37 / 2 = 0.19 s or 0.0031 of a minute

Strap extension required to equal Instron maximum extension rate (X_{mi})

X_{mi} = time per half step x max Instron speed

$X_{mi} = 0.0031 \times 500$

$X_{mi} = 1.54$ mm

Strap extension of 1.54 mm or greater results in a higher extension rate than that of the Instron 5569. Therefore, the maximum speed was selected as it was thought strap extension was likely to exceed 1.54 mm during running conditions.

The force applied to the bra strap was calculated using breast mass and nipple acceleration data. The mass of the mode breast size tested (34D) was calculated using Turner and Dujon (2005) breast mass estimation system to be 0.460 kg. A peak nipple acceleration of 26 ms^{-2} was found by Scurr et al. (2008) in D cup subjects during treadmill running at 2.8 ms^{-1} (10 km/h). Only vertical forces were considered in the calculation. It was assumed that 50% of the force acting on breast was transferred through the bra strap and that all breast mass acts at the nipple (McGhee et al., 2013, Haake and Scurr, 2010).

$$\textit{Force on strap} = ((\textit{mass} \times \textit{breast acceleration}) + (\textit{mass} \times \textit{gravitational acceleration})) \times \textit{percentage of force transferred to strap}$$

$$\textit{Force on strap} = ((0.460 \times 26) + (0.460 \times 9.81)) \times 0.5$$

$$\textit{Force on strap} = 8.23\ N$$

A preliminary study found that the initial loading cycle exhibited slightly different behaviour to subsequent cycles with minimal differences observed between 5, 10 and 20 cycles. Therefore, a five cycle loading protocol was used.

The Instron 5569 was set up with ± 100 N load cell (Load measurement accuracy ± 0.4% down to 1 N and ± 0.5% down to 0.4 N) and the safety stops positioned appropriately (Instron Corporation, 2005). The clamps used were modified specifically for fabric testing by adhering coarse sandpaper to the clamp jaws to prevent the fabric from slipping (Saville, 2004). The clamps were vertically aligned using a metal rule and spirit level. The strap was secured with the lower clamp secured level with the top of cup and the upper clamp level with start of strap (Figure 7.2a). The load head was moved until the bra strap was lengthened but still slack and the load was zeroed (Figure 7.2b). The load head was then moved upwards until tension of 0.2 N was achieved, the test was started with a small amount of tension in the strap to enable a more consistent start position. The length was then zeroed and test protocol run (the tensile load was increased from 0.2 to 8.23 N at 500 mm/min then returned to the start position at the same rate, this was repeated for 5 cycles) (Figure 7.2c). Load, extension and time data was recorded at 10 Hz. Instron 5569 extension accuracy is ± 0.02 mm or ± 0.05% whichever is greatest (Instron Corporation, 2005).

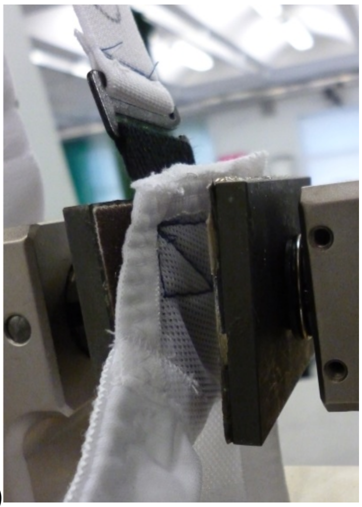
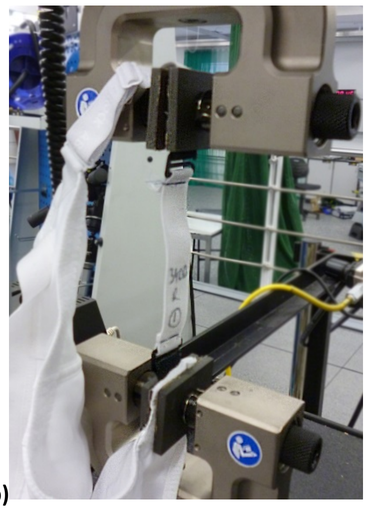
(a)  (b)  (c) 

Figure 7.2 - Bra strap material testing using Instron 5569 (a) Modified lower clamp used to secure the bra cup just below the strap (b) Mass zeroed when bra strap slack (c) Bra strap during cyclical tensile test

7.2.3.2 Data Processing

Some settling in of the fabric appeared to occur during the initial loading cycle, therefore, peak extension and maximum tensile load during the second loading cycle were used to calculate nominal strap stiffness using Hookes law (stiffness = force / extension).

7.2.4 Breast Kinematics

This section details the methods used to for data collection, data processing and statistical analysis of breast kinematics.

7.2.4.1 Data Collection

Body kinematics were collected using 10 infra-red emitting markers and a four-head Coda motion system (Charnwood Dynamics Ltd; Leicestershire, UK; 200 Hz) (detailed in §3.2). The torso segment was defined using the marker set previously developed for measuring breast kinematics (Chapter 4) this comprised markers on the spinal processes (T1, T10), sternal notch (CLAV), clavicles directly above the nipple (RCNIP and LCNIP) and the anterior inferior aspect of the 10^{th} ribs (RA10R and LA10R) (Figure 7.3). The torso segment local coordinate system (LCS) was defined using CLAV, RA10R and LA10R as detailed in §4.2.2.2 and Figure 4.2. Markers were also placed on the sports bra directly over the nipples and one on the right heel for gait cycle determination. As recommended in Chapter 6, as over bra markers are used within this study they are referred to as tracking bra motion rather than breast motion.

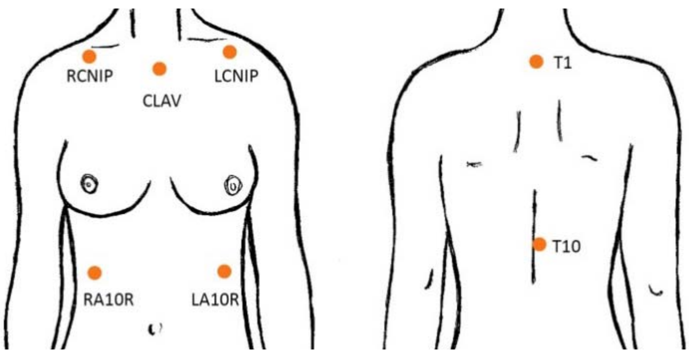


Figure 7.3 - Marker locations used to define the torso segment

Subjects initially performed a 10 second static trial over two complete breathing cycles (S1 - in Table 3.2). Following a three minute warm up and familiarisation period on the treadmill, the subjects performed three running trials (R1 - in Table 3.3). Data was collected after 30 seconds at speed. A minimum of two minutes rest was given between trials.

7.2.4.2 Data Processing

The running trials were processed following the procedure outlined in §3.3. The torso segment was modelled and relative bra motion calculated using Visual3D then filtered at 15 Hz (v4, C-Motion Incorporated, Germantown, MD, USA). Further analysis of the kinematic data was completed in Matlab (R2010a, MathWorks Incorporated, Natick, Massachusetts, USA). Displacement ranges, minimum and maximum velocities and accelerations were determined for each gait cycle and then averaged over 30 gait cycles and three trials for each condition to give the mean and standard deviation on a per condition and subject basis.

In order to monitor any changes in running gait between conditions torso vertical displacement, anterior-posterior lean, lateral bend and axial rotation ranges plus the average torso anterior-posterior lean angle were measured in the global coordinate system. These parameters, along with running cadence were determined for each analysed gait cycle and the mean values determined similarly to the bra kinematics detailed above.

7.2.4.3 Statistical Analysis

All statistical analysis was performed using IBM SPSS Statistics for Windows (Version 22.0, IBM Corp, Armonk, NY, USA). Bra kinematics and gait variables were analysed using a one-way repeated measures ANOVA followed by post hoc pairwise comparisons using a Bonferroni correction (significance set at $p < .05$). A Boneferroni correction was used as it is generally conservative, controls type 1 errors well and has more power than Tukey with a small number of comparisons (Field, 2009). Cohen's d effect sizes were calculated with d = 0.2 considered to be a small effect, d = 0.5 a medium effect and d = 0.8 a large effect (Cohen, 1988).

7.2.5 Bra Perception

7.2.5.1 Data Collection

Three aspects of bra perception (comfort, fit and breast support) were assessed (as detailed in §3.2.8) immediately after each strap condition using a seven point Likert scale (Roberts bra scale, Progressive Sports Technology (2011)).

7.2.5.2 Statistical Analysis

Data from the perception questionnaire was considered to be interval data with equal intervals on the scale representing equal differences in property. Mauchly's test indicated that the assumption of sphericity had been violated for fit, comfort and support ($p < 0.05$). Therefore, a Friedman's ANOVA followed by a post hoc Wilcoxon signed-rank test with Bonferroni adjustment (critical level of significance is 0.05 / 3 = 0.0167) was performed for each perception parameter (Field, 2009).

7.3 Results

7.3.1 Mechanical Testing

The three bra elastic strap sections and the original bra strap were tested using a 5 cycle tensile loading protocol designed to replicate conditions experienced during treadmill running. The results clearly illustrate that the three elastic strap sections tested were of different stiffness and all less stiff than the original strap (Tables 7.1 and 7.2). All straps exhibited the same pattern of load-extension plot, with three distinct phases; a very gradual slope on initial loading followed by a steeper linear section which then flattens to a more gentle slope (except for original strap where the third phase was not present). The hysteresis loops shown on the load-extension plots (Figure 7.4) demonstrate that the strap material is not perfectly elastic. The area between the loading and unloading curves represents the energy lost during the recovery process. A small amount of settling in of the fabric can be observed in the initial loading cycle.

Table 7.1 - Summary of bra strap tensile testing results

	Original	Triple	Double	Single
Extension at maximum tensile load (8.23N) (mm)	6.63	12.27	28.40	67.43
Nominal stiffness, k (N/m)	1246	672	290	122
Strain	5%	10%	22%	52%

Table 7.2 - Strap stiffness during linear decrimping phase of tensile loading

	Original	Triple	Double	Single
Change in Extension (mm)	4.19	3.25	2.97	2.60
Change in Load (N)	5.98	3.63	2.31	1.27
Stiffness, k (N/m)	1425	1117	780	487

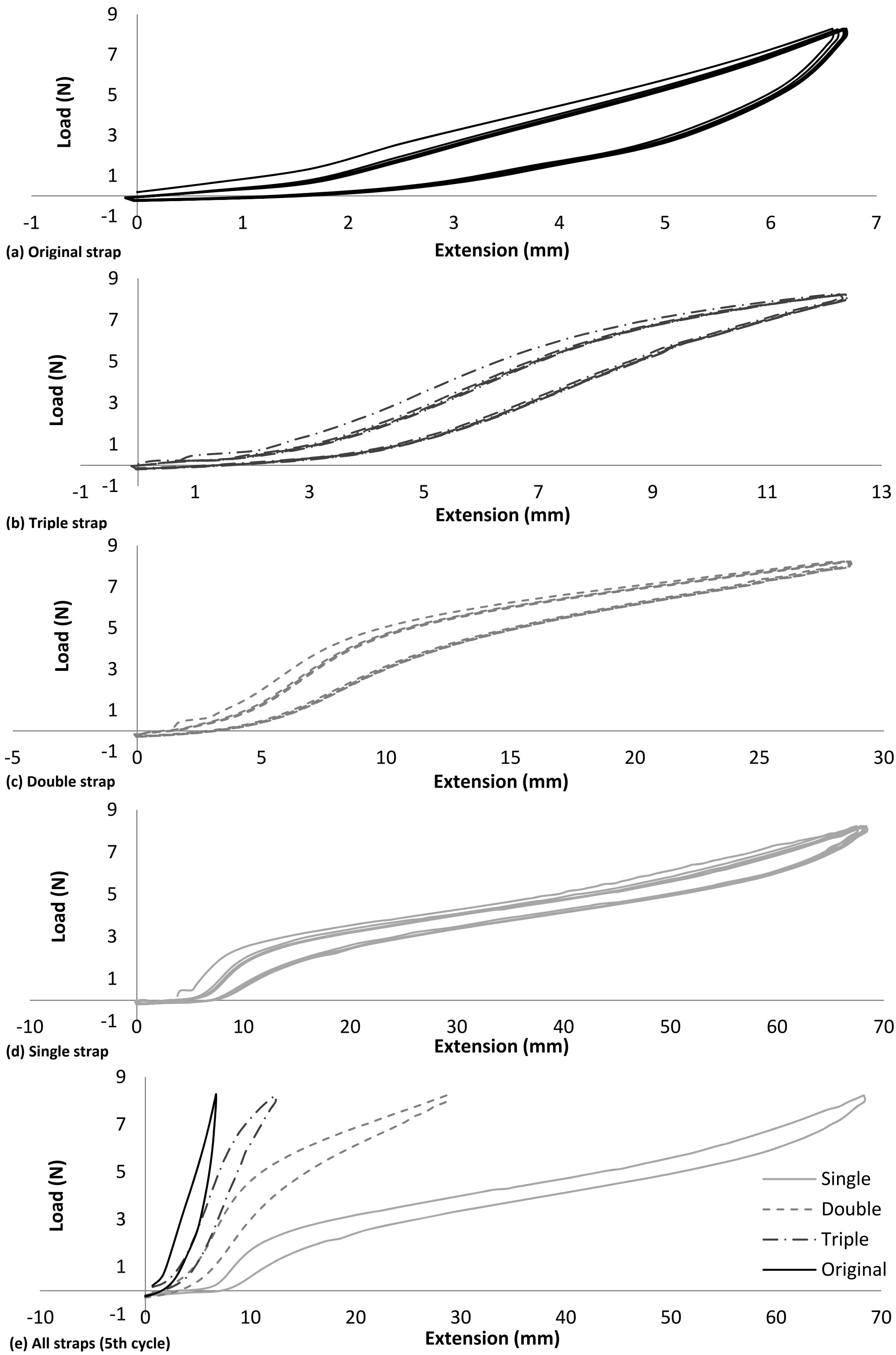


Figure 7.4 - Load-extension plots during tensile testing (a) Original strap (b) Triple strap (c) Double strap and (d) Single strap (e) All straps (5th loading-unloading cycle)

7.3.2 Biomechanics

Bra kinematics were assessed for three different strap conditions, single, double and triple strap. A one way repeated measures ANOVA found the main effect of strap to be statistically significant for all superior-inferior bra kinematics ($p < 0.01$) except peak superior-inferior (S-I) displacement above the static bra position. Strap was also found to have a statistically significant effect in anterior-posterior (A-P) peak accelerations ($p < 0.05$).

Post-hoc pairwise comparisons for the main effect of strap indicated several significant differences between straps (Figure 7.5). Significant differences were observed between all three bra straps for S-I bra motion inferior to the static bra position (negative displacement, negative velocity and positive acceleration) ($p < 0.05$). In comparison to the single strap downward bra displacement was reduced by an average of 7 mm for double strap and 15 mm for triple strap. Similarly, in comparison to the single strap, peak downward velocity and positive acceleration were lower for double and triple straps (by 0.17 ms^{-1}; 0.29 ms^{-1} and 7 ms^{-2}; 11 ms^{-2} respectively). Fewer differences were observed between bra straps for vertical motion above the static bra position and these differences were of a smaller magnitude. Peak upward velocity for triple strap was on average 0.1 ms^{-1} lower than for the single strap and 0.04 ms^{-1} lower than for the double strap. Statistically significant differences were also observed in peak A-P accelerations, on average peak accelerations were 5-7 ms^{-2} higher for the single strap compared to the double and triple straps.

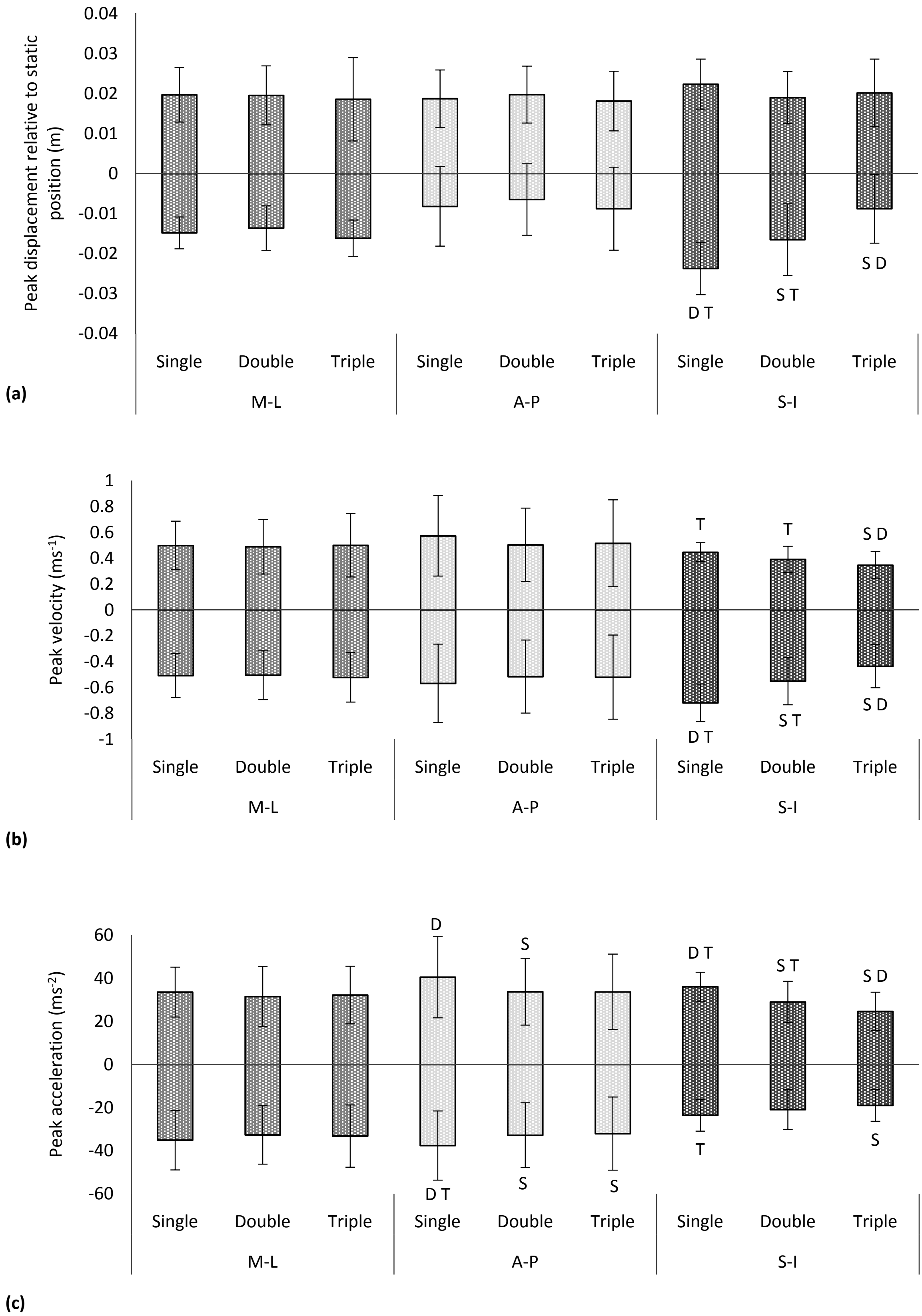


Figure 7.5 - Three dimensional relative bra kinematics using marker over nipple for single, double and triple bra straps. (a) Displacement relative to static bra position in static trial (b) Peak velocity (c) Peak acceleration. Significant differences between straps are denoted by S = significant difference to single strap, D = double strap and T = triple strap ($p < 0.05$)

A one-way repeated measures ANOVA found strap had no significant effect on gait variables with the exception of torso axial rotation (p = 0.019) (Table 7.3). Axial rotation was significantly lower for the double strap compared to the triple strap (28.0 ± 4.5° versus 28.9 ± 4.5° respectively). The Cohen's d effect size was calculated to be d = 0.20, a small effect (Cohen 1988).

Table 7.3 - Gait variables for three strap conditions (Mean, SD)

		Single (Mean ± SD)	Double (Mean ± SD)	Triple (Mean ± SD)	ANOVA (F, p)
	Cadence (strides/s)	1.34 ± 0.04	1.34 ± 0.04	1.34 ± 0.03	(0.191, 0.828)
Torso	Vertical displacement (mm)	113 ± 9.77	112 ± 8.8	114 ± 9.4	(1.584, 0.233)
	Lateral bend range (°)	6.8 ± 2.3	6.5 ± 2.2	6.8 ± 2.3	(1.359, 0.282)
	Anterior-posterior lean range (°)	9.5 ± 2.7	9.1 ± 3.0	9.3 ± 3.0	(1.788, 0.196)
	Mean anterior lean angle (°)	0.9 ± 4.0	1.3 ± 4.2	1.1 ± 4.4	(1.723, 0.207)
	Axial rotation range (°)	28.3 ± 4.1	28.0 ± 4.5	28.9 ± 4.5	(4.945, 0.019*)

* Indicates statistically significant difference (p < 0.05)

7.3.3 Bra Perception

The perception parameters comfort, fit and support were assessed for three different strap conditions, single, double and triple strap (Figure 7.6). A Friedmans ANOVA's found strap stiffness had a statistically significant effect in all three perception parameters (Table 7.4).

The Wilcoxon post-hoc tests indicated a statistically significant reduction in perceived support between triple strap and single strap (r = -0.64) and also between triple strap and double strap (r = -0.57) (Table 7.5). No significant difference in perceived support was found between double and single strap. All subjects rated the triple strap most supportive and all except one subject ranked the single strap the least supportive. Support ratings of the single strap varied considerably between 'very supportive' and 'very unsupportive' (score 2 to -2), typically larger breasted subjects gave a lower rating of support.

The Wilcoxon signed rank test identified no significant differences between bra straps for fit. Six of the ten subjects reported no difference in bra fit between the straps (Figure

7.7). Interestingly, satisfaction with bra fit tended to be slightly lower for larger breasted subjects.

Similarly the Wilcoxon tests identified no significant differences in comfort between bra straps. Five of the ten subjects gave all three bra straps the same comfort rating, the other subjects perceived only small differences in comfort between strap conditions.

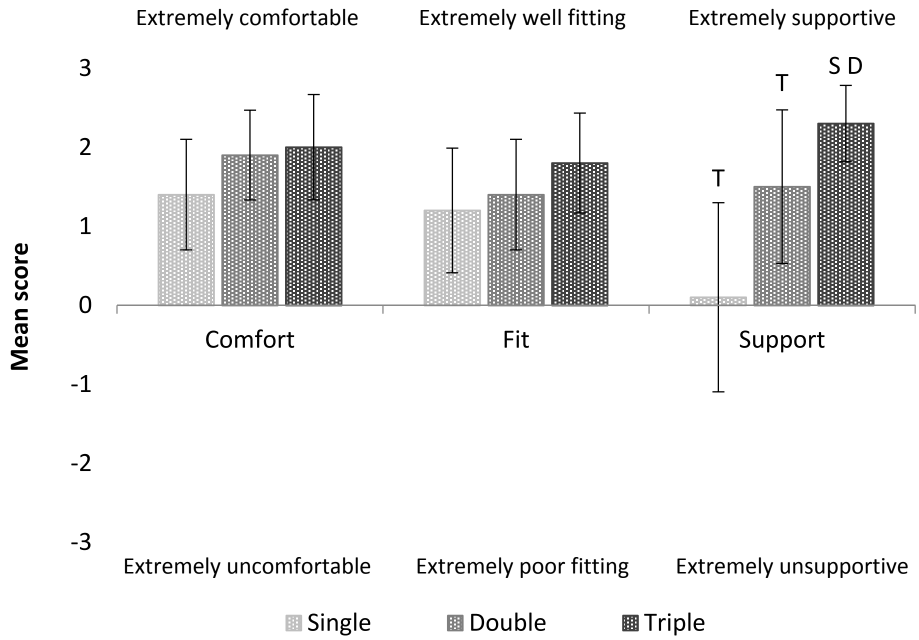


Figure 7.6 - Comfort, Fit and Support perception scores for three straps (Mean, SD). Significant differences between straps are denoted by S = significant difference to single strap, D = double strap and T = triple strap (p < 0.0167)

Table 7.4 - Perception parameters for three strap conditions (Mean, SD)

	Single (Mean ± SD)	**Double (Mean ± SD)**	**Triple (Mean ± SD)**	**Friedmans ANOVA (X^2 (2) , p)**
Comfort	1.4 ± 0.7	1.9 ± 0.6	2.0 ± 0.7	(9.50, 0.01*)
Fit	1.2 ± 0.8	1.4 ± 0.7	1.8 ± 0.6	(7.42 , 0.02*)
Support	0.1 ± 1.2	1.5 ± 1.0	2.3 ± 0.5	(15.23, < 0.01**)

* Indicates statistically significant effect (p < 0.05)
** Indicates statistically significant effect (p < 0.01)

Table 7.5 - Wilcoxon signed rank test results for bra perception parameters

		Double - Single	**Triple - Single**	**Triple - Double**
Comfort	Sig., p	0.025	0.034	0.317
	Effect size, r	-0.500	-0.474	-0.224
Fit	Sig., p	0.157	0.063	0.046
	Effect size, r	-0.316	-0.415	-0.447
Support	Sig., p	0.033	0.004*	0.011*
	Effect size, r	-0.478	-0.635	-0.566

* indicates statistically significant difference p < 0.0167 due to Bonferroni correction

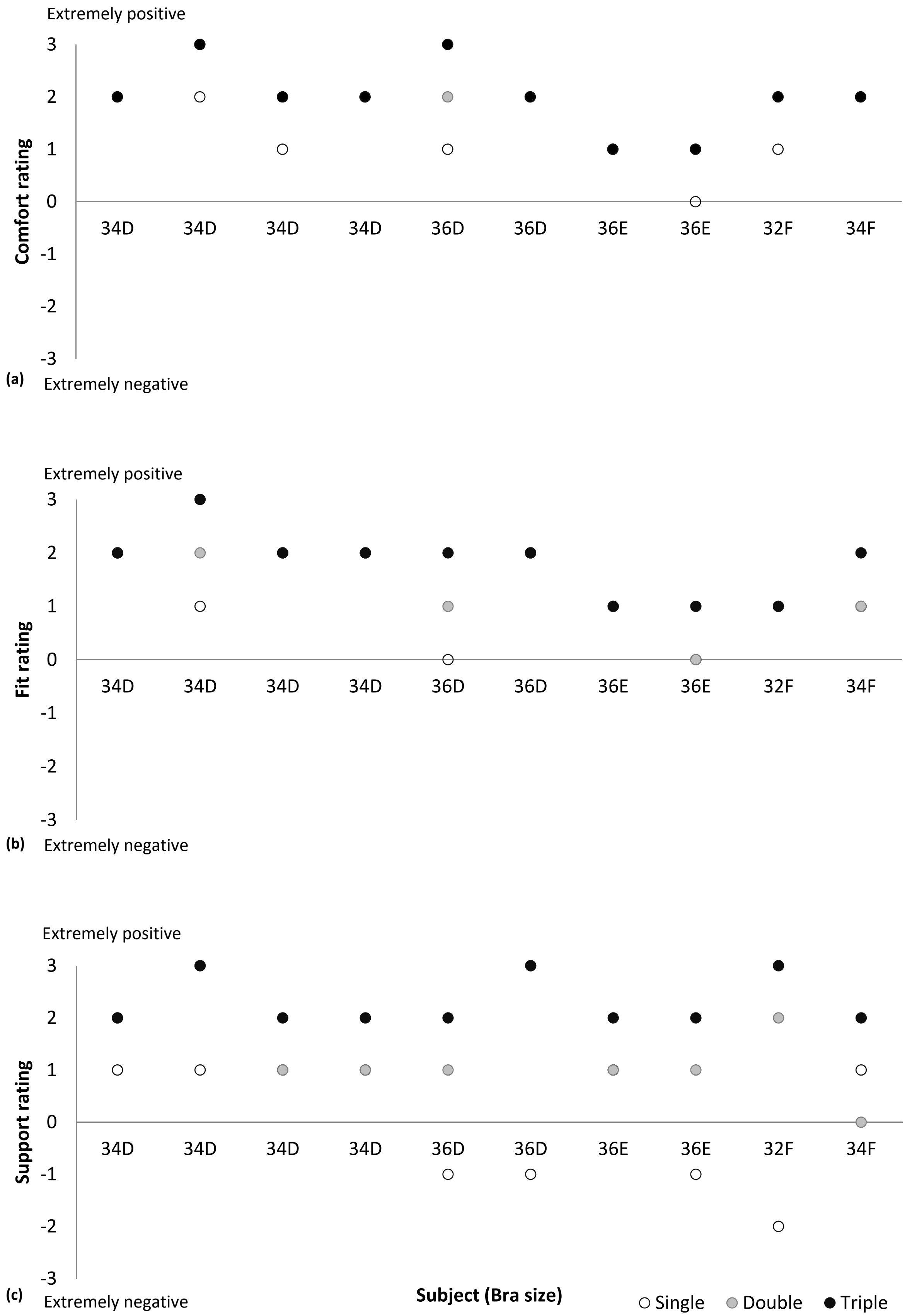


Figure 7.7 - Variation in perception of bra performance with bra size. (a) Comfort rating (b) Fit rating (c) Support rating (Maximum score +3, Minimum score -3)

7.3.4 Relationship between Mechanics and Biomechanics

Strap condition was found to primarily affect superior-inferior bra kinematics, post-hoc pairwise comparisons identified the greatest differences in S-I bra motion inferior to the bra static position (Figure 7.5). Negative displacement, negative velocity and positive acceleration all demonstrated steep reductions in bra kinematics with increasing stiffness (Figure 7.8).

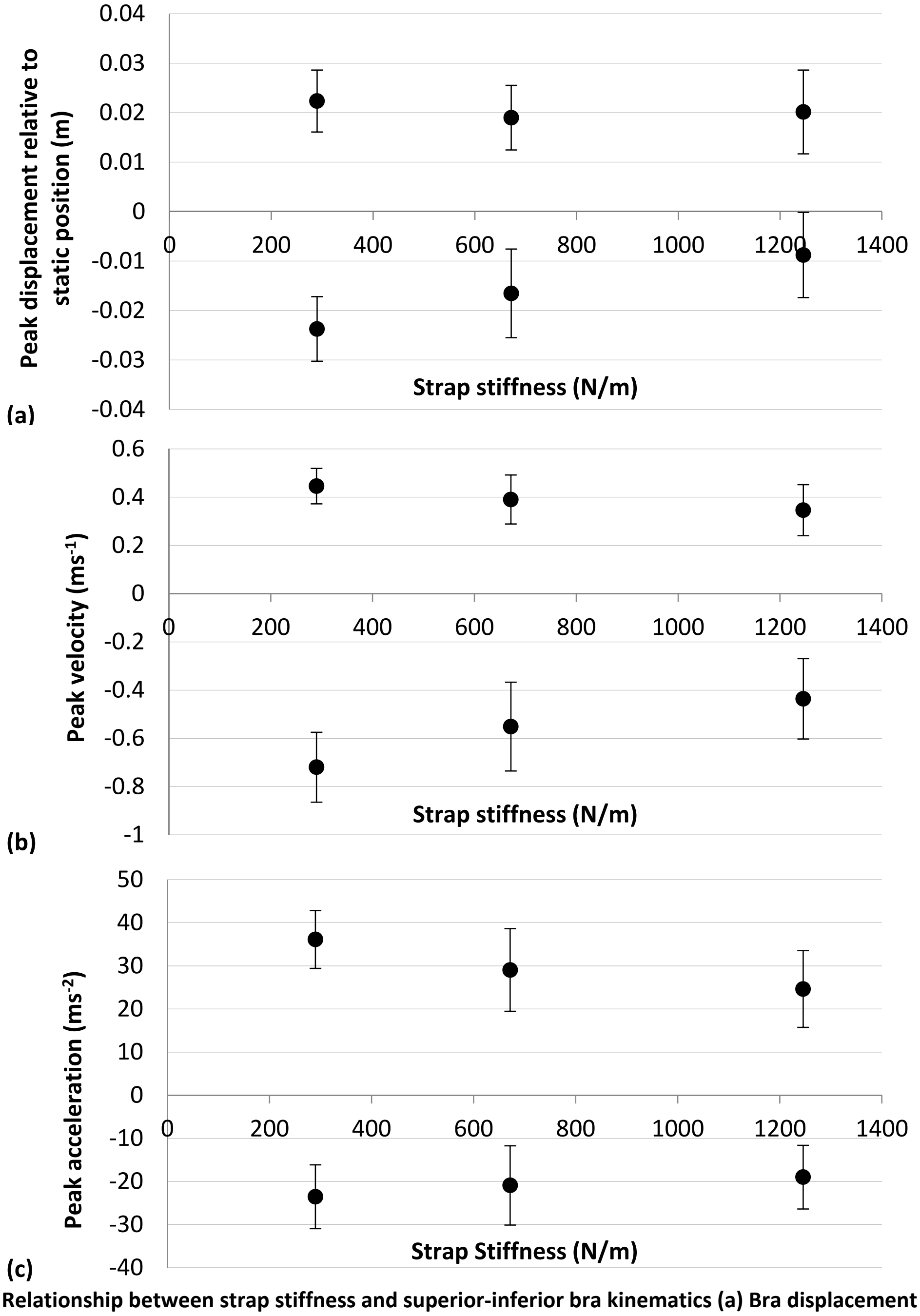


Figure 7.8 - Relationship between strap stiffness and superior-inferior bra kinematics (a) Bra displacement relative to static position (b) Peak bra velocity (c) Peak bra acceleration

7.4 Discussion

Whilst it is widely acknowledged that sports bras reduce breast motion and breast discomfort during running compared an everyday bra, the relationship between bra mechanical properties and performance (breast kinematics and subject perception) is currently unclear. Bra strap stiffness has been identified as a potentially important factor in sports bra performance. Therefore, the objective of this study was to investigate the relationship between the mechanical properties of sports bra straps and both breast kinematics and subject perception of bra performance during treadmill running. The results are largely in support of the hypothesis. Increasing strap stiffness was associated with a significant decrease in superior-inferior bra kinematics particularly in the downward motion of the bra. However, in contrast to the hypothesis increasing strap stiffness also led to a significant reduction in peak anterior-posterior acceleration. Strap stiffness was found to have a statistically significant effect on the subjective ratings of comfort ($p < 0.05$), fit ($p < 0.05$), and support ($p < 0.01$), all three demonstrated a general trend of improved rating with increased stiffness (Table 7.4). The strongest trend was observed in perceived support, significant increases in supportiveness were perceived between the triple and double strap and also between the triple and single strap (Table 7.5). No statistically significant differences between strap conditions were found for fit or comfort.

7.4.1 Mechanical

If the bra strap is modelled as a simple spring obeying Hookes law, then adding an identical layer of strap material can be considered as an identical spring in parallel (Zhou and Yu 2013). Using $F = kx$ where k is the spring constant of a strap, F is force and x is extension. If the same force (F) is applied strap extension for each case is expected to be;

Single layer strap $x = F/k$

Double layer strap $x = F/ 2k$

Triple layer Strap $x = F / 3k$

N^{th} layer strap $x = F / Nk$

This simple model predicts that additional bra strap layers (extra springs) will reduce bra strap extension, but the magnitude of that effect will level off with increasing numbers of strap layers. However, the hysteresis loop observed in the force-extension plots (Figure 7.4), suggest the strap sections do not behave as 'perfect springs' with some energy lost during unloading cycle. The tensile behaviour of fabric is complex. The initial deformation may result from straightening out of the test sample, followed by a steeper slope during decrimping of the fibres followed by a third phase when the fibres begin to extend on a molecular level (Hu, 2004). Strap stiffness was measured at peak load (~8.23 N). The simple spring model predicts the double and triple straps to be 2 and 3 times stiffer than the single strap respectively, whereas the actual values obtained were 2.4 and 5.5 times stiffer. In comparison, the original strap was 10 times stiffer than single strap and almost twice as stiff as the triple strap.

The load-extension curves demonstrate three distinct phases of behaviour, with the exception of the original strap where the third stage was not reached. The straps exhibit very non-linear behaviour, therefore, in addition to nominal stiffness obtained at maximum extension stiffness was also measured in the linear 'decrimping phase'. As discussed in §7.4.7 the mechanical testing protocol is likely to have utilised a higher force and slower loading speed than that experienced during running, therefore, the straps may be more likely to operate in second linear phase. Examining the load extension curves in the decrimping phase the four straps are of a more similar stiffness (Table 7.2). During the decrimping phase the double, triple and original straps are 1.6, 2.3 and 2.9 times stiffer than the single strap respectively.

Whilst the bra strap has been studied in isolation, in reality the bra strap is part of a much more complex system comprising multiple bra components, thus, the effect of the straps on controlling breast displacement will depend on the very broad design of the bra. For example, adding increasingly stiff strap sections to a bra with highly extensible bra cups is likely to have a negligible effect on breast kinematics, as the least stiff part of springs in a series has the dominating effect. Highlighting the relevance of the approach used here, the bra tested had a relatively stiff cup, therefore, the effect of modifying strap stiffness was more easily studied.

7.4.2 Biomechanics

Bra straps hold the upper cup in place, they act to limit the downward motion of the bra and breast (as straps resist downward movement of the bra cups under tension), and therefore, it is unsurprising that greater differences were observed between straps in bra displacement below static bra position, downward velocity and positive acceleration of bra (Figure 7.5). The reduction in upward bra velocity and negative acceleration with increasing strap stiffness is likely to have resulted from a reduction in total superior-inferior bra motion, through the restriction of downward bra motion. Therefore, as the bra is moving over a smaller range within the same time period, upward breast velocity and the rate breast deceleration are lowered. Further improvements in bra performance may be achieved by investigating ways to reduce upwards motion of the bra and underlying breast.

Strap stiffness was also found to have a significant effect on A-P peak accelerations. Negative A-P acceleration was significantly higher in the single strap condition compared to the double and triple straps ($p = 0.025$ in both cases). Positive A-P acceleration was only found to be significantly higher in single strap compared to double strap ($p = 0.029$). Strap stiffness was not found to have an effect on A-P displacement or velocity. The three directions of bra motion are not independent, therefore, some effect may have carried over from changes in S-I acceleration.

Analysis of the gait and torso data revealed no statistical differences between straps with the exception of axial torso rotation which was found to be significantly larger for triple compared to double strap condition ($p = 0.019$) (Table 7.3). However, the mean difference (0.88^{o}) was calculated to have a small effect size ($d = 0.2$), therefore, whilst statistically significantly the difference may not be meaningful (Cohen, 1988). These results suggest that the bra kinematic results presented above represent the effect of the bra rather than any contribution from an accommodation in running style.

7.4.3 Perception

Increasing bra strap stiffness was associated with improved bra comfort and fit, however, the overriding and most significant effect was an increased perception of support. All subjects rated the support offered by the triple strap highly, with many describing it as 'extremely supportive'. This suggests the triple strap may be approaching a stiffness level beyond which further increases in strap stiffness have little beneficial subjective effect.

The significant effect of strap stiffness on bra fit and comfort was somewhat unexpected, although no significant differences observed between individual strap conditions. Static bra fit was carefully controlled, by using the same base bra and all straps used were the same length. The difference in perceived fit may reflect changes in dynamic bra fit. To date bra fit research has focused solely upon the static fit, suggesting dynamic bra fit should be considered as an area of future research (McGhee, 2009, McGhee and Steele, 2010b). Alternatively, a subjects interpretation of the words 'fit' and 'comfort' may vary considerably or the ratings given may just reflect their overall preference for that strap. For example, 'comfort' may have been interpreted by some subjects to relating to material feel, others may have considered breast comfort relating to breast motion or emotional comfort wearing the garment. Further exploration of sports bra perception parameters and terminology used similar the study of Roberts et al. (2001) would assist in the development of a more robust protocol to assess sports bra perception.

7.4.4 Relationship between Mechanics and Biomechanics

The results demonstrated a trend of reducing S-I kinematics with increasing strap stiffness particularly limiting bra motion below static position (Figure 7.5). Exploring this relationship further, negative displacement, negative velocity and positive acceleration results suggest a curved relationship line, with the effect of increasing stiffness levelling off between the double and triple strap conditions (Figure 7.8). The number of straps used in this study was limited by the number of strap sections it was possible to fit to the modified bra. Examining a greater number of straps with smaller increments in stiffness may clarify this relationship and allow a threshold stiffness to be established, beyond which further increases in stiffness have negligible effect on bra kinematics. This threshold value would be unique to the bra model tested, since as described above, the strap stiffness must be considered within the wider context of the bra.

7.4.5 Relationship between Mechanics and Perception

Statistically significant differences in supportiveness were identified between triple and single ($p = 0.004$) and also between triple and double straps ($p = 0.011$). No significant difference in support was observed between double and single straps. The difference in stiffness between triple and single straps was 560 N/m, between triple and double straps was 383 N/m whereas the difference between double and single straps was only 168 N/m (Table 7.1). This suggests that there may be a minimum detectable difference in strap stiffness from the different breast kinematics. Interestingly, larger breasted subjects ≥ 36D tended to be more able to distinguish between different strap stiffness (Figure 7.7c).

7.4.6 Relationship between Biomechanics and Perception

The statistical correlation between bra kinematics and perception was not explored due to the relatively small amount of perception data. Qualitatively, the results appear to be in agreement with Lawson and Lorentzen (1990) who found a correlation between subjective bra support ratings and quantitative vertical breast displacement scores.

7.4.7 Limitations

The peak load used during the mechanical testing is likely to be an overestimation of the force applied to the bra strap. Force due to breast motion was calculated using acceleration values measured at the nipple (Scurr et al., 2008) and the breast mass considered to act at the nipple (Haake and Scurr 2010, McGhee 2013). In addition, the breast centre of mass may be better approximated by assuming the breast to be a homogeneous density hemisphere, with the centre of mass at 3/8th of the radius (Beyer, 1987). The nipple has previously been reported to be the location of greatest breast displacement, therefore, acceleration may also to be highest at this location (Mason et al., 1999). Acceleration experienced at the centre of breast is likely to be substantially lower. Therefore, the force acting on the breast mass due to motion will be reduced but force due to gravitational acceleration remains unchanged. The loading speed was limited to 500 mm/min where as in reality it may be much higher, however, as the net force and extension values the findings were highly unlikely to be affected. Thus, differences in strap stiffness experienced during the run may not exactly match the mechanical test data. However, the straps tested clearly demonstrated a trend of increasing stiffness from single to double then triple straps enabling the effect of strap stiffness to be explored in this study. Thus, although qualitatively the three experimental conditions were met, accurately quantifying the differences in stiffness between the three straps is more challenging.

Over bra markers were used within this study, therefore, in accordance with the recommendation made in Chapter 6, are referred to as representing bra motion. The findings of Chapter 6 suggest that movement may occur between the breast and bra during running. However, as same base bra is used for all straps positioned over the bra any movement between breast and bra were likely to be similar in all strap conditions. Therefore, changes in bra motion are likely to represent changes in motion of the underlying breast.

The original strap was not included within the running trials, as this would require two base bras to used, one with original straps intact the other modified to take the strap sections. A preliminary study found clearly observable differences in bra fit between two bra samples of the same model and bra size. Therefore, to remove the additional variable of bra fit the same base bra was used for all strap sections.

The study also highlighted a number of limitations with the methodology used to assess bra perception. Several subjects reported difficulty in rating the first bra strap tested without a means of comparison. Additionally, several subjects reported that they would change their rating of the first bra straps after testing subsequent bra straps. For example, one subject rated the double strap as ‘extremely supportive’ then following the triple strap trials commented that she felt the level of support was higher than the double strap but could only record it as ‘extremely supportive’, the same as double strap.

At present there is no standardised protocol for studying bra perception parameters (§2.6.1.2). This suggests the timing of data recording whether during the trial, at the end of each bra or following all bras trialled is an area for further research. The use of a baseline bra to which subjects can make comparative ratings could also be investigated as an aspect of the study design. Despite the limitations of the perception testing, the main outcome is unlikely to be affected and that increasing strap stiffness was associated with increased perception of supportiveness.

7.4.8 Implications

Strap stiffness was found to have an important role in limiting S-I bra motion, particularly below the static position. As reduced vertical displacement has been previously associated with reduced breast discomfort, this suggests strap stiffness has an important role to play in bra design to reduce breast discomfort during exercise (Gehlsen and Albohm, 1980, Lorentzen and Lawson, 1987, Mason et al., 1999, McGhee et al., 2007, Starr et al., 2005, White et al., 2009b). This is reinforced by the subjective perception of supportiveness increasing with increased strap stiffness.

Further study investigating a greater number straps at smaller stiffness increments may help to further clarify the relationships observed and establish if a threshold strap stiffness is reached. The most pressing area for further study, which has been somewhat neglected to date is an in-depth investigation of factors affecting bra perception and the development of a robust validated perception testing protocol.

7.5 Conclusion

Increasing bra strap stiffness has been shown to improve sports bra performance with respect to bra kinematics and subjective perception ratings. Increasing bra strap stiffness was found to primarily reduce superior-inferior bra kinematics, with the strongest trends observed in bra displacement below static position, peak negative velocity and peak positive acceleration. The perception of support was most markedly improved with increased strap stiffness. Subjective ratings of bra fit and comfort were also found to be affected by strap stiffness but no statistically significant differences were observed between individual strap conditions.

Chapter 8

Conclusions

8.1 Introduction

The research aim addressed within this thesis was the 'Development and application of methods used in the biomechanical assessment of sports bra performance with the end goal of better biomechanical tools for use in the sports bra design process'. A systems approach was taken when planning the research programme to address this aim and four research questions were proposed. The initial research focus was placed on the torso, as it provides the reference frame from which relative breast motion is measured. Research Questions 1 and 2 address the torso. The research focus was shifted to the breast, and is addressed in Research Question 3. The final research focus addressed in Research Question 4 was to apply the outcomes of Research Questions 1-3 to assess sports bra performance, with a view to better informing the sports bra design process. A summary of the outcomes of these research questions is presented with the novelty and implications of the research identified. Future research directions based on the outcomes of this research are also outlined.

8.2 Research Questions

Q1. What does a torso marker set specifically developed for measuring breast kinematics look like and how does this compare to existing models?

The absence of a universally accepted torso tracking model, and information regarding the sensitivity of breast kinematics to the selected torso model were identified as limitations to the existing biomechanical sports bra research. The development of a specific torso tracking model was addressed using a two stage process. The first evaluated all possible marker locations on an individual basis, based on considerations such as occlusion and soft tissue artefact. During this stage 16 of the original 25 torso marker locations were eliminated. The second stage examined the 9 remaining markers in terms of their contribution to the performance of the torso tracking model, resulting in the removal of a further two markers. The final torso tracking model consisted of seven markers (CLAV, RCNIP, LCNIP, T1, T10, RA10R and LA10R; Figure 8.1). The current seven marker torso tracking model is the first to be specifically developed for analysing relative breast motion during activities such as treadmill running. Whilst the results indicated that the two ribs markers (RA10R and LA10R) were less rigid in their tracking of the torso than the other markers, they were retained for the final model to ensure a good marker distribution over the torso. The torso tracking model used was shown to have a significant effect on the calculated relative breast kinematics. As the torso tracking model developed within this chapter is the first specifically designed to quantify relative breast kinematics it is recommended that this model is implemented in future research in this area. This torso tracking model was applied within all subsequent chapters (Chapters 5 - 7).

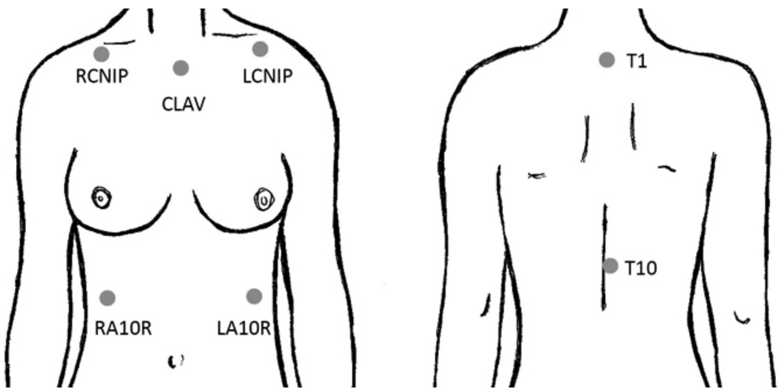


Figure 8.1 - Marker locations used in the current torso tracking model

Q2. Does breathing affects breast kinematic measurement during running?

The torso segment used to calculate relative breast kinematics is assumed to be rigid, however, as the ribcage expands and contracts during respiration some torso of the markers are likely to move, particularly those positioned over the ribcage. Breast movement resulting from respiration has been reported for a static condition, however, the effect of breathing is yet to be considering when studying breast kinematics. This chapter presents the first study to investigate the effect of breathing on breast kinematics during treadmill running. Significant differences were observed in the breast kinematics between breathing and non-breathing conditions, notably in the superior-inferior direction; however, these cannot definitively be directly linked to breathing since significant differences in running gait were also observed. However, the results do suggest that increasing the number of gait cycles analysed can reduce any effects of breathing on breast kinematics due to phase-locking, the synchronisation of breathing with running locomotion. Analysing breast kinematics over 30 gait cycles may help minimise any potential effects of phase-locking across all commonly used phase-locking ratios. Breast kinematic analysis conducted in subsequent chapters (Chapters 6 -7) was performed over 30 gait cycles.

Q3. How does motion vary across the breast and do markers placed on the bra represent the underlying breast?

Further understanding of breast motion and whether markers placed on the bra represent the underlying breast were identified as pertinent to advancing biomechanical assessment of sports bra performance. Motion between the breast and bra (either during an initial bedding in phase or steady state running) has yet to be explored within the existing literature and is assumed to be negligible for a correctly fitted bra. The research was undertaken in two phases. A preliminary study was performed to assess how quickly the static breast position settled down following running, this enabled the equivalent positions on the bra versus on the skin under the bra to be identified. A settling in period of ~30 seconds between the breast and bra was found to occur during the initial phase of treadmill running. Whilst the study is recognised to be exploratory in nature, the findings suggest future breast kinematic study should consider the possibility of a settling in effect. Therefore, experimental protocols may benefit from including a short period of activity after the subject has changed into the bra to help eliminate any settling in effect prior to data capture or application of over bra markers.

The results of the main study suggest motion occurs between the breast and bra irrespective of bra size and that over bra markers underestimate superior-inferior (S-I) breast displacement and anterior-posterior (A-P) displacement at the upper breast. Markers positioned over the bra were also found to be less sensitive to variation in A-P and S-I displacement in different regions of the breast. This effect is likely to be greater in very stiff or padded bra cups, therefore, in these cases particular caution should be exercised if over bra markers are utilised. However, until advances in technology are made the use of over bra markers remains current best practice. Future studies are recommended to state whether breast markers were located over or under the bra and recognise that over bra markers represent bra motion.

Breast motion appears to be very ‘non-rigid’, therefore, multiple breast markers appear advantageous to provide more information and help better understand breast motion. Further study is recommended across a wider population before determining the most appropriate breast marker protocol. However, results showed the bra tended to ‘move as one’ with much less variation in motion between marker locations, therefore, a single marker appears to be a reasonable approximation of bra motion. The nipple provides an easily identifiable landmark to ensure greater protocol consistency.

Q4. How do mechanical properties of bra straps affect sports bra performance during running?

Sports bras are widely acknowledged to reduce breast motion and breast discomfort during running compared an everyday bra. However, relatively little is understood about how a specific sports bra design (structure and material properties) influences the mechanical properties of the bra and thereby its performance (breast kinematics and subject perception). Bra strap stiffness was identified as a potentially important factor in sports bra performance. The research was conducted using a modified bra with removable strap sections of three differing stiffness. A specifically developed tensile testing protocol was used to characterise the bra strap mechanical properties. Sports bra performance during treadmill running was assessed using biomechanical and perceptual measures. As markers were positioned on the bra they are described as tracking bra motion. However, as the same base bra was used for all straps any changes in bra motion are likely to represent changes in motion of the underlying breast. Increasing bra strap stiffness was found to improve sports bra performance with respect to bra kinematics and subjective perception ratings. Increasing strap stiffness primarily reduced superior-inferior (S-I) bra kinematics, with the strongest trends observed in bra displacement below static position, peak negative velocity and peak positive acceleration. The perception of support was most markedly improved with increased strap stiffness. Subjective ratings of bra fit and comfort were also found to be affected by strap stiffness but no statistically significant differences were observed between the individual strap conditions. This suggests strap stiffness may have important role to play in bra design to reduce breast discomfort and breast motion during exercise.

8.3 Future Research Directions

Sports bra research is a relatively young and developing area, therefore, there are numerous directions in which future research could advance. During the course of this thesis a number of future research directions were identified.

The exploratory study of breast markers in Chapter 6 recommended that multiple breast markers should be used to help better understand the complex nature of breast motion. However, further research is required to better understand breast movement across a wider population before determining the most appropriate breast marker protocol. Additional study of multiple bra markers is also warranted to better understand the sensitivity to bra design and subject variation.

A comprehensive exploration of aspects contributing to sports bra comfort is lacking within the current literature. Chapter 6 further highlighted the pressing need for further study in this area. Establishing the key factors and terminology used to describe sports bra comfort may assist the development a more sophisticated tool to assess sports bra comfort. Alongside this, further work to explore the methodology used and timing of data collection may help to develop reliable test protocols. An in-depth investigation of factors affecting bra perception and the development of a robust validated perception testing protocol are pertinent to advancing the assessment of sports bra performance, and better informing design development.

The research undertaken in Chapter 7 suggested strap stiffness plays an important role in sports bra performance. Further study utilising of a greater number straps, over a wider range covering greater and less than the original strap stiffness and at smaller stiffness increments may help to further clarify the relationships observed and establish if a threshold strap stiffness is reached.

Additional areas of future research discussed within the literature review (Chapter 2) include: mechanical and virtual test modalities as exciting areas for future development. For example, advances in virtual breast-bra models and mechanical test dummies may enable the development and testing of bra design prior to human testing. The use of breast imaging e.g. MRI scans to better understand the source of breast discomfort, whether it is an indicator of injury and effect of breast support during exercise on breast structure. Finally, the potential of sports bra design to affect elite sporting performance is another interesting area.

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Appendices

Appendix A - Full list of torso markers considered in preliminary work prior to Part A (Study 1) in Chapter 4

Marker	Location description	Bra papers	Trunk papers	Std. gait marker set	Notes
CLAV	Suprasternal notch	Bowles (2003), Mason et al. (1999), Himmelsbach et al. (1992), McGhee and Steele (2010), Haake and Scurr (2010), White et al. (2010), Scurr et al. (2010a), Scurr et al. (2010b), Campbell et al. (2007)	Sartor et al. (1999), Wu et al. (2005) and Baker (2006) in Leardini et al. (2009)	Yes	
PCLAVR	Proximal clavicle right	Eden et al. (1992), Scurr et al. (2008)			
PCLAVL	Proximal clavicle left	Eden et al. (1992), Scurr et al. (2008)			
RCNIP	Right clavicle directly above nipple	Scurr et al. (2007), White et al. (2009a), Scurr et al. (2009)			
LCNIP	Left clavicle directly above nipple	Scurr et al. (2007), White et al. (2009a), Scurr et al. (2009)			
LSHO	Left acromio-clavicular joint	McGhee and Steele (2010), Scurr et al. (2007)	Davis III (2005), Fantozzi et al. (2003), Nguyen and Baker (2004)	Yes	
RSHO	Right acromio-clavicular joint	McGhee and Steele (2010), Scurr et al. (2007)	Davis III (2005), Fantozzi et al. (2003), Nguyen and Baker (2004)	Yes	
STRN3R	Sternum level with articulation of 3rd rib	McGhee et al. (2007)			
STRN	Xiphoid process of the sternum		Nguyen and Baker (2004), Wu et al. (2005)		
RA10R	Right anterior aspect of 10th rib	Scurr et al. (2010a), Scurr et al. (2010b) Haake and Scurr (2010), White et al. (2010)			
LA10R	Left anterior aspect of 10th rib	Scurr et al. (2010a), Scurr et al. (2010b), Haake and Scurr (2010) White et al. (2010)			
C7	Directly over C7		Davis III (2005), Fantozzi et al. (2003), Ferrarin et al. (2002), Ferrarin et al. (2004), Nguyen and Baker (2004), Wu et al. (2005)	Yes	
T1	Directly over T1		Crosbie et al. (1997)		
T1R	Level with T1 midway between spine and right s/c joint		Crosbie et al. (1997)		
T1L	Level with T1 midway between spine and left s/c joint		Crosbie et al. (1997)		
T2	Directly over T2		Baker (2006) in Leardini et al. (2009)		Not used may be obstructed by sports bra
T4	Directly over T4		Sartor et al. (1999)		
T6	Directly over T6		Crosbie et al. (1997)		
T6R	Level with T6 right of spinae erectus muscles		Crosbie et al. (1997)		
T6L	Level with T6 left of spinae erectus muscles		Crosbie et al. (1997)		
T8	Directly over T8		Wu et al. (2005)		
T9	Directly over T9		Sartor et al. (1999)		Not used similar to T10

Appendix A (continued) - Full list of torso markers considered in preliminary work prior to Study A in Chapter 4

Marker	Location description	Bra papers	Trunk papers	Std. gait marker set	Notes
T10	Directly over T10		Baker (2006)		
T12	Directly over T12	McGhee and Steele (2010)	Crosbie et al. (1997)		
T12R	Level with T12 lateral to spinae erectus muscles		Crosbie et al. (1997)		
T12L	Level with T12 lateral to spinae erectus muscles		Crosbie et al. (1997) Ferrarin et al. (2002), Ferrarin et al. (2004)		
L5	Directly over L5	McGhee and Steele (2010)	Fantozzi et al. (2003)		
SACR	Sacrum		Frigo et al (2003) in Leardini et al. (2009)		
S2	Directly over S2, midpoint between PSIS		Sartor et al. (1999)		Not used similar to Sacrum
RPSIS	Right PSIS		Baker (2006) in Leardini et al. (2009), Davis III (2005), Fantozzi et al. (2003), Nguyen and Baker (2004), Wu et al. (2005)	Yes	
LPSIS	Left PSIS		Baker (2006) in Leardini et al. (2009), Davis III (2005), Fantozzi et al. (2003), Nguyen and Baker (2004), Wu et al. (2005)	Yes	
RASI	Right ASIS	McGhee and Steele (2010), Scurr et al. (2007) White et al. (2009b) Scurr et al. (2009)	Baker (2006) in Leardini et al. (2009), Davis III (2005), Fantozzi et al. (2003), Nguyen and Baker (2004), Wu et al. (2005), Sartor et al. (1999)	Yes	
LASI	Left ASIS	McGhee and Steele (2010), Scurr et al. (2007), White et al. (2009b), Scurr et al. (2009)	Baker (2006) in Leardini et al. (2009), Davis III (2005), Fantozzi et al. (2003), Nguyen and Baker (2004), Wu et al. (2005), Sartor et al. (1999)	Yes	

Appendix B – Post-hoc pairwise comparisons of gait variables (Chapter 6)

Bra (I)	Bra (J)	Cadence (strides/s)		Vertical displacement (m)		Lateral bend range (deg)		Flex-ext. range (deg)		Mean flexion angle (deg)		Axial rotation (deg)	
		Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.
36DD	**36E**	.000	1.000	-.003*	<0.001	-.982*	<0.001	-.404*	.004	.289*	<0.001	.709*	<0.001
	36F	-.002	.399	-.004*	<0.001	-.876*	<0.001	-1.025*	<0.001	-.188*	.024	.721*	.007
36E	**36F**	-.002	.418	.000	1.000	.106	.991	-.621*	<0.001	-.477*	.000	.011	1.000

Trial (I)	Trial (J)	Cadence (strides/s)		Vertical displacement (m)		Lateral bend range (deg)		Flex-ext. range (deg)		Mean flexion angle (deg)		Axial rotation (deg)	
		Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.	Dif. (I-J)	Sig.
1	**2**	-.008*	.000	.001	.220	.255	.074	.181	1.000	-.071	1.000	.631	.104
	3	-.001	1.000	-.001	.355	.268	.448	-.046	1.000	.148	.340	.229	1.000
	4	.008*	.005	-.005*	<0.001	-.502*	.003	.058	1.000	.188	.052	-1.068*	.002
2	**3**	.007*	.001	-.003*	.002	.013	1.000	-.227	.367	.219*	.038	-.402	.224
	4	.016*	.000	-.007*	<0.001	-.758*	<0.001	-.123	1.000	.260*	.039	-1.698*	<0.001
3	**4**	.009*	.000	-.004*	<0.001	-.771*	<0.001	.105	1.000	.041	1.000	-1.297*	<0.001

* Indicates statistically significant difference ($p < 0.05$)

Trial 1 = Over bra (All)
Trial 2 = Under bra (NIPL & NIPL)
Trial 3 = Under bra (NIPS & NIPI)
Trial 4 = Under bra (NIPS2 & NIP)

Appendix C - Participant Information Sheet

Analysis of Sports Bra Testing Methodology

Participant Information Sheet

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What is the purpose of the study?

The purpose of the study is to determine the reliability of a testing method to assess sports bra performance during running on a treadmill. The study is designed to examine the effect of different bra designs on the amount of breast movement and comfort in the most non-invasive fashion possible.

Who is doing this research and why?

This research is being carried out by Laura Whittingham who is a PhD student under the supervision of Dr. S. Forrester and Prof. M. Caine who both have extensive experience in research. This research is supported by Progressive Sports Technologies Ltd.

Are there any exclusion criteria?

The study is only available to female participants aged over 18 years old. All participants should be free from injuries that would affect their gait (running style) and should not have breast fed within the past 6 months or any cosmetic augmentation to their chest.

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have, we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

Will I be required to attend any sessions and where will these be?

One testing session will take place in the Sports Technology Institute Biomechanics Laboratory, Loughborough University.

How long will it take?

The testing session should take approximately 2 hours

Is there anything I need to bring with me?

You should **bring your normal trainers, shorts and a drink**. You will need to wear shorts in order for the skinfold calliper measurements to be taken.

What will I be asked to do?

Initially, height and weight will be measured. Skinfold measurements will be taken at 7 different sites around the body (Upper arm, back, abdomen, shoulder, front of thigh).

You will be asked to wear 3 different sports bras. After putting on each sports bra, the bra will be checked to ensure it fits you correctly. A number of small markers (similar to the image below) will be attached at key points on your body (shoulder, breast, back, ankle, wrist) these allow the motion of the body to be tracked.

For each bra you will be asked to run on a treadmill 3 times for 1 minutes (15 seconds acceleration, 30 seconds at 10 km/h and 15 seconds deceleration) so that the marker movement can be captured. For one bra you will be asked to repeat the three treadmill runs and hold your breath for as long is comfortable whilst running. Following the treadmill runs you will be asked to perform 5 drop landings (stepping off a 30cm / 1ft box and landing with 2 feet). You will be asked to complete a short feedback questionnaire about the bra. The test sessions will be run entirely by female researchers to protect your privacy.

What personal information will be required from me?

Your name, contact details, D.O.B and bra size.

Are their any risks in participating?

You may find that some of the bras may not suit your personal preference, but they have all been selected for your size so the degree of discomfort should be minimised. The running should be easily achievable, but if you find it uncomfortable the test procedure will be stopped immediately.

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Will my taking part in this study be kept confidential?

All questions, answers and results of this study will be treated with absolute confidentiality. In manuscripts, reports or other publications resulting from this study, subject codes rather than names will be used. If photographs are taken, features of recognition will be distorted so as to maintain anonymity.

What will happen to the results of the study?

The data will be retained in accordance with Loughborough University's Data Protection Policy.

What do I get for participating?

You will be able to keep one of the sports bras used during testing.

I have some more questions who should I contact?

Laura Whittingham, Sports Technology Institute, Loughborough University Sports Technology Institute
Email: l.whittingham@lboro.ac.uk

What if I am not happy with how the research was conducted?

The University has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Appendix D – Informed Consent Form

Sports Bra Study Assessing Test Methodology

INFORMED CONSENT FORM
(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I am not aware of any reason why I should not take part in the study. I am currently in good health and have had no relevant significant medical problems in the past. Furthermore, I have not been advised to refrain from exercise or playing sport by my Doctor or other health professionals.

I agree to participate in this study.

Your name ______________________________

Date of Birth ______________________________

Email ______________________________

Your signature ______________________________

Date ______________________________

Signature of investigator ______________________________