Identifying a vertical neutral position of the breast using simple measures.

KNIGHT, Miranda K.

Identifying a Vertical Neutral Position of the Breast Using Simple Measures

Miranda Knight

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Contents

Abstract

During physical activity, many women suffer from breast discomfort due to excessive breast motion. It has been hypothesised that movement-induced breast discomfort is caused by straining the tissue of the breast. To understand the stress applied to the breast tissue during exercise and in turn understand the motion of the breast in engineering terms, the breasts need to be placed in a position where the tissue is neither in tension nor compression. Haake and Scurr (2010) developed a method, the lift and drop test, to locate this position and termed it the neutral position.

The three-dimensional motion capture system was assessed as to whether it was capable in measuring accelerations of -1 g, in a simple oscillating system. Eight cameras, sampling at 200 Hz, captured the motion of the metal plate attached to a wooden structure by either one or two elastic cords. Accelerations of -1 g were found when the metal plate was unloaded, therefore the elastic cords were not under tension. The results showed that the system was able to measure accelerations of -1 g, however, the motion was too simple and therefore testing was needed to be completed on a women's breast.

A participant (34D cup size) placed two markers on the body (right nipple and suprasternal notch). Eight cameras placed in a semi-circle tracked the markers, during the lift and drop exercises. The maximum negative acceleration found during the exercise was -0.64 ± 0.04 g. The lift and drop exercise was deemed inappropriate in locating the neutral position. Therefore, further work in identifying an appropriate method in locating the neutral position was required.

Seven participants with breast sizes ranging from 34A to 36D placed three markers on their body (right and left nipple and suprasternal notch). Ten cameras tracked the markers during running (10 $km.hr^{-1}$); stepping off a low box (0.26 m) and a high box (0.51 m); vertical countermovement jump; and lifting and dropping the right and left breast.

The vertical countermovement jump forced the breasts to oscillate nearly one and a half times (1.3 ± 0.2), causing the breasts to move through a neutral position multiple times in a single trial. During a single trial a higher and lower neutral position was recorded. The accelerations between these positions were -0.13 g and -1.80 g and therefore the neutral position was reconceptualised as a neutral zone. The exercise also produced low discomfort scores of 0.6 ± 0.7.

Breast motion during running (10 $km.hr^{-1}$) and walking (4 $km.hr^{-1}$) of a participant with a breast size of 34A was used to demonstrate the effects of breast motion with respect to the neutral zone and perceived breast discomfort. The work showed that breast discomfort was reduced when wearing a sports bra compared to no support. This could be due to 1) the magnitude of vertical breast displacement being reduced; 2) breasts lifted closer to the neutral zone; and 3) level of breast support increased.

This research indicates that the previously defined vertical neutral position, should instead, be considered a neutral zone defined by upper and lower boundaries, which are found most effectively by performing a countermovement jump. The vertical neutral zone could allow for greater understanding of the stress applied to the breast tissue during movement which in turn could inform the design of bras.

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1 Introduction

1.1 Background

It has become apparent in recent years that breast pain, termed mastalgia, is one of the most common breast complaints presented to doctors (Smith, Pruthi and Fitzpatrick 2004) affecting up to 60% of women (Ader and Shriver 1997). Many women, in particular larger breasted women, found that during physical activity excessive breast motion caused breast discomfort and embarrassment associated with physical appearance, both of which cause barriers to women participating in physical activity (Robbins, Pender and Kazanis 2003). This then has a knock on effect on reduced energy expenditure associated with decreased physical activity, creating a vicious cycle that can contribute to weight gain leading to increased breast mass (Valea and Katz 2007).

Inactivity and unhealthy eating habits are associated with weight gain, which are the major underlying causes for modern diseases such as cardiovascular heart disease or type 2 diabetes mellitus (Warburton, Nicol and Bredin 2006). With worldwide rates of overweight and obesity levels nearly doubling since 1980 and forecast to increase even further (World Health Organization 2014), there are only three options doctors can advise patients to do: 1) change their diet; 2) uptake of physical activity; and/or 3) medical intervention. The overall trend found in a systematic review of longitudinal studies of long-term health benefits of physical activity is that there is a negative relationship between physical activity and weight gain over time (Reiner et al. 2013).

Brown et al. (2013) found that 32% of 1285 females who took part in the London 2012 Marathon suffered from mastalgia. It was also noted that the frequency of mastalgia increased with breast size. Abdel-Hadi (2000) found that wearing a fitted bra such as a sports bra alleviates all symptoms of breast pain in 80% of women. However, research suggests that only 41% of women and 13% of adolescent females wear a sports bra during exercise (Bowles, Steele and Munro 2008; McGhee, Steele and Munro 2010).

Today's sports bra has developed considerably since its evolvement from the corset. Ancient Greek women wore a band of cloth over their breasts to prevent/reduce the sagging and bouncing of them and in turn decrease breast discomfort. The reason for this was to hold the breasts firmly in place and prevent them from bouncing (Fontanel 1997). The bra was developed from corsets and first introduced in the 1920s. Throughout the decade, bras were designed to lift, enlarge, support, confide, flatten, reveal and modestly cover women's breasts, making them the most important element in a women's wardrobe (Bressler, Newman and Proctor 1998).

In 1972, Title XI legislation was passed allowing women to take part in sport and physical activity. In 1977, Lisa Lindahl, Poly Smith and Hinda Schreiber sewed two jockstraps together and marketed it as the jockbra, which became the Jogbra (Bastone, 2014). Since 1977, two forms of sports bras have been developed, encapsulated and compression bras. The function of the compression bra is to flatten and redistribute the mass evenly across the chest, thus minimizing motion. Encapsulated bras, on the other hand, have cups to separate and support the breast mass in a more feminine shape. By the 1990s the bra became the most complex piece of lingerie ever created as it was composed of 43 components and designed with a structure and function comparable to those of a cantilever staircase or a suspension bridge (Bressler, Newman and Proctor 1998). However, with all this advanced technology, "they can put a man on the moon, but they can't put a woman in a sports bra that is very comfortable" - (Miller 1998) - suggesting that the anatomy and movement of the breast is highly complex.

In the last two decades, researchers have looked into correlating breast kinematics with breast discomfort with a large proportion of literature suggesting excessive vertical breast displacement causes discomfort (Mason, Page and Fallon 1999; White, Scurr and

Smith 2009). McGhee and Steele (2010) showed that elevating the breasts on the chest wall rather than decreasing vertical breast displacement, reduced movement-induced breast pain. Additionally, Mason, Page and Fallon (1999) hypothesised that movement-induced breast pain may be caused by tension on the supporting structures. Page and Steele (1999) suggested that the mechanics of the breast need to be investigated to achieve a better designed sports bra. Recent studies investigating stress of the breast tissue during motion and discomfort evolved from related studies on the mechanics of skin. It is known that the behaviour of skin is a non-linear viscoelastic material. The stress-strain curve of skin can be divided into three phases (Dunn and Silver 1983; Silver, Freeman and DeVore 2001):

- Strains up to 0.3, collagen offers little resistance to deformation and the behaviour is dominated by elastic fibres.
- Strains between 0.3 to 0.6, collagen fibres begin to offer resistance to deformations.
- Strains above 0.6, the individual fibres break.

Studies in breast research are conducted in a laboratory predominantly using motion capture equipment. Therefore, stress and/or strain need to be calculated from displacements. Displacements can be classified as a change of length, which are associated with the local deformation of the body. Strain (ε) is defined as the deformation of a solid due to stress (σ) and calculated as follows (Eq. 1):

$$\varepsilon = \frac{\Delta L}{L_o} = \frac{\sigma}{E} \qquad \text{Eq. 1}$$

where, ΔL is the change in length of the material from its initial length, L_o and E is Young's modulus. Stress is linked to strain as stress is proportional to load and strain is proportional to deformation and is expressed as (Eq. 2):

$$E = \frac{\sigma}{\varepsilon} \qquad \text{Eq. 2}$$

Haake and Scurr (2011) defined L_o in Eq. 1 as the neutral position of the breast and was found using a static lift and drop activity. The neutral position is a position on the chest wall where the breast tissue is neither in tension nor compression. The position can be located during movement where the acceleration of the breast in the vertical direction is about -1 g, known as free-fall. This position is required as the unsupported length of the breast tissue is under both tension and compression due to gravity. Therefore, the neutral position may be important in calculating the stress of the breast tissue and in turn understanding the motion of the breast in engineering terms.

1.2 Statement of the purpose

The purpose of this thesis is to identify a vertical neutral position of the breasts through the use of simple movements. In this analysis, the biomechanical variables included vertical displacement and acceleration of the suprasternal notch and breast. Participants also quantified a measure of perceived discomfort during the data collection.

1.4 Scope of the study

Eight volunteers participated in this study and had varied fitness levels but were able to maintain a 2 minute run at 10 $km.hr^{-1}$ on a treadmill. Participants' breast size ranged from 34A to 36D and age ranged between 19 to 32 years. Data were collected in the Biomechanics Laboratory in the Academy for Sport and Physical Activity, located in the Collegiate Hall building at Sheffield Hallam University.

1.5 Assumptions of the study

The breast is assumed to resemble a cantilever beam represented by a spring-damper model. The nipple represents the vertical position of the centre of mass of the breast and the cantilever beam theory assumes that the dynamic motion of the breast above and below the static position is symmetrical. The vertical breast displacement was used as a proxy for vertical strain of the breast tissue.

1.6 Limitations of the study

Due to the nature of the study, recruitment was difficult and therefore participants that volunteered were from a limited population with variations in body/breast mass, breast shape and gait pattern. However, as the vertical neutral position of the breast is specific to an individual the analysis was based on a single subject design.

1.7 Operational definitions

The following is a list of definitions of terms that are used in this thesis:

Kinematics is the descriptive analysis of movement which encompasses displacement, velocity, acceleration and temporal relationships.

Neutral position is the point in the vertical direction (relative to the sternum) where the surface of the breast tissue is assumed to be neither in tension nor compression and is defined by breast acceleration of -1 g during motion.

Resting height is the position of the breast on the chest wall (relative to the sternum) without support when standing stationary.

Strain is calculated from vertical breast displacements.

Perceived discomfort score is a subjective measure of breast discomfort collected pre- and post-trials, which was calculated as follows: post-trial discomfort score - pre-trial discomfort score = Activity perceived discomfort score.

1.8 Structure of the thesis

The thesis contains seven chapters beginning with a literature review to identify the underlying problem. A further three chapters of the experimental work were separated into first a chapter on error in calculating acceleration in simple motion using a motion capture system and assessing whether the system is able to detect periods of free-fall. The second chapter is to identify whether true fee-fall occurs in a female breast when performing a static lift and drop test. The final experimental chapter assesses a range of simple activities in their repeatability and suitability in locating the vertical neutral position. This was followed by a pilot work section on the effects of the neutral position on breast comfort. Finally, the thesis ends with an overall discussion and conclusion.

2 Literature Review

2.1 Anatomy of the breast

The breast can differ between individuals with anatomical variation in the volume, width, length, projections, shape and position on the chest wall (Avsar et al. 2010). The breasts lie on the deep pectoral fascia, which in turn overlies the pectoralis major muscle (Figure 2.1). The breast spreads vertically from the 2^{nd} or 3^{rd} rib up to the 6^{th} rib and medially from the sternal edge to almost the mediaxillary line (Drake, Vogl and Mitchell 2014). The submammary space - between the breast and the deep fascia - is loose connective tissue. This allows the breast some degree of movement on the deep pectoral fascia.

A mature breast is composed of about 80% fat and 20% glandular tissue (Valea and Katz 2007); however, breast composition can vary depending on the individual (Poplack et al. 2004). The Cooper's ligaments offer some internal support to the breast as they extend from the skin to the underlying pectoralis fascia (Valea and Katz 2007). Stretching of these ligaments is believed to be the cause of pain and sagging (Page and Steele 1999). The only additional support to the Coopers ligaments is the external overlying skin; therefore, females wear extra external support such as a bra to prevent the stretching of these tissues.

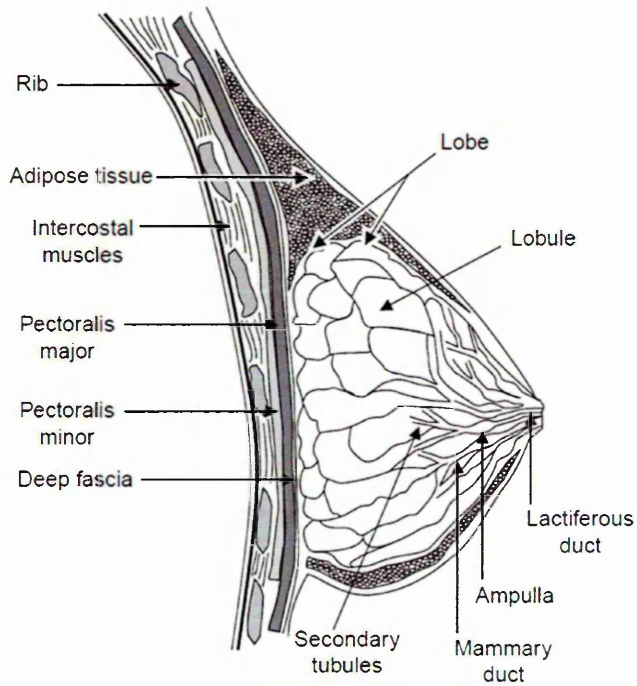


Figure 2.1: Structure of the breast (Page and Steele 1999).

2.2 Mastalgia

Mastalgia is defined as a 'benign disorder arising from hormonal activity' according to the Cardiff group classification of benign breast conditions (Hughes, Mansel and Webster 1987). Women can suffer from three types of mastalgia: cyclical mastalgia, non-cyclical mastalgia and musculoskeletal pain. Cyclical mastalgia is linked to the menstrual cycle. The pain is released by the onset of the menses – a change in hormone levels. Non-cyclical mastalgia is unrelated to the menstrual cycle, but associated with continuous or intermittent pain but with irregular exacerbations. The mean age of the women at presentation is greater than that of cyclical breast pain, often in their 30's and 40's (BeLieu 1994). Pain which is located behind the breast in the muscle is known as musculoskeletal pain. The most common of the three types of mastalgia is cyclical pain, making up 67% of the women with mastalgia; 31% suffer from non-cyclical pain and about 2% suffer from musculoskeletal pain (Gatley and Mansel 1990; Smith, Pruthi and Fitzpatrick 2004).

The results of previous research contradict the Cardiff Groups definition of mastalgia and suggests that mastalgia can occur due to exercise and therefore the term mastalgia encompasses any pain that occurs in the breast (Iddon and Dixon 2013). Gehlsen and Albohm (1980) and Brown et al. (2013) reported that up to 70% of female athletes complaining of movement-induced mastalgia during exercises that involved running and jumping. Mason, Page and Fallon (1999) hypothesised the aetiology of movement-induced breast pain to arise from tension on both the skin and fascia of the breast during motion. Similarly, Page and Steele (1999) hypothesised that breast pain would occur due to stretching of the support structures when repeatedly being loaded during physical activity, leading to sagging of the breast. Breast pain varies in severity from individual to individual therefore affecting the type of treatment that may be used.

2.3 Current treatments

Treatments for mastalgia often fail due to doctors and clinicians not fully understanding the condition and the breast anatomy and physiology (Abdel-Hadi 2000). Due to an unsatisfactory understanding of mastalgia, the medical community find it difficult to identify and treat (Blichert-Toft et al. 1979). Initially, 85% of patients with mastalgia are relieved of symptoms or could live with the pain when reassured that it is benign, with the remaining 15% of patients requiring medical treatment (Pye, Mansel and Hughes 1985).

There are a range of drugs which have been used in trying to cure mastalgia. Some of these drugs are used as treatments for breast cancer (e.g. tamoxifen), pituitary tumours (e.g. bromocriptine), and marketed as cancer remedies (e.g. evening primrose oil). Prescribing a drug requires taking into account the efficacy, cost and side effects, however treatments are usually prescribed with little or no scientific support (Smith, Pruthi and Fitzpatrick 2004; Qureshi and Sultan 2005).

Even though danazol, bromocriptine, and tamoxifen provide good clinical responses to treatment, they do have side effects associated with them. Danazol can cause menstrual irregularity, depression, acne, hirsutism, deepening of the voice, change in libido and muscular pains. Bromocriptine side effects include increased fertility, nausea, constipation and mental changes (Montgomery et al. 1979; Faiz and Fentiman 2000). Tamoxifen has been associated with endometrial cancer, hot flushes and vaginal discharge (Fentiman et al. 1986; Fisher et al. 1996). The relapse rate for danazol and tamoxifen has been reported to be about 50% (Pye, Mansel and Hughes 1985), therefore lowering their effectiveness as a treatment for mastalgia.

The majority of women do not want to take drugs for their symptoms due to the many side effects associated with them (Qureshi and Sultan 2005). Abdel-Hadi (2000) found that in a group of 100 females a mechanical support such as a sports bra can relieve all symptoms of mastalgia in up to 85% of patients. Researchers have begun to investigate the kinematics of the breast to try and aid designers in creating a more supportive bra.

2.4 Breast size and shape

With fluctuating asymmetry present in all parts of the body, it is possible for differences to occur in size and shape between pairs of breasts. In morphology, static breast asymmetry does exist, but the exact reason why is unclear (Losken et al. 2005). Russo and Russo (2004) believe that breast development is significantly influenced by hormones; which if unevenly distributed between left and right side of the body may alter growth. Another reason may be due to asymmetrical torsos which causes the breasts to sit on the chest wall at different positions. Variables that are frequently used to define marked asymmetries between left and right breasts are volume and vertical distance between the suprasternal notch and nipple.

McGhee et al. (2013) found that the breast volume of 15 women had a greater right breast volume than the left breast by a mean difference of 8 ml. Smith et al. (1986) showed that left breast volume was greater than right breast volume by a mean difference of 16.2 ml. Conversely, Loughry et al. (1987) found that 99.6% of 248 women had a difference in size between left and right breast volume, however there was no predominance as to which side is greater in volume. Hussain et al. (1999) found that breast volume is also dependent on where the women were in their menstrual cycle, with the largest breast volumes recorded during the last week before the onset of the menses. The unequivocal results in breast volume and the change in volume throughout the menstrual cycle suggest breast volume is dependent on the individual.

Most clinicians would agree that breast size and shape are different among the majority of individuals (Brown et al. 1999). Surface measurements are frequently used in breast reconstructive surgery to assess the static bilateral symmetry, in particular nipple to sternal notch distance. Brown et al. (1999) used 60 women and took tape measurements whilst the participant was standing. They found that 70% of the participants showed no directional asymmetry between bilateral breasts (i.e. $R - L = 0$), therefore no significant difference ($p < 0.05$) was found when comparing the mean distance of the right breast (223 ± 45 mm) to the mean distance of the left breast (223 ± 46 mm) from the suprasternal notch. Losken et al. (2005) took three-dimensional images of 87 women's breasts and found that the nipple to sternal notch distance for 62% of the participants was greater in the left breast (243 ± 33 mm) than the right breast (238 ± 31 mm). Avsar et al. (2010) found that the mean nipple to notch distance for the left breast (197 ± 22 mm) was significantly higher than the right breast (196 ± 22 mm) in 379 women. The significant result found in this study compared to Brown et al. (1999) may be due to the larger number of participants.

2.5 Kinematics of the breast during movement

Breast motion studies have been conducted since the late 1970s with an emphasis on correlating breast kinematics with discomfort/pain. Research in this area has generated some inconsistent findings due to small sample sizes, experimental set up, marker positions and the way in which the biomechanical variables are calculated. Almost all the research in breast kinematics focuses on or includes the vertical component of breast motion. The three main reasons are: 1) the vertical component makes up about 50% of breast motion (Scurr, White and Hedger 2011); 2) it is most affected by gravity (McGhee et al. 2013); and 3) it has been associated with movement-induced breast discomfort (Gehlsen and Albohm 1980; Lorentzen and Lawson 1987; Mason, Page and Fallon 1999; Starr et al. 2005). The different approaches which have been taken are shown in Table 2.1.

Table 2.1: Summary of breast kinematic studies

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Haycock 1978	5	N/A	B, C, D	Everyday Bra Fitted bra	16 mm movie film	W: 4.83 $km.hr^{-1}$ R: 9.66 $km.hr^{-1}$	1 stride	N/A	Nipple	BMT
Gehlsen & Albohm 1980	40	23. 2 ± 4.7	B & D	8 Sports bras	Locam Camera, Van Guard Motion Analyser	J: 9.66 $km.hr^{-1}$ J: 10.46 $km.hr^{-1}$	2 strides	Centre of left clavicle	Nipple	$z, \dot{z}$, BMT
Lorentzen & Lawson 1987	59	18-60	A, B, C, D	No support 8 Sports bras	16 mm Photosonics action master camera, Lafayette motion analyser	J: 9.66 $km.hr^{-1}$	3 strides	Lower sternum	Nipple	z

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Lawson & Lorentzen 1990	59	19-58	A, B, C, D	7 Sports bras	16 mm Photosonics Action Master camera	J: 9.66 $km.hr^{-1}$	3 strides	Sternum	Nipple	z
Boschma 1994	15	19 - 58	B, C, D (USA) [C - DD (UK)]	No support 2 sports bras	3 cameras	R: 7.2 $km.hr^{-1}$	1 minute	Sternum	Nipple	z, y
Mason, Page & Fallon 1999	3	17 - 21	C & D	No support crop top fashion bra sports bra	2 photosonics biomechanics 500, 16 mm high speed cine cameras filming	W: 7 $km.hr^{-1}$ J: 10 $km.hr^{-1}$ R: 13 $km.hr^{-1}$ Aerobics	2 strides	Sternum-notch	Nipple	$z, \ddot{z}$

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Shivitz 2001	17		C & D (US) [D & DD (UK)]	3 sports bras	3 MacReflex Infrared Cameras	R: 9.65 $km.hr^{-1}$	40 s	Sternum	Nipple	$z, \ddot{z}$
Starr et al. 2005	6	23 - 37	C - DD	3 sports bras	Peak Motus Movement System	R: Velocity not available	3 Strides	Lateral points of acromion processes & sternal angle	Nipple	z
Campbell et al. 2007	2	30 &39	D & DD	Everyday bra	OptoTRAK 3020 motion	W: 7 $km.hr^{-1}$ J: 10$km.hr^{-1}$	20 s	Sternal notch	Nipple	z
McGhee, Steele & Power 2007	16	19 - 43	C to J	Crop top	Camcorder MV600i digital video camera, Poolcam video camera	Self-selected pace	15 strides	Sternum & 3rd rib	Nipple	$z, \dot{z}$

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Scurr, White & Hedger 2009	15	24 ± 4.8	D	No support, Everyday bra Sports bra	5 ProReflex Infrared cameras	W: 5 $km.hr^{-1}$ R: 10 $km.hr^{-1}$	5 gait cycles	Left & right clavicles & ASIS	Nipple	z
White, Scurr & Smith 2009	8	24.8 ± 6.4	D	No support, Everyday bra, Sports bra	5 ProReflex Infrared Cameras	R: 10.8 $km.hr^{-1}$	2 Strides	Clavicles & ASIS	Nipple	z, x, y
Scurr, White & Hedger 2010	15	25.1 ± 4.8	D	No support Everyday bra Sports bra	8 Oqus Infrared cameras	R: 10 $km.hr^{-1}$	10 gait cycles	Suprasternal notch, left & right anterior inferior aspects of the 10th rib	Nipple	$z, \dot{z}, \ddot{z}$ $x, \dot{x}, \ddot{x}$ $y, \dot{y}, \ddot{y}$

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Haake & Scurr 2010	1	34	C	No support, Everyday bra Sports bra	5 ProReflex Infrared cameras	W: 4 km.hr^{-1} R: 10 km.hr^{-1}	30 s	Suprasternal notch, left & right anterior inferior aspects of the 10th rib	Nipple	z Spring-damper model
McGhee & Steele 2010	20	31 ± 8	C - F	Encapsulation sports bra, Compression and elevation sports bra, placebo bra	2 OptoTRAK 3020 sensors	R: 8.3 ± 1.3 km.hr^{-1}	30 strides	Sternal notch	Nipple	$z, \dot{z}$
Haake & Scurr 2011	3	31 ± 6.2	A, C, E	No support, Everyday bra Sports bra	8 Oqus Infrared cameras	Standing Slow W: 4 km.hr^{-1} Fast W: 7 km.hr^{-1} Slow R: 10 km.hr^{-1} Fast R: 14 km.hr^{-1}	2 min	Suprasternal notch	Nipple	$z, \ddot{z}$ Vertical strain

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Scurr, White & Hedger 2011	21	25.1 ± 4.8	D	No support Everyday bra 2 Sports bra	8 Oqus Infrared cameras	Incremental protocol: 5 $km.hr^{-1}$ increased by 1 $km.hr^{-1}$	5 gait cycles	Suprasternal notch & left and right anterior inferior aspects of the 10th rib	Nipple	z, x, y
Haake, Milligan & Scurr 2012	8	27.3 ± 5.1	A - G	No support Everyday bra Sports bra	8 Oqus Infrared cameras	Standing Slow R: 10 $km.hr^{-1}$ Fast R: 14 $km.hr^{-1}$	10 gait cycles	Suprasternal notch & left and right anterior inferior aspects of the 10th rib	Nipple	$\ddot{z}$ Vertical strain

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Zhou, Yu & Ng 2012	2	25 & 40	B	No support sports bras	6 Vicon Motion Analysis System	R: 7 $km.hr^{-1}$	15 breast cycles	2 on the sternum and 2 on the back vertebrae	1 on the nipple - 4 surround the nipple 4 cm apart and 6th marker 4 cm above the superior outside marker.	z, x, y BMTs
McGhee et al. 2013	15	19 - 44	D - G	No support Everyday bra Sports bra	2 OptoTRAK 3020 sensors	R: 8-9 $km.hr^{-1}$	30 breast cycles	sternal notch and left heel	Left nipple	$z, \ddot{z}$

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Mills et al. 2014[a]	10	22 ± 2	D	No support Everyday bra Sports bra	Opto-electronic Cameras	R: 10 km.hr^{-1}	5 gait cycles	Suprasternal notch & left and right anterior inferior aspects of the 10th rib	Right nipple	z, x, y
Mills et al. 2014[b]	10	22 ± 2	D	No support Everyday bra Sports bra	12 Opto-electronic Cameras	R: 10 km.hr^{-1}	5 gait cycles	Suprasternal notch & left and right anterior inferior aspects of the 10th rib	Right nipple	z, x, y

Author, Year	No. of Participants	Age	Bra size	Bra style	Equipment	Activities	Length of film	Reference Points	Study Points	Output
Mills, Risius & Scurr 2015	10	22 ± 2	D	No support Everyday bra Sports bra	11 Opto-electronic Cameras	R: 10 $km.hr^{-1}$	5 gait cycle	Suprasternal notch & left and right anterior inferior aspects of the 10th rib	Left & right nipple	$z, x, y,$
Risius et al. 2015	16	22 ± 2	D	No Support	Opto-electronic Cameras	R: 10 $km.hr^{-1}$, Agility test, Counter-movement jump		Suprasternal notch & left and right anterior inferior aspects of the 10th rib	Right nipple	$z, \dot{z}, \ddot{z}$ $x, \dot{x}, \ddot{x}$ $y, \dot{y}, \ddot{y}$

Definitions:

N/A = Not Applicable, BMT = Breast Motion Trajectory, W = walking, J = jogging, R = running

z = vertical, x = Anterior-posterior, y = Mediolateral, z = displacement; $\dot{z}$ = velocity; $\ddot{z}$ = acceleration

Boschma (1994) investigated the effects of full, medium and no supports on breast biomechanical variables in 15 participants with breast cup size of C to DD, running at 7.2 $km.hr^{-1}$. The motion of the nipple and sternum markers were recorded using three cameras, two of which were directed at the activity and one at the heel to record heel strike. The results showed that as support decreased, vertical breast displacement, perceived discomfort and stride rate increased while stride length and vertical trunk displacement decreased. From the results it was concluded that perceived discomfort was affected by cup size and bra style, rather than quantitative vertical breast displacement. This was supported by Lawson and Lorentzen (1990) who found that only one out of seven sports bras showed a significant correlation coefficient for comfort with quantitative breast displacements. The results suggest that comfort during exercise is more than just a feeling that the motion of the breast in the vertical direction is limited.

Alternatively, Mason, Page and Fallon (1999) used three participants with C to D cup size breasts. Markers on the suprasternal notch and nipple were tracked during gait at 7, 10 and 13 $km.hr^{-1}$ and an aerobic activity in four support conditions, using two 16 mm Photosonic high-speed cine cameras. The results suggested that perceived comfort followed the pattern of vertical breast movement, rather than maximum deceleration force. As the breast support decreased, breast displacement increased resulting in increased perceived discomfort.

White, Scurr and Smith (2009) found from the mean discomfort scores obtained from eight participants with size D cup bras that the compression bra was the most comfortable as it produced the least amount of resultant breast displacement out of all the support conditions (encapsulated bra, fashion bra and bare-breasted). Markers were placed on the right and left clavicles and ASIS to convert the global coordinate system to a local coordinate system with the origin at the right clavicle. Therefore, the right nipple resultant displacements were made independent and eliminated the six-degrees-of-freedom movement of the body.

Conversely, McGhee, Steele and Power (2007) found that increase in breast comfort was attributed to the significant reduction in mean peak vertical breast velocity in deep-water running compared to treadmill running. Sixteen participants (C to J cup size) ran on a treadmill above ground and 2.4 m under water at a self-selected pace. Markers were placed on the sternum, level with the articulation of the 3rd rib, on the participants' nipple and superior aspect of the breast immediately above the nipple. The markers were tracked with either a camcorder digital video camera or a poolcam video camera.

McGhee and Steele (2010) used 20 participants with cup size of C to F. The participants had markers placed at the suprasternal notch and on the nipple. The markers were tracked using two OptoTRAK 3020 sensors during an average speed run of 8.3 $km.hr^{-1}$ on a treadmill, while wearing either an encapsulated bra; compression bra; or experimental bra (encapsulated sports bra, incorporating elevation and compression). They found that the experimental bra produced lower subjective ratings of perceived breast movement, breast discomfort and bra discomfort than the other support conditions. It was noted that there was no significant difference in the vertical breast displacement in each condition. The results suggest that elevating the breasts higher on the torso reduced the tension and loading on the anatomical structures of the breast. One possible reason for this is that these structures are further away from their end of range compared to the other support conditions.

McGhee, Steele and Munro (2010) used 15 participants with cup sizes of D to G. Markers were placed on the suprasternal notch, left nipple and left heel. The markers were tracked using two OptoTRAK 3020 sensors during an 8 - 9 $km.hr^{-1}$ run on a treadmill, in two support conditions (an everyday bra and bare-breasted). They found that the mean vertical component of the maximum net bra-breast force of the left breast during the downward phase was on average, significantly less when the participants wore the sports bra compared to the fashion bra and was associated with less movement-induced breast discomfort with no change in rate of perceived exertion.

A common theme in this literature is the level of discomfort a women experiences during the exercises. Mason, Page and Fallon (1999) with Heil's (1993) designed a visual analogue scale (VAS) in the form of a Likert scale. The scale ranges from '0' (comfort) to '10' (pain), with '5' representing uncomfortable. They presented the scale to the participants immediately after the treadmill exercise. This scale and method have been adopted by many researchers (e.g. White, Scurr and Smith 2009; Scurr, White and Hedger 2010). The main advantage of VAS's is that they are easy to implement. A potential disadvantage of this approach of rating breast discomfort during an activity is that there was no measure of a baseline level before each activity. The rest period provided between each activity may have been insufficient for perceived breast discomfort to return to baseline levels before undertaking the next activity.

McGhee and Steele (2010) modified the scale to show '10' as extreme discomfort and presented the scale to the participants immediately before and after the exercise, to understand the participants level of breast and bra discomfort pre- and post-trial. This approach reduces the effect movement-induced breast discomfort generated in the previous exercise has on the next measure of perceived breast discomfort of the next exercise. This method of measuring perceived breast discomfort can be influenced by internal and external factors that the participants are feeling.

There has been very little breast biomechanics research focused on the experimental set up and data processing/analysis. Recently, the construction of the local coordinate system originating at the suprasternal notch (Mills et al. 2014[a]), the torso marker set (Mills et al. 2014[b]), bilateral breast motion (Mills, Risius and Scurr 2015), and the modality of the exercise (Risius et al. 2015) have been investigated. Mills et al. (2014[a]) recruited ten women all with size 32D breasts. Each participant placed markers on the suprasternal notch, right and left anterior-inferior aspect of the 10^{th} rib, right nipple and the heel. Each participant ran on the treadmill at 10 $km.hr^{-1}$, after a 2-min familiarisation period five gait cycles were recorded. The right-hand local coordinate system was constructed in two different ways, the first method defined the mediolateral axis as the primary axis of rotation and the second method defined the longitudinal axis as the primary axis of rotation. The results showed that the definition of the first axis of rotation of the trunk significantly alters the magnitude of breast displacement and the direction in which the greatest magnitude of breast displacement occurred in.

Mills et al. (2014[b]) used the same protocol as Mills et al. (2014[a]) to investigate the effect of the anterior-inferior 10^{th} aspect of the rib as an anatomical location to define the torso reference frame. They compared two segment optimisation position and orientation estimation (POSE) algorithms (direct and segment optimisation) to assess torso segment rigidity. The direct POSE algorithm, was assessed using the maximum change in vector length of the torso segment (defined using the suprasternal notch and mid-rib markers). The segment optimised POSE algorithm was confined to retaining a constant segment length. Any deviation of the torso markers from their static template position was quantified using a segment residual. The results showed that the markers placed on the torso do move relative to each other due to tissue vibrations, created from the foot impacting the ground, causing the length of the torso segment to deform. This then affects the magnitude that the breast deflects from the origin of the local coordinate system.

Mills, Risius and Scurr (2015) found that there was no significant difference between the groups left and right breast displacement within any of the three breast support conditions. However, the left breast displacement was greater for 70% of the women in the no bra, 90% in the everyday bra and 60% in the sports bra, suggesting that any individual differences may have been masked in the sample group when comparing the sample group mean. They also found that the correlation coefficient between breast pain and displacement differed for the left and right breast. The results were found in ten women with 32D cup size breasts with markers placed on the suprasternal notch, left and right anterior-inferior aspect of the 10th rib, left and right nipple and the heel. Each participant ran at 10 km.hr^{-1}, after a 2-min familiarisation period, five gait cycles were recorded with 11 Optoelectronic cameras, sampling at 200 Hz.

Risius et al. (2015) used 16 women with 32D cup breast size, to assess multi-planar breast displacement during different exercise modalities. Markers were placed on the suprasternal notch, left and right anterior-inferior aspect of the 10th rib, right nipple and heel. The markers were recorded with Optoelectronic cameras during each exercise at a sampling rate of 200 Hz. The results showed that exercise modality had a strong influence on the magnitude of breast displacement and peak breast velocity. Jumping produced the greatest vertical and less mediolateral breast motion than either running or the agility task.

One of the main trends in the literature that was concluded was that as vertical breast displacement decreased, perceived discomfort decreased. The reduction in breast displacement was achieved by reducing the speed of the treadmill or increasing the level of breast support (Mason, Page and Fallon 1999; White, Scurr and Smith 2009). However, there were conflicting results in the literature. The earlier work in this area suggested that bra style and cup size were the main contributing factors to movement-induced breast discomfort (Boschma 1994; Lawson and Lorentzen 1990). Conversely, McGhee, Steele and Power (2007) provided evidence to suggest that vertical peak breast velocity caused breast discomfort. However, the underwater running trials would affect the participants' gait and provide buoyancy, altering the static resultant position of the breasts. Interestingly, McGhee and Steele (2010) suggested that tension of the breast tissue causes movement-induced breast discomfort. Their results showed that breast displacement did not alter between support conditions; however, the combination of elevation and compression of a bra, lift the breasts higher on the chest wall, moving the breasts further away from the end of their range of motion. The discrepancies in the results may be due to methodological variations, such as calculating the variables of interest in the local coordinate system rather than the global coordinate system, different marker sets and the use of group results compared to a single subject design.

2.6 Neutral position

It has been hypothesised by Mason, Page and Fallon (1999) that breast discomfort during exercise occurs from tension on the skin and fascia. All materials including living tissue have a point of failure, where they endure too much stress. Failure occurs in metals when the material is fatigued from repeatedly being loaded and unloaded below the ultimate tensile stress or even the yield stress (Benham and Crawford 1993).

Haake and Scurr (2011) began to investigate the strain (ε) of the breast during walking and running on a treadmill. Strain was calculated as follows (Eq. 3):

$$\varepsilon = \frac{\delta}{L_O} = \frac{d - L_O}{L_O} = \frac{d}{L_O} = 1 \qquad \text{Eq. 3}$$

where d was the distance of the nipple from the suprasternal notch; δ was the extension of the viscoelastic element; and L_O was the undeflected length. L_O was considered to be the vertical distance between the suprasternal notch and the neutral position. The vertical neutral position of the breast was defined as the point in which the breasts were in free-fall, where accelerations of the nipple reached -1 g. Newton's second law was used to find the force acting on the nipple during motion (Eq. 4):

$$m\ddot{y} = F - mg \qquad \text{Eq. 4}$$

where y is the vertical position of the breast with respect to the suprasternal notch and F is the force acting on the breast tissue. The mass, m, is the effective mass at the nipple. Therefore, when the breast is in the static position F = mg ≈ 0, such that $\ddot{y} \approx -g$, thus the neutral position (y = L_O) is where $\ddot{y} \approx -g$.

Haake and Scurr (2011) used three participants with a range of breast sizes from 32A to 34E. Two retroreflective makers were placed on the suprasternal notch and right nipple. Markers were tracked using eight Oqus infrared cameras. The vertical neutral position was initially found by performing static lift and drop trials. Each participant then performed 2-min treadmill trials at 4; 7; 10; and 14 $km.hr^{-1}$ in three breast support conditions (no bra, everyday bra and sports bra). They found that within the cohort the static strain of the right breast ranged from -10% to -71%. It was noted that during running the breast underwent non-linear accelerations when experiencing strains larger in magnitude than the static strain during the downward phase of the breast motion. The results suggest that the application of any bra appeared to reduce the static strain of the breast by lifting the breasts towards the vertical neutral position.

Haake, Milligan and Scurr (2012) aimed to determine whether acceleration and strain could be used as objective measures of discomfort in the breast during running. They used the same method to identify the vertical neutral position of the breast as Haake and Scurr (2011). Eight participants with a range of breast sizes from 32A to 34G were used. Four retroreflective markers were attached to the suprasternal notch, right and left anterior-inferior aspect of the 10^{th} rib and the right nipple. Ten gait cycles were recorded after a 2-min familiarisation period at 10 $km.hr^{-1}$ and 14 $km.hr^{-1}$ on a treadmill in three bra conditions - no bra, everyday bra and sports bra. They found that as breast size increased maximum strain increased in the no bra condition while the use of a bra limited the variation across participants. The maximum vertical acceleration of the breast decreased when a bra was worn; and the discomfort scores seemed to be affected by both the level of support and breast size.

There are two possible engineering theories as to why failure may occur, these are: 1) Miner's rule (Figure 2.2), and 2) Goodman's rule (Figure 2.3). Miner's rule suggests that the materials are repeatedly loaded at a certain stress until failure occurs. Therefore, at smaller amplitudes the material can withstand a greater number of cycles whereas at larger amplitudes, fewer cycles are required to reach failure. Goodman's rule suggests that the relationship between mean stress and stress amplitude can be defined as linear or a parabola depending on how the limiting factors are connected. Between these limits it is required to have a line, which represents the locus of all combinations of stress amplitude and mean stress, which result in the same fatigue endurance.

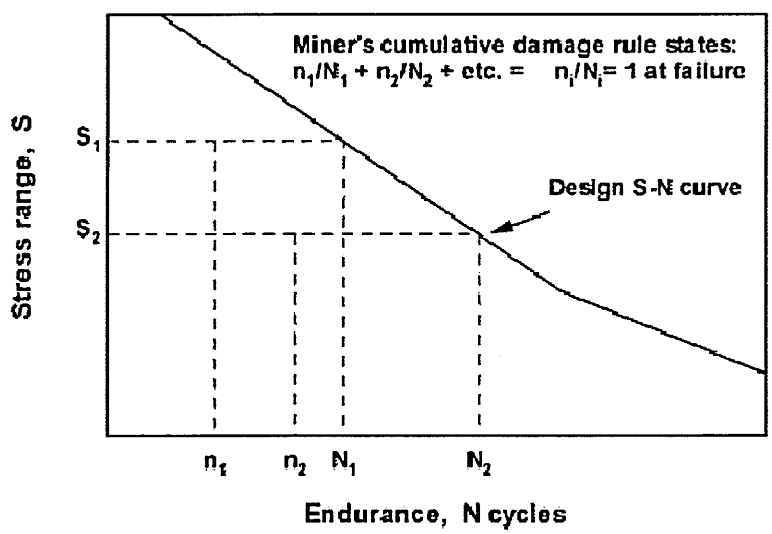


Figure 2.2: Miner's rule - diagrammatic representation of cumulative damage (Maddox 2003).

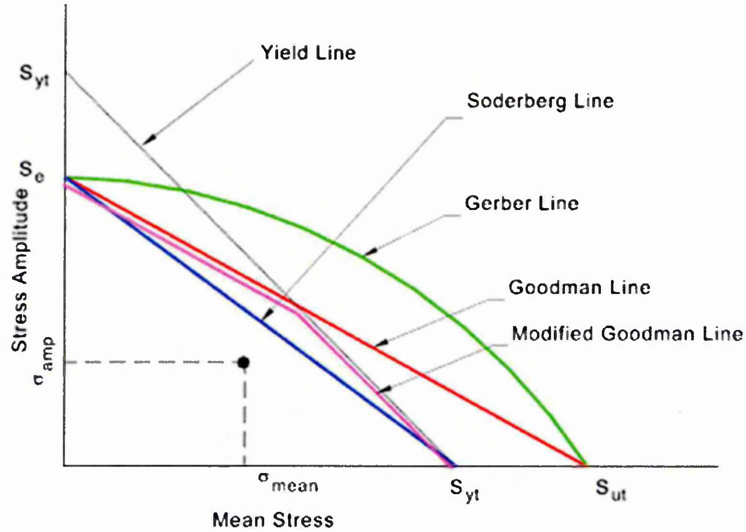


Figure 2.3: Goodman's rule – left hand side of each line is classed as the safe zone and the right hand side is the failure zone (Roymech 2013).

Haake, Milligan and Scurr (2012), modified the Goodman's rule to predict discomfort in living tissue (Figure 2.4). Goodman's rule is based on linear assumptions of the material's mean and amplitude stress. Haake, Milligan and Scurr (2012) modified the theory to include maximum strain, which was actually a measure of normalised displacement from a vertical neutral position to represent a single-point analysis for a complex wobbly mass and maximum acceleration. The implications of the theory in this scenario, was to identify the point where the participants transfer from breast comfort to discomfort to predict the kinematic variables that cause discomfort.

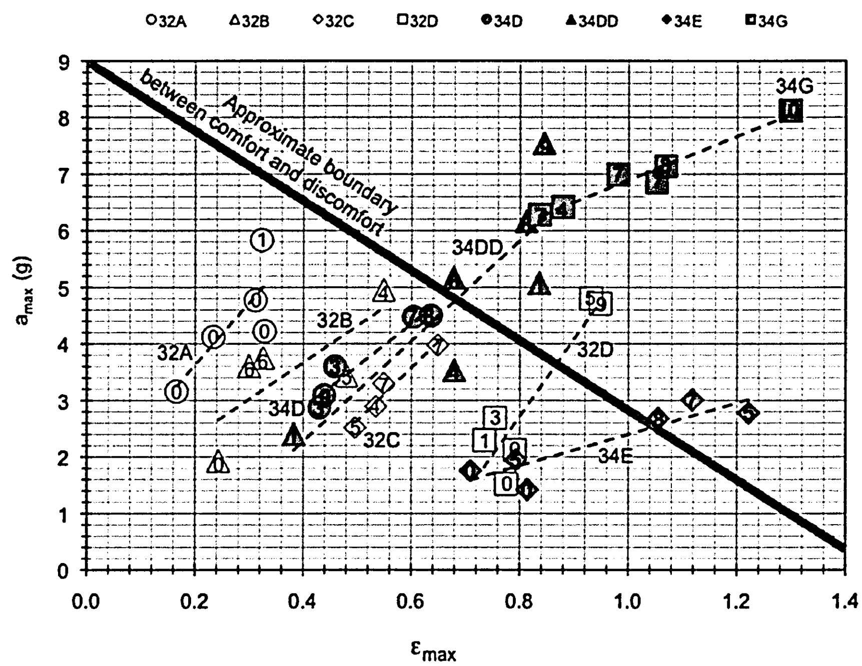


Figure 2.4: Haake, Milligan and Scurr (2012) maximum acceleration vs. maximum strain.

It is known that ligament and skin stiffness varies non-linearly with force. At lower levels of force, there is less resistance to deformation, whereas at high forces, the tissue becomes stiffer, providing more resistance to increases in deformations (Nigg and Herzog 2007). A force-deformation curve (Figure 2.5) shows that as a load is applied to a ligament, the tissue undergoes four distinct regions. As tension is increased the collagen crimp gradually flattens out (Figure 2.5: 1). Region 2 begins as the whole crimp has gone and the whole matrix is under tension, causing a more constant linear stiffness. Neither fibre nor crimp is homogenously distributed along the length of ligaments. Therefore, different fibres are recruited into load-bearing at different displacements. When all fibres have been recruited, the stiffness behaviour becomes more linear until some fibres fail. At this point the net stiffness of the structure begins to drop (Figure 2.5: 3). As some fibres fail, the load is redistributed onto remaining fibres, increasing the load on them and likelihood of their failure. It then takes additional deformation to produce gross structural failure of the ligament through all the remaining fibres (Figure 2.5: 4) (Nigg and Herzog 2007). However, Haake, Milligan and Scurr (2012) did not alter the relationship between the variables to account for the non-linear behaviour of living tissue.

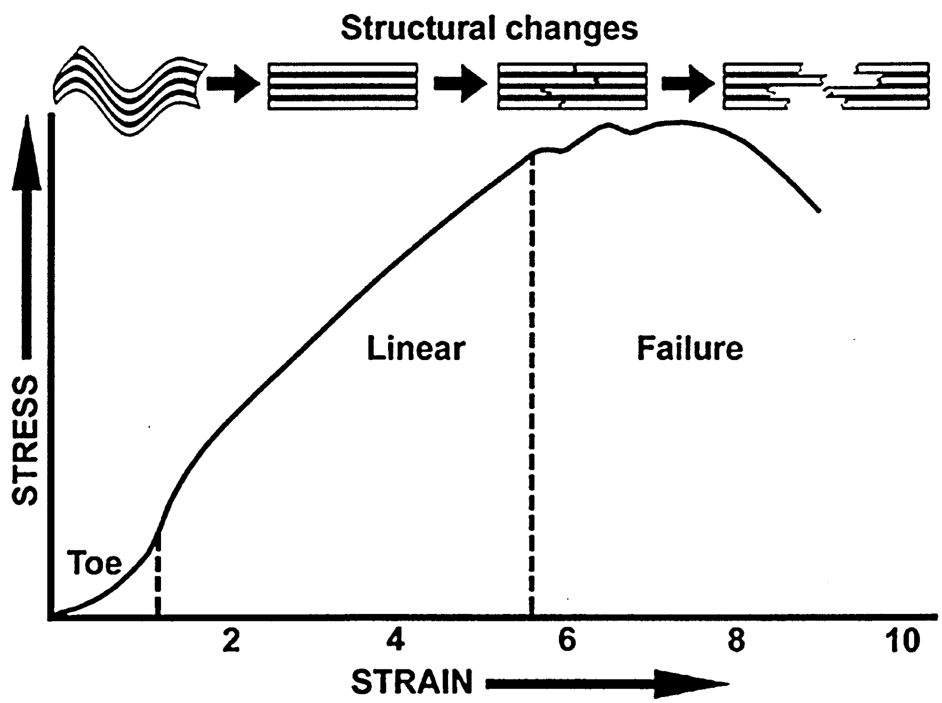


Figure 2.5: Stress-strain curve of the nonlinear elastic behaviour of a ligament (Bindra 2004).

2.7 Summary

Research has shown that mastalgia can occur due to exercise and therefore the term mastalgia encompasses any pain that occurs in the breast (Iddon and Nixon 2013). Many authors have investigated the kinematics of breast motion and breast pain. Several authors have alluded to the concept of discomfort being caused by the stretching of the breast tissue and can be overcome by compressing and elevating the breasts on the chest wall.

Haake and Scurr's (2011) results indicated that reducing the strain (a measure of normalised displacement from the vertical neutral position) of the breast tissue through the use of a mechanical support (e.g. sports bra) reduced the individuals discomfort score during exercise. It was identified by Haake, Milligan and Scurr (2012) that to clearly identify the transition from comfort to discomfort a larger number of participants and a more refined measure of discomfort is required.

3 Detecting free-fall using the three-dimensional motion capture system

3.1 Introduction

Mason, Page and Fallon (2009) hypothesised that movement-induced breast discomfort is caused by straining the tissue of the breast. To calculate strain on the breast during exercise, the undeflected length of the breast is needing to be measured. This is calculated by working out the distance from the suprasternal notch to the vertical neutral position of the breast. The vertical neutral position could allow for a greater understanding of the stress applied to the breast tissue during movement.

Haake and Scurr (2011) developed a lift and drop test to locate the vertical neutral position of the breast using a three-dimensional motion capture system. Locating the neutral position in the vertical direction is possibly the most important of the three directions. Scurr, White and Hedger (2009) quantified that 56% of breast motion during treadmill walking and running occurred in the vertical direction. The vertical motion has been associated with movement-induced breast discomfort (Mason, Page and Fallon 1999; Starr et al. 2005).

This chapter is made up of three studies: a) assessing the error in calculating accelerations using the motion capture system, when a single marker is dropped from an unspecified height, b) detecting -1 g within a known period during oscillating motion, and c) detecting -1 g within a very defined range, which is more synonymous with breast motion.

3.2 Aim and objectives

Aim

To assess whether free-fall (-1 g) can be detected in the vertical direction during simple motion using the three-dimensional motion capture system (Motion Analysis Corporation, Santa Rosa, CA, USA).

Objectives

- Perform dynamic movement / measurements with a marker;
- Identify an appropriate filter;
- Work out errors in acceleration;
- Satisfy the prediction of free-fall using a single and two elastic cord bungee setup.

3.3 Prediction

The breast is a complex structure made of fatty tissue, glandular tissue, skin and ligaments, which affect the motion of the breast. It has been noted since the 1980s that women suffer from movement-induced breast pain (Gehlsen and Albohm 1980; Brown et al. 2013). Mason, Page and Fallon (1999) believe that stretching of the breast tissue causes breast pain. Recently, Haake and Scurr (2011) developed a technique to elicit a position where the breast tissue is neither in tension nor compression, where the breast reaches an acceleration of -1 g, termed the neutral position. Therefore, the aim of this experiment was to simulate simple motion of the breast to assess whether the three-dimensional motion capture system was sensitive enough to capture periods of free-fall.

The breast was simulated using either single or double elastic cords attached to a metal plate, to mimic the upper and lower breast tissue. Theoretically, a single elastic cord attached to the metal plate should produce accelerations of -1 g when the metal plate is at or above its resting height (Figure 3.1).

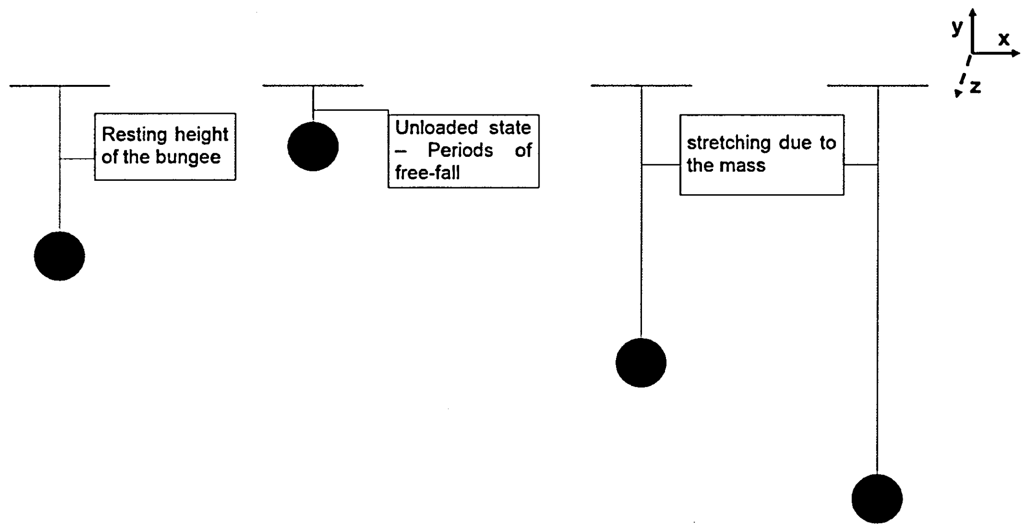


Figure 3.1: Sketch of the resting height, loaded and unloaded states of a mass attached by a single elastic cord. The vertical direction is the y-axis of the global coordinate system.

When two elastic cords are attached to the metal plate it is still possible for the metal plate to be in free-fall. Theoretically, both elastic cords need to be unloaded at the same time this may create a region of free-fall. The highest vertical resting height of the metal plate (static unloaded state of the lower elastic cord) defined the upper boundary of free-fall. The lowest vertical resting height of the metal plate (static unloaded state of the upper elastic cord) defined the lower boundary of free-fall, illustrated in Figure 3.2.

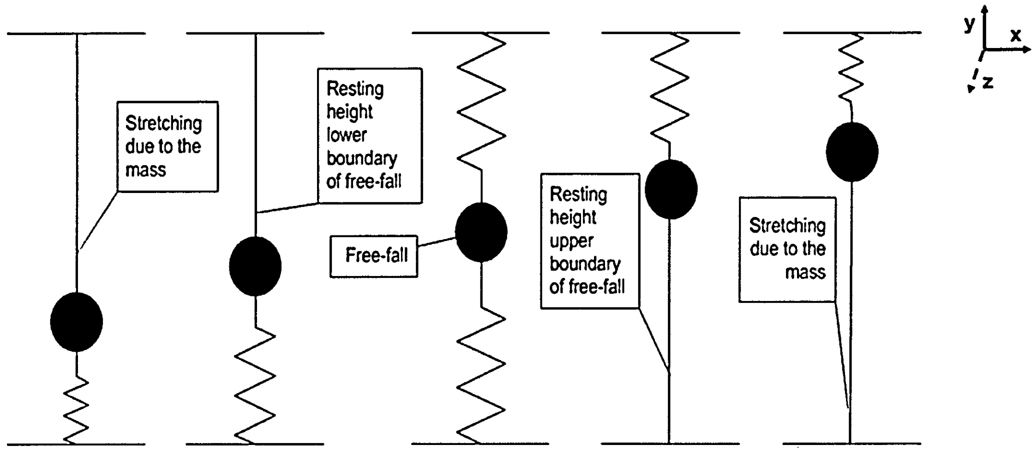


Figure 3.2: Sketch of upper and lower boundaries of free-fall defined by the resting height of the metal plate when the two elastic cords are unloaded. The vertical direction is the y-axis of the global coordinate system.

3.4 Method

Laboratory set-up

Eight three-dimensional infrared motion capture cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) were placed in a semi-circle around the capture volume, sampling at 200 Hz. The cameras were calibrated using manufacturers recommended calibration procedures. The global coordinate system was defined with respect to the laboratory with the positive vertical co-ordinate in the upward direction.

A metal plate (950 x 75 x 3 mm), with a 12 mm diameter retroreflective marker placed on the centre of the plate, was attached to a wooden frame by either one or two elastic cords at the top or top and bottom of the metal plate to simulate the upper and lower tissues of the breast (Figure 3.3). The structure was placed in the centre of the capture volume. A further 12 mm diameter retroreflective marker was attached to the top of the wooden frame as a reference marker. This marker was used to represent that of the thorax marker which Haake and Scurr (2011) used. The mass of the metal plate was 612 g and could travel 450 mm in the single elastic condition and 380 mm in the double elastic condition as the knots of the elastic cords restricted the vertical motion. The thickness of the elastic cord was 5 mm. A mass attached to one or two bungee cords was used instead of a female breast due to 1) the nature of the testing, and 2) the female breast is a complex structure which moves in all axes.

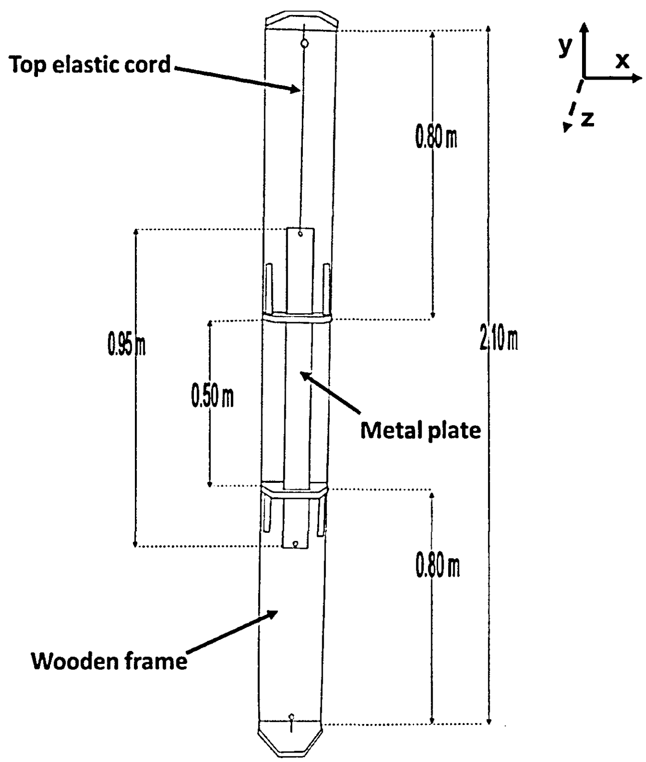


Figure 3.3: Sketch of the metal plate in the single elastic cord set-up. The vertical direction is the y-axis of the global coordinate system. An additional elastic was attached at the bottom of the metal plate.

Data collection

The first study used a 12 mm diameter retroreflective marker, which was dropped from an unspecified height, within the capture volume. Each drop was recorded for 5 s and repeated five times.

The second study used a 12mm diameter retroreflective marker that was placed on the metal plate which was attached to the wooden frame by a single elastic cord. Initially the mass was lifted to the point where the elastic was no longer loaded for a 2 second capture to calculate the resting height of the metal plate. After the static trial the metal plate was pulled down to the point where the knot in the elastic cord stops the metal plate being pulled any further. The three-dimensional camera captured the metal plate in this position and was then released. The metal plate oscillated vertically before reaching a stationary position. This was repeated five times.

In the third study, a second elastic cord was fastened to the bottom of the metal plate to be more synonymous with breast motion. The top elastic cord remained the same length, while the length of the bottom elastic was altered to create three test conditions. The altered length of the bottom elastic affected the resting height of the metal plate and the size of the zone where the metal plate was in free-fall, this was used to simulate different sized breasts. The mass was raised to capture the static resting height of the metal plate, for when the bottom elastic cord was unloaded (Table 3.1). The mass was then pulled down as far as the elastic cord would allow and then released. The metal plate oscillated vertically before reaching a stationary position. This was repeated five times and for the following two conditions (2 and 3) with different bottom elastic cord lengths.

Table 3.1: Resting heights of the metal plate with respect to the reference marker on the wooden frame when the top and bottom elastic cord were unloaded.

Unloaded elastic cord	Condition	Resting height of the metal plate with respect to the reference marker on the wooden frame (mm)
Top		-690.7
	1	-654.3
Bottom	2	-694.7
	3	-698.9

It is predicted that the single elastic trials should show the metal plate in free-fall when the elastic cord is unloaded at -690.7 mm and above. Only condition 1 of the double elastic cord set-up should show the metal plate in free-fall as the region between the upper and lower boundary of the metal plates resting height was 36.4 mm.

Data processing

Each trial was post-processed in Cortex (Motion Analysis Corporation, Santa Rosa, CA, USA) to identify and track the marker of interest. The raw vertical coordinate for the marker in each trial was exported into MS Excel and filtered. Filtering was used to attenuate the noise in the data to reveal the true signal. The noise in the raw displacement signal was amplified at each level when double differentiated which became apparent in Figure 3.4c.

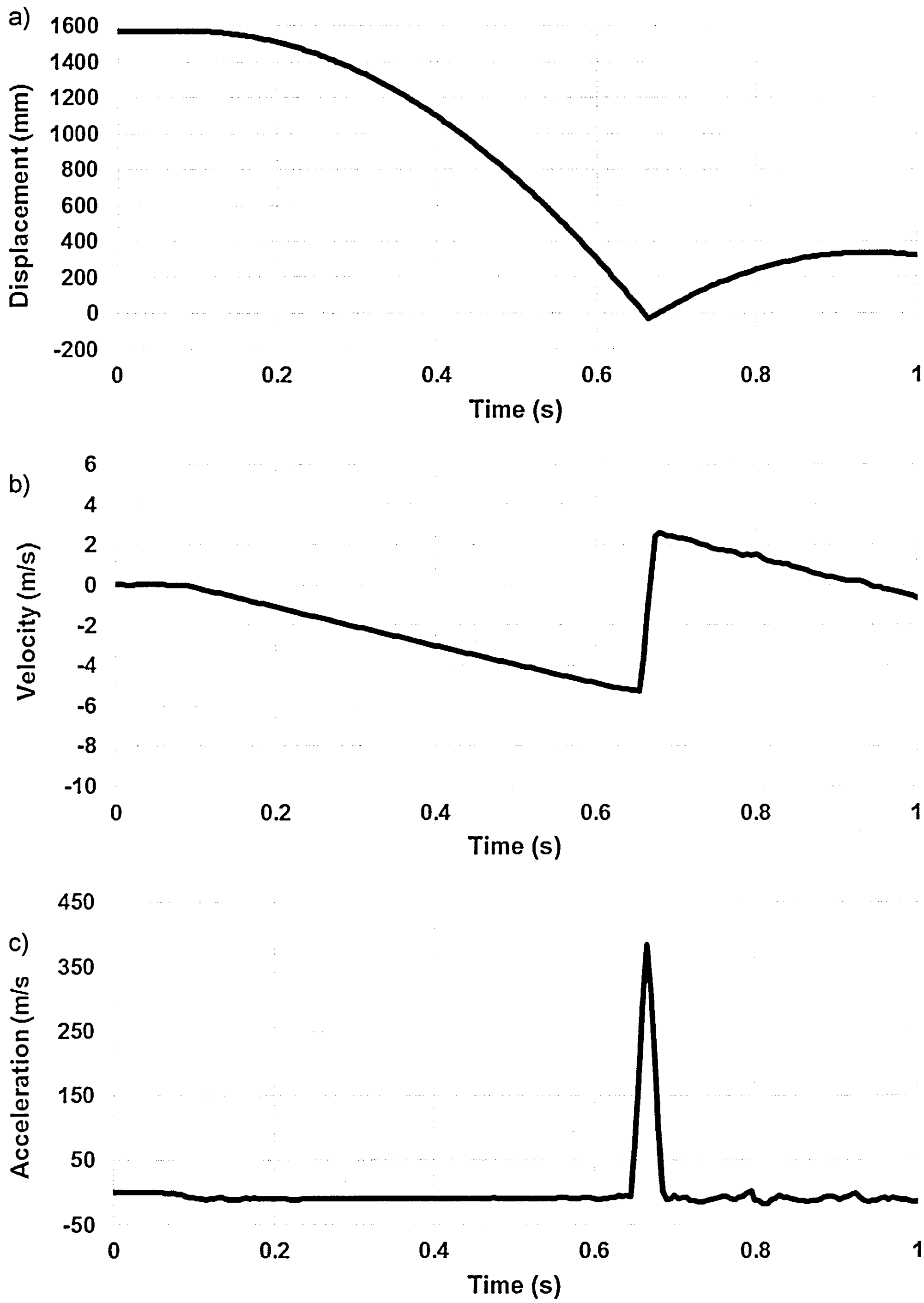


Figure 3.4: a) Raw displacement of a retroreflective marker dropped from an unspecified height differentiated to b) velocity, and then c) acceleration.

While there are many types of filters used in data processing, the low-pass Butterworth filter is frequently used in the literature (Table 3.2).

Table 3.2: Filtering techniques used by previous authors.

Author(s)	Year	Filter	Order	Cut-off frequency (Hz)
Boschma	1994	Low pass Butterworth filter	4th	2 - 9
Mason, Page and Fallon	1999	Low pass digital filter	N/A	4
Haake and Scurr	2010	Low pass Butterworth filter	N/A	10
McGhee and Steele	2010	Low pass Butterworth filter	4th	10
Scurr, White and Hedger	2011	Low pass Butterworth filter	N/A	10
McGhee et al.	2013	Low pass Butterworth filter	4th	10
Zhou, Yu and Ng	2012	Low pass filter	N/A	8

The order of the filter defined the sharpness or the width of the region of the cut-off frequency the signal was attenuated. The most common order in breast kinematics was 4^{th} order (Table 3.1).

The most important parameter in the filter is the cut-off frequency. The cut-off frequency is sensitive to the input signal and although it can be estimated from the Nyquist frequency, it is best found by assessing the residual between the raw data and the Butterworth filter at varying cut-off frequencies. The cut-off frequency was mathematically determined from the second derivative of the residual based on the residual versus cut-off frequency plot (Figure 3.5 - Winter 2005).

Nagano et al. (2003) suggested the optimum cut-off frequency was the frequency at which the second derivative of the residual with respect to the cut-off frequency fell below the threshold value of 0.8 mm/Hz^2 (see appendix 1). This was performed on each trial. The data was filtered in MATLAB® (The MathWorks. Inc, Massachusetts, USA) using a 4th order zero-phase Butterworth filter with a cut-off frequency in the range of 5 Hz to 9 Hz. The cut-off frequencies were established from the residual analysis performed on the vertical direction of each marker in each trial.

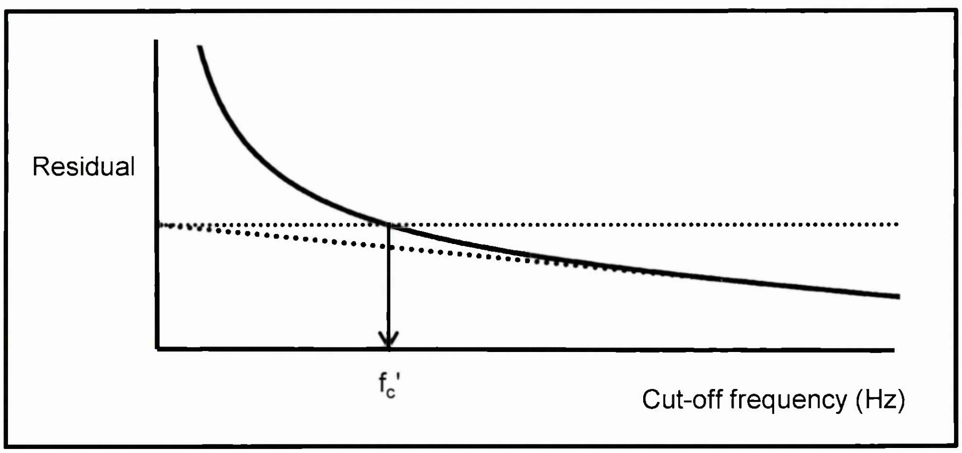


Figure 3.5: Plot of the residual between a filtered and an unfiltered signal as a function of the filter cut-off frequency (adapted from Winter 2005).

Data analysis

The vertical displacement data for each marker was double differentiated using a five-point central differencing method to give acceleration. The absolute dynamic vertical marker error was calculated, using the data from the first study, by comparing the prediction of free-fall (-1 g) to the actual measured acceleration values. The absolute root mean square error (Abs. RMS error) value was reported (Eq. 5).

$$Abs. RMS\ error = \sqrt{\frac{1}{N}\sum(y_i - y_t)^2} \qquad \text{Eq. 5}$$

In the second and third study, the calculated periods of free-fall correspond to a vertical displacement of the metal plate, which was made relative to the reference marker on the wooden frame (metal plate vertical position - reference marker vertical position). The results were presented as minimum, maximum, mean and range of vertical displacement of the metal plate with respect to the reference marker on the wooden frame.

3.5 Results

In the first study, the vertical marker drop showed an absolute RMS error of 0.04 g when calculating accelerations using the motion capture system. The results of the second and third study, of the motion of the metal plate during both the single and double elastic cord set-ups are shown in Figures 3.6 and 3.7 and Table 3.3. All the points of free-fall during the single elastic cord set-up were either at (-690.7 mm) or above the resting height of the metal plate (Figure 3.6).

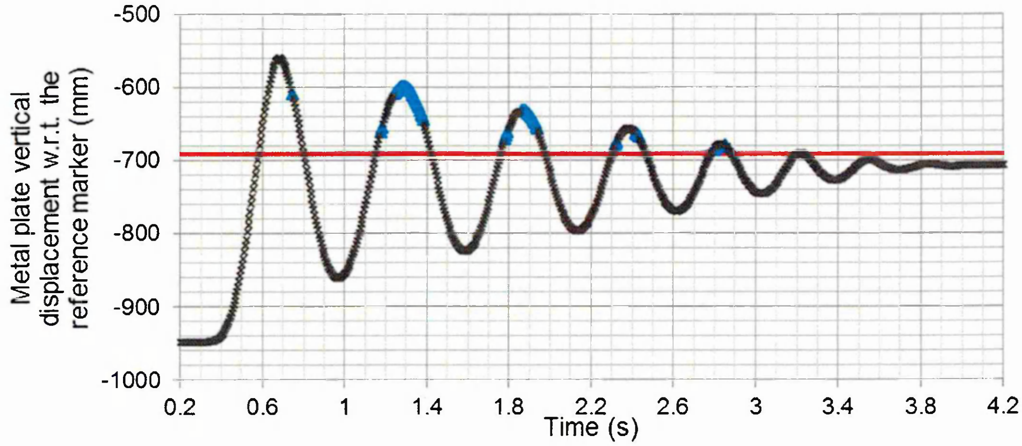


Figure 3.6: Vertical displacement of the metal plate with respect to the reference marker on the wooden frame during a typical single elastic cord set-up. (Blue triangle points = metal plate positions where acceleration equals -1.00 g ± 0.04 g; the red line = resting height of the metal plate when the top elastic cord was unloaded).

In the first condition of the third study, the region which the metal plate was unloaded was 36.4 mm (Figure 3.7a). It was predicted that the region between the boundaries of the metal plates resting height should be the region where the metal plate moves through free-fall. In conditions 2 and 3 of the double elastic cord set-up, the metal plate was loaded throughout the motion. Therefore, there should not be a region where the metal plate goes through free-fall. Figure 3.7b and 3.7c show that there are several points in the trial where the metal plate was recorded to be in free-fall.

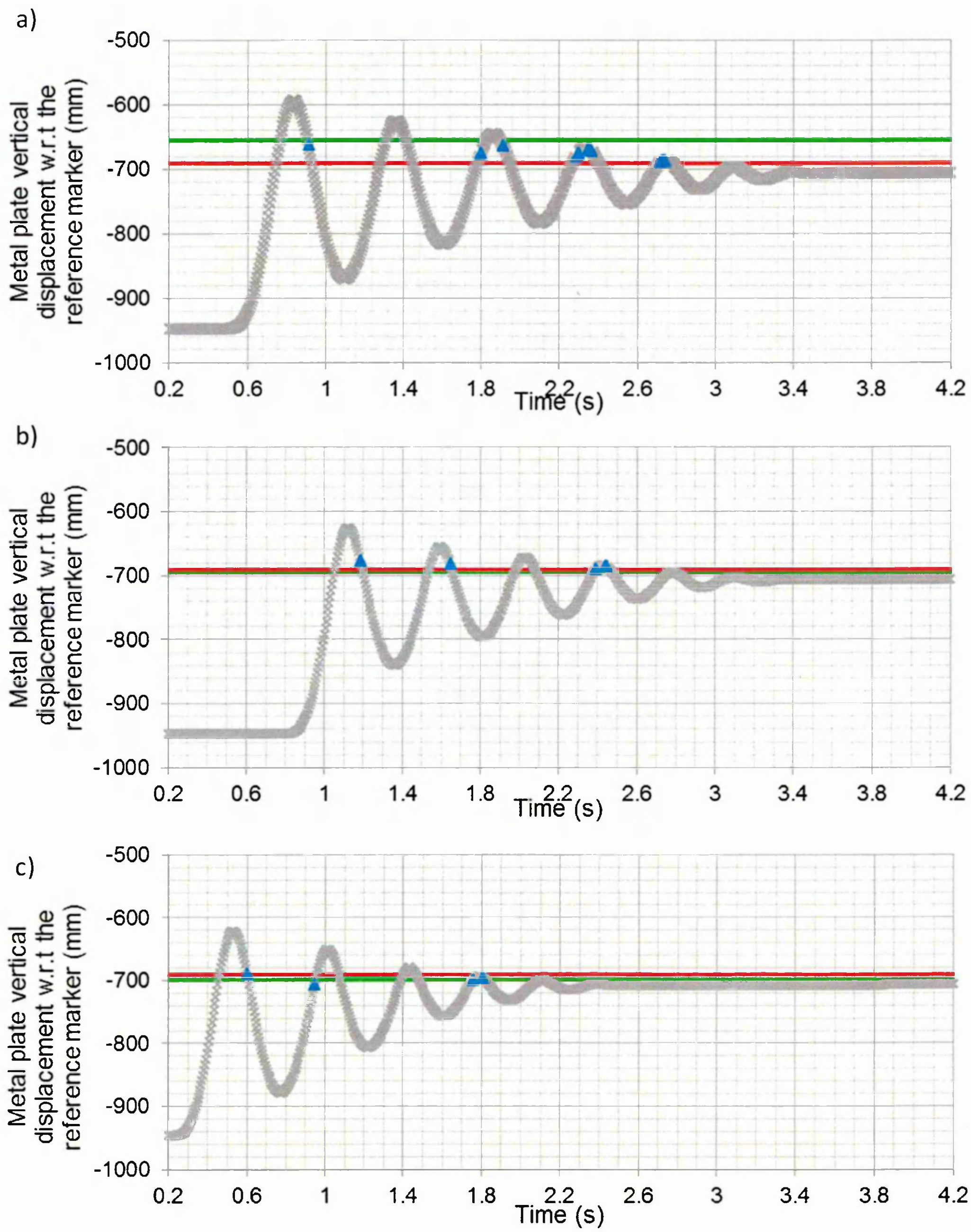


Figure 3.7: Vertical displacement of the metal plate with respect to the reference marker on the wooden frame during typical double elastic cord set-ups for, a) condition 1, b) condition 2, c) condition 3. (Blue triangle points = metal plate positions where the accelerations reached -1.00 g ± 0.04 g; the red line = resting height of the metal plate when the top elastic cord was unloaded; the green line = resting height of the metal plate when the bottom elastic cord was unloaded).

The maximum and minimum position of the metal plate during the recorded free-fall was above the resting height of the metal plate (Table 3.4). The mean, maximum and minimum position of the metal plate in the first condition of the double elastic was within the boundaries. The range of positions for this condition was smaller than the actual boundary region. The second and third condition of the double elastic cord set-up showed a range of 16.3 mm and 11.7 mm with a standard deviation of 7.4 mm, respectively.

Table 3.3: The regions of vertical displacements of the metal plate with respect to the reference marker during free-fall across five trials.

Condition	Minimum (mm)	Maximum (mm)	Mean (mm)	Range (mm)
Single Elastic	-688.1 ± 6.6	-596.5 ± 6.0	-634.9 ± 2.3	91.6 ± 12.4
Double Elastic 1	-687.3 ± 0.6	-662.3 ± 1.8	-676.9 ± 1.1	25.0 ± 2.4
Double Elastic 2	-692.8 ± 4.4	-676.5 ± 4.7	-684.5 ± 2.0	16.3 ± 7.4
Double Elastic 3	-705.1 ± 4.9	-693.3 ± 3.4	-698.9 ± 2.1	11.7 ± 7.4

3.6 Discussion

The aim of this chapter was to identify whether the three-dimensional motion capture system was sensitive to capture periods of free-fall, in the vertical direction, in simple motion. It was predicted that periods of free-fall of the metal plate in both the single elastic cord set-up should only occur when the metal plate is unloaded. The motion capture system detected the metal plate passing through free-fall, Figure 3.6. The points of free-fall occurred above the resting height of the metal plate. The large standard deviations seen in the range of vertical displacement of the metal plate in the single elastic cord set-up (Table 3.3) may be due to two factors. Firstly, the metal plate may have moved in all three directions causing the mass to collide with the wooden frame, losing kinetic energy and therefore reducing the range of movement of the metal plate. Secondly, holding the metal plate between the thumb and second finger may have created friction, dampening the motion of the metal plate, causing the metal plate to vary in speeds for each trial, which in turn affects the range of vertical displacement.

The double elastic cord set-up was used to resemble the upper and lower breast tissue more realistically. It was predicted that free-fall will occur when the metal plate is within the resting height zone. This zone is defined by the unloaded state of the elastics creating an upper and lower boundary of the zone. In the first condition of the double elastic cord set-up, the metal plate had a resting height zone of 36.4 mm (Table 3.1). Figure 3.8a showed that all the free-fall points laid within the resting height zone; therefore, agreeing with the prediction.

The metal plate in conditions 2 and 3 of the double elastic cord set-up do not have a resting height zone due to the elastic cords being continuously loaded (Table 3.1), therefore periods of free-fall should not be present. Figures 3.7b and 3.7c showed that the motion capture system measured sparse and sporadic points of free-fall, disagreeing with the prediction. In the single elastic cord set-up and the first condition of the double elastic cord set-up (Figure 3.6 and 3.7a) the motion capture system measured periods of consecutive frames of free-fall. The results suggest that true free-fall should occur in consecutive frames, therefore, the motion capture system is able to capture periods of free-fall.

The main advantage of the mass attached to a wooden frame by elastic cords was that it was a simple set-up and limited the majority of the motion to the vertical direction. However, women's breasts are far more complex, with the difficulties of isolating the motion of the breast in the vertical direction. The results suggest that smaller sized breasts (cup AA and A) may not have a neutral position as the breast tissue may always be under tension. However, periods of true free-fall should occur in consecutive frames.

3.7 Chapter summary

The aim of this chapter was to assess whether periods of free-fall can be captured using the three-dimensional motion capture system. The results show that points of free-fall (-1.00 ± 0.04 g) can be detected with a three-dimensional motion capture system in dynamic trials of an oscillating metal plate. The motion of the metal plate in both the single and double elastic cord set-ups were too simple to be a true representation of the motion of a complex breast. Therefore, testing needs to be completed on a female breast to locate the vertical neutral position during a lift and drop test established by Haake and Scurr (2011).

4 Measuring free-fall in a female breast

4.1 Introduction

All materials including living tissue have a point of failure, where they endure too much stress (Garrett et al. 1988; Benham and Crawford 1993). Failure occurs when the material is fatigued from repeatedly being loaded and unloaded below the ultimate tensile stress or even the yield stress (Benham and Crawford 1993) which would link into the hypothesis that movement-induced breast pain may occur due to the tissue being strained (Mason, Page and Fallon 1999). However, it is difficult to calculate stress or strain directly from the tissue. Surface displacements have been used as a proxy, as displacements can be classified as a change in length, which are associated with the local deformation of the body. Therefore, strain is calculated as (Eq. 6):

$$\varepsilon = \frac{\delta}{L_O} = \frac{d - L_O}{L_O} = \frac{d}{L_O} = -1 \qquad \text{Eq. 6}$$

Haake and Scurr (2011) made the assumption that the breast consists of a point mass, m, attached to the body and supported by a viscoelastic element of undeflected length L_O; d is the distance of the nipple from the suprasternal notch; and δ is the extension of the viscoelastic element. The undeflected length, L_O, was defined as the vertical distance between the suprasternal notch and the neutral position. This is the point at which the upper and lower tissues of the breast are neither in tension nor compression. Newton's second law was used to find the force acting on the nipple during motion (Eq. 7):

$$m\ddot{y} = F - mg \qquad \text{Eq. 7}$$

where y is the vertical position of the breast with respect to the suprasternal notch and F is the force acting on the breast tissue. The mass m is the effective mass at the nipple.

In the static position $\ddot{y} = 0$, the supporting force of the breast given by the breast/bra combination is given by F = mg. Therefore, the breast will be in the neutral position when $F \approx 0$ such that $\ddot{y} \approx -g$.

It has been quantified in previous literature that 56% of breast motion during treadmill walking and running occurred in the vertical direction (Scurr, White and Hedger 2009). Therefore, Haake and Scurr (2011) developed a technique, the static lift and drop test, to isolate the motion of the breast to the vertical direction, to identify the vertical neutral position. In chapter 3 it was identified that the motion capture system was able to measure periods of free-fall in simple motion. Thus it is important to identify whether true-fall in a female breast occurs in consecutive frames when performing a static lift and drop test.

4.2 Aim and objectives

Aim

To identify the neutral position in a female breast using the method developed by Haake and Scurr (2011).

Objectives

- Collect three-dimensional breast kinematics from a single participant;
- Identify and locate the vertical neutral position.

4.3 Methods

Participant

Following institutional ethics approval, one female participant was recruited [age: 20 years; body mass: 60 kg; height: 1.65 m] and gave written informed consent. The participant was recreationally active, had experienced no surgical procedures to the breast, had not gone through pregnancy within the last year and was pre-menopausal.

Data collection

The participant's breast size was measured by the principal investigator. Following the recommendations of McGhee and Steele (2006), the participant stood braless in a t-shirt with their arms relaxed by their side, all measurements were taken using a dress maker's tape measurer. Following expiration, the under bust chest circumference (UBCC) was determined by measuring from around the back to under the breast level with the inframammary fold. If the UBCC value was even, 4 inches were added to the value. If the number was odd, 5 inches were added. This provided the band size. The over bust chest circumference (OBCC) was obtained by measuring around the back and over the most prominent part of the breast. The difference between UBCC and OBCC determined the cup size, e.g. 1 inch equated to an A cup, 2 inches equals a B cup etc. The participant's breast size was a 34D.

Two 12 mm diameter retroreflective markers were attached to the right nipple and the suprasternal notch (Figure 4.1). The marker on the suprasternal notch was used as a body reference marker. This is a common anatomical landmark used in breast biomechanics. One of the main reasons is that the suprasternal notch is a rigid structure which has very little subcutaneous tissue overlying the bone and is easy to locate in all participants. This marker was used in the calculation of the displacement of the breast during motion in the Global Coordinate System.

The three-dimensional marker positions were tracked using eight calibrated three-dimensional infrared motion capture cameras (Motion Analysis Corporation, Santa Rosa, USA), sampling at 200 Hz and positioned in a semi-circle around the front of the capture volume. The global coordinate system was defined with respect to the laboratory and identified x as mediolateral, y as vertical and z as the line of progression (anteriorposterior) (Figure 4.1). The global coordinate system was not converted to a local coordinate system as Mills et al. (2014[a]) showed that depending on how the local coordinate system is created can affect the magnitudes of the breast motion calculated.

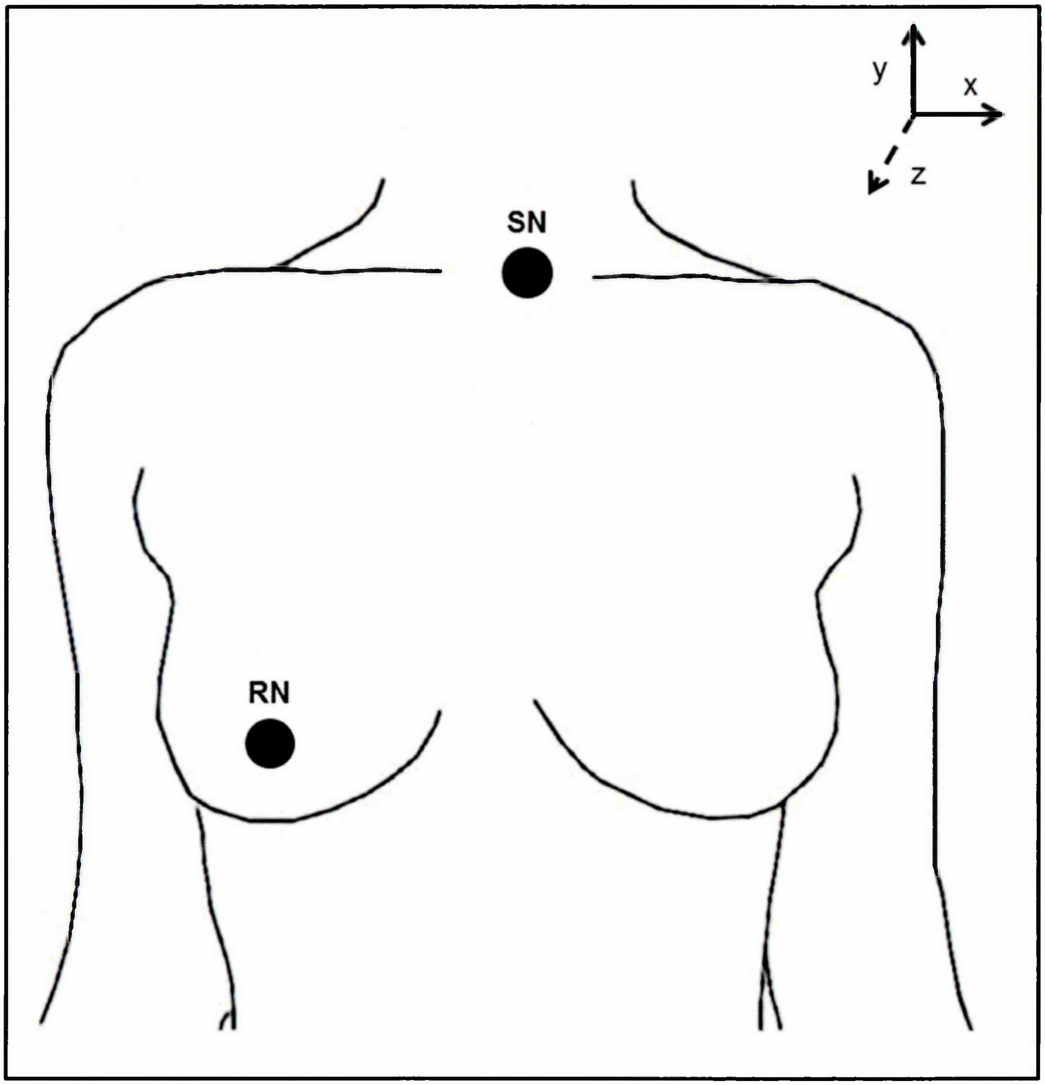


Figure 4.1: Marker positions on the upper body (SN = suprasternal notch; RN = right nipple) and orientation of the global coordinate system.

Using the method developed by Haake and Scurr (2011), the participant was asked to stand stationary without a bra and lift their right breast and then let it drop under gravity. This was repeated three times.

Data processing

Each trial was post-processed in Cortex (Motion Analysis Corporation, Santa Rosa, USA) to identify and track the two markers of interest. The three-dimensional coordinates for each marker were exported into MS Excel. Each marker was filtered in MATLAB® (The MathWorks. Inc, Massachusetts, USA) using a 4^{th} order zero-phase Butterworth filter, with a range of cut-off frequencies of 7 to 9 Hz. The cut-off frequencies were established from the residual analysis performed on the vertical direction of each marker and each trial.

Data analysis

The vertical nipple displacement during the static lift and drop was double differentiated using a five-point central differencing method to identify the time at which free-fall (-1.00 g ± 0.04 g) occurred after the unsupported breast was released to before the first breast bounce. The vertical nipple displacement was made relative to the suprasternal notch (vertical nipple coordinate - vertical suprasternal notch coordinate) to identify the neutral position at that point in time.

4.4 Results

During the first static lift and drop test (Figure 4.2), the greatest vertical breast displacement was -93.1 mm at 0.15 s where the breast was lifted before being released. The breast reached a minimum displacement of -154.9 mm at 0.44 s where the breast had reached the bottom of the drop. The breast then went through a series of oscillations before reaching the static resting height at a minimum breast displacement of -156.2 mm occurring at 0.67 s (Figure 4.2a). Peak upward acceleration of approximately 0.98 g occurred at point A (Figure 4.2b). The acceleration - displacement graph (Figure 4.2C) shows that between point O to A, the nipple spent the first half of the falling phase in a negative acceleration until rising in a non-linear fashion at an approximate displacement of -119.0 mm to a maximum acceleration at A.

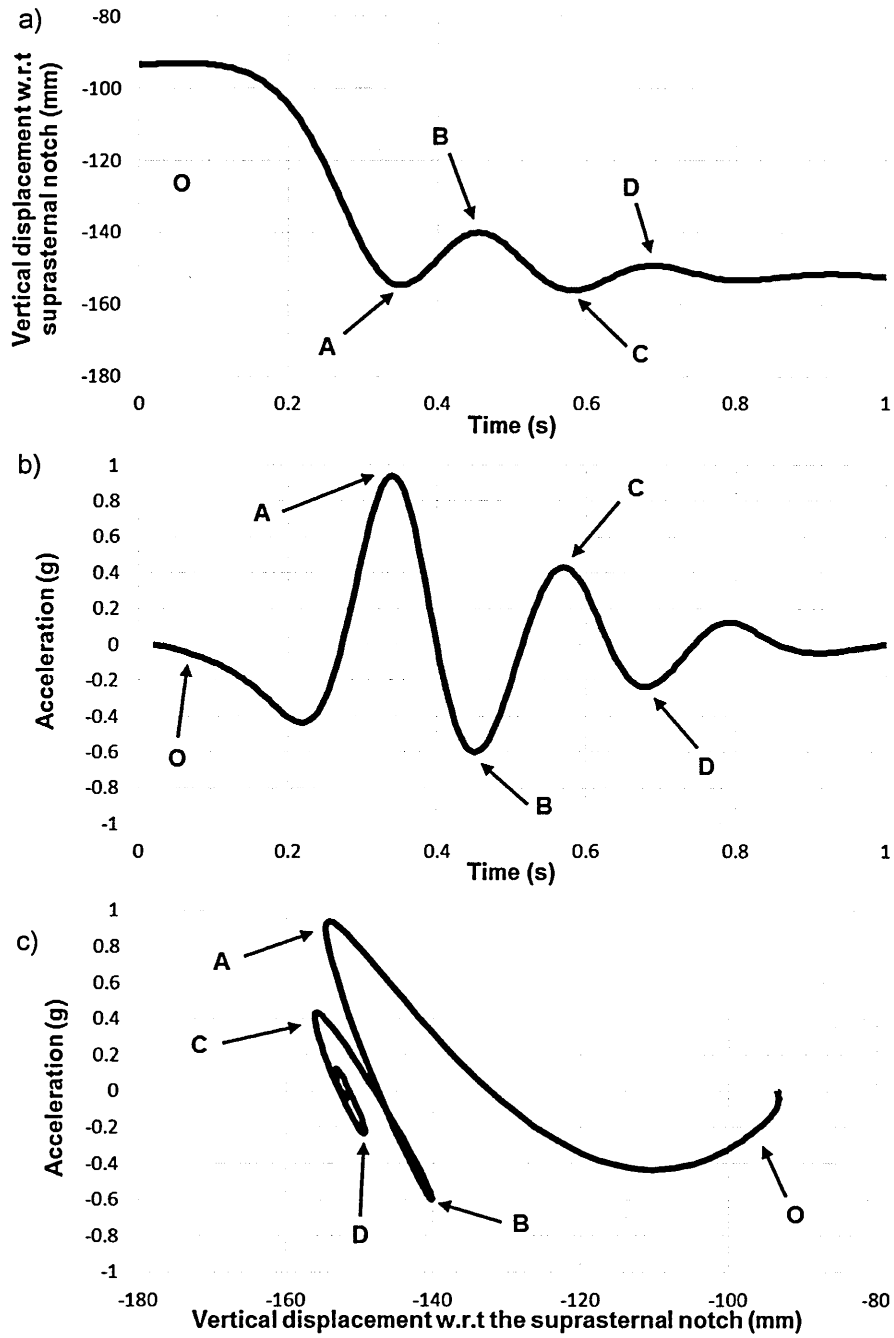


Figure 4.2: Typical trial of a static lift and drop test with no breast support; a) displacement versus time; b) acceleration versus time; and c) acceleration versus displacement. Letters represent the following: O at initial lifted breast position, A initial breast bounce, B - D subsequent oscillations.

The greatest maximum negative acceleration between the point of release and the first breast bounce in all trials was found in trial 2 at -0.64 g ± 0.04 g (Table 4.1).

Table 4.1: Maximum negative acceleration found in each trial from point O to A (max ± Abs. RMS error).

Trial	Maximum negative acceleration (g)
1	-0.44 ± 0.04
2	-0.64 ± 0.04
3	-0.41 ± 0.04

4.5 Discussion

The aim of this study was to identify a true vertical neutral position in a female breast using the lift and drop test developed by Haake and Scurr (2011). It was found in this particular participant that during the drop tests, the breast did not reach an acceleration of -1.00 g.

Haake and Scurr (2011) and Haake, Milligan and Scurr (2012) used participants with a range of cup sizes 32A to 34G. The cup size of the participant used in this study was within this range. Figure 4.2 in this study reflected those presented in the previous papers. Haake and Scurr (2011) suggested that a neutral position should be located between the moment the breast was released until the first breast bounce. Both Haake and Scurr (2011) and Haake, Milligan and Scurr (2012) studies found a vertical neutral position for each of their participants. However, an acceleration of -1.00 g was not achieved in the three trials of the single participant in this study. Therefore, the results suggest that the method is not robust for different participants to identify a vertical neutral position. There are several possible reasons for the difficulties in obtaining the vertical neutral position using this method. Firstly, the participant may not have lifted the breast above the region of free-fall. Secondly, the motion of the breast may not be entirely vertical, which may have been caused by the participant using the right hand to lift the right breast. Finally, the participant may not have lifted all of the breast tissue.

The main advantages of this method were that it was simple and reduced the motion of the breast to the vertical direction. The potential limitation of this study was that there was only one reference marker that was rigidly attached to the suprasternal notch. This limits the measurements of the breast to the global coordinate system, as the construction of the local coordinate system requires at least three rigid markers. Haake and Scurr (2011) use only the suprasternal notch as the reference marker and calculate their variables in the global coordinate system. Previous literature have used the left and right anterior aspect of 10th rib to calculate the local coordinate from. Mills et al. (2014[b]) assessed torso rigidity using a vector between the suprasternal notch and virtual mid-rib marker (created from the left and right anterior aspect of the 10th rib). The study showed that the markers placed on the torso move relative to each other, therefore changing the length of the torso segment. This then affects the magnitude that the breast deflects from the origin of the local coordinate system. Mills et al. (2014[a]) showed that depending on how the local coordinate system is created can affect the magnitude of breast displacement.

Further work is therefore required to identify and locate a vertical neutral position as a proxy for the undeflected length of the viscoelastic element in calculating stress. An array of techniques need to be developed and systematically investigated for their suitability and repeatability in isolating the motion of the breast to the vertical direction, locating the vertical neutral position and produce little to no breast discomfort.

4.6 Chapter summary

The technique developed by Haake and Scurr (2011) to locate the neutral position was replicated in this study. The results suggest that the lift and drop test was inappropriate as a neutral position was not identified in this participant. Therefore, further work in identifying an appropriate method in locating the neutral position is required.

5 Assessing simple movements in identifying a neutral position

5.1 Introduction

The previous case study showed that the vertical neutral position of the breast could not be found using the lift and drop test developed by Haake and Scurr (2011). Three possible reasons for this were: 1) the participant may not have lifted the breast above the region of free-fall, 2) the motion of the breast may not have been entirely vertical, and 3) the participant may not have lifted all of the breast tissue. Therefore, a more appropriate method of locating the vertical neutral position is required that meets the following criteria:

1. Simple activity: requires low skill and little equipment;
2. Suitable: produces low breast discomfort scores (<3)
3. Repeatability: the breast acceleration during the activity reaches -1.00 g in the vertical direction.

5.2 Aim and objectives

Aim

To systematically assess an array of techniques for their suitability and repeatability in identifying and locating a vertical neutral position of the breasts.

Objectives

- Develop simple activities;
- Collect three-dimensional breast kinematics from multiple participants with a range of breast sizes;
- Explore the characteristics of breast and body kinematics for each movement;

- Explore the temporal characteristics of the breast and body markers for each movement;
- Identify and locate the vertical neutral position;
- Assess the suitability and repeatability of each activity in locating the vertical neutral position.

5.3 Methods

Participant

Following institutional ethics approval, seven women were recruited and gave written informed consent. Participants had an average age of 24.6 years (± 4.0 years), body mass of 66.1 kg (± 4.5 kg), height of 1.7 m (± 0.1 m) and body mass index of 22.7 (± 2). The participants were recreationally active, had experienced no surgical procedures to the breast, had not gone through pregnancy within the last year and were pre-menopausal.

Data collection

The participants' breast sizes were measured by the principal investigator, following McGhee and Steele's (2006) method - see section 4.3 - and ranged from 34A to 36D. Three 12 mm diameter retroreflective markers were attached to the right and left nipple (to represent the motion of the centre of mass of the breast), and the suprasternal notch (to represent the motion of the whole body) (Figure 5.1). The three-dimensional marker position was tracked using ten calibrated three-dimensional infrared motion capture cameras (Motion Analysis Corporation, Santa Rosa, USA), sampling at 200 Hz and positioned in a semi-circle around the front of the capture volume. The laboratory coordinate system identified x as mediolateral, y as vertical and z as the line of progression (anteriorposterior) (Figure 5.1).

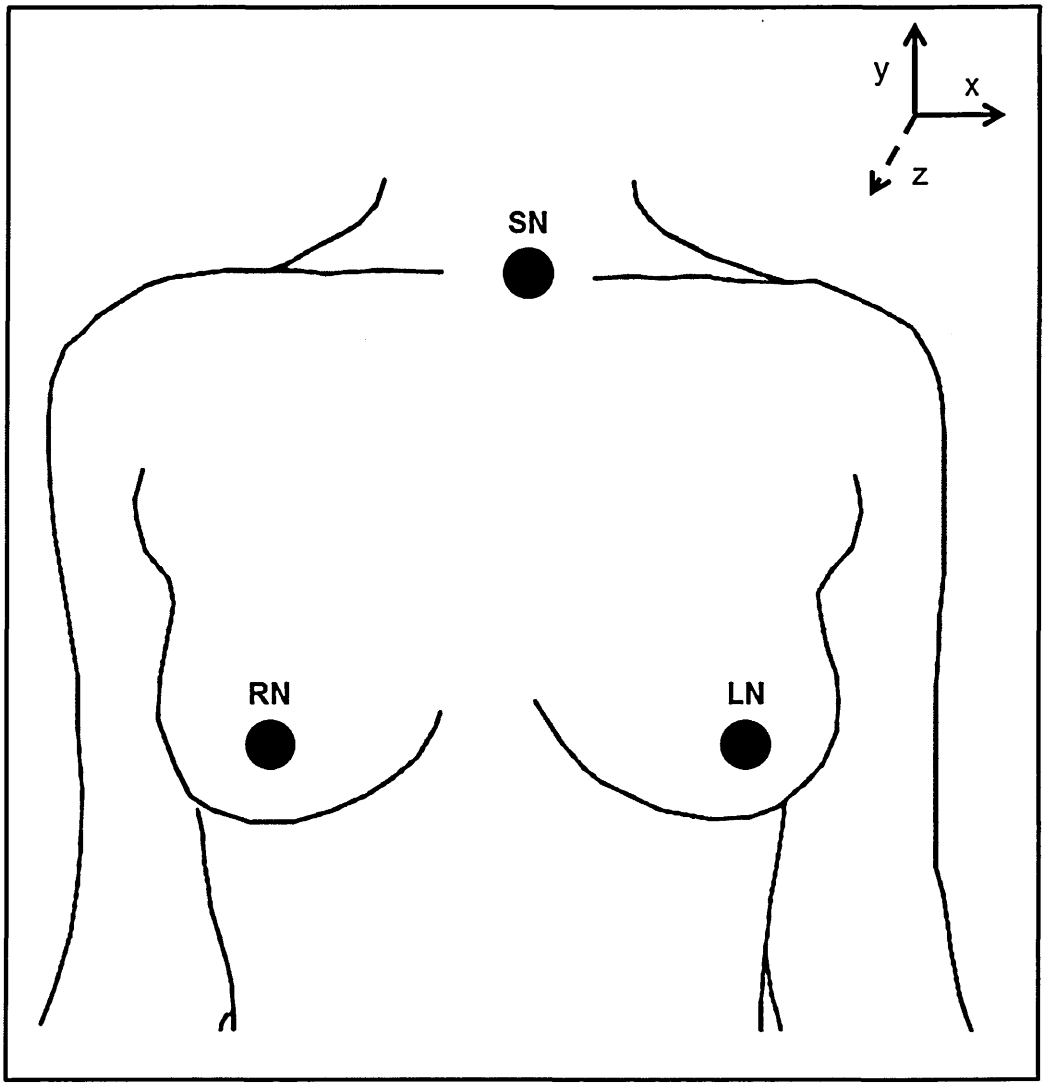


Figure 5.1: Marker positions on the upper body (SN = suprasternal notch; RN = right nipple; LN = left nipple) and orientation of the global coordinate system.

The participants performed a five-minute warm-up on a treadmill H-P-Cosmos-Kistler Gaitway II S (H-P-Cosmos Sports and Medical/Kistler Instrument Corporation) wearing their own exercising bra at a self-selected speed. The participant was habituated to six activities, these were: 1) running on a treadmill at 10 $km.hr^{-1}$ for 19 s; 2) a vertical countermovement jump with arms akimbo; 3) stepping off a low box (0.26 m) with arms akimbo; 4) stepping off a high box (0.51 m) with arms akimbo; and 5) lifting the right breast with the left hand and letting the breast drop due to gravity and repeated on the left breast with the right hand. All tasks were performed bare breasted and apart from the treadmill activities they were repeated five times. The participants rated their perceived breast discomfort on a 10 cm VAS (0 = comfort, 10 = discomfort) before and after each trial (McGhee and Steele 2010). Participants rested for up to 2 minutes between each activity.

Data processing

Each trial was post-processed in Cortex (Motion Analysis Corporation, Santa Rosa, USA) to identify and track the three markers of interest. The x, y, z coordinates for each marker were exported into MS Excel. The three-dimensional coordinates for each marker were filtered in MATLAB® (The MathWorks. Inc, Massachusetts, USA) using a 4th order zero-phase Butterworth filter, with a range of cut-off frequencies of 6 to 12 Hz. The cut-off frequencies were established from a residual analysis on the vertical direction of each marker. The vertical positions of the nipple and suprasternal notch were double differentiated using a five-point central differencing method to give acceleration. The vertical nipple displacement was also calculated relative to the suprasternal notch.

Data analysis

The vertical acceleration of the supraste68rnal notch was used to determine the region where the body was in free-fall (-1.00 ± 0.04 g). During this region, times were taken where the nipple reached vertical accelerations of -0.96 g, -1.00 g, and -1.04 g. A linear interpolation method between two data points was used to locate the exact times that the left and right breast reached these accelerations. The breast displacements relative to the suprasternal notch at these time points were recorded as the vertical neutral positions, separated into upward and downward motion, where the breast tissue was neither in tension nor compression. The resting height of the participants' right and left breast were calculated as the mean ± SD of the stationary data at the start of each high box trial. The vertical displacements of the suprasternal notch and left nipple markers were calculated as a percentage of the resultant displacements for each trial. This was calculated by summing the vectors during the period in which the body was in free-fall. The graphs presented throughout the results are of a typical trial of participant 3 (size 36D breasts).

5.4 Results

Run

During the run at 10 km.hr^{-1} (Figure 5.2a), the participant was in the stance phase of the gait cycle on the left leg between C to D, maximum height of the flight phase at B, indicated by a body acceleration of -1.00 g ± 0.04 g. Before entering into the stance phase on the right leg (Figure 5.2a: E - A). The body was in the air for about 0.095 s (Figure 5.2a: D - E). The suprasternal notch and nipple markers followed a similar trajectory, oscillating at about 2.5 Hz. There was a slight time delay in the nipple markers reaching maximum peak displacement by about 0.05 s after the ipsilateral leg was in contact with the ground and approximately 0.03 s after the contralateral leg was in contact with the ground; whereas the minimum displacements were approximately in phase.

A double peak in the vertical breast displacement relative to the suprasternal notch was found during the flight phase of the run (Figure 5.2b). The double peak was more apparent in the upwards motion of the breast relative to the suprasternal notch (t = 11.10 s to 11.30 s) when pushing off the ground with the contralateral foot. As the participant begins to straighten the leg in the stance phase the nipple marker moved upwards closer to the suprasternal notch. When the participant pushed off the ground the suprasternal notch and nipple moved upwards at the same rate creating a plateau before the nipple was pulled upwards due to the tension in the upper breast tissue. Due to gravity, the body moved downwards to the ground causing the suprasternal notch to move in the same direction. The nipple continued to move upwards towards the suprasternal notch, reaching a peak in displacement (Figure 5.2b: C). When the foot came into contact with the ground the breast moved downwards away from the suprasternal notch reaching a minimum peak displacement. The minimum peak in displacement created tension in the upper breast tissue which caused the breast to be pulled upwards. It was noted that when the ipsilateral foot contacted the ground the breast reached greater minimum and maximum peak displacement than when the contralateral foot was in contact with the ground.

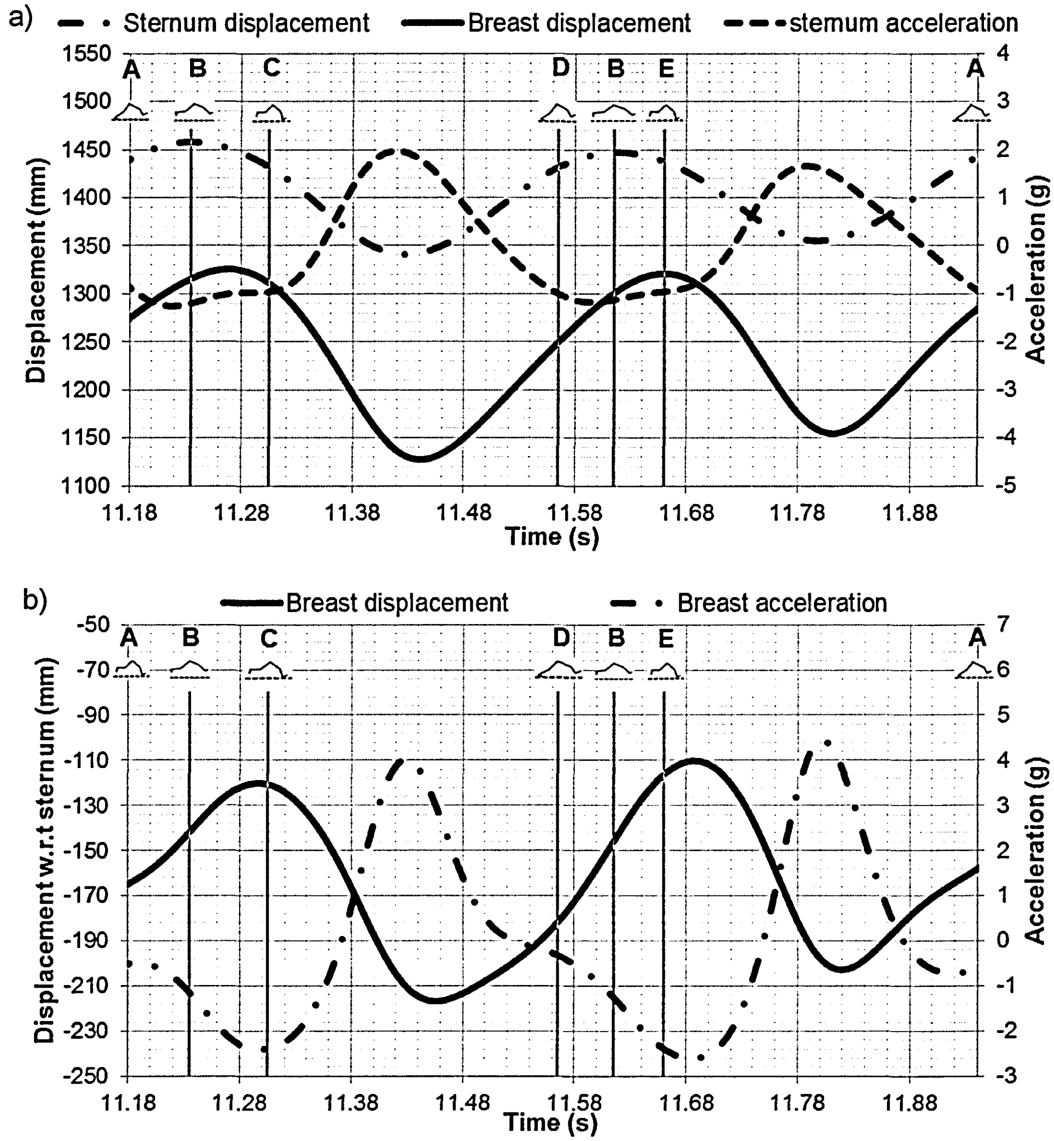


Figure 5.2: Motion of the left nipple of a 36D - sized participant during a typical gait cycle in a bare breasted run. a) Breast and suprasternal notch vertical displacement (left axis) and suprasternal notch vertical acceleration (right axis). b) Vertical breast displacement with respect to the suprasternal notch and vertical breast acceleration. (B = maximum height of the sternal notch during the flight phase; C - D = left leg support phase; E - A = right leg support phase).

The vertical neutral positions calculated over five gait cycles during the running trial are shown in Figure 5.3 and compared to the static resting height of the breast before testing. Error bars indicate the standard deviation. It can be seen that the neutral positions are consistently above the static resting height. The neutral positions found in the right breast were similar to those of the left breast. However, the neutral positions were not consistently found in all five gait cycles within each participant.

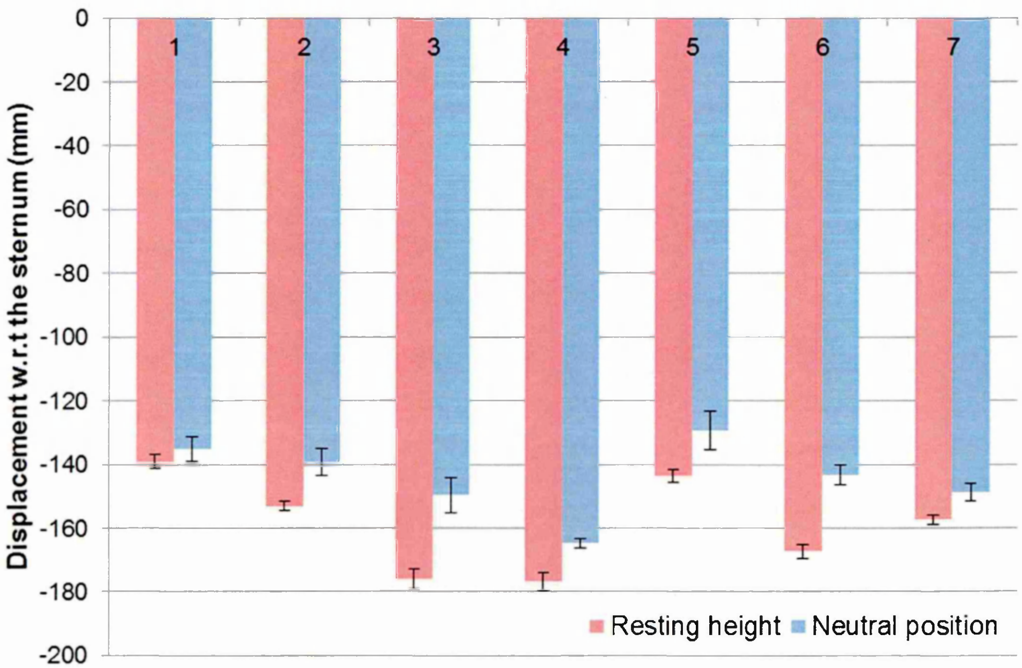


Figure 5.3: Mean ± SD of the resting height and vertical neutral position of the left breast during five gait cycles in a bare breasted 10 $km.hr^{-1}$ running trial for each participant.

The vertical displacement as a percentage of the resultant displacement for the suprasternal notch marker ranged from 54.5% to 88.7% and the left nipple marker varied from 60.3% to 97.1% (Table 5.1).

Table 5.1: Mean ± SD of the vertical displacement as a percentage of the resultant displacement occurring in the vertical global coordinate system for the suprasternal notch and left nipple markers during the free-fall regions of the body over five gait cycles in a bare breasted 10 km.hr^{-1} run for each participant.

		% of the resultant displacement in the vertical direction	
Participant	Bra size	Suprasternal notch	Left nipple
1	34 C	76.6 ± 14.2	86.2 ± 19.8
2	34 A	88.7 ± 7.5	87.5 ± 18.8
3	36 D	61.7 ± 11.1	79.4 ± 8.9
4	36 B	66.5 ± 16.4	97.1 ± 2.1
5	36 C	75.1 ± 1.5	66.6 ± 35.6
6	36 D	54.5 ± 23.7	60.3 ± 33.0
7	38 B	57.9 ± 10.5	80.5 ± 10.4

Vertical countermovement jump

During the vertical countermovement jump (Figure 5.4a) the participant started off stationary at A, bent the knees at B, lifted off the ground between C and E, bent the knees after making contact with the ground at F and returned to the stationary position at G. The body was in the air between C and E for 0.41 s.

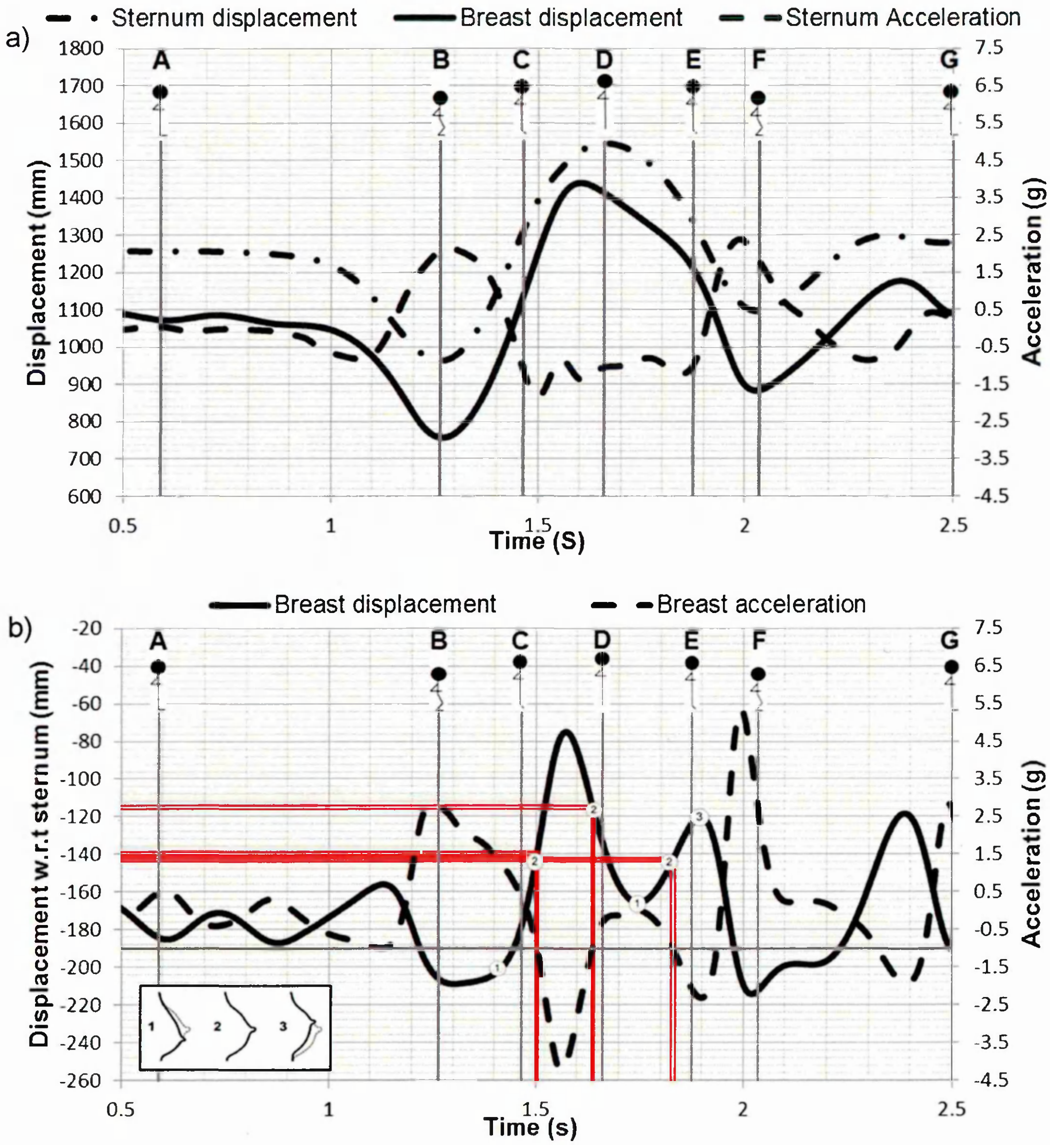


Figure 5.4: Motion of the left nipple of a 36D - sized participant during a typical counter-movement jump. a) Breast and suprasternal notch vertical displacement (left axis) and suprasternal notch vertical acceleration (right axis). b) Vertical breast displacement with respect to the suprasternal notch (left axis – solid line) and vertical breast acceleration (right axis – dashed line). (A, G = stationary; B = pre-jump knee flexion; C to D = upwards flight; D to E = downwards flight; F = knee flexion on landing; red lines = vertical neutral position boundaries; 1 = tension in upper breast tissue; 2 = vertical neutral position; 3 = compression in upper breast tissue).

The vertical displacement of the breast relative to the suprasternal notch illustrated that the breast experienced almost two oscillations during flight (Figure 5.4b: C – E). The initial height of the breast in the vertical direction was -161.6 mm relative to the suprasternal notch, where the upper-side of the breast tissue was in tension due to gravity. When the participant pushed off the ground between B and C, tension in the upper-side of the breast tissue increased (Figure 5.4b: 1), causing the breast to be pulled up, passing through the resting height. As the tissue on the upper-side of the breast compressed, the lower-side of the breast tissue was in tension (Figure 5.4b: 3). The tissue on the lower-side of the breast pulled the breast downwards, passing through a vertical neutral position (Figure 5.4b: 2). The breast tissue on the lower-side then went into compression while the tissue on the upper-side went into tension (Figure 5.4b: 1). The tension in the upper-side pulled the breast upwards, passing through a neutral position (Figure 5.4b: 2), reaching the second peak. After the second peak during the downward motion of the breast, the body comes into contact with the ground (Figure 5.4b: E), which caused the breast to reach a minimum position (t = 2.02 s).

The vertical neutral positions were found in both the upward and downward direction of motion and have been split into initial and final upwards and downwards motion. The vertical neutral positions of the left breast in the initial upwards direction were all above the resting height of the breast (Figure 5.5a). It was also found that all neutral positions in both the downwards and final upwards direction were above the resting height of the breast (Figure 5.5b). The vertical neutral positions in the upwards direction were further away from the suprasternal notch than the neutral positions in the downward direction. Also the vertical neutral positions in the upwards direction coincided with each other apart from in participant 5. The right breast followed a similar pattern as that of the left breast.

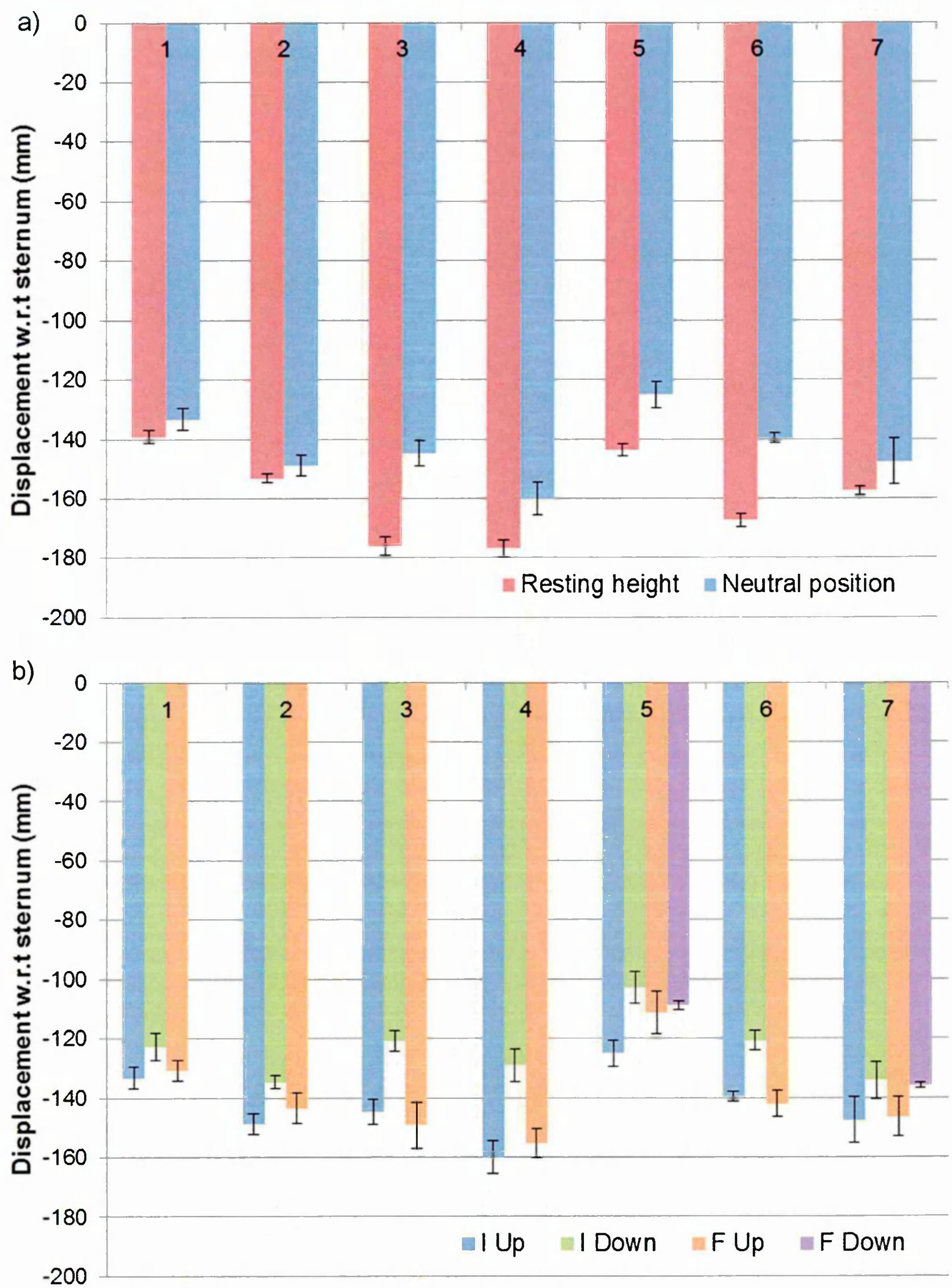


Figure 5.5: Mean ± SD of a) the resting height and vertical neutral position in the initial upwards direction; and b) initial (I) and final (F) neutral positions of the left breast during five vertical countermovement jump trials for each participant.

Vertical displacement contributed approximately 98% to the resultant displacement in both the suprasternal notch and left nipple markers (Table 5.2).

Table 5.2: Mean ± SD of the vertical displacement as a percentage of the resultant displacement occurring in the vertical global coordinate system for the suprasternal notch and left nipple markers during the free-fall region of the body over five vertical countermovement jump trials in each participant.

		% of t the resultant displacement in the vertical direction	
Participant	Bra size	Suprasternal notch	Left nipple
1	34 C	99.3 ± 0.6	99.1 ± 0.5
2	34 A	99.3 ± 0.7	99.3 ± 0.8
3	36 D	98.4 ± 2.9	97.2 ± 3.2
4	36 B	98.7 ± 1.6	98.0 ± 2.0
5	36 C	99.5 ± 0.6	99.3 ± 0.6
6	36 D	98.7 ± 1.9	98.4 ± 1.9
7	38 B	99.6 ± 0.7	99.7 ± 0.4

Low box

At the start of the low box activity (Figures 5.6a) the participant stood stationary on top of the box at A, stepped off the box with straight legs and fell to the ground due to gravity between B and C, bends the knees after contacting the ground at D and returned to a stationary position at E. The body was in the air for 0.08 s.

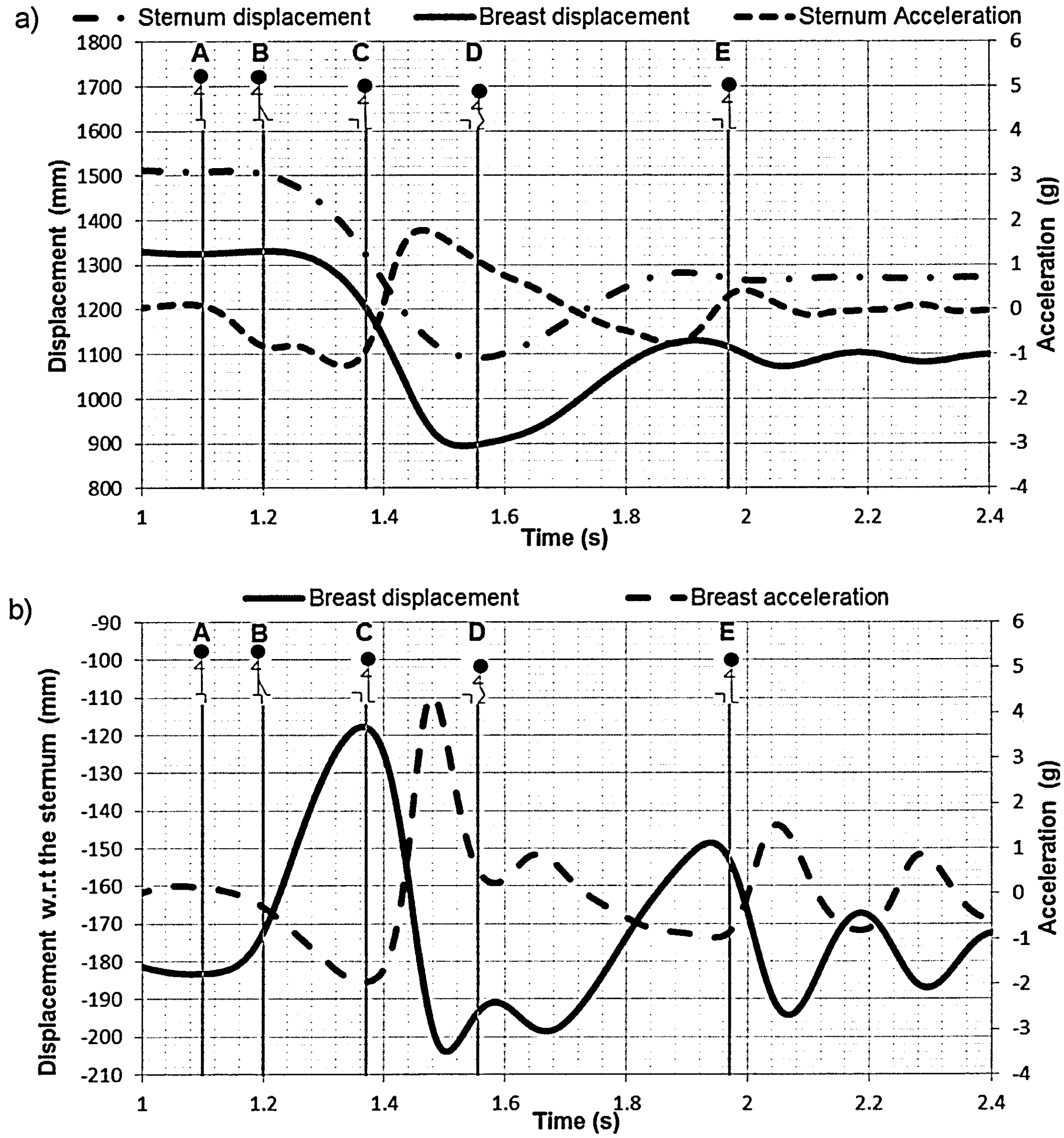


Figure 5.6: Motion of the left nipple of a 36D - sized participant during a typical low box activity. a) Breast and suprasternal notch vertical displacement (left axis) and suprasternal notch vertical acceleration (right axis). b) Vertical breast displacement with respect to the suprasternal notch (left axis – solid line) and vertical breast acceleration (right axis – dashed line). (A, E = stationary; B to C = downwards flight; D = knee flexion on landing).

The relative vertical displacement of the breast (Figure 5.6b) showed that prior to point B (t = 1.00 to 1.20 s) the left breast was at a minimum position, which created tension in the upper-side of the breast tissue. The tension in the upper-breast tissue caused the breast to be pulled upwards towards the suprasternal notch (Figure 5.6b: B - C). At C the participant landed causing the breast to be pulled downwards to a minimum position (t = 1.51 s). The breast then oscillated before returning to a stationary position.

For the participants who showed a vertical neutral position in the left breast during either upwards or downwards motion, was above the breast's resting height (Figure 5.7). Similar vertical neutral positions were found in the right breast. Not all participants managed to experience a free-fall region during the activity and the participants that showed a neutral position, did not produce one in every trial.

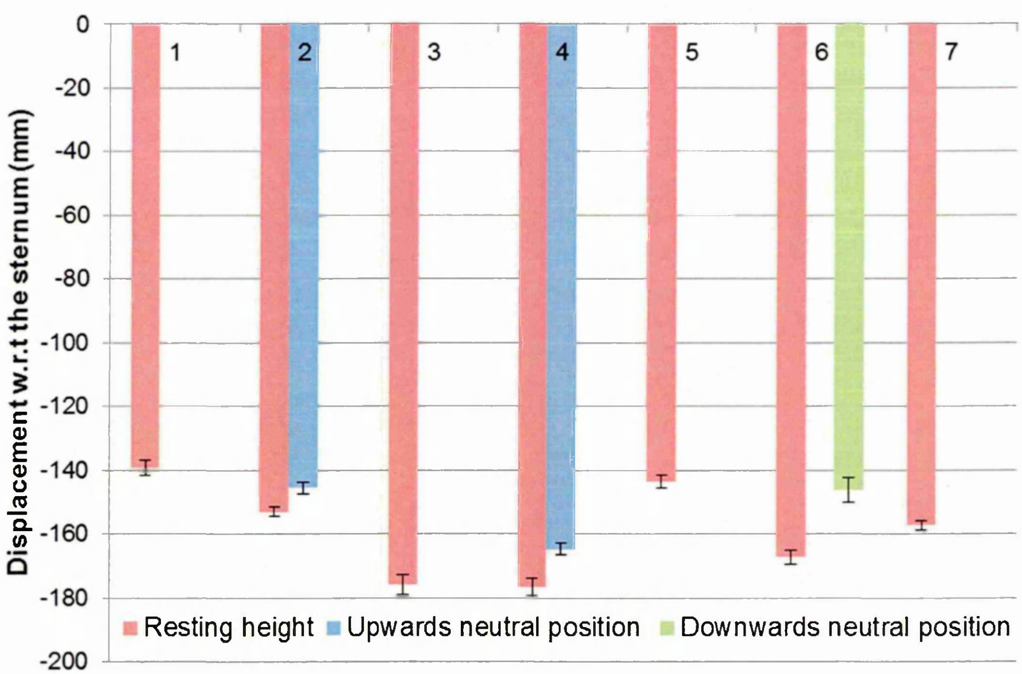


Figure 5.7: Mean ± SD of the resting height and vertical neutral position of the left breast during five low box trials for each participant.

During the five trials of the low box activity the body of participants 1, 5 and 7 did not reach an acceleration of -1.00 g. Therefore, results of the mean vertical displacement of the suprasternal notch and left nipple markers as a percentage of the resultant displacement were not presented in table 5.3. It was shown in the other four participants that the suprasternal notch and left nipple markers produced a mean vertical displacement of 92.5% to 97.7% of the resultant displacement (Table 5.3).

Table 5.3: Mean ± SD of the vertical displacement as a percentage of the resultant displacement occurring in the vertical global coordinate system for the suprasternal notch and left nipple markers during the free-fall region of the body over five low box trials in each participant.

		The mean vertical displacement as a % of the resultant displacement	
Participant	Bra size	Suprasternal notch	Left nipple
1	34 C	-	-
2	34 A	95.9 ± 2.7	97.0 ± 3.0
3	36 D	99.6 ± 0.2	99.7 ± 0.2
4	36 B	98.7 ± 30.9	92.5 ± 0.9
5	36 C	-	-
6	36 D	97.5 ± 0.8	98.0 ± 1.9
7	38 B	-	-

High box

The motion of the breast and suprasternal notch during the high box activity was similar to that of the low box shown in Figure 5.8. During the high box activity, the participant's body was in the air for approximately 0.25 s. The relative vertical displacement of the left breast illustrated that the breast experienced nearly one oscillation (Figure 5.8 b: B - C). Prior to B, the breast experienced tension in the upper-side of the breast tissue (Figure 5.8b: 1). The tension in the upper-side caused the breast to be pulled upwards through a neutral position (Figure 4.8b: 2) and then reached a maximum displacement creating tension in the lower breast tissue (Figure 5.8b: 3). Due to the tension in the lower breast tissue, the breast was pulled downwards through a neutral position (Figure 5.8b: 2) reaching a plateau before the participant made contact with the ground (Figure 5.8b: C) causing the breast to be pulled downwards to a minimum position (t = 1.85 s).

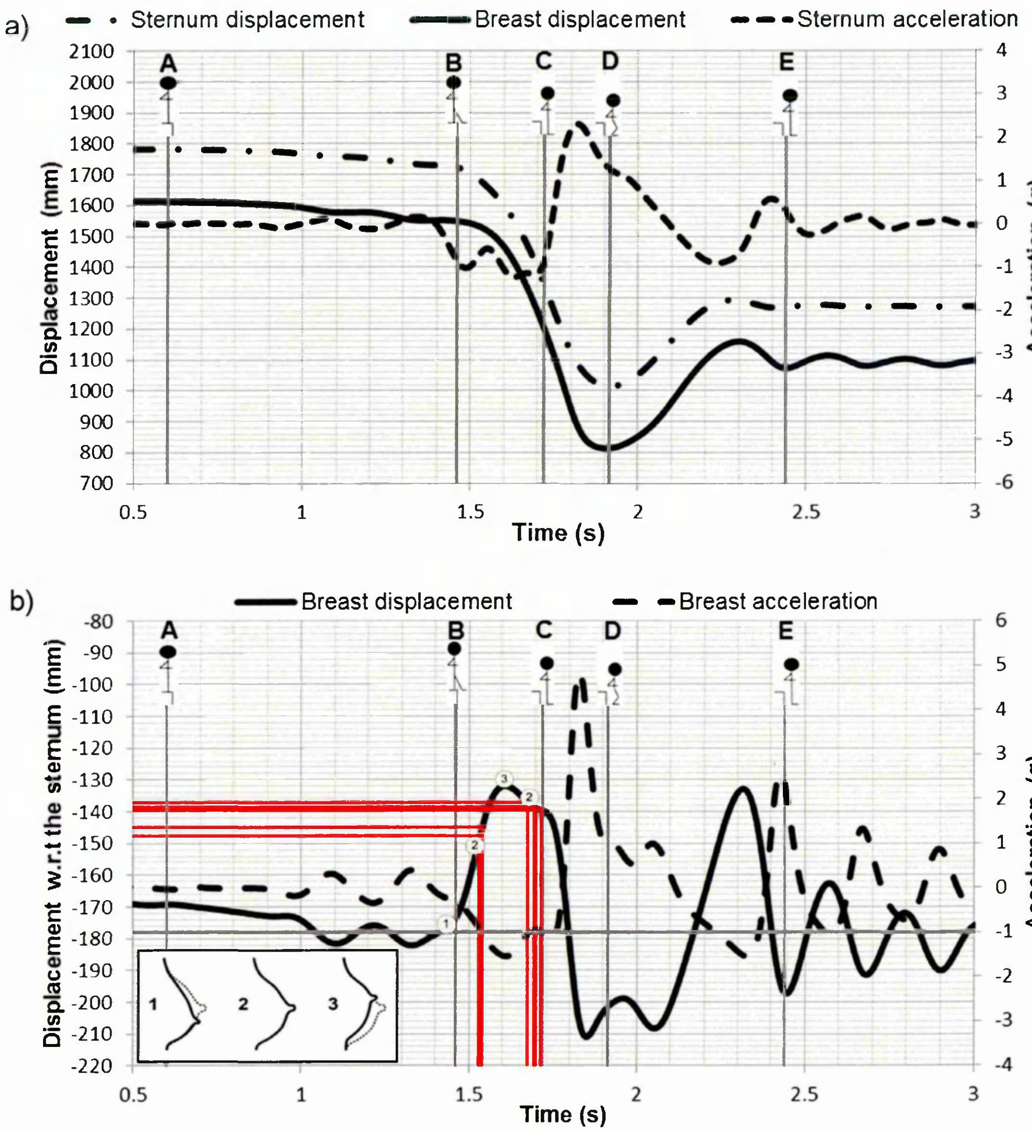


Figure 5.8: Motion of the left nipple of a 36D- sized participant during a typical high box activity. a) Breast and suprasternal notch vertical displacement (left axis) and suprasternal notch vertical acceleration (right axis). b) Vertical breast displacement with respect to the suprasternal notch (left axis – solid line) and vertical breast acceleration (right axis – dashed line). (A, E = stationary; B to C = downwards flight; F = knee flexion on landing; red lines = vertical neutral position boundaries; 1 = tension in upper breast tissue; 2 = vertical neutral position; 3 = compression in upper breast tissue).

The vertical neutral positions of the left breast found during the high box activity were all above the resting height of the breast (Figure 5.9). The neutral positions found during the downwards motion coincide with the neutral positions found in the upwards motion.

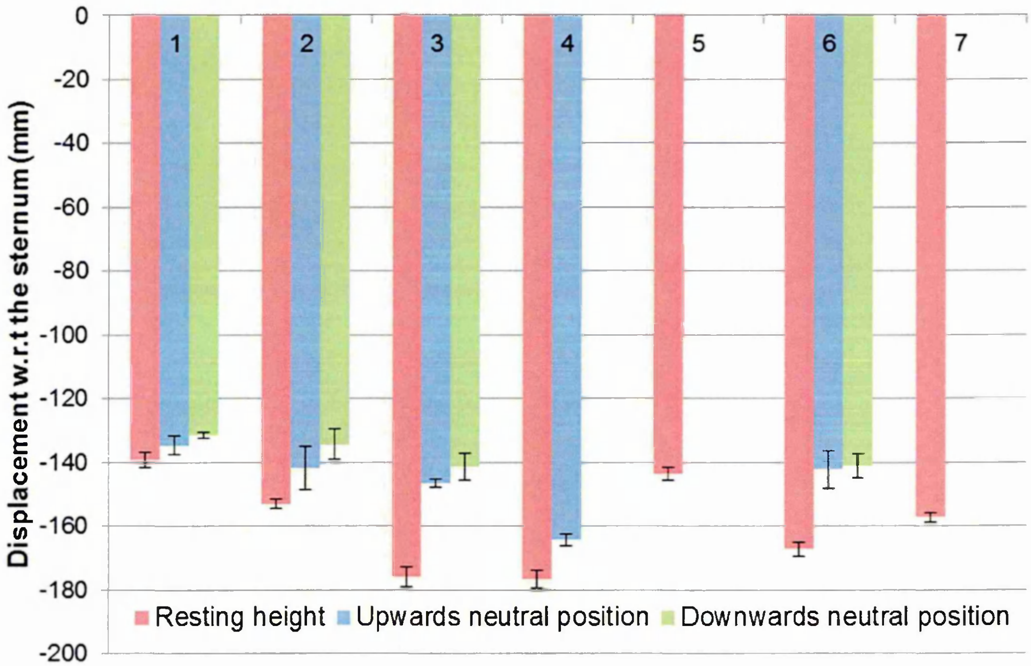


Figure 5.9: Mean ± SD of the resting height and vertical neutral position of the left breast during five high box trials for each participant.

During the five trials of the high box activity the body of participants 5 and 7 did not go through a region of free-fall, indicated by an acceleration of -1.00 g. The suprasternal notch and left nipple markers in the remaining five participants produced a mean vertical displacement greater than 99.0% of the resultant displacement (Table 5.4).

Table 5.4: Mean ± SD of the vertical displacement as a percentage of the resultant displacement occurring in the vertical global coordinate system for the suprasternal notch and left nipple markers during the free-fall region of the body over five high box trials in each participant.

		% of the resultant displacement in the vertical direction	
Participant	Bra size	Suprasternal notch	Left nipple
1	34 C	99.7 ± 0.2	99.6 ± 0.6
2	34 A	99.8 ± 0.2	99.9 0.1
3	36 D	99.7 ± 0.0	99.5 ± 0.2
4	36 B	99.8 ±0.2	99.7 ± 0.2
5	36 C	-	-
6	36 D	99.0 ± 0.5	99.5 ± 0.2
7	38 B	-	-

Lift and drop

During the lift and drop activity in this particular trial (Figure 5.10) the breast was lifted to an initial height of -98.6 mm (Figure 5.10: O). The breast was lifted further to -78.6 mm before being released. The breast dropped through two neutral positions, -95.6 mm and -107.2 mm between t = 1.57 s to 1.59 s (Figure 5.10: A), reaching a minimum displacement of -181.5 mm at B (t = 1.80 s). The breast went through a series of oscillations (Figure 5.10: C to E) before reaching a stationary position at F.

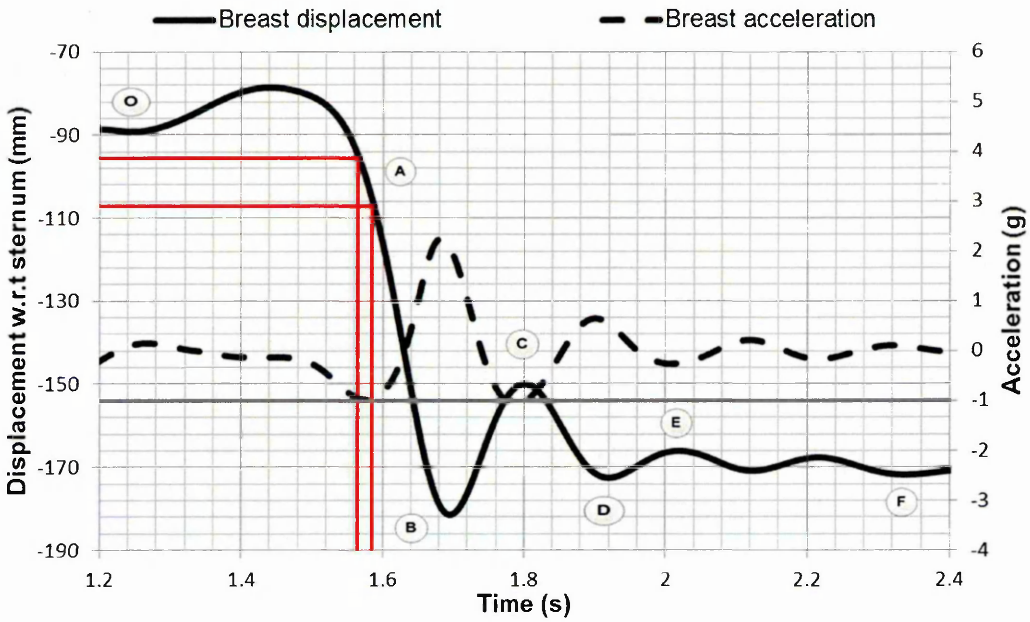


Figure 5.10: Motion of the left nipple of a 36D - sized participant during a typical lift and drop activity. Vertical breast displacement with respect to the suprasternal notch and vertical breast acceleration (O = initial lifted breast position; A = vertical neutral position; B = initial breast bounce; C - E = subsequent breast oscillation; red lines = vertical neutral position).

The vertical neutral positions of the left breast found in the participants during the lift and drop activity were closer to the suprasternal notch than the resting height of the breast (Figure 5.11). The spread of the neutral positions were greater in the lift and drop activity than in any of the other activities. The vertical neutral positions found in the right breast were similar to those in the left breast.

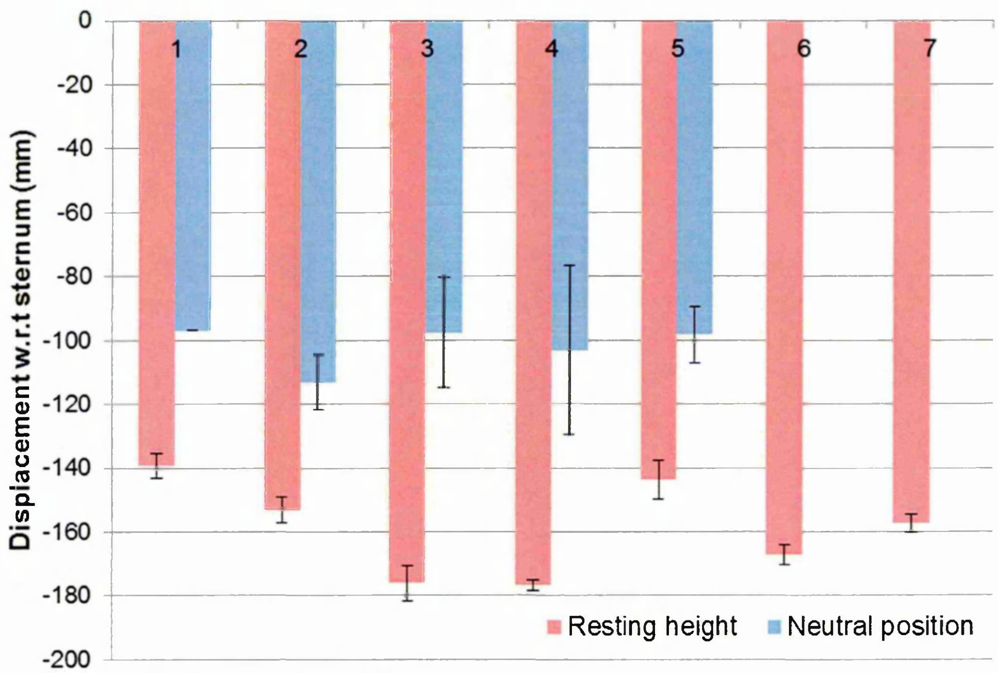


Figure 5.11: Mean ± SD of the resting height and vertical neutral position of the left breast during five lift and drop trials for each participant.

The mean vertical displacement as a percentage of the resultant displacement for the suprasternal notch marker varied from 30.5% to 63.4% whereas the left nipple marker ranged from 88.0% to 97.9% (Table 5.5).

Table 5.5: Mean ± SD of the vertical displacement as a percentage of the resultant displacement occurring in the vertical global coordinate system for the suprasternal notch and left nipple markers from the moment the breast was dropped under gravity until the first breast bounce over five lift and drop trials in each participant.

		% of the resultant displacement in the vertical direction	
Participant	Bra size	Suprasternal notch	Left nipple
1	34 C	43.4 ± 7.6	88.0 ± 4.4
2	34 A	30.5 ± 14.0	97.0 ± 3.0
3	36 D	63.4 ± 9.5	96.2 ± 2.0
4	36 B	35.2 ± 4.6	97.9 ± 0.6
5	36 C	50.8 ± 6.6	94.3 ± 1.1
6	36 D	62.7 ± 7.7	95.9 ± 1.7
7	38 B	44.7 ± 5.4	92.3 ± 4.7

Table 5.6: Summary of the five activities: flight times (mean ± SD), number of oscillations (mean ± SD), whether the breast reached an acceleration of -1.00 g ± 0.04 g, consistently found these accelerations in all the trials for each participant, above the resting height of the breasts and the level of discomfort.

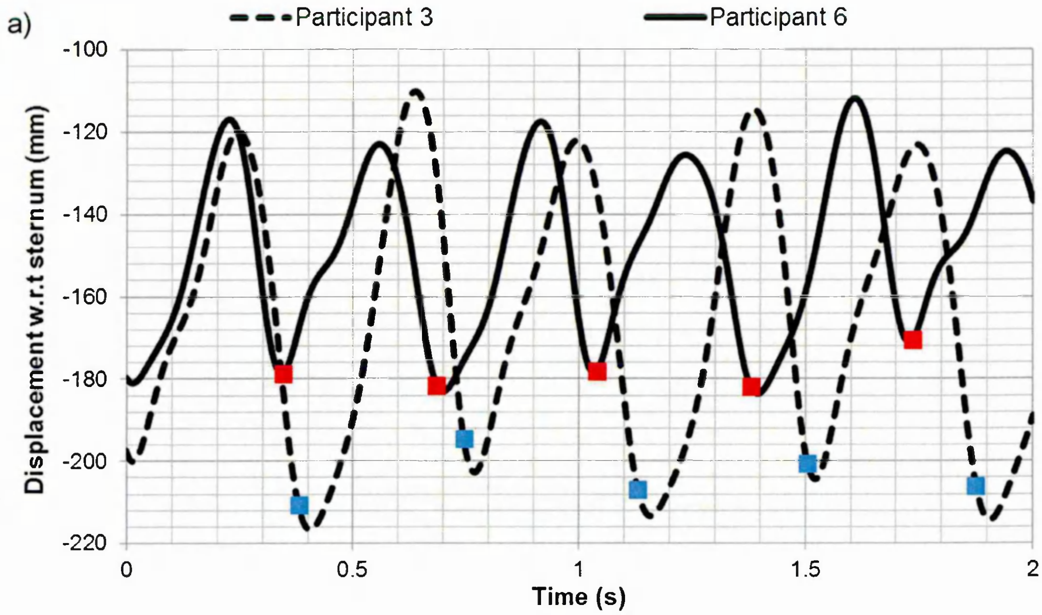
Activity	Flight times	Number of oscillations?		-1.00 g ± 0.04 g reached?	Consistent?	Perceived discomfort score
	(s)	Left	Right	(Yes/No)	(Yes/No)	
Run	0.11 ± 0.02	0.2 ± 0.2	0.2 ± 0.2	Yes	No	5.6 ± 1.6
Jump	0.40 ± 0.05	1.3 ± 0.2	1.2 ± 0.2	Yes	Yes	0.6 ± 0.7
High Box	0.11 ± 0.1	0.4 ± 0.5	0.4 ± 0.5	Some Participants	No	0.6 ± 0.8
Low Box	0.04 ± 0.05	0.1 ± 0.1	0.1 ± 0.2	Some Participants	No	0.3 ± 0.5
Lift and Drop	N/A	N/A	N/A	Some Participants	No	0.8 ± 1.3

The five activities were assessed on a number of criteria shown in Table 5.7. The vertical countermovement jump activity had the greatest flight time, which corresponded to a greater number of breast oscillations (Table 5.7). This was closely followed by the high box and run activities. The vertical neutral positions were not consistently found over the five trials of the high box, low box and lift and drop activities, in the participants who showed a neutral position. Only the vertical countermovement jump showed a vertical neutral position in all trials and produced low levels of perceived breast discomfort. It was found that all vertical neutral positions produced for both the left and right breast in all activities were higher than the resting height.

Observations

Through analysing the 10 km.hr^{-1} bare breasted run, two observations were noted. Firstly, participants with similar sized breasts produced similar shaped breast kinematic trajectory paths but the magnitudes and frequency differed. Secondly, the left and the right breasts of the same participant produce similar kinematic trajectories but the magnitudes varied (Figure 5.12 and 5.13).

Figure 5.12 shows that the breast of participant 6 oscillated in the vertical global coordinate system at approximately 3.00 Hz whereas participant 3's breast oscillated at approximately 2.75 Hz. The reduced breast frequency may have caused an increase in range of breast displacement by 34.7 mm and in turn had a greater range of acceleration of 7.04 g. According to Turner and Dujon (2005) the mass of a 36D breast is 860 g. If the mass of the left breast for both participants were the same then other factors such as stride frequency and length and breast shape and structure, may have caused the discrepancy in the recorded values. Based on the vertical motion of the suprasternal notch marker in the global coordinate system, the body of participant 6 oscillated at about 2.75 Hz whereas the body of participant 3 oscillated at approximately 2.50 Hz, suggesting that the pattern of the participants' gaits were different. If the difference in body oscillation between participants is great enough it might affect the motion of the breasts. However, if the difference in frequency is not large enough then general engineering principles suggest that breast structure can be linked to flexural rigidity, which is the product of young's modulus (tissue stiffness) and the second moment of area (breast shape). The accelerations of participant 6 were smaller than participant 3 suggesting that the inertial forces, such as skin stiffness, acting on the breasts were different. An uneven amount and distribution of subcutaneous tissue in the breast would alter the shape. These two aspects (skin stiffness and breast shape) can therefore alter the breasts resistance to movement, which may have caused the displacements between participants to vary. This observation suggests that participants with the same measured breast size may not dynamically behave the same, due to potential uncontrollable factors such as gait pattern and shape/structure of the breast. Therefore, single subject analysis may be more beneficial, as grouping participants could mask any differences in breast kinematics. However, further testing in same breast size participants is required.



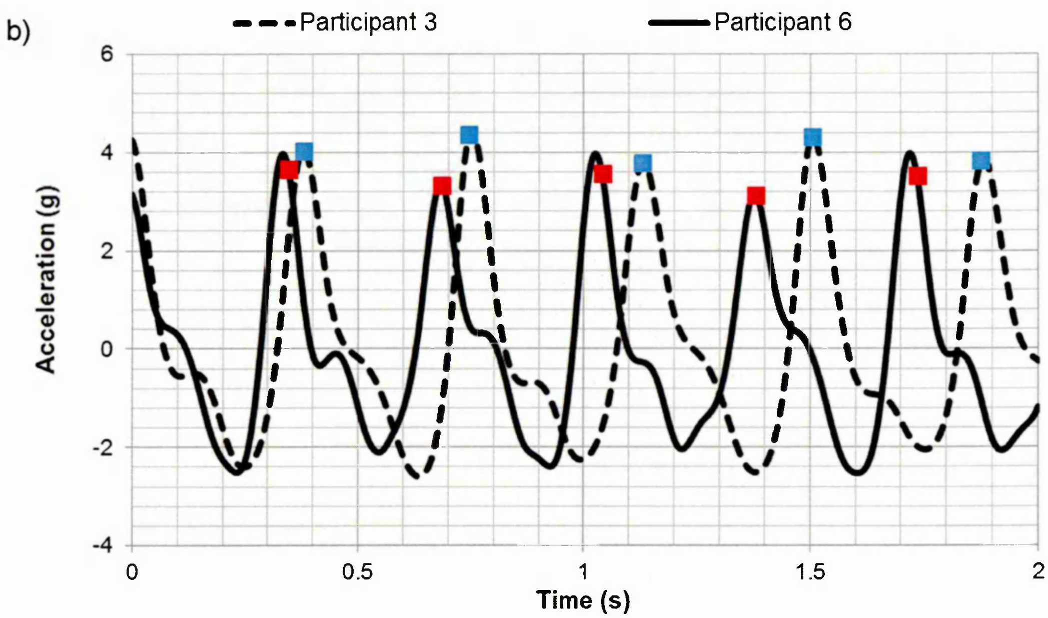
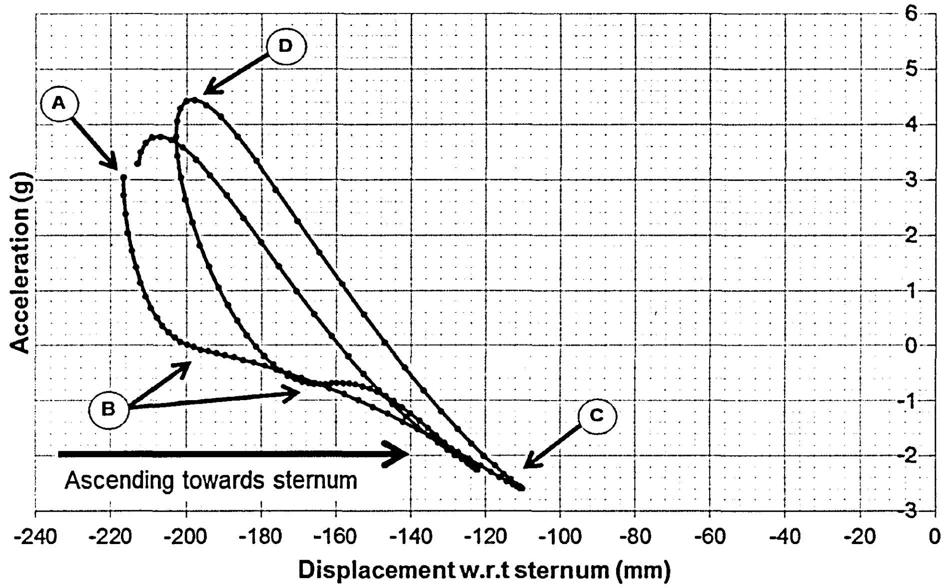


Figure 5.12: Motion of the left nipple of participant 3 and 6 (cup size - 36D) during a typical bare breasted run at 10 km.hr^{-1}. a) Vertical breast displacement with respect to the suprasternal notch against time; and b) vertical breast acceleration against time. (Red and blue squares = foot contact).

During a typical gait cycle of a bare breasted run at 10 $km.hr^{-1}$, the left and right breast of the same participant followed a similar trajectory (Figure 5.13). As the ipsilateral foot contacts the ground the breast reached a minimum displacement at A. The participant then pushed off the ground causing a plateau at B. The breast then moved upwards towards the sternum reaching a second peak at C. The participant then landed with the contralateral foot causing the breast to reach a minimum displacement at D. It was noted that the magnitudes of the right and left breast kinematics varied during motion. In this particular participant the right breast during a typical gait cycle moved closer towards the suprasternal notch during the upward motion than the left breast. The left breast reached a greater minimum displacement than the right breast. Both the left and right breast had a similar maximum negative acceleration but the right breast had a greater maximum positive acceleration. Differences in left and right breast kinematics were found in all participants but there was no particular side that stood out to produce greater values. This supports Mills, Risius and Scurr' (2015) results that showed a high proportion of women's left breast displacement was greater than the right breast in all support conditions, suggesting that any individual differences may have been masked in a sample group when comparing the sample group mean. The observation in this study suggests that the left and right breasts of a participant may need to be considered in future testing.

a)



b)

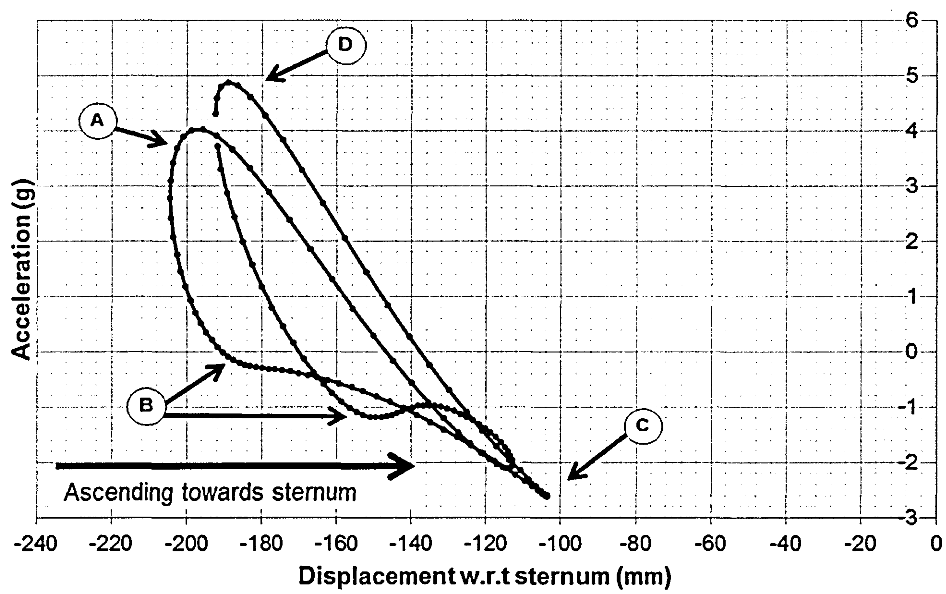


Figure 5.13: Motion of the breasts of a 36D - sized participant during a typical gait cycle at 10 $km.hr^{-1}$. a) Vertical right breast displacement relative to the suprasternal notch and vertical right breast acceleration, b) vertical left breast displacement relative to the suprasternal notch and vertical left breast acceleration. (A = ipsilateral foot contact; B = first breast peak; C = second breast peak; D = contralateral foot contact).

5.5 Discussion

The aim of this study was to develop and systematically assess an array of activities for simplicity, suitability and repeatability in locating the vertical neutral position of the breast. The results suggest that the vertical countermovement jump was the most appropriate out of the five techniques as the motion caused the breast tissue to oscillate from tension to compression on the upper and lower side of the breast.

In the present chapter a vertical neutral position was not found in all five trials of the lift and drop activity and in three of the participants a neutral position was not found all together in either the left or the right breast. This supports the results of not locating a vertical neutral position in the single participant used in chapter 4. Both the vertical countermovement jump and running produced breast accelerations of -1 g, however, running was deemed unsuitable. Firstly, the activity could only be performed once or the participant would require a longer rest period to reach baseline comfort, as the activity resulted in high perceived breast discomfort. Secondly, the results in table 5.1 show that up to 45% of the total range of motion at the suprasternal notch occurred in the other two directions, suggesting that the body rotates during running; potentially affecting the true value of the vertical neutral position.

During the vertical countermovement jump, the breast oscillated up- and down-wards, vertically so it went through a vertical neutral position more than once in a trial. The vertical neutral positions found in the upward motion were further away from the suprasternal notch than the positions found in the downwards direction. It was noted that the accelerations produced between the highest and lowest vertical neutral positions were reasonably low (-0.13 g to -1.80 g), when the initial upwards motion was not taken into consideration. Suggesting that between the upper and the lower neutral position values, the breast was under very little or no strain, therefore, the highest and lowest neutral position values can be used as upper and lower boundaries of a comfort zone.

Thus, placing the breasts above the highest neutral position or below the lowest neutral position may cause breast discomfort during movement. McGhee and Steele's (2010) findings support this as they found that lifting the breast higher on the chest wall did not alter the magnitudes of the displacements in different breast supports but reduced the tension on the breast tissue by moving it further away from its end of range of motion and in turn increasing breast comfort. As a result of this finding in this study, a more appropriate term to use is vertical neutral zone/region.

The advantage of using a vertical countermovement jump is that it is a simple test, which excites approximately 1.3 ± 0.2 breast oscillations during flight (body in free-fall), causing the breasts to move through a region where the breast tissue is neither in tension nor compression. The activity produced little breast discomfort and is simple enough to implement in a retail outlet or in a doctors surgery with ease (providing a suitable measurement system was available).

Similar to Haake and Scurr (2011) the motion of the breast was modelled as a cantilever beam. This presents a potential limitation as the breast was assumed to be a point mass located at the nipple as the centre of mass is considered to be located inside the breast between the nipple and ribcage. However, the breast is not a rigid body and the motion of the nipple may not be representative of the motion of the breast centre of mass. Therefore, to attribute the displacements of the nipple marker to the centre of mass of the breast may not be correct. Furthermore, cantilever beam theory assumes that the dynamic motion of the breast above and below the static equilibrium is symmetrical. However, the dynamic properties of a breast are not symmetrical. Another limitation is that the vertical neutral zone was located in the global coordinate system, which does not eliminate the driving force of the body. The vertical neutral zone of the breast was considered as 'true' when the body was also in free-fall. This was to eliminate the effects of the driving force of the body. The rotation of the body during the flight phase in each activity was not explored and may have influenced the position of the vertical neutral zone.

Further work is required to create a new marker set to track the three-dimensional motion of the centre of mass of the breast, to identify a more appropriate measure of the vertical neutral zone. The marker set would need to incorporate body reference markers to convert the global coordinate system to a local coordinate system to eliminate the effect body on breast kinematic data. The next stage of this work is to use the vertical countermovement jump to locate the vertical neutral zone and place the breasts into this position to assess the effects on the individual's comfort.

5.6 Chapter summary

The aim of the study was to assess a variety of activities for their simplicity, suitability and whether a vertical neutral position is consistently located. Vertical neutral positions were consistently measured in a range of breast sizes using a vertical countermovement jump. It was also noted that there is a neutral zone, which the breast can move in and experience low accelerations, therefore little to no strain on the breast. The neutral zone can be used to calculate the amount of strain the breast experiences during exercise when using different mechanical supports.

6 Pilot work

6.1 Introduction

The purpose of finding the vertical neutral zone was to enable positioning of the breasts such that the breast tissue is neither in tension nor compression, potentially improving breast comfort whilst exercising. Lawson and Lorentzen (1990) and Boschma (1999) found that perceived breast comfort was not affected by vertical breast displacement. This was supported by McGhee and Steele (2010) who found that the range of vertical breast displacements did not alter between bra conditions during exercise but the distance from the breasts end range of motion did. They suggested lifting the breasts higher on the chest wall, improved breast comfort. Mason, Page and Fallon (1999) hypothesised that movement-induced breast discomfort would be affected by the strain applied to the breast tissue during exercise. Haake and Scurr (2011) developed a simple method to locate the undeflected length of the breasts to estimate strain of the breasts during exercise. Using this method Haake, Milligan and Scurr (2012) suggested that excessive displacements, if the breasts are far away from the neutral position, causes strain on the breast tissue and in turn causes movement-induced breast discomfort.

For the study presented in chapter 5, breast kinematics were collected for a 4 $km.hr^{-1}$ walk and a 10 $km.hr^{-1}$ run in two support conditions (a sports bra and t-shirt bra) and in a bare breasted condition. The vertical neutral zones found during the vertical countermovement jump for each participant were used. Therefore, in this chapter, running and walking vertical displacement of the nipple with respect to the highest point in the neutral zone (found over the five trials) and vertical displacement of the sternum with respect to its mean position over 19 s are presented, to show the effects of breast motion with respect to the neutral zone and perceived breast discomfort.

6.2 Results

Data was collected from all seven participants. Bates (1996) suggested that group analysis can mask the effects in individual participants therefore a single participant was used in this chapter. The left breast of a 34A participant was used as it was the only participant with a full data set. The suprasternal notch marker oscillated up to 80 mm above and below the mean position. This caused the breast to oscillate approximately -37.5 mm to +14.1 mm from the neutral position in the bare breasted condition (Figure 6.2a). In the everyday bra condition (Figure 6.2b) the breast oscillated from -49.5 mm to -0.2 mm and from -23.1 mm to +13.1 mm in the sports bra condition (Figure 6.2c) about the neutral position. The vertical neutral position was 135 mm from the suprasternal notch and the static resting height was 153 mm from the suprasternal notch. Therefore, the breast was 18 mm from the neutral position in the static position (Figure 6.2: dashed line). The breast oscillated about the static resting height of the breast in the bare breasted condition. In the everyday bra the majority of the motion of the breast occurred below the resting height of the breast. In the sports bra condition, the bra lifted the breast higher on the chest wall and reduced the magnitude of the displacements. In this condition, the majority of the breast motion occurred between the neutral position and the resting height of the breast. Perceived breast discomfort was greatest when running bare breasted (6.9) than running in a sport bra (1.0) (Table 6.1).

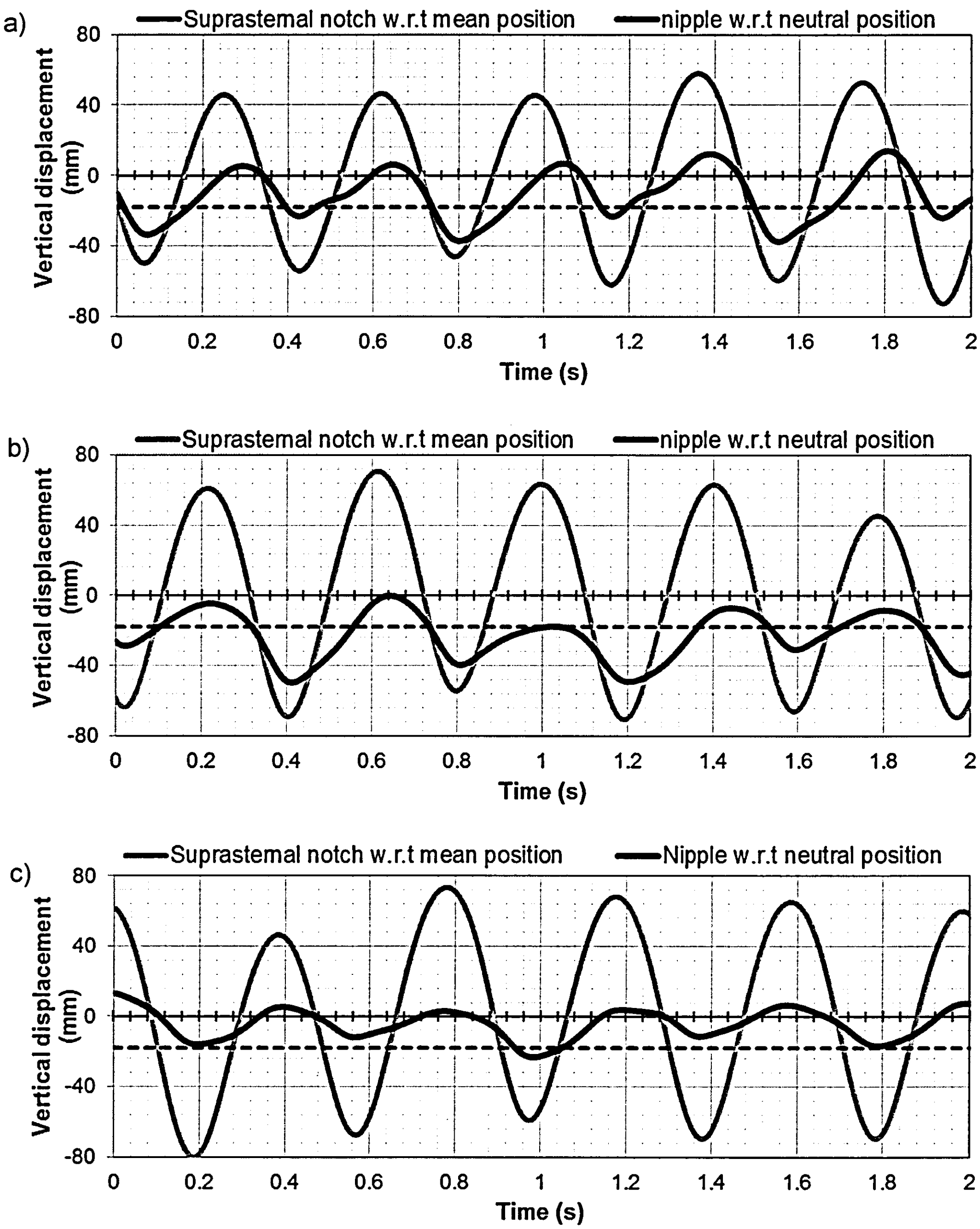


Figure 6.1: Vertical left breast displacement with respect to the neutral position and vertical suprasternal notch displacement with respect to its mean position during a typical 10 km.hr^{-1} run for participant 2 (34A) in a) no-bra; b) everyday bra; and c) sports bra conditions. (Dashed line = static resting height of the nipple without a bra).

Table 6.1: Perceived breast discomfort scores out of 10 (0 = comfort, 10 = discomfort) in bare breasted, everyday bra and sports bra conditions during a 10 $km.hr^{-1}$ run for participant 2 (34A).

Support condition	Discomfort score
Bare breasted	6.9
Everyday bra	5.8
Sports bra	1

During a 4 $km.hr^{-1}$ walk the suprasternal notch of the participant oscillated 15 to 20 mm below and 8 to 13 mm above the mean position (Figure 6.2). This caused the nipple to oscillate between -30.5 mm to -18.5 mm, which was below the static resting height of the breast during the bare breasted condition (Figure 6.2a). During the everyday bra condition (Figure 6.2b) the motion of the breast oscillated about -26.0 mm and -14.4 mm of the resting height. The motion of the breast in the sports bra condition oscillated above the resting height but below the neutral position of the breast (-5.4 mm and -0.7 mm). Perceived breast discomfort was greatest in the bare breasted condition (0.9) when walking. The everyday bra and sports bra condition during walking reduced the individuals perceived breast discomfort by 0.8.

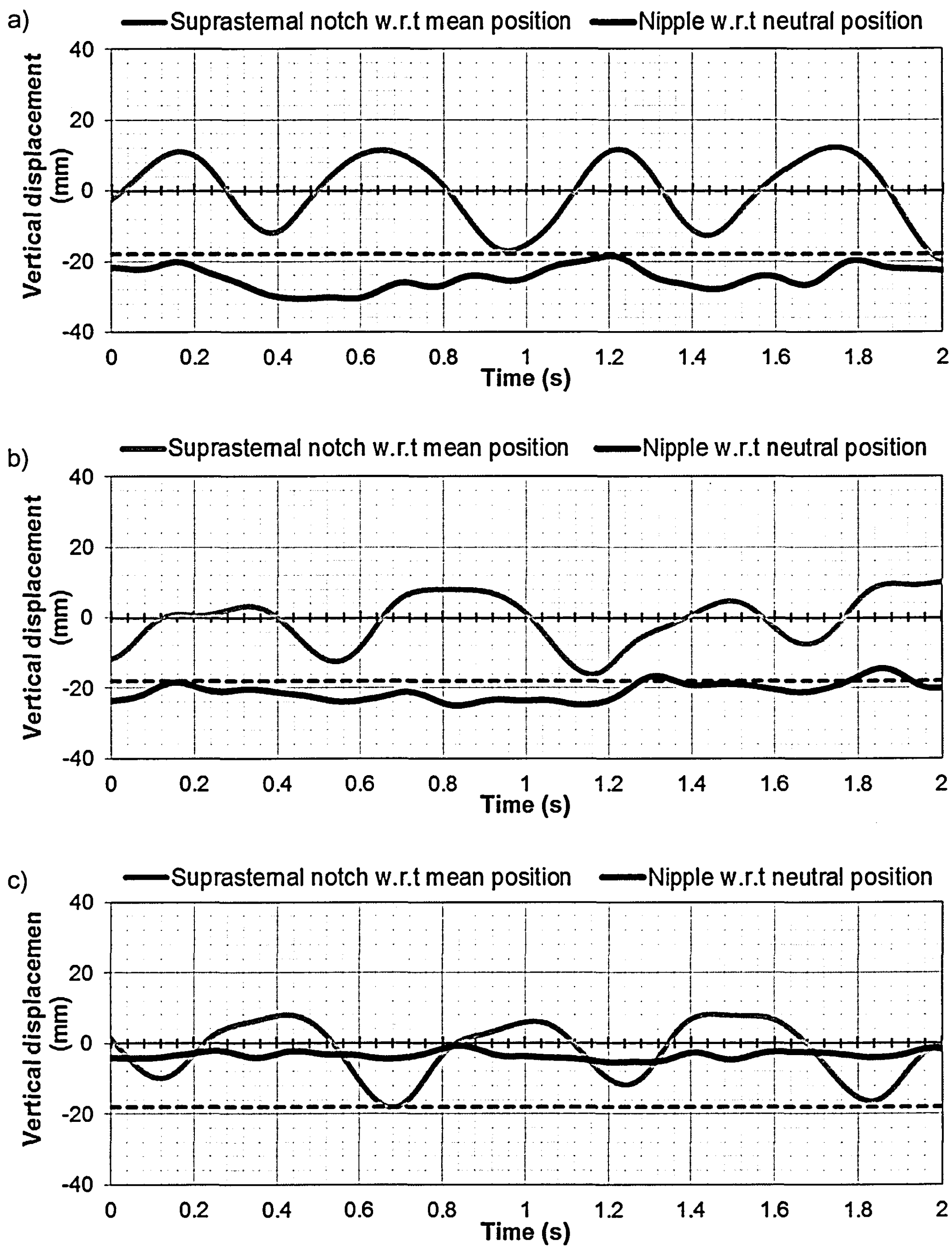


Figure 6.2: Vertical left breast displacement with respect to the neutral position and vertical suprasternal notch displacement with respect to its mean position during a typical 4 km.hr-1 walk for participant 2 (34A) in a) no-bra; b) everyday bra; and c) sports bra conditions. (Dashed line = static resting height of the nipple without a bra).

Table 6.2: Perceived breast discomfort scores out of 10 (0 = comfort, 10 = discomfort) in bare breasted, everyday bra and sports bra conditions during a 4 $km.hr^{-1}$ walk for participant 2 (34A).

Support condition	Discomfort score
Bare breasted	0.9
Everyday bra	0.1
Sports bra	0.1

6.3 Discussion

The aim of the pilot work was to understand the dynamics of the breast during running and walking. The results showed in this specific individual that when running in an everyday bra the participant's level of discomfort was reduced by 1.1 from the bare breasted condition and was decreased further by 4.8 when running in a sports bra. This could be attributed to three possible factors: firstly, the magnitude of the vertical breast displacement was reduced; secondly, the breasts were lifted closer to the vertical neutral zone; and finally the level of breast support increased. The motion of the breast in the everyday bra during running for this participant occurred mainly below the static resting height with a 2.3 mm reduction in the magnitude of the vertical breast displacement from the bare breasted condition. However, Boschma (1999) found that breast comfort can increase by the woman perceiving the bra to provide support.

Mason, Page and Fallon (1999) hypothesised that movement-induced breast discomfort occurs from the breast tissue being strained. McGhee and Steele (2010) showed that breast discomfort decreased as the vertical motion of the breast occurred higher on the chest wall, away from its end range of motion. The results of the sports bra condition when running shows promise of supporting the findings of previous research. In this trial the majority of the motion of the breast occurred between the resting height and the neutral position. The sports bra for this individual did reduce the magnitude of the vertical breast displacement by 13.1 mm from the bare breasted condition. However, further work is required to identify if lifting the breasts into the neutral zone is the main factor in reducing breast discomfort.

6.4 Chapter summary

The vertical neutral zone can be used to understand the dynamics of the breast during gait. The observations of the single participant in this chapter are promising, showing that lifting the breasts closer to the neutral zone, reducing the vertical displacements, or increasing the level of breast support could decrease breast discomfort during exercise. However, due to only analysing one participant, the other variables that were statistically correlated in previous research could cause movement-induced breast discomfort. Therefore, further work is required to identify the extent to which placing the breasts into the vertical neutral zone affects the level of breast comfort during exercise.

7 Discussion

The overall aim of the thesis was to locate the vertical neutral position of the breasts through the use of simple movements. Haake and Scurr (2011) developed the static lift and drop method to locate a vertical position of the breast on the chest wall, where the breast tissue is neither in tension nor compression, termed the neutral position. The results of the single participant in chapter 4 showed that a vertical neutral position was not achieved using this method. A range of activities were systematically assessed using seven participants in chapter 5. The results of this chapter showed that multiple positions in the vertical direction could be located in a range of breast sizes using a vertical countermovement jump. The countermovement jump was suggested to be the most appropriate method of locating this position as: 1) the body was in free-fall for ~ 0.40 s, 2) the motion forced the breast tissue to oscillate from tension to compression and vice versa, therefore, moving through a region of free-fall, and 3) produced low levels of breast discomfort. It was noted that in the vertical countermovement jump different values were recorded for the vertical neutral position during the upward and downward motion in a single trial. Further analysis revealed that between the minimum and maximum neutral positions the accelerations were low, therefore, suggesting that these values are upper and lower boundaries of a vertical neutral zone of the breast.

In chapter 6 the vertical neutral zone of one participant was used to show the possible effects of different breast supports whilst exercising on perceived breast discomfort. It was noted for this participant that exercising in a sports bra reduced movement-induced breast discomfort from exercising in no support. This could have been due to three possible factors: 1) level of breast support increased, 2) breast displacements were reduced; and 3) breasts were lifted closer and moved about the vertical neutral zone.

The limitation of this research is that the breast is modelled as a spring-damper and the motion of the breast was determined by a single marker placed on the nipple. The cantilever beam theory assumes that the breast moves symmetrically above and below the static equilibrium; however, the dynamic properties are not symmetrical. In this thesis, the breasts were assumed to be a rigid body with the centre of mass located at the nipple, which may not be correct. The breasts are complex, wobbly masses, which move in all directions and are rarely, if at all, restricted to moving in only the vertical direction. Therefore, the concept of a vertical neutral zone may be inappropriate and a three-dimensional neutral zone may be required. The main advantage of the protocol was that it was easy to implement for the following reasons: 1) small marker set - nipple and suprasternal notch; 2) easy activity to perform; 3) majority of the motion restricted to the vertical direction; and 4) low discomfort scores. Due to the ease and low breast discomfort, the activity could be performed in a retail outlet or a clinical surgery, as long as the appropriate tracking equipment is in place.

The implication of this research is that the vertical neutral position is a zone defined by upper and lower boundaries, which are found most effectively using a vertical countermovement jump. Two aspects of future work that are required to improve and advanced this area of research are: 1) a more appropriate breast marker set to track the breast centre of mass to provide a more accurate vertical neutral zone; and 2) by placing the breasts into, above and below the neutral zone in the same breast support, it may help to identify the kinematic variables that cause the transition from breast comfort to discomfort.

8 Conclusion

To conclude, a vertical neutral position was consistently measured in a range of breast sizes using a vertical countermovement jump. The forced oscillations of the breasts during the vertical countermovement jump produced multiple vertical neutral positions which can be used to define the upper and lower boundaries of the vertical neutral zone, as the accelerations between the boundaries are low. The vertical countermovement jump is a simple exercise that elicits a vertical neutral zone, which could allow for a greater understanding of the stress applied to the breast tissue during movement which in turn could inform the design of bras.

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Appendix

Appendix 1: The optimal cut-off frequency for each marker and trial was calculated by working out the second derivative of the residual with respect to the cut-off frequency. The optimum cut-off frequency was selected where the second derivative dropped below 0.8 mm/Hz^2.

	A	B	C	D
1	**Single marker drop test**			
2	Cut-off frequency	Residual	1st Derivative of Residual	2nd Derivative of Residual
3	(Hz)	(mm)	(mm/Hz)	(mm/Hz)
4				
5	0.2	433.5908		
6	0.4	258.4562	-875.673	
7	0.6	164.1014	-471.774	2019.49416
8	0.8	125.9176	-190.919	1404.27629
9	1	111.2478	-73.3489	587.849927
10	1.2	101.9569	-46.4546	134.471643
11	1.4	93.82877	-40.6406	29.0701493
34	6	42.68309	-3.73902	1.02082291
35	6.2	41.97265	-3.55225	0.9338774
36	6.4	41.29648	-3.38084	0.85704433
37	6.6	40.65187	-3.22306	0.78889352
38	6.8	40.03638	-3.07741	0.72821854
39	7	39.44786	-2.94261	0.6739991
40	7.2	38.88435	-2.81754	0.62537087
41	7.4	38.34411	-2.70122	0.58160093
42	7.6	37.82555	-2.59281	0.54206728