Breast characteristics of Australian women

Celeste E. Coltman

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BREAST CHARACTERISTICS OF AUSTRALIAN WOMEN

Celeste E. Coltman

Bachelor of Science (Honours Class I)

Supervisors:

Dr Deirdre E. McGhee
Professor Julie R. Steele

This thesis is presented as part of the requirements for the conferral of the degree of

Doctor of Philosophy

This research has been conducted with the support of the Australian Government Research Training Program Scholarship

University of Wollongong
School of Medicine
Faculty of Science, Medicine and Health

August 2017
DECLARATION

I, Celeste E. Coltman, declare that this thesis, submitted in partial fulfilment of the requirements for the conferral of the degree of Doctor of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Celeste E. Coltman
3 August 2017
DEDICATION

This thesis is dedicated to my family.

I am very fortunate to have grown up in a supportive and loving family where education was valued and opportunities could be pursued. You each have supported me in your own way throughout the highs and lows of this journey and I couldn’t be more grateful for your unwavering love and endless encouragement.
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PUBLICATIONS

This thesis includes chapters that have been written as the following journal articles:


As the primary supervisor, I, Dr Deirdre McGhee, declare that the greater part of the work in each article listed above is attributed to the candidate, Celeste Coltman. In each of the above manuscripts, Celeste contributed to the study design, recruited participants, was solely responsible for data collection and data analysis, and was largely responsible for statistical analysis and data interpretation. The first draft of each manuscript was written by the candidate and Celeste was then responsible for responding to the editing suggestions of her co-authors. The co-authors, Deirdre McGhee and Julie Steele were responsible for assisting in study design, data interpretation and editing the manuscripts. Celeste has been solely responsible for submitting each manuscript for publication to the relevant journals, and she has been primarily in charge of responding to reviewer’s comments, with assistance from her co-authors.

Celeste Coltman  
3 August 2017

Deirdre McGhee  
3 August 2017
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ABSTRACT

Background: Insufficient breast support from an ill-fitting bra is a known barrier to participating in physical activity. Improvements to current bra designs are necessary in order to improve breast support and bra fit for women.

Research question: The overall aim of this thesis was to quantify the breast characteristics of Australian women across the breast size spectrum upon which to develop evidence-based recommendations to improve bra designs for these women.

Methods: Two separate biomechanical studies were conducted, which are presented in four thesis parts. In the first part of this thesis a valid and reliable method to quantify the volume of large and ptotic breasts was determined and subsequently used in Study 2. The second part of the thesis collected comprehensive three-dimensional breast volume, shape and skin data in order to characterise the breasts of a large cohort of Australian women across varying age and body mass index (BMI) ranges (Chapters 3, 4 and 5). The third part of the thesis utilised objective data on the breasts and upper torsos of women (breast volume, shape and skin; structure and function of the upper torso and physical activity levels), as well as upper torso musculoskeletal pain scores to explore predictors of musculoskeletal pain in the upper torso (Chapter 6). The fourth and final part of this thesis utilised professional bra fit criteria to establish the impact of current bra design components upon incorrect bra fit (Chapter 7).

Major conclusion: Based on the results of this thesis, six evidence-based recommendations have been made for future bra designs. Bra designers and manufacturers can use these recommendations, in conjunction with data collated in this thesis, to improve bra designs for Australian women. Incorporating such evidence-based data could substantially improve the fit of breast support garments and, therefore, the ability of these garments to properly support the breasts of women. Enhanced bra fit and breast support will, in turn, enable women to participate in physical activity in comfort.
Chapter 1

The problem

1.1 Introduction

Excessive breast motion during physical activity is associated with discomfort, pain and embarrassment, which for many women act as barriers to participating in physical activity (Gehlsen and Albohm 1980; Gehlsen and Stoner 1987; Lorentzen and Lawson 1987; Starr et al. 2005). The breasts have been reported to move during physical activity up to approximately 19 cm in the vertical plane (Bridgman et al. 2010; Campbell et al. 2007; Gehlsen and Albohm 1980; Lorentzen and Lawson 1987; Mason et al. 1999; Starr et al. 2005; McGhee and Steele 2010a; Scurr et al. 2011) and up to 4 cm in the medial-lateral and anterior-posterior planes (Scurr et al. 2009; White et al. 2009). This amount of motion is concerning because exercise-induced breast discomfort has been associated with as little as 2 cm of vertical breast displacement (Gehlsen and Stoner 1987). Given the importance of limiting excessive breast motion, extensive research has highlighted the need for sports bras to provide external support to the breasts (Gehlsen and Albohm 1980; Lorentzen and Lawson 1987; McGhee et al. 2013; Starr et al. 2005).

The most supportive sports bras tend to be encapsulation style bras, where the breasts are supported individually in separate structured cups. Encapsulation style sports bras have been found to be superior to both fashion bras and low support sports bras, such as crop-tops, at reducing breast motion and the associated exercise-induced breast discomfort (Gehlsen and Albohm 1980; Lorentzen and Lawson 1987; McGhee et al. 2013; Starr et al. 2005). However, to provide a high level of support it is imperative that a bra fits the wearer properly (Page and Steele 1999). Unfortunately, a large percentage (85%) of both adolescent and adult females have been reported to be wearing the wrong
size encapsulation style sports bra (McGhee and Steele 2010a), which will compromise their breast support.

One factor likely to be contributing to the high percentage of poor bra fit is a mismatch between the characteristics of the breasts of women and the bras they wear. Currently, encapsulation style sports bras are designed based on a series of relatively simple physical measurements of the breasts and torso, taken from a model (commonly a 12B bra size) in order to identify a core size. Grading is then applied to these measurements to create different sizes from this core size, with this grading process known to vary from bra brand to brand. However, to fit properly, bra designs need to be based on more complex characteristics such as the three-dimensional breast volume and breast shape of women across the breast size spectrum (McGhee and Steele 2011; Pandarum et al. 2011), as well as other factors that affect breast support.

The breasts are supported by anatomical structures such as the skin overlying the breast, as well as the fascia within the breasts (Gefen and Dilmoney 2007; Mason et al. 1999; McGhee et al. 2008). Although these anatomical support structures are poorly understood, they can influence the level of external breast support required from a bra (Mason et al. 1999; McGhee et al. 2008; Gefen and Dilmoney 2007). Therefore, any changes to these anatomical breast support structures, such as the skin overlying the breast, should be considered when designing sports bras. Ageing is associated with declines in the structure and function of human skin (Rittié and Fisher 2015; Watson et al. 2014; Yaar and Gilchrest 2007). Therefore, determining the extent of changes to breast skin due to ageing is important from a breast support perspective because it will have implications for bra design. For example, the mechanical properties of breast skin may decline to varying levels across different regions of the breast, such that the support structures within a bra might need to be specific to each breast region. However, no
previous research has documented age related changes to anatomical breast support structures such as breast skin.

Although breast volume and breast shape have been identified as fundamental to bra design (Chen et al. 2011; McGhee and Steele 2011; Pandarum et al. 2011), there has been limited research investigating these characteristics among large cohorts of women (Chen et al. 2011; McGhee and Steele 2011; Pandarum et al. 2011). Consequently, limited normative population data exist upon which bra designers and manufacturers can base improvements to bra designs. The lack of information related to breast volume and shape has been attributed to the diverse characteristics of the breast, which have made obtaining accurate and reliable measurements difficult (Westreich 1997). The emergence of new technologies such as three-dimensional scanning, however, has enabled more accurate and detailed measurements of the body to be obtained (Devarajan and Istook 2004; Istook and Hwang 2001; Simmons and Istook 2003). Given a bra is a close fitting garment, measurement accuracy is vital to ensure that any designs that are developed fit correctly.

Although three-dimensional scanning can provide detailed and accurate measurements of breast volume and breast shape (McGhee et al. 2011), limitations with scanning breasts have been reported. For example, visualising the entire breast when scanning women with large ptotic breasts in a standing position can be difficult (Moyer et al. 2008; Lee et al. 2004; Thomson et al. 2009; Veitch et al. 2012). This is because large ptotic breasts often rest on the anterior abdominal wall (Moyer et al. 2008; Lee, Hong and Kim 2004; Thomson et al. 2009; Veitch et al. 2012), occluding the inferior aspect of the breast and, in turn, causing inaccuracy when calculating variables such as breast volume. A scanning position in which the entire breast can be visualised in women with large ptotic breasts therefore needs to be developed in order to accurately
measure the size and shape of women’s breasts as input to ultimately improve bra designs.

Comprehensive data on the breast characteristics of women to be utilised in bra design and manufacture should include women of different ages and body masses to ensure the data represent the demographics of Australian women. For example, 33% of the Australian female population are over 50 years of age (ABS 2011). Furthermore, currently 60% of Australians are overweight and one in every four Australian women is obese (AIHW 2012). Previous research has found larger breast volumes to be associated with higher BMI (Avşar et al. 2010; Benditte-Klepetko et al. 2007; Brown et al. 2012; Hasenburg et al. 2000; Janiszewski et al. 2010; Jernstrom and Olsson 1997). Consequently, older, overweight women are likely to have large breasts (Den Tonkelaar et al. 2004). Improving breast support through better bra designs is important for women with large breasts because these women are most likely to experience exercise-induced breast discomfort during physical activity (Lorentzen and Lawson 1987; Mason et al. 1999; McGhee et al. 2013; Scurr et al. 2010; Starr et al. 2005) and musculoskeletal pain secondary to their large breast size. Reported areas of pain include nerve pain in the upper limbs, deep bra grooves caused by excessive strap pressure and neck and back pain (BeLieu 1994; Greenbaum et al. 2003; Kaye 1972; Ryan 2000). Changes to the structure of the upper torso has also been associated with a large breast size (Findikcioglu et al. 2007; McGhee et al. 2018), which has been postulated to lead to changes in the function of the upper torso, including an increased experience of musculoskeletal pain (Atterhem et al. 2000; Benditte-Klepetko et al. 2007; Coltman et al. 2013; McGhee et al. 2018; Spencer and Biffa, 2013). This notion however has not been investigated systematically on a large cohort of women. Therefore, determining whether breast characteristics predict musculoskeletal pain in the upper torso will
increase our understanding of symptoms experienced by women across the breast size spectrum. This information will also enable breast support garments to be designed to minimise these potential negative symptoms and improve comfort.

In order to develop better breast support garments it is also necessary to identify which components of current bra designs most need improving. Therefore, research is needed to systematically determine which bra features are most frequently found to be ill-fitting across the breast size spectrum. When paired with detailed information on the breast characteristics of women across a range of ages and body sizes, such data can be used to substantially improve bra design and bra fit.

1.2 Statement of the problem

The overall aim of this thesis was to quantify the breast characteristics of Australian women across the breast size spectrum upon which to develop evidence-based recommendations to improve bra designs for these women. To achieve the overall aim of this thesis, two studies were conducted, which are presented in four thesis parts. The purpose of these four thesis parts were to determine:

(i) a valid and reliable method of quantifying breast volume using three-dimensional scanning in women with large ptotic breasts (Chapter 2). It was imperative to develop a valid and reliable three-dimensional scanning method to quantify the volume of large ptotic breasts before determining the breast characteristics of Australian women, because of the errors inherent in scanning methods described previously (see Section 1.1),

(ii) the breast characteristics of Australian women, including the breast skin properties, breast volumes and breast shapes, and how these characteristics were influenced by age and body mass index (BMI; Chapters 3, 4 and 5),
The problem

(iii) whether factors associated with the breasts and upper torso (such as breast volume, breast shape parameters, breast skin properties, thoracic kyphosis angle and shoulder range of motion), as well as factors known to be associated with musculoskeletal pain (such as age, BMI and physical activity level), predict musculoskeletal pain in the upper torso (Chapter 6), and

(iv) the components of current bra design that were associated with incorrect bra fit across a range of breast sizes (Chapter 7).

The results of the studies provided evidence upon which recommendations to improve bra design were formulated (Chapter 8). How each part of the thesis contributed to the overall thesis aim is shown in Figure 1.

1.3 Significance of the thesis

Given the high prevalence of women wearing the incorrect bra size (Greenbaum et al. 2003; McGhee and Steele 2010a; McGhee et al. 2010) and the recognised negative health consequences of insufficient breast support, current bra designs need to be improved to enhance bra fit and breast support so that women can exercise comfortably (Lorentzen and Lawson 1987; Mason 1999; McGhee and Steele 2011; Starr et al. 2005).

The present thesis contains the first comprehensive research to examine the breast characteristics, including breast skin properties, breast volume and breast shapes, of a large cohort of Australian women of varying age and BMI ranges. It will also be the first research to determine whether some of these factors can predict musculoskeletal pain in the upper torso, as well as the contribution of current bra design components to incorrect bra fit. The ultimate goal of this thesis is to use the results of this systematic research to develop evidence-based recommendations for improved bra designs so that all women irrespective of age, body mass or breast size have access to a correctly fitted and supportive bra.
The problem

Thesis aim: To systematically investigate the breasts characteristics of Australian women across the breast size spectrum

Part I: Method validation

Chapter 2: Three-dimensional scanning in women with large ptotic breasts: Implications for bra cup sizing and design

Chapter 3: Effect of ageing on breast skin thickness and elasticity: Implications for breast support

Chapter 4: Breast volume is affected by body mass index but not age

Chapter 5: Characterising breast morphology: The influence of age and body mass index

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Chapter 7: Which bra components contribute to incorrect bra fit in women across a range of breast sizes?

Thesis outcomes: Evidence-based recommendations for improved bra designs for Australian women

Figure 1: Schematic representation of the thesis structure, and how each part contributes to address the overall thesis aim.
Part I

Method validation
Chapter 2

Three-dimensional scanning in women with large ptotic breasts: Implications for bra cup sizing and design


Abstract

This study aimed to compare breast volume calculated from scanning large ptotic breasts of women while they were standing upright relative to when lying prone in order to identify the error associated with breast volume calculations. Breast volume and visualisation were compared in 50 women with large breasts (D+ bra cup size) while they were scanned in three different positions. Full visualisation of both breasts occurred in 100% of participants in the prone position and only 5% of participants in either standing position. Breast volume was significantly greater ($p < 0.01$) in the prone position, with the percentage of underestimation in the standing position increasing as breast volume increased. Breast volume measured by three-dimensional scanning in the standing position will be underestimated by 7 – 10% in large ptotic breasts. Consideration of these inaccuracies in breast volume relative to breast size can assist bra manufacturers when designing bras.
2.1 Introduction

Use of three-dimensional scanning technologies in the apparel industry is increasing as manufacturers seek to improve garment fit and mass customisation of clothing (Istook and Hwang 2001). Three-dimensional scanning technologies aid this quest because scanners can provide accurate body measurements that characterise both size and shape (Istook and Hwang 2001). One area of the apparel industry in which three-dimensional scanning technologies present substantial potential for improvement is the fit and design of bras. Research shows that 85% of women wear the wrong size bra (McGhee and Steele 2010a) and incorrect bra fit can lead to several negative health consequences, such as poor posture, musculoskeletal pain and decreased exercise participation (Findikcioglu et al. 2007; Lorentzen and Lawson 1987; McGhee and Steele 2010a). Three-dimensional scanning, which involves projecting light onto the surface to be scanned, in this case a woman’s breasts, can provide a three-dimensional computer mesh of an individual’s breast shape (Kovacs et al. 2006; Lee, Hong and Kim 2004; Nahabedian and Galdino 2003). Important design and fit parameters, such as breast volume, can then be calculated from this computer mesh to aid bra manufacturers in designing bra cups that are the correct size and shape to encase the volume of breast that they are required to support (McGhee and Steele 2011).

Accurate breast volume measurement, however, is dependent upon a scanner being able to visualise the entire breast. Although three-dimensional scanning has been validated by direct measurement of mastectomy specimens (Losken et al. 2005; Bulstrode et al. 2001), it has limitations when measuring the volume of large breasts (Lee et al. 2004; Moyer et al. 2008; Veitch et al. 2012). Large breasts tend to be ptotic (Regnault 1976), where the lower aspect of the breast sits on the anterior abdominal wall (Lee et al. 2004; Moyer et al. 2008; Thomson et al. 2009; Veitch et al. 2012). This
Method validation

makes it difficult for the scanner to visualise, and hence measure, the volume of this lower aspect of the breast, resulting in an underestimation of breast volume. Although this limitation has been previously identified, it is currently unknown how much of breast volume is underestimated and, in turn, the level of error associated with this measurement.

Breasts are commonly scanned using a whole body scanner, which requires women to be standing in an upright position, with their arms in slight shoulder abduction (30 degrees; Kovacs et al. 2006; Kovacs et al. 2007; Lee et al. 2004; Nahabedian and Galdino 2003; Thomson et al. 2009). Two previous studies have attempted to increase visualisation of large ptotic breasts during scanning by elevating the breasts off the anterior abdominal wall with tape (Lee et al. 2004) or by having women place their hands on their head (Kovacs et al. 2006). Although these previous studies reported some success in elevating the breasts and improving breast visualisation, the mean breast volumes of the participants in both studies were relatively small (547 ± 114 cm³ and 426 ± 142 cm³, respectively; Lee et al. 2004; Thomson et al. 2009). Another study measured breast volume using a computerised three-dimensional model, which was created by two video cameras that filmed a lattice grid of light reflected onto the breasts by a mirror while the women adopted a prone position (Thomson et al. 2009). In this position, the breasts hung away from the trunk through an opening in an examination table, which allowed complete visualisation of the breast. Unfortunately, the mean breast volume of participants in this study was also small (271 mL), so it is unknown whether the same effect could be achieved in women with breasts that were both large and ptotic.

The recent development of hand-held three-dimensional scanners, which are compliant with VDI2634 standards (German Association for Electrical, Electronic and
Information Technologies 2002), and have the potential to scan breasts while women adopt a prone position, could improve breast visualisation. Hand-held three-dimensional scanners are also relatively inexpensive, lightweight and compact and therefore suitable to use in the manufacturing or retail setting if they provide accurate data. Therefore, this study aimed to compare the breast volume calculated from scanning the large ptotic breasts of women while they were standing upright relative to when lying prone in order to identify the degree of error associated with breast volume calculations. Improved knowledge on the degree of error associated in calculating the volume of large ptotic breasts can allow bra manufacturers to account for this when designing bra cups, which could in turn improve bra fit (McGhee and Steele 2011). It was hypothesised that scanning large ptotic breasts in the prone position would allow complete visualisation of the breasts and, in turn, greater breast volume, compared to when the same breasts were scanned in the standing position. It was also hypothesised that the percentage error will vary with breast size and the level of breast ptosis.

2.2 Materials and methods

2.2.1 Participants

Fifty women (mean age: 37.1 ± 13.0 years; mean BMI: 29.5 ± 5.2 kg/m²), professionally fitted to wear ≥ D bra cup (average cup size: F, range: D – I; average band size: 16, range: 8 – 18; see Appendix A for international bra sizing), were recruited as participants. Participants were excluded from the study if they: (i) were pregnant or breastfeeding, (ii) had any musculoskeletal condition that caused them discomfort in or limited them in assuming the postures required for the study (described below), or (iii) if they had epilepsy that could be induced by the flashing light of the scanner. Approval for the study was obtained from the University of Wollongong Human Research Ethics Committee (HE 13/051). All participants signed written
informed consent prior to testing and all testing was conducted according to the National Health and Medical Research Council Statement on Human Experimentation (2007).

2.2.2 Breast ptosis, volume and visualisation

The level of breast ptosis for each participant’s right and left breast was characterised by measuring the sternal notch-to-nipple distance (Westreich 1997), where a greater distance was associated with greater ptosis. Each participant’s level of breast ptosis was also graded from 0 – 3 (Regnault 1976).

A hand-held three-dimensional scanner (Artec™ Eva 3D Scanner, Artec Group, San Jose) was used to measure the breast volume of both breasts of each participant while they assumed three positions: (i) standing up straight and looking forward with their arms in slight abduction, heel of their hands resting on their hips (Lee et al. 2004; Moyer et al. 2008; Veitch et al. 2012), (ii) standing up straight and looking forward with their hands on their head in an attempt to elevate the breasts up off the chest wall to improve breast visualisation (Kovacs et al. 2006), and (iii) lying prone. In this third position the participants lay prone across two tables, with a 50 cm gap between the tables, such that each participant’s trunk was horizontal and their breasts hung away from their trunk in the space between the two tables (Figure 2; Thomson et al. 2009). In order to visualise the medial aspect of the breast while in the prone position, a research assistant held one of the participant’s breasts away from their trunk in a superior/lateral direction using a gloved hand, while the other breast was scanned.

As the breasts were the key body landmarks in this study, the same experienced investigator identified and placed all the markers and performed all scanning. Prior to scanning, adhesive markers (approximately 1 cm in diameter) were placed directly on each participant’s skin at the sternal notch, on both nipples and around the outline of
Method validation

each breast to highlight the borders of the breasts. The borders of the breasts were identified by manipulating each participant’s breasts by cupping and lifting their breasts up and down and side to side, until the breast borders were clearly visible. Participants were instructed to stay as still as possible during scanning with talking prohibited. One scan was taken of each participant in each scanning position and visually inspected immediately after capture to ensure all landmarks were visible and the scan was of a quality sufficient for analysis. If any problems were detected with the scan, the procedure was repeated with one scan per position for each participant subsequently imported into Geomagic Studio® software for analysis (Version 12; 3DSystems, South Carolina, USA).

Figure 2: The three scanning positions: standing with hands on hips (A), standing with hands on head (B) and lying prone (C).
Method validation

Where the inferior aspect of the breast was unable to be captured by the scanner, the missing aspect of the breast was digitally created by matching the area to be filled to the curvature of the surrounding mesh. A three-dimensional model of each breast was then created from the scanned images by tracing around the border of each breast, which was then removed from the torso and attached to a posterior breast wall. The posterior breast wall was created with a curved surface by filling the anterior chest wall once the breast was removed, with a series of tangential cut planes to mimic the curvature of the superficial surface of the pectoralis major muscle, which the posterior wall of the breast sits on, following methods previously reported (Yip et al. 2012; Geomagic Studio® software; Version 12; 3DSystems, South Carolina, USA). The volume (mL) of each three-dimensional breast model was then calculated using Geomagic software for the three different scanning positions. The error of measurement was calculated by the difference in the breast volume measured (mL and percentage volume) in the prone position compared to the standing positions, where it was hypothesised full breast visualisation would be achieved in the prone position. The primary investigator had high reliability in scanning and analysing the breast volume in each of the three scanning positions (all Cronbach’s $\alpha \geq 0.95$). Breast visualisation was rated as either “complete” or “incomplete” by the primary investigator [CEC] after visually inspecting the scanned mesh representing each breast derived during the three scanning positions (Figure 3).
**Method validation**

**Figure 3:** The scanned mesh of one participant’s breasts in the three scanning positions: standing with hands on hips (A), standing with hands on head (B) and lying prone (C). For this participant the inferior aspect of their breast cannot be visualised when scanned in a standing position (A and B – note the loss of image indicated by the yellow), but complete breast visualisation is achieved when the participant is scanned while lying prone (C).

*Note: (C) also shows how a gloved hand holds the left breast away from the midline of the participant’s torso while the right breast is scanned.

### 2.2.3 Statistical analysis

Descriptive statistics (means and standard deviations) were calculated for the volume of the participants’ right and left breasts in each of the three scanning positions. A repeated measures ANOVA design with one within factor (scanning position: standing with hands on hips, standing with hands on head, lying prone) was then used to determine whether there were any significant ($p < 0.05$) differences in the breast volume data among the three scanning positions, with Bonferroni post hoc analyses. Bland-Altman plots were used to determine any difference in agreement between the three scanning positions for the breast volume data across the range of breast sizes. The frequency of complete or incomplete breast visualisations in the three scanning positions was documented. All statistical calculations were conducted using the Statistical Package for the Social Sciences (Version 15.0; SPSS Inc., Chicago, IL) and GraphPad Software (Prism; Version 6.0; GraphPad Software Inc., San Diego, CA).
2.3 Results

Characteristics of the participants’ breast volumes, bra sizes and breast ptosis, grouped according to their breast volume, are shown in Table 1. The frequency of complete and incomplete breast visualisation in each of the three scanning positions is shown in Table 2. Complete breast visualisation for all participants was only found when they were scanned in the prone position.

Table 1: Characteristics of the participants’ (n = 50) bra sizes and breast ptosis, grouped by breast volume.

<table>
<thead>
<tr>
<th>Unilateral breast volume range (mL)</th>
<th>N</th>
<th>Professionally fitted bra size</th>
<th>Sternal notch-to-nipple distance (cm) mean (range)</th>
<th>Ptosis stage mean (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;499</td>
<td>4</td>
<td>32DD/E, 34E, 36DD</td>
<td>23 (21-24)</td>
<td>0.5 (0-1)</td>
</tr>
<tr>
<td>500-749</td>
<td>10</td>
<td>30F, 32E/F, 34E/F</td>
<td>26 (21-28)</td>
<td>2 (0-2)</td>
</tr>
<tr>
<td>750-999</td>
<td>10</td>
<td>32F, 34E/F, 36E</td>
<td>28 (23-30)</td>
<td>2 (0-2)</td>
</tr>
<tr>
<td>1000-1249</td>
<td>9</td>
<td>32G, 34F/G, 36E, 38E/F</td>
<td>30 (26-32)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td>1250-1499</td>
<td>8</td>
<td>34G, 36F, 38E/F, 40DD/E</td>
<td>31 (28-35)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td>1500-1749</td>
<td>7</td>
<td>34I, 36H, 38F/G/H, 40E/F</td>
<td>32 (29-34)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td>1750-1999</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000+</td>
<td>2</td>
<td>38H</td>
<td>33 (32-34)</td>
<td>2.5 (2-3)</td>
</tr>
</tbody>
</table>

*a Unilateral breast volume represents the average of each participant's right and left breast volume.

*b Ptosis grading system: 0 = Pseudoptosis: the nipple lies above the submammary fold, the breast is not ptotic; 1 = Stage 1 ptosis: nipple is level with submammary fold; 2 = Stage 2 ptosis: nipple lies below the level of the fold but remains above the lower contour of the breast; 3 = Stage 3 ptosis: nipple lies below the fold level and at the lower contour of the breast (Regnault 1976).

Table 2: Frequency of complete and incomplete breast visualisations in each of the three scanning positions (n = 50).

<table>
<thead>
<tr>
<th>Scanning Position</th>
<th>Complete</th>
<th>Incomplete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing with hands on hips</td>
<td>2</td>
<td>48</td>
</tr>
<tr>
<td>Standing with hands on head</td>
<td>4</td>
<td>46</td>
</tr>
<tr>
<td>Lying prone</td>
<td>50</td>
<td>0</td>
</tr>
</tbody>
</table>

The mean and standard deviation values for the participants’ breast volume measured in each of the three scanning positions are shown in Table 3. Breast volume was significantly greater when based on scans taken when the participants were in the prone position compared to the both standing positions (hands on hips or hands on heads), with no significant difference in the breast volume measured in the two standing
This result was confirmed by the Bland-Altman plots, which showed good agreement between the two standing positions (Figure 4A) but a large degree of error between either standing position and the prone position (Figure 4B), with the error increasing as breast volume (Table 4) and breast ptosis increased (Table 1). Breast volume was underestimated in both standing positions compared to the prone position, with the margin of error as high as 473 mL at an individual participant level and 103 mL at a group level.

Table 3: Mean and standard deviation values for the volume of the participants’ (n = 50) right and left breasts in the three scanning positions.

<table>
<thead>
<tr>
<th>Scanning Position</th>
<th>Right breast volume (mL)</th>
<th>Left breast volume (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>95% CI</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>Lower bound</td>
</tr>
<tr>
<td></td>
<td>Upper bound</td>
<td></td>
</tr>
<tr>
<td>Standing with hands on hips</td>
<td>973 ± 409</td>
<td>857</td>
</tr>
<tr>
<td>Standing with hands on head</td>
<td>990 ± 432</td>
<td>867</td>
</tr>
<tr>
<td>Lying prone</td>
<td>1072 ± 470*</td>
<td>939</td>
</tr>
</tbody>
</table>

* Indicates a statistically significant difference in breast volume compared to the two standing positions.

Table 4: Estimated percentage error in breast volume data, grouped by differing breast volume ranges, when women are scanned in a standing position (n = 48).

<table>
<thead>
<tr>
<th>Unilateral breast volume (mL)</th>
<th>Number of participants</th>
<th>Percent error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-499</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>500-749</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>750-999</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>1000-1249</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>1250-1749</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>1750-2250c</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>

* As data for only two participants were included in the 1750-2250 category, its percentage error should be interpreted with caution.
Figure 4: The Bland-Altman plot (bias and the limits of agreement ± 1.96*SD) for the breast volume measured for the 50 participants in the standing with hands on hips and hands on head scanning positions (A), and the standing with hands on hips and lying prone scanning positions (B).

2.4 Discussion

This is the first study to investigate the potential error when measuring the breast volume of large ptotic breasts using three-dimensional scanning (Kovacs et al. 2006; Lee et al. 2004; Thomson et al. 2009). The volume of large ptotic breasts has the potential to be underestimated when women are scanned in the standing position, which may then compromise bra cup design, size and, in turn, bra fit. This study provides evidence of the measurement error in breast volume associated with different breast sizes and levels of breast ptosis.

The mean breast volume of the participants (1065 ± 450 mL) was consistent with previous research of women with large breasts (Benditte-Klep et al. 2007; McGhee and Steele 2011; McGhee et al. 2013) and breast reduction mammoplasty candidates (Benditte-Klep et al. 2007). Ninety per cent of the participants (n = 45) were classified as having ptotic breasts (mean: stage 2; range: stage 1 – 3), with a mean sternal notch-to-nipple distance of 28.5 cm (range 20.8 – 35.2 cm; Table 1; Regnault 1976). The prone position allowed complete breast visualisation of these large ptotic breasts.
breasts in 100% of the participants, whereas each standing position only allowed complete breast visualisation in 5% of cases. These findings suggest that the strategy to improve visualisation of large ptotic breasts by a three-dimensional scanner through placing the participant's hands on their heads instead of their hips will do little to improve the accuracy of the breast volume measurement. It also confirms that the breast volumes and level of ptosis of the participants used in previous studies attempting to improve the scanning visualisation of large ptotic breasts were not large enough (Kovacs et al. 2007; Lee et al. 2004).

In line with the visualisation results, the breast volume measured in the prone position was also significantly greater than that measured in either standing position. This suggests that the prone position is the most accurate of the three positions to measure the breast volume of large ptotic breasts using three-dimensional scanning because it enables the entire breast to be visualised (Thomson et al. 2009). Although the prone position may not be feasible to use in all situations, the results provide information of the level of inaccuracy in breast volume data when large ptotic breasts are scanned in the standing position and how this varies with the magnitude of breast volume and ptosis. This is also useful information for breast surgeons who use breast volume measurements to aid surgical outcomes of breast symmetry and the desired post-operative breast size (Kovacs et al. 2006; Lee et al. 2004).

In agreement with our hypothesis, the level of error increased with both breast size and ptosis. The volume of the smaller breasts of the cohort (i.e. volumes between 400 – 500 mL) was underestimated by approximately a 3% error when scanned in the standing position compared to the prone position, with good agreement in the Bland-Altman analyses (Figure 4B). The percentage error, however, increased and the level of agreement decreased as breast size increased (i.e. volumes > 500 mL). In fact, breast
volume was underestimated by 7 – 11% (Table 4) when the participants with breasts > 500 mL were scanned in the standing position compared to the prone position. The most accurate measure of breast volume using three-dimensional scanning tested in the present study was achieved when the breasts were scanned in the prone position. When this is not possible or feasible, such as when whole body scanners and a standing position are used, these errors need to be taken into consideration so that bra cup design and sizes can be made to fit the true breast volumes.

2.5 Conclusion

Breast volume can be underestimated by between 7 – 11% for women with large ptotic breasts (volume > 500 mL) and approximately 3% for women with breasts of 400 – 500 mL in volume if these women are scanned standing upright. This error has the potential to negatively affect bra cup sizing, design and bra fit and therefore should be taken into consideration when using three-dimensional scans to manufacture and size bras for women with large breasts.
Part II

Who are we catering for?
Chapter 3

Effect of ageing on breast skin thickness and elasticity:
Implications for breast support


Abstract

The skin overlying a woman's breast acts as an anatomical support structure to the breast. Although ageing is known to affect the thickness and elasticity of human skin, limited research has examined age-related changes to skin covering the breast or related these changes to breast support requirements. The purpose of this study was to determine the effect of age on female breast skin thickness and elasticity. The left breast of 339 women (18 – 84 years), classified into four age groups (18 – 24 years, 25 – 44 years, 45 – 64 years and 65+ years), was divided into four quadrants. Skin thickness (dermal layer; 20 MHz ultrasound probe) and skin elasticity (Cutometer® MPA 580) were measured for each breast quadrant and then compared to determine whether there was any significant ($p < 0.05$) effect of ageing on breast skin. Breast skin thickness significantly decreased between 45 – 64 years of age and thereafter. A significant decline in breast skin elasticity was evident from between 25 – 44 years of age and thereafter. Ageing is associated with a significant decline in breast skin thickness and elasticity, which is likely to reduce anatomical breast support. Women might therefore benefit from increased external breast support (i.e. a more supportive bra) with increasing age.
3.1 Introduction

Ageing is associated with a progressive decline in function and capacity of all organs in the body, including the skin (Yaar and Gilchrest 2007). Changes in the function and appearance of human skin with increased age is a consequence of both intrinsic and extrinsic factors, with extrinsic ageing known to accelerate the effects of intrinsic skin ageing (Rittié and Fisher 2015; Watson et al. 2014; Yaar and Gilchrest 2007). Intrinsic ageing is characterised by three main features: (i) atrophy of the dermis due to loss of collagen, (ii) degeneration of the elastic fibre network, and (iii) loss of hydration (Escoffier et al. 1989; Uitto 2008). The two predominant tissue components of the dermis, collagen (primarily, type I and III) and elastin, comprise 70 – 80% and 2 – 4% of dermal dry weight, respectively (Langton et al. 2010; Uitto 1989; Uitto 2008; Weinstein and Boucek 1960). Together they form an interconnected mesh that dictates the skin’s mechanical properties (Langton et al. 2010) and any age-related changes to the dermis primarily involve changes to the structure of these networks (Tzaphlidou 2004).

Within the dermis, collagen is organised into tightly packed bundles, orientated parallel to the surface of the skin, which function to give the skin tensile strength (Lavker et al. 1987; Rittié and Fisher 2015; Uitto 2008). Elastic fibres, also found within the dermis, are interlaced with collagen and are comprised of an elastin centre and a microfibrillar shell containing glycoproteins and fibrillin. This network of fibres acts to provide the skin with elasticity and resilience (Langton et al. 2010; Uitto 2008). The rate of biosynthesis of collagen and elastin, however, differ with age. Collagen biosynthesis rate is known to decline steadily from birth until the third or fourth decade after which the degradation of collagen exceeds the synthesis of new collagen (Uitto 1971; Uitto 2008). In contrast, elastin biosynthesis has been shown to remain stable.
Breast skin

until the third or fourth decade, declining dramatically thereafter (Fazio et al. 1988; Uitto 1971; Uitto 2008). At the same time, glycosaminoglycan (or ground substance) levels decline, which reduces skin hydration (Uitto 2008). The level of mechanical tension of fibroblasts that is necessary for sufficient collagen synthesis is also reduced (Fisher et al. 2008; Rittié and Fisher 2015; Varani et al. 2006). It is the combined effect of changes to these proteins within the dermis that lead to its atrophy with ageing (Uitto 2008).

In order to quantify the consequences of intrinsic skin ageing, changes to skin thickness and elasticity with increasing age have been investigated. The changes have primarily been quantified using non-invasive methods in the skin of the ventral forearm (De Rigal et al. 1989; Escoffier et al. 1989; Kim et al. 2013), as well as at the cheek, neck, dorsal forearm and dorsal hand (Braverman and Fonferko 1982; Diridollou et al. 2001; Kim et al. 2013; Krueger et al. 2011; Luebberding et al. 2014). Skin thickness of the ventral forearm has been reported in three studies (Escoffier et al. (1989): n = 123; De Rigal et al. (1989): n = 142 and Diridollou et al. (2001): n = 206) to significantly decrease from 60 – 70 years of age onwards. Some studies, however, have reported this decline to commence from as early as 40 – 60 years onwards in women (Diridollou et al. 2001; Yaar and Gilchrest 2001), coinciding with the onset of menopause where the dermis has been reported to thin by approximately 20% (Baumann 2007; Brincat et al. 1987; Calleja-Agius et al. 2013; Ulger et al. 2003). Contrary to these studies, one study reported the skin thickness of the volar forearm to increase by 4.5% in elderly women (age range: 60 – 90 years) compared to their younger counterparts (age range: 27 – 31 years), however, the study sample size was small (n = 24; Seidenari et al. 1994).

To date, minimal research has investigated any age-related changes to breast skin thickness or elasticity. This is despite the important role that skin covering the
breast plays in supporting the weight of the breast (Gefen and Dilmoney 2007; McGhee et al. 2008). Although breast skin thickness has previously been quantified (Huang et al. 2008; Pope Jr et al. 1984; Sutradhar and Miller 2013; Willson et al. 1982), only one published study was found that measured the effects of ageing on breast skin thickness (Ulger et al. 2003). Using mammography, Ulger et al. (2003) measured the breast skin thickness of 120 women and found the breast skin thickness of post-menopausal women (mean age: 50.3 ± 6.1 years) to be significantly less compared to pre-menopausal women (mean age: 41.7 ± 4.7 years). The effects of ageing on the skin in different regions of the breast are also yet to be investigated, despite reported changes to breast shape with advancing age (Machida and Nakadate 2015; Risius et al. 2014; refer to Chapter 5, Section 5.3.2). Regional variations in breast skin thickness (Sutradhar and Miller 2013) were found in one ultrasound study conducted on a small cohort of women (n = 23) across a wide age range (29 – 75 years of age). The magnitude of these reported differences, however, was only small (< 0.1 mm between different regions of the breast), questioning their clinical relevance and the possibility of measurement error. A masking effect may also have occurred given the large age range over which these data were averaged across. Although other studies using mammography have also reported finding variations in skin thickness in different regions of the breast, results from these studies have been inconsistent (Pope Jr et al. 1984; Ulger et al. 2003; Willson et al. 1982).

Regional variation in breast skin elasticity (Sutradhar and Miller 2013) was reported in one study (n= 23; age range: 29 – 75 years; Sutradhar and Miller 2013), however, no published research was found on the effects of ageing on breast skin elasticity. The skin of the ventral forearm, dorsal forearm, neck, cheek, hand and cleavage (on the madubrium between the top of the breasts, not on actual breast tissue)
have all been found to progressively lose the ability to return to its initial state with ageing and this has been found to occur from an early age (~ 20 – 30 years; Diridollah et al. 2001; Escoffier et al. 1989; Krueger et al. 2011).

Changes to breast skin thickness and elasticity with increased age have important implications for breast support because the weight of the female breast is supported anatomically by skin overlying the breast and fascia within the breast (Gefen and Dilmoney 2007; McGhee et al. 2008). Sufficient breast support is vital in order for women, particularly those with large breasts, to achieve and maintain an upright posture and to limit excessive breast movement, which can act as a barrier to women participating in physical activity (McGhee et al. 2013). If support provided by anatomical structures decreases with age, the level of support required externally from the bra will need to be modified for sufficient support to be achieved. Additionally, age related changes to breast skin may contribute to age related changes in breast shape (Elsahy 1990; Machida and Nakadate 2015; McGhee and Steele 2006) resulting in implications for breast support and bra design (refer to Chapter 5). This study therefore aimed to investigate the effect of ageing on female breast skin thickness and elasticity. It was hypothesised that age would influence breast skin properties, such that reduced breast skin thickness and elasticity would be observed in older participants compared to younger participants. It was also hypothesised that regional variations in skin thickness and elasticity would be observed across the breast.

3.2 Materials and methods

3.2.1 Participants

Following approval from the University of Wollongong Human Research Ethics Committee (HE 13/051), 378 women (18 – 84 years of age) volunteered to participate in the current study. Women with any skin disease, physical skin disorder or cutaneous
Breast skin

manifestation; women who had bilateral breast surgery, or those who had applied creams or ointments to their breast skin in the 12 hours preceding the test session (Luebberding et al. 2014) were excluded, reducing the sample size to 339. Smoking was not deemed an exclusion criterion because post hoc analysis of the participant smokers (n = 8; 2%) and age-matched non-smokers within this study found no significant (p > 0.05) between-group difference in any outcome variable. The participant cohort was divided into four age groups (18 – 24 years, 25 – 44 years, 45 – 64 years and 65+ years) based on standard international age classifications guidelines (United Nations, 1982). The participant characteristics, grouped according to age, are shown in Table 5. Data were obtained for the left breast only except for participants who had unilateral breast surgery, whereby data from their unaffected breast were collected (n = 24; ~7%). Ambient room temperature conditions (24˚C; 65 – 70% humidity) were maintained in the testing laboratory and participants were acclimatised for 30 minutes before being measured (Krueger et al. 2011). All participants provided written informed consent prior to testing and all testing was conducted according to the National Health and Medical Research Council Statement on Human Experimentation (2007).

Table 5: Participant characteristics (mean ± standard deviation) and menopausal status (n) for each age group category (n = 339).

<table>
<thead>
<tr>
<th>Group</th>
<th>18-24 years</th>
<th>25-44 years</th>
<th>45-64 years</th>
<th>65+ years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 85)</td>
<td>(n = 95)</td>
<td>(n = 80)</td>
<td>(n = 79)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>22.2 ± 1.6</td>
<td>31.6 ± 6.1</td>
<td>54.8 ± 5.7</td>
<td>72.0 ± 4.4</td>
</tr>
<tr>
<td>Breast volumea (mL)</td>
<td>514 ± 356</td>
<td>580 ± 482</td>
<td>680 ± 417</td>
<td>875 ± 493</td>
</tr>
<tr>
<td>Body Mass Index (m²/kg)</td>
<td>25.4 ± 5.2</td>
<td>26.3 ± 6.1</td>
<td>28.1 ± 5.5</td>
<td>30.6 ± 6.5</td>
</tr>
<tr>
<td>Menopausal status:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-menopause</td>
<td>85</td>
<td>88</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>Currently menopausal</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Post menopause</td>
<td>0</td>
<td>2</td>
<td>38</td>
<td>78</td>
</tr>
</tbody>
</table>

*a Breast volume for the left breast of each participant was calculated using the methods described in Section 2.2.2 from a prone three-dimensional scan of each participant’s breasts.*
3.2.2 Skin thickness

Skin thickness was captured with a SonoSite 180PLUS ultrasound system (SonoSite, Australia) while participants lay supine on a plinth. To identify the five skin thickness measurement sites, each participant’s left breast was marked at the midpoint of the superior, inferior, medial and lateral quadrants, relative to the nipple, and at the volar forearm (see Figure 5), while they lay supine on a plinth. An off-set gel pad was then placed on each site. Aquasonic translucent gel was applied to a 20 MHz ultrasound probe (SonoSite 180PLUS, SonoSite, Australia), which was then used to capture an image of the skin thickness. The thickness of the dermal layer of the skin was measured from the ultrasound image by the same experienced investigator, using ImageJ software (National Institute for Health, Bethesda, USA), as the distance (mm) between the surface of the epidermis and subcutaneous tissue (Sutradhar and Miller 2013). The mean of three measurements at the five sites was recorded. Skin thickness measurements were found to have high reliability (ICC = 0.96; \( p < 0.001 \); n = 12; blinded measurements taken on three consecutive days).

Figure 5:
Measurement sites for the four breast quadrants (A) and the volar forearm (B).
3.2.3 Skin elasticity

The same experienced investigator measured each participant’s breast skin elasticity, at the same five sites described for skin thickness (Section 3.2.2), using a Cutometer® MPA 580 (2 mm aperture sized probe, Courage & Khazaka Electronic GmbH, Cologne, Germany; device measurement accuracy: ± 3%). The skin at each site (Figure 5) was drawn into the Cutometer probe by a negative pressure of 450 mbar. A strain-time mode was used whereby three consecutive cycles of a 2 s suction application followed by a 2 s relaxation period was used at each site (Figure 6; Luebberding et al. 2014). The probe was displaced 5 mm in the same plane before the next measurement was taken at that same skin site (Krueger et al. 2011). The mean of three values was recorded per skin site. Skin elasticity measurements were found to have high reliability (mean ICC = 0.83; p < 0.001; n = 7; blinded measurements taken on three consecutive days).

Three key parameters as per previous research were calculated to quantify skin elasticity (Krueger et al. 2011): (i) gross elasticity (R2; Ua/Uf), (ii) net elasticity (R5; Ur/Ue), and (iii) the ratio of elastic recovery to distensibility (R7; Ur/Uf; Figure 6).
Figure 6: An example of the skin deformation versus time curve generated following each suction and relaxation phase using the Cutometer MPA580. R2 was calculated by dividing total deformation (Ua) by total distensibility (Uf). R5 was calculated by dividing immediate deformation (Ur) by immediate distensibility (Ue). R7 was calculated by dividing immediate deformation (Ur) by total distensibility (Uf).

3.2.4 Statistical analysis

Descriptive statistics (mean and standard deviation) were calculated for the skin thickness and skin elasticity data across all four participant age groups at each of the five skin sites. A one-way ANOVA was then used to determine whether there was any significant main effect of age on breast skin thickness, with Bonferroni post hoc analyses to identify where the differences lay. Kurskal Wallis tests were used to determine whether there were any significant effects of age on the three skin elasticity parameters (ratio data). Multiple Mann-Whitney tests were then performed to determine where any differences lay. Spearman’s correlations were calculated to determine whether the three elasticity parameters were correlated to one another or to skin thickness. The strength of the correlation coefficients was interpreted as weak ($\leq 0.50$),
low (0.5 – 0.7), moderate (0.7 – 0.8), or strong (≥ 0.8; Vincent 1999). All statistical calculations were conducted using the Statistical Package for the Social Sciences (Version 21.0; SPSS Inc., Chicago, IL) with an alpha level set at $p < 0.05$.

### 3.3 Results

#### 3.3.1 Skin thickness

The mean and standard deviation values for skin thickness for the four participant age groups at the five skin sites are shown in Table 6. There was a significant main effect of age on skin thickness at all breast quadrants, with a reduction in skin thickness at each breast quadrant with increasing age (Figure 7). The thinnest breast skin across all ages (mean value) was found at the lateral and superior breast quadrants and the greatest percent change in skin thickness with increased age was observed in the lateral and medial skin sites (magnitude of change in all four quadrants: 8 – 21%; Table 6). There was no significant difference in skin thickness between Group 1 and Group 2 or between Group 3 and Group 4 at any of the four breast quadrants. Group 1, however, had significantly thicker breast skin at all four breast quadrants compared to Group 3 and Group 4. Group 2 displayed significantly thicker breast skin at all four breast quadrants compared to Group 3 and Group 4. Volar forearm skin was significantly thinner than breast skin at all four breast quadrants. Skin of the volar forearm was significantly thicker for Group 3 and Group 4 compared to Group 2, although these changes were very small (2% change).
Table 6: Overview of the mean ± standard deviation values for skin thickness and elasticity parameters (R2, R5 and R7) at the five measurement sites for each participant group.

<table>
<thead>
<tr>
<th>Skin thickness (mm)</th>
<th>Group 1 (18-24 years; n = 85)</th>
<th>Group 2 (25-44 years; n = 95)</th>
<th>Group 3 (45-64 years; n = 80)</th>
<th>Group 4 (65+ years; n = 79)</th>
<th>Mean (n = 339)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volar forearm</td>
<td>1.30 ± 0.14</td>
<td>1.26 ± 0.13</td>
<td>1.34 ± 0.17</td>
<td>1.33 ± 0.22</td>
<td>1.30 ± 0.17</td>
</tr>
<tr>
<td>Superior</td>
<td>1.84 ± 0.24</td>
<td>1.85 ± 0.24</td>
<td>1.72 ± 0.25</td>
<td>1.67 ± 0.33</td>
<td>1.77 ± 0.28</td>
</tr>
<tr>
<td>Lateral</td>
<td>1.74 ± 0.21</td>
<td>1.73 ± 0.23</td>
<td>1.50 ± 0.26</td>
<td>1.38 ± 0.24</td>
<td>1.59 ± 0.28</td>
</tr>
<tr>
<td>Inferior</td>
<td>1.97 ± 0.27</td>
<td>1.94 ± 0.31</td>
<td>1.80 ± 0.31</td>
<td>1.82 ± 0.45</td>
<td>1.89 ± 0.34</td>
</tr>
<tr>
<td>Medial</td>
<td>1.97 ± 0.26</td>
<td>1.95 ± 0.30</td>
<td>1.80 ± 0.31</td>
<td>1.81 ± 0.42</td>
<td>1.88 ± 0.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R2 (%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volar forearm</td>
<td>87.8 ± 7.5</td>
<td>85.2 ± 8.1</td>
<td>75.5 ± 11.8</td>
<td>64.2 ± 9.9</td>
<td>78.7 ± 13.1</td>
</tr>
<tr>
<td>Superior</td>
<td>86.7 ± 8.0</td>
<td>84.6 ± 7.1</td>
<td>84.5 ± 5.1</td>
<td>81.4 ± 5.1</td>
<td>84.3 ± 7.0</td>
</tr>
<tr>
<td>Lateral</td>
<td>86.8 ± 7.8</td>
<td>84.4 ± 8.4</td>
<td>85.0 ± 7.0</td>
<td>83.9 ± 6.5</td>
<td>85.0 ± 7.6</td>
</tr>
<tr>
<td>Inferior</td>
<td>84.8 ± 8.4</td>
<td>79.5 ± 10.5</td>
<td>79.5 ± 8.8</td>
<td>79.7 ± 7.8</td>
<td>80.9 ± 9.0</td>
</tr>
<tr>
<td>Medial</td>
<td>86.3 ± 7.7</td>
<td>81.2 ± 10.2</td>
<td>79.2 ± 9.3</td>
<td>73.4 ± 11.1</td>
<td>80.2 ± 10.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R5 (%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volar forearm</td>
<td>87.5 ± 11.9</td>
<td>79.1 ± 12.2</td>
<td>58.0 ± 14.7</td>
<td>41.0 ± 12.1</td>
<td>67.3 ± 22.0</td>
</tr>
<tr>
<td>Superior</td>
<td>79.6 ± 13.4</td>
<td>73.9 ± 15.4</td>
<td>72.4 ± 13.1</td>
<td>63.7 ± 12.6</td>
<td>72.6 ± 14.7</td>
</tr>
<tr>
<td>Lateral</td>
<td>75.7 ± 11.3</td>
<td>67.9 ± 15.5</td>
<td>67.4 ± 12.7</td>
<td>63.3 ± 14.8</td>
<td>68.7 ± 14.4</td>
</tr>
<tr>
<td>Inferior</td>
<td>71.0 ± 14.5</td>
<td>59.3 ± 16.1</td>
<td>58.7 ± 13.3</td>
<td>55.9 ± 13.6</td>
<td>61.3 ± 15.5</td>
</tr>
<tr>
<td>Medial</td>
<td>69.7 ± 14.3</td>
<td>59.7 ± 16.2</td>
<td>56.3 ± 15.8</td>
<td>47.6 ± 13.4</td>
<td>58.6 ± 15.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R7 (%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Volar forearm</td>
<td>58.5 ± 6.9</td>
<td>53.2 ± 7.4</td>
<td>38.4 ± 8.9</td>
<td>26.7 ± 7.4</td>
<td>44.9 ± 14.6</td>
</tr>
<tr>
<td>Superior</td>
<td>56.6 ± 9.0</td>
<td>50.5 ± 9.7</td>
<td>47.7 ± 7.4</td>
<td>41.6 ± 7.8</td>
<td>49.3 ± 10.1</td>
</tr>
<tr>
<td>Lateral</td>
<td>56 ± 8.3</td>
<td>49.5 ± 10.6</td>
<td>48.9 ± 8.1</td>
<td>45.8 ± 9.1</td>
<td>50.2 ± 9.8</td>
</tr>
<tr>
<td>Inferior</td>
<td>52.2 ± 10.0</td>
<td>43.6 ± 11.5</td>
<td>41.9 ± 8.9</td>
<td>38.1 ± 9.2</td>
<td>44.1 ± 11.2</td>
</tr>
<tr>
<td>Medial</td>
<td>52.8 ± 9.3</td>
<td>44.0 ± 11.6</td>
<td>40.5 ± 10.9</td>
<td>33.9 ± 9.7</td>
<td>43.0 ± 12.4</td>
</tr>
</tbody>
</table>

*a* represents a statistically significant (*p* < 0.05) difference between Group 1 and Group 2

*b* represents a statistically significant (*p* < 0.05) difference between Group 1 and Group 3

*c* represents a statistically significant (*p* < 0.05) difference between Group 1 and Group 4

*d* represents a statistically significant (*p* < 0.05) difference between Group 2 and Group 3

*e* represents a statistically significant (*p* < 0.05) difference between Group 2 and Group 4

*f* represents a statistically significant (*p* < 0.05) difference between Group 3 and Group 4
Figure 7: Percentage change in breast skin thickness with increasing age at each breast quadrant (n = 339). The skin thickness value for Group 1 was set at 100% for each quadrant and all other participant group values are expressed relative to this group, together with the standard deviation of the change. This figure does not depict the difference in each breast quadrant, only the effect of age at each breast quadrant.

3.3.2 Skin elasticity

Mean and standard deviation values for the three skin elasticity parameters (R2, R5, R7), expressed as ratios (%), measured at the five skin sites, are shown in Table 6. There was a significant main effect of age on all breast skin elasticity parameters (R2, R5, R7). Skin elasticity parameters (R2, R5, R7) were significantly greater at all breast quadrants for women in Group 1 compared to the three other participant age groups. After 18 – 24 years (Group 1) there was a steady decline in some but not all breast skin elasticity parameters, with the trend for each age group to have significantly greater breast skin elasticity than the adjacent older age group. The most elastic skin was observed at the lateral breast skin site followed by the superior, inferior and medial skin sites and the greatest percentage change (decrease) in elasticity was observed at the
medial and superior skin sites (Table 6). The statistically significant differences detected between groups among the different regions of the breast and volar forearm are shown in Table 6. Low to strong correlations (ranging from $r = 0.637 – 0.909$) were observed between the three elasticity parameters (R2, R5, and R7) for the five skin sites (Table 7). However, weak correlations were observed between skin thickness and skin elasticity parameters for the five skin sites (Table 7).

**Table 7:** Correlation coefficients for R2* relative to R5, R7 and skin thickness (n = 339).

<table>
<thead>
<tr>
<th>Skin thickness</th>
<th>Volar forearm</th>
<th>Superior</th>
<th>R2 Lateral</th>
<th>Inferior</th>
<th>Medial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volar forearm</td>
<td>-0.103</td>
<td>-0.085</td>
<td></td>
<td>-0.129</td>
<td></td>
</tr>
<tr>
<td>Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.033</td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
<td>-0.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior</td>
<td></td>
<td></td>
<td></td>
<td>-0.129</td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>0.894</td>
<td>0.682</td>
<td>0.637</td>
<td>0.744</td>
<td>0.792</td>
</tr>
<tr>
<td>Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
<td>-0.033</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R7</td>
<td>0.909</td>
<td>0.710</td>
<td>0.649</td>
<td>0.752</td>
<td>0.825</td>
</tr>
<tr>
<td>Superior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Because all elasticity parameters were correlated low-strongly to one another only R2 values are shown to illustrate the correlation between elasticity parameters and skin thickness.

**3.4 Discussion**

This study aimed to determine the effect of age on the thickness and elasticity of female breast skin. Results of this study revealed that breast skin thickness significantly decreased with increasing age, with the decline commencing between ages 45 – 65 years. Breast skin elasticity also showed a steady, step-wise decline in women with increasing age, with the decline commencing earlier, between ages 25 – 44 years. The
Breast skin

implications of these changes in breast skin as a function of ageing, with implications for breast support, are discussed below.

The magnitude and reported variation in the range of skin thickness were consistent with previous research (Huang et al. 2008; Miller 2013; Pope Jr et al. 1984; Sutradhar and Ulger et al. 2003; Willson et al. 1982). The significant decline found in breast skin thickness with ageing (Table 6) was also consistent with previous research whereby the breast skin thickness of post-menopausal women has been found to be significantly less than that of pre-menopausal women, with this decline thought to be accelerated by hormonal effects (Ulger et al. 2003). The decline in skin thickness between 45 – 64 years has similarly been attributed in non-breast skin sites to hormonal effects with the reduction in estrogen associated with menopause occurring during this time (between ages 45 – 60 years; Calleja-Agius et al. 2013; Farage et al. 2009; Hall and Phillips 2005; Ohta et al. 1998). Consistent with this notion, 70% of participants from the current study in the 45 – 64 year age group reported being either menopausal or post-menopausal.

Interestingly, thickness of the participants’ volar forearm skin was not found to decrease with age, remaining essentially unchanged (Table 6; increase by 2%). This was consistent with one study which found skin thickness at the volar forearm to increase with age (4.5% increase; Seidenari et al. 1994). However, this finding is in contrast to other research that has shown skin thickness at the volar forearm to decrease in participants after 70 years of age (De Rigal et al. 1989; Diridollou et al. 2001; Escoffier et al. 1989). The different results obtained between these previous studies and the current study were attributed to differences in participant numbers (the present study had 3 – 4 times the participant number in each grouping; De Rigal et al. 1989; Diridollou et al. 2001; Escoffier et al. 1989; Seidenari et al. 1994); different
measurement protocols and device technology (previous research conducted > 15 years ago) and, differences in sun exposure of participants due to geography (all previous studies were conducted in France where sun exposure is less than in Australia, where the current study was conducted; Lens and Dawes 2004). Increased sun exposure has been reported to induce skin thickening in the sub-epidermal non-echogenic band, which accounts for the majority of dermal thickness in aged participants (De Rigal et al. 1989; Diridollou et al. 2001). The volar forearm of the participants in the current study may therefore have been affected but, as the breasts are more likely to be covered and therefore protected from sunlight, the skin of the breasts was consistent with the results of studies conducted in countries where the exposure to high UV radiation is much less (Sutradhar and Miller 2013; Ulger et al. 2003). It should also be noted that the slight increase in volar forearm thickness (2% increase) was much less than the change in breast skin thickness (8 – 21% decrease).

The skin of the lateral and medial breast quadrants had the most marked decrease in thickness between ages 45 – 64 years (21% and 16% respectively; Figure 7). This regional variation in breast skin thickness was greater than the results reported in the only other previously published study that used ultrasound to measure regional variation in breast skin thickness (current study: 16% variation; Sutradhar & Miller 2012: 5% variation). The between-study difference were attributed to differences in sample size (current study: n = 339; Sutradhar & Miller 2012: n = 23), where the large cohort of the current study may better represent the population data. Considering the magnitude of the change in breast skin thickness measured at each region (i.e. 0.16 – 0.36 mm; 8 – 21% change), the regional variation in breast skin thickness observed in the current study was deemed to be both statistically significant and clinically relevant.
Breast skin

(Huang et al. 2008; Pope Jr et al. 1984; Sutradhar and Miller 2013; Ulger et al. 2003; Willson et al. 1982).

Data characterising elasticity of the skin of the breast and volar forearm in the current study was consistent with previous research of non-breast skin sites (Daly and Odland 1979; Diridollou et al. 2001; Escoffier et al. 1989; Fleischmajer et al. 1972; Uitto 1989), showing a steady, step-wise decline with increasing age that commenced from 25 – 44 years of age (Table 6). This decline in skin elasticity has been attributed to degrading of the elastic fibres in the dermis associated with ageing (Braverman and Fonferko 1982), with the decline in the biosynthesis of elastin reported to commence from the third decade (Fazio et al. 1988; Uitto 2008). Also contributing to the reduced skin elasticity with age is the decrease in collagen synthesis as a result of reduced fibroblast tension (Calleja-Agius et al. 2013; Fisher et al. 2008; Imokawa and Ishida 2015; Rittié and Fisher 2015; Varani et al. 2006). It is speculated that these structural alterations in the collagen and elastic fibres of the dermis might also contribute to the clinical changes in breast shape observed with ageing, such as drooping or sagging of the breasts (Machida and Nakadate 2015; Risius et al. 2014).

The changes in breast skin elasticity with increased age were not uniform across the breast quadrants with the superior and medial breast quadrants showing the greatest decline relative to the other breast quadrants. These regional changes in breast skin elasticity are consistent with the reported changes in breast shape associated with increasing age, where the breasts tend to splay downward and outward with advancing age (Elsahy 1990; Machida and Nakadate 2015; McGhee and Steele 2006; refer to Chapter 5, Section 5.4). This change in breast shape has been attributed to the force of gravity acting downward on the breasts (Elsahy 1990; Machida and Nakadate 2015; McGhee et al. 2013). This may be due to the insufficiency of the superior (McGhee et
Breast skin

al. 2013) and medial anatomical supports of the breast allowing this shift in mass. The
greater reduction in skin elasticity observed in the superior and medial breast quadrants
in the current study supports this notion. Additional external support in the form of a
bra, with particular support laterally and inferiorly, might alleviate the strain medially
and superiorly on the breast skin. As these declines in skin elasticity were found to
occur between the ages of 25 – 44 years, increased external support is recommend for
women from the mid 20’s onwards. Furthermore, the breast regions where the thickest
skin was identified in the present study (inferior and medial breast) were found to be the
least elastic regions, highlighted by the weak correlation between skin thickness and
skin elasticity (Table 7). The lack of correlation between thickness and elasticity was
consistent with previous research (Kim et al. 2013; Krueger et al. 2011; Smalls et al.
2006; Sutradhar and Miller 2013). Only one published study was located that found skin
thickness and elasticity to have a low correlation at the shoulder ($r = -0.53$; Smalls et al.
2006), although the same study found weak correlations at the calf and thigh (Smalls et
al. 2006).

The changes to breast skin thickness and elasticity with increased age revealed
in the current study have important implications for breast support. This is because the
skin overlying the breast, as well as fascia within the breast (including the Cooper’s
Ligaments), anatomically supports the weight of the female breast (Gefen and Dilmoney
2007; McGhee et al. 2008; McGhee et al. 2013). The skin thickness and elasticity
changes with advancing age suggest that the level of anatomical breast support
decreases with age, such that a greater level of external breast support (from a bra) is
likely to be required as women age. Sufficient breast support is vital in order for
women, particularly those with large breasts, to limit excessive breast movement so
they can participate comfortably in physical activity (McGhee et al. 2013). Furthermore,
the current study found the decrease in anatomical breast support with increasing age to coincide with an increase in breast mass, as both breast volume and BMI were found to increase with age (Table 5). Previous research has reported bra size to increase in as many as one in five women due to the weight gain associated with menopause (Den Tonkelaar et al. 2004). The decrease in skin thickness (especially at the medial and lateral quadrants) combined with an increase in weight that occurs peri- and particularly post-menopause, suggests that a greater level of external breast support is required for women 45 years and over.

3.5 Conclusion

The changes to the thickness and elasticity of breast skin that occur with ageing suggest that the anatomical breast support structure is significantly affected by increasing age. The age-related decline in breast skin thickness and skin elasticity was observed from between 45 – 64 years and from between 25 – 44 years, respectively. The elasticity declines were most evident at the superior and medial regions of the breast corresponding to the shift in breast mass downwards and outwards with increased age. Due to the decline in anatomical breast support, women are likely to benefit from greater external breast support, particularly structures laterally and inferiorly, as they age.
Chapter 4
Breast volume is affected by body mass index but not age

This chapter is an amended version of the published manuscript: Coltman, C.E., Steele, J.R. & McGhee, D.E., 2017. Breast volume is affected by body mass index but not age. 
*Ergonomics*, 60(11): 1576-1585.

Abstract

This study aimed to establish normative breast volume data for women of varying ages, body masses and breast sizes, and to determine the effect of age and BMI on breast volume. The breast volume of 356 women (age range: 18.1 – 83.7 years; BMI range: 18.4 – 54.5 kg/m²) was measured using three-dimensional scanning in a prone position. Breast volumes ranged from 48 mL – 3100 mL. Although breast volume was not significantly affected by age, it was significantly affected by BMI, with the breast volume of overweight and obese women being two-to-three times greater than women with normal BMI’s. It is recommended that bra cups must be designed to support the wide range and increasing magnitude of breast volumes exhibited by women.
4.1 Introduction

Breast size is commonly represented as a bra size, which is a combination of a number (e.g. 10, 12 and 14 in Australian sizing; see Appendix A for international bra band sizing conversions) that represents the band size, and a letter (e.g. A, B, and C; see Appendix A for international bra cup sizing conversions), which represents cup size. Although the breast is a three-dimensional object, the size of the bra cup is typically determined from two simplistic anthropometric measurements; (i) the under bust chest circumference and, (ii) the over bust chest circumference. Intimate apparel designers use the difference between these two measurements, in combination with several other bra design parameters, to develop three-dimensional bra cup structures. In order for a bra cup to fit correctly, however, it must match the complex three-dimensional shape and volume of the breast it is required to contain (Chen et al. 2011; Lee et al. 2004; Pandarum et al. 2011).

Normative data on the volume of women’s breasts have the potential to enable bra cups to be designed to better match the breasts of women in terms of both size (volume) and shape. Despite the large number of three-dimensional body scan databases that exist (e.g. SAE International), no data that specifically characterise breast volume are publicly available for bra manufactures and designers to base their bra cup designs and sizing upon. In fact, limited research has been conducted to acquire normative breast volume data despite the fact that bra cup volume should match the volume of the breasts they are covering. Only one previous published study has reported normative breast volume data on a relatively large sample (n = 107) of women (range: 125 – 1900 mL, per breast; McGhee and Steele 2011) across a broad age spectrum (19 – 67 years). However, the method used to measure breast volume in this study (i.e. water displacement) was restricted to quantifying breast volumes less than 2000 mL, and the
Breast volume

authors reported that the volume of broad and small breasts was underestimated due to the nature of the measuring device (McGhee and Steele 2011). The only other study to report normative breast volume data (range: 132 – 889 mL, per breast; Smith et al. 1986) was restricted to a small sample of young women (n = 55; age range 18 – 31 years). Furthermore, breast volume was measured using casting, which is not as accurate as three-dimensional scanning (Bulstrode et al. 2001; Kovacs et al. 2007). Apart from these two studies, research reporting breast volume data has been limited to non-representative populations, such as women with hypertrophic breasts seeking breast reduction surgery (Cruz-Korchin et al. 2002; Ikander et al. 2014; Karabekmez et al. 2014; Sigurdson and Kirkland 2006). Although the breast volumes of these women with hypertrophic breasts (breast volumes ≥ 1500 mL per breast) do not represent the general population of women, their breast volume data highlight the wide range of breast volumes exhibited by women and, as such, the magnitude and range of volumes that bra cups must be designed to fit and support.

Within the literature, breast size has commonly been classified according to bra size. An A cup bra size has been used to represent a small breast size and ≥ D cup to represent a large breast size (Bowles et al. 2005; Brown et al. 2012; Coltman et al. 2015; McGhee et al. 2013; McGhee et al. 2011; White et al. 2015). Some studies have related these bra sizes to corresponding breast volumes. An A cup bra size has been equated to breast volumes of < 250 mL and breasts greater than a D cup bra size have been equated to breast volumes between 350 – 3100 mL (Coltman et al. 2014; McGhee et al. 2011). Classifying breasts into merely two size categories (small and large) is not adequate because the range of breast volumes included in the large breast size category is extremely wide. More importantly, using bra cup size to represent breast size is also flawed because bra cup sizes are not consistent amongst different band sizes or
standardised between different styles and makes of bra. Data from previous studies, however, have classified breast size as small-moderate in women with breasts of volumes < 500 mL (Brown et al. 2012; Brown and Scurr 2016; Ikander et al. 2014; Pamplona and De Abreu Alvim 2004) and breast size as either large or hypertrophic in women with breasts of volumes > 1200 mL (Benditte-Klepetko et al. 2007; Coltman, McGhee and Steele 2017; Ikander et al. 2014; Kerrigan et al. 2001). No objective standard classification system has been agreed upon, however, to characterise breasts size based on the magnitude of different breast volumes despite its applicability to research studies investigating breast health, as well as to bra design and manufacturing processes.

When designing and fitting bras, any effects of age and body mass on breast volume should also be considered, particularly given the changing demographics of the world’s population. Currently, 12% of the world’s population is over the age of 60 years, with this expected to reach 22% by 2050 (World Health Organisation 2015). Furthermore, 40% of women worldwide are overweight and 15% are obese (World Health Organisation 2014). Previous research has found breast volume (calculated using mammography) increased with advancing age (three age groups examined; ≤ 46 years; 46 – 55 years and ≥ 55 years), with this increase attributed to increases in adipose tissue (Hammann-Kloss et al. 2014). Unfortunately, the authors of this study did not publish the body mass of their participants to establish whether these age-related changes in breast volume were independent of body mass changes. Bra size has also been found to increase in as many as 1 in 5 women post-menopause due to an increase in total body weight (Den Tonkelaar et al. 2004), although the participants in this study self-reported their bra size rather than using an objective measure of breast volume. As body mass has been found to increase with age (Colombel and Charbonnel 1997; Williams et al.
Breast volume

2006), particularly around the menopausal years (Macdonald et al. 2003; Wing et al. 1991), the effect of age on breast volume independent of body mass warrants systematic investigation.

Although increased breast volume has been associated with increased BMI in several studies (Avşar et al. 2010; Benditte-Klepetko et al. 2007; Brown et al. 2012; Hasenburg et al. 2000; Janiszewski et al. 2010; Jernström and Olsson 1997), the research design of these studies has been limited. For example, breast volume was often measured using methods (e.g. water displacement or MRI; Benditte-Klepetko et al. 2007; Bulstrode et al. 2001; Janiszewski et al. 2010; Losken et al. 2005) that are less accurate than current techniques, such as three-dimensional scanning. Others only estimated the participant’s breast size through self-reported bra size (Avşar et al. 2010; Hasenburg et al. 2000). Restricted cohorts of homogenous groups of women with small breasts and low BMI’s (Brown et al. 2012) or sedentary, obese, premenopausal women (Janiszewski et al. 2010) also limited the applicability of the results of previous studies to the general population of women. Further systematic research is therefore required to determine the breast volume of women across a range of BMI’s as reliable and valid evidence to improve bra cup designs and bra fit. Although often dismissed as a trivial issue, poor bra fit is problematic because insufficient breast support has been associated with numerous negative health outcomes in women, such as poor posture, headaches and back ache (Findikcioglu et al. 2007; Greenbaum et al. 2003; Letterman and Schurter 1980; McGhee et al. 2013; Ryan 2009). The discomfort associated with incorrect bra fit can also be severe enough to inhibit women, particularly those with large breasts, from participating in physical activity and enjoying the health benefits associated with an active lifestyle (BeLieu 1994; Greenbaum et al. 2003; Kaye 1972; Lorentzen and Lawson 1987; Mason et al. 1999; McGhee et al. 2013; Ryan 2000; Scurr et al. 2010).
The aim of this study was firstly to establish normative data of the breast volumes of women, who represented a wide range of ages, body masses and breast sizes. Secondly, this study aimed to determine the effect of age and BMI on breast volume and the interaction among these variables. These data will provide evidence upon which to develop bra cups that better match the size (volume) of a woman’s breasts with respect to her age and BMI. Based on a review of the literature it was hypothesised that women of varying age, body mass and breast sizes will display a wide range of breast volumes. Furthermore, older women will display greater breast volume relative to their younger counterparts, independent of BMI, and women with a higher BMI will display increased breast volume relative to their leaner counterparts.

4.2 Materials and methods

4.2.1 Participants

Three hundred and seventy eight Australian women aged 18 years and over volunteered to participate in this study (age range: 18.1 – 83.7 years, mean: 44.3 ± 19.7 years; BMI range: 18.4 – 54.5 kg/m², mean: 27.7 ± 6.3 kg/m²; mode bra cup size: DD/E, range: A–H; mean band size: 12 – 14, range: 8 – 20). Participants were recruited by advertising the study broadly throughout the local community via media sources (including television and newspapers), across all sectors of the University of Wollongong (including students, general staff and academic staff), and through a variety of Women’s Health Centres throughout the state of NSW, Australia. These recruitment strategies were used to attract women from a broad range of age and body mass categories to participate in the study, and to ensure that the data were unbiased and representative of women over 18 years of age in the general population. The flow of participants through the study, including recruitment and exclusion criteria, is shown in Figure 8. Approval for the study was obtained from the University of Wollongong Human Research Ethics
Committee (HE 13/424). All participants provided written informed consent prior to testing and all testing was conducted according to the National Health and Medical Research Council Statement on Human Experimentation (2007).

Figure 8: Flow of participants through the present study.

4.2.2 Age and BMI classifications

Participants were divided into four age categories (18 – 24 years, 25 – 44 years, 45 – 64 years and 65+ years) based on standard international age classification guidelines (United Nations 1982), and three BMI categories (Normal: 18.5 – 24.9 kg/m², Overweight: 25–29.9 kg/m², Obese: ≥ 30 kg/m²) based on the World Health Organisation's international BMI classifications (World Health Organisation 2006; Table 8). Body mass index was calculated as body mass (kg)/height² (m) whereby height was measured using a portable stadiometer (Model: 214, Seca Corp., Maryland,
Breast volume was calculated from a three-dimensional scan of each participant’s breasts in a prone scanning position as shown in Figure 2C and described in detail in Chapter 2, Section 2.2.2.

4.2.4 Statistical analysis

Descriptive statistics (means and standard deviations) were calculated for the volume of the participants’ breasts, grouped according to right and left side, as well as the age (18 – 24 years, 25 – 44 years, 45 – 64 years and 65+ years) and BMI (Normal, Overweight, Obese) categories. As the breast volume data were positively skewed, the data were log transformed (Lg10) to meet the normality and homogeneity of variance assumptions.
Breast volume

underlying parametric statistics. A paired sample \( t \)-test was used to determine whether there were any significant (\( p < 0.05 \)) differences in breast volume between the participants’ right and left breasts. A two-way ANOVA design was then used to determine whether there were any significant (\( p < 0.05 \)) main effect of age or BMI on breast volume, and whether there was any significant age x BMI interaction. Where a main effect or interaction was found, Bonferroni post-hoc analyses were conducted to identify where the difference lay. Pearson product-moment correlation coefficients were calculated to determine the strength of the relationship between BMI and breast volume across the whole participant cohort. The strength of the correlation coefficients was interpreted as weak (\( \leq 0.50 \)), low (0.5 – 0.7), moderate (0.7 – 0.8), or strong (\( \geq 0.8 \); Vincent 1999). All statistical calculations were conducted using the Statistical Package for the Social Sciences (Version 21.0; SPSS Inc., Chicago, IL).

4.3 Results

Table 9 provides information on the study participants’ age, height, mass and body mass index compared to Australian population data (Australian Bureau of Statistics 2012, 2015). On average, the data for the study participants are representative of Australian women aged 18 years and over.

<table>
<thead>
<tr>
<th></th>
<th>Australian Women</th>
<th>Study participants</th>
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<tbody>
<tr>
<td>Median age (years)</td>
<td>38.3</td>
<td>43.2</td>
</tr>
<tr>
<td>Mean height (m)</td>
<td>1.62</td>
<td>1.64</td>
</tr>
<tr>
<td>Mean mass (kg)</td>
<td>71.1</td>
<td>74.0</td>
</tr>
<tr>
<td>Mean body mass index (kg/m²)</td>
<td>27.1</td>
<td>27.7</td>
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4.3.1 Breast volume

The breast volumes of participants measured in this study ranged from 48 – 3100 mL (Figure 9). As the transformed breast volume data showed similar trends to the
untransformed data, the untransformed breast volume data has been presented in this section for ease of interpretation. There was no significant difference in breast volume between the left and right breasts of the participants ($p \geq 0.05$; Figure 10).

**Figure 9:** The breast volume distribution for the right and left breasts of all participants measured in this study ($n = 346$).
Breast volume

Figure 10: Median and interquartile range for the breast volume (mL) of the left and right breasts of participants (n = 346).

4.3.2 Breast volume, age and BMI

Although the median breast volume appeared to increase with age, there was no significant main effect of age on breast volume ($p > 0.05$; Figure 11). However, there was a significant main effect of BMI on breast volume ($p < 0.01$; Figure 12 A and C). Participants who were classified as Overweight had significantly greater breast volumes than those classified as being of Normal BMI ($p < 0.01$), and participants classified as being Obese had significantly greater breast volumes than both the Normal and Overweight participants (Figure 12 A and C). However, a significant interaction was found between age and BMI, such that the main effects of BMI were moderated by age for those women within the Normal BMI category (Figure 13). That is, older women (65+ years) in the Normal BMI category displayed a significantly greater breast volume than their younger counterparts (18 – 24 years, 25 – 44 years and 44 – 64 years; Figure 13). The direct relationship between breast volume and BMI for the entire participant cohort is shown in Figure 12 B (right) and D (left). The Pearson correlation coefficient
Breast volume varied from $r = 0.69$ (left) to $r = 0.70$ (right), indicating that as BMI increased, breast volume also increased.

**Figure 11:** Median and interquartile range for the breast volume (mL) of the left and right breast across the four age group categories assessed in this study. No significant main effect of age on breast volume was detected ($p \geq 0.05$).
Figure 12: Median and interquartile range for the breast volume (mL) data of the left and right breasts across the three BMI categories assessed in this study is shown in A (right) and C (left). The direct relationship between BMI and breast volume for each breast is shown in B (right breast) and D (left breast), along with the respective coefficient of determination ($r^2$ value).

* indicates a significant ($p \leq 0.05$) main effect of BMI grouping.

** indicates a significant correlation between breast volume and BMI.
Figure 13: Geometric mean ± standard error breast volume (right and left) for each age group (x-axis) relative to each BMI category is displayed (n = 346), highlighting the interaction between age and BMI on breast volume. The geometric mean was calculated by taking the exponential of the log transformed data.

* indicates a significant age x BMI effect (p < 0.05).

4.4 Discussion

This is the first study to provide normative breast volume data on a large cohort of Australian women aged 18 years and older (n = 346), who represented a wide range of
Breast volume

ages, body masses and breast sizes. The results reveal the extensive range of breast volumes (left: minimum: 70 mL, maximum: 2789 mL, mean (geometric): 653 mL; right: minimum: 48 mL, maximum: 3100 mL, mean (geometric): 647 mL) within this representative sample of women. The implications of these unique findings are discussed below.

The mean (geometric) breast volume of participants in this study was similar to that reported by McGhee and Steele (2011) (642 mL (L) and 643 mL (R); current study: 653 mL (L) and 647 mL (R)), although the magnitude of breast volumes exceeded those previously reported (McGhee and Steele 2011; Figure 9). Unlike this previous research, there was no limit on the magnitude of breast volume able to be measured using a three-dimensional scanner, with breast volumes up to 3100 mL (per breast) recorded in the current study.

Based on the breast volumes measured in this study (48 – 3100 mL), what has traditionally been considered as “large breasts” is extremely wide (i.e. 500 – 3100 mL; 2600 mL range, bra cup sizes D – H). Considering the limitations within the literature pertaining to breast size classifications, with such a wide range of breast volumes considered to be “large”, we recommend an alternate system for classifying breast size based on the data reported in the current study, combined with classification terminology used in previous studies. Using this new system, breast volumes are divided into four sub-groups: small, medium, large and hypertrophic, based on breast volume ranges as shown below (Table 10). We recommend that this system should be used to classify participants in future research studies on breast health, pathology and biomechanics, as well as to guide bra designers and manufacturers on the level of support required for women based on breast size (volume), as discussed below.
Table 10: Breast size classification based on breast volume range (n = 346).

<table>
<thead>
<tr>
<th>Breast Volume Range</th>
<th>Breast Size Classification</th>
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<tr>
<td>&lt;350 mL</td>
<td>Small</td>
</tr>
<tr>
<td>350-700 mL</td>
<td>Medium</td>
</tr>
<tr>
<td>701-1200 mL</td>
<td>Large</td>
</tr>
<tr>
<td>&gt;1200 mL</td>
<td>Hypertrophic</td>
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</table>

Using this new classification system, 28% of the current study participants were classified as having small breasts, 37% as having medium sized breasts, 24% as having large breasts and 11% as having hypertrophic breast volumes. Just over half of the study cohort (n = 178; 52%) had breast volumes > 500 mL (classified as medium, large or hypertrophic). Women with breasts > 500 mL have previously been recognised as requiring high levels of breast support when they participate in physical activity (McGhee et al. 2012; McGhee and Steele 2011). The results of the current study therefore have important implications for bra design. That is, bras must be designed with features that adequately support the varying loads created by a very wide range of breast volumes, including a wide range of large breast volumes (i.e. 500 – 3100 mL).

Sufficient breast support for women with large breasts is extremely important due to the increased breast volume and, in turn, the large breast forces generated on the upper torso when these women move (McGhee et al. 2013). The consequences of poor bra fit, and subsequently insufficient breast support, have been suggested to be far worse for women with large and hypertrophic breasts due to these high breast forces (Greenbaum et al. 2003; McGhee et al. 2013; Spencer and Briffa 2013).

The positive, moderate relationship between breast volume and BMI (Figure 12 B and D) confirms that increases in breast volume are associated with increases in BMI. In fact, almost half of the variance in breast volume (left breast 47%; right breast 49%) could be attributed to its relationship with BMI. Interestingly, the median breast volume of Overweight participants (645 mL) was almost double that of the participants with a
Normal BMI (327 mL) and the median breast volume of the Obese participants (954 mL) was almost triple that of participants with a Normal BMI (Figure 12 A and C). Given the high prevalence of overweight (40%) and obese (15%) women worldwide (World Health Organisation 2014), and considering 56% of the current study cohort were classified as overweight or obese, there is high demand for bras to be designed to cater for the increased torso size (related to bra band size or under-bust chest circumference measurement; Table 8) and the increased breast volume (related to bra cup size) of these women. As insufficient breast support is a barrier to physical activity and physical activity is recommended for overweight and obese women in order to lose weight (Donnelly et al. 2009), it is important that high support bras are designed to cater for the increased support needs and larger dimensions of this high percentage of our global population.

Although there was no main effect of age on breast volume, the proportion of overweight and obese women within each age group in this study was found to increase with increasing age (18–24 years: 39% Overweight or Obese; 25–44 years: 51% Overweight or Obese; 45–64 years: 60% Overweight or Obese; 65+ years: 76% Overweight or Obese). Due to the effect of increased BMI on breast volume, this resulted in a trend for increased breast volume with age (Figure 11). This finding has important implications for breast support because a larger breast size requires an increased level of breast support and the number of women needing this increased support increases with age. As ageing is also associated with a decline in anatomical breast support (breast skin; refer to Chapter 3, Section 3.3), increased external breast support for older women is of high importance (Coltman, Steele and McGhee 2017a). It also has important public health implications for the ageing population to ensure that women maintain a healthy diet and participate in regular physical activity to better
Breast volume

manage body weight with increasing age (Donnelly et al. 2009). Ensuring women can exercise in comfort, in terms of breast support, is an important component of this public health message.

The significant age x BMI interaction detected in the current study revealed that within the Normal BMI category, women in the 65+ year age group displayed a significantly greater breast volume compared to women in the other three age groups (18–24 years, 25–44 years and 45–64 years). We attribute this finding, in part, to the low participant numbers in the Normal BMI 65+ year age group (n = 17; Table 8) compared to the younger age groups within this BMI category (n = 54, n = 50 and n = 33, respectively). That is, despite trying to recruit participants across the BMI spectrum, most of the women aged 65+ years who participated in this study were either overweight or obese (76%; Table 8). Furthermore, this oldest age group within the Normal BMI category also had the highest average BMI (BMI 65+ years: 23.2 ± 1.3 kg/m²) compared to other age groups within this category (BMI 18–24 years: 22.2 ± 1.5 kg/m²; BMI 25–44 years: 22.4 ± 1.4 kg/m² and BMI 45–64 years: 22.8 ± 1.4 kg/m²; Table 8), which may have further biased these data. These results suggest that as women age, greater levels of breast support will be required to support an increased breast size, particularly if ageing is associated with an increased body mass.

The small number of women within the Normal BMI category in the 65+ age group (n = 17) is acknowledged as a limitation of the current study. Further research on a larger cohort of women in this category is necessary to confirm this age x BMI interaction. A further limiting factor of the study was the small number of women within the Obese BMI category in the 18–24 year age group (n = 15). Participant recruitment within this cohort was particularly difficult, most likely due to the young obese women being less confident being topless during testing, which was required for
the breast volume measurement. In contrast, the older obese women appeared to be more comfortable about participating in the study, suggesting that such confidence is potentially acquired over time.

5.4 Conclusion

This study is the first to present normative breast volume data for Australian women 18 years and older who represented a wide range of ages, body masses and breast sizes. Within the study cohort, breasts volumes ranged from 48 to 3100 mL. Although breast volume was not influenced by age, it was significantly affected by BMI, with the breast volume of overweight and obese women being two-to-three times greater than women with normal BMI’s. Given the high prevalence of overweight and obese women globally and the wide range of breast volumes present in the general population of women, these findings highlight the need for bra cups to be designed to support the wide range and increasing magnitude of breast volumes exhibited by women. This will enable women, irrespective of age, body mass or breast size, to have access to bras that are designed to match the three-dimensional volume of their breasts.
Chapter 5

Characterising breast morphology:
The influence of age and body mass index

This chapter is an amended version of the manuscript: Coltman, C.E., Steele, J.R. & McGhee, D.E., Effects of age and body mass index on breast characteristics: A cluster analysis. *Ergonomics*, re-submitted March 2018.

Abstract

Limited research has quantified variation in breast shape among women and determined how breast shape is influenced by age and body mass. The aim of this study was to classify the breasts of women in the community into different breast shape categories based on a comprehensive and objective measurement of their breasts and torsos, and to determine the effect of age and BMI on the prevalence of these breast shapes. Four breast shapes were identified (X-Large, Very-ptotic & Splayed; Large, Ptotic & Splayed; Medium & Mildly-ptotic; and Small & Non-ptotic), with age and BMI shown to significantly affect breast shape. These results highlight the difference in breast shape exhibited among the general population of women and how these shape types are affected by age and BMI. The breast shapes identified in this study could be used as a basis for future bra designs and sizing systems in order to improve bra fit for women.
5.1 Introduction

The female breast is composed of fibro-glandular and adipose tissue (Boyd et al. 2009; Lee et al. 1997; Page and Steele 1999). The composition of these tissue components within the breast are influenced by several factors, including hormones, age and body mass, such that the proportion of these tissues fluctuate within a woman’s breast and between women’s breasts overtime (Boyd et al. 2009; Lee et al. 1997; Page and Steele 1999; Vandeweyer and Hertens 2002). Consequently, the size and shape of the female breast varies widely (Bulstrode et al. 2001; Gefen and Dilmoney 2007; McGhee and Steele 2011; Page and Steele 1999; Starr et al. 2005). This variation in breast size has been documented in terms of breast volume, with breast volume being reported to vary between 48 – 3100 mL (Coltman, Steele and McGhee 2017b; McGhee and Steele 2011; Smith et al. 1986; see Chapter 4). No published research, however, has objectively quantified variations in breast shape among women, or attempted to classify typical breast shapes. Understanding common breast shapes exhibited among women is important because this knowledge could aid in better designing and fitting garments such as bras, which have been shown to be poorly fitted among women in the community (Greenbaum et al. 2003; McGhee and Steele 2010a; McGhee et al. 2010; White and Scurr 2012). Poor bra fit is not only uncomfortable, but it can lead to numerous negative health outcomes, including back, neck and shoulder pain (BeLieu 1994; Greenbaum et al. 2003; Kaye 1972; Ryan 2000). This musculoskeletal pain can be so severe as to lead women to seek reduction mammoplasty (BeLieu 1994; Greenbaum et al. 2003; Kaye 1972; Ryan 2000), as well as inhibit participation in physical activity (Lorentzen and Lawson 1987; Mason et al. 1999; McGhee et al. 2013; Scurr et al. 2010).
As the female breast is three-dimensional, its shape is largely determined by the relationship between the volume and surface area of the breast (Thomson et al. 2009). Although several studies have objectively assessed breast volume (Bulstrode et al. 2001; Coltman, Steele and McGhee 2017b; Kovacs et al. 2006; Losken et al. 2005; McGhee and Steele 2011; refer to Chapter 4), only two previous studies have reported normative breast surface area data (Eder et al. 2011; Thomson et al. 2009). These studies, however, were limited to low participant numbers (both studies n = 14) and small breast volume ranges among the participants (Thomson et al. 2009: breast volume range: 80 – 600 mL, mean: 271 mL; Eder et al. 2011: 230.5 ± 75.9 mL).

Beyond three-dimensional breast volume and surface area, the shape of female breasts has been classified subjectively by simply observing different breast shapes (three shapes observed: pert, broad and ptotic; n = 104; ages 18 – 70 years; bra cup sizes A–G cup; McGhee and Steele 2011). However, such a subjective method of classifying breast shape is susceptible to individual observer bias. Alternatively, others have used anthropometric data to describe the shape of breasts, with these data often collected on two-dimensional variables such as sternal notch-to-nipple distance and nipple-to-nipple distance (Agbenorku et al. 2011; Chetty and Ndobe 2016; Coltman, McGhee and Steele 2017; Kececi and Sir 2014; Liu and Thomson 2011; Penn 1954; Portincasa et al. 2017; Smith et al. 1986; Steele et al. 2017; Stevens et al. 2008; Westreich 1995). Although these two-dimensional anthropometric measurements can describe some characteristics of breast shape (e.g. sternal notch-to-nipple distance to determine ptosis; and nipple-to-nipple distance to determine breast breadth), they do not take into account the complex three-dimensional structure of breasts. Furthermore, these two-dimensional anthropometric variables have also been predominantly collected on specific cohorts of women, including women with “aesthetically perfect breasts” (Agbenorku et al. 2011;
Liu and Thomson 2011; Penn 1954; Smith et al. 1986; Vandeput and Nelissen 2002; Westreich 1995) or breast reduction candidates (Kececi and Sir 2014; Stevens et al. 2008), rather than women within the general female population. Measurements reflective of torso size have also rarely been included in any breast shape assessment, despite the highly interconnected relationship between the breasts and the torso when designing and fitting garments such as bras.

Given that female breast shape changes across a lifetime (Brown et al. 1999), understanding how breast shape varies with age is also important. Although some data exists demonstrating changes to breast shape with increasing age, this evidence has been limited to the singular measure of breast ptosis, where sternal notch-to-nipple distance was found to increase with increasing age (n = 60; age range: 15 – 88 years; Brown et al. 1999). This increase in ptosis (breast sagging) is consistent with changes in breast skin that have been reported to occur with ageing (Coltman, Steele and McGhee 2017a), whereby the level of anatomical support provided by the skin to the breast is reduced (Brown et al. 1999; Coltman, Steele and McGhee 2017a; Ulger et al. 2003; refer to Chapter 3, Section 3.3).

The breasts of women with an increased BMI have also been found to display greater ptosis (suprasternal notch-to-nipple distance), as well as splay further away from the midline of the torso (greater horizontal distance from the midline of the torso to the nipple; Brown et al. 1999). These changes in breast shape associated with an increased BMI have been attributed to changes in mass distribution within the breast (Pandarum et al. 2011). That is, the breasts of 176 plus-sized women (BMI range: 25 – 46 kg/m²) were divided into four quadrants, relative to the nipple, and the volume (mL) of each breast quadrant was subsequently measured. The greatest volumes were found in the upper, medial breast quadrant, and the smallest were found in the lower, lateral breast
Breast shape

quadrant (Pandarum et al. 2011). These findings, which appear inconsistent with a ptotic and widely splayed breast shape, are likely to be the consequence of the measurement method used, whereby automated software was used to divide each breast into four quadrants relative to the nipple. As nipple size and position can vary widely across women’s breasts (Sanuki et al. 2009; Westreich 1995), this landmark is likely to be problematic as a reference point when dividing the breast into quadrants. Therefore, although these previous studies provide some evidence upon which breast shape is perceived to change with age and body mass, objective data characterising breast morphology at the population level across women who represent a wide range of ages and body masses is not available. Comprehensive and objective assessment of breast morphology has the potential to substantially improve our understanding of the range of breast shapes displayed among women and how these breast shapes differ between women. Furthermore, understanding how breast shape changes as we age or vary in BMI is important given the changing demographics of the world’s population. The percentage of the world’s population over 60 years (12%) is expected to almost double by 2050 (22%; World Health Organisation 2015) and 40% of women worldwide are overweight and 15% are obese (World Health Organisation 2014).

The purpose of this study was to document the morphology of the breasts of a large cohort of women who represented a wide range of ages and BMIs within the community. We aimed to classify the breasts of these women into different breast shape categories based on a comprehensive range of objective measures of both the breasts and the torso and to determine the effect of age and BMI on the prevalence of these breast shape groups. It was hypothesised that the participants would display a range of breast shapes, which could be classified into breast shape groups, and that age and BMI would significantly affect breast shape.
5.2 Materials and methods

5.2.1 Participants

The recruitment and study approval procedures were the same as those listed in Chapter 4, Section 4.2.1. Participants were also consistent with those reported in Section 4.2.1, with the addition of n = 1 participant excluded from analysis due to substantial breast asymmetry. This reduced the participant cohort to 345 (age range: 18.3 – 83.7 years, mean: 43.0 ± 19.6 years; BMI range: 19 – 55 kg/m², mean: 27.5 ± 6.1 kg/m²). On average study participants were representative of Australian women within the community aged 18 years and over (Chapter 4, Table 9).

5.2.2 Age and body mass index

Participants were divided into four age categories and three BMI categories as per Chapter 4, Section 4.2.2. Participant characteristics are shown in Table 11.

<table>
<thead>
<tr>
<th>Table 11:</th>
<th>Descriptive data (mean ± standard deviation) for each participant group (n = 345) classified by age and body mass index (BMI: Normal: 18.5 – 24.9 kg/m², Overweight: 25 – 29.9 kg/m², Obese: ≥ 30 kg/m²).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Normal:</td>
<td></td>
</tr>
<tr>
<td>18 – 24 years</td>
<td>54</td>
</tr>
<tr>
<td>25 – 44 years</td>
<td>50</td>
</tr>
<tr>
<td>45 – 64 years</td>
<td>33</td>
</tr>
<tr>
<td>65+ years</td>
<td>17</td>
</tr>
<tr>
<td>Overweight:</td>
<td></td>
</tr>
<tr>
<td>18 – 24 years</td>
<td>21</td>
</tr>
<tr>
<td>25 – 44 years</td>
<td>31</td>
</tr>
<tr>
<td>45 – 64 years</td>
<td>24</td>
</tr>
<tr>
<td>65+ years</td>
<td>19</td>
</tr>
<tr>
<td>Obese:</td>
<td></td>
</tr>
<tr>
<td>18–24 years</td>
<td>15</td>
</tr>
<tr>
<td>25–44 years</td>
<td>19</td>
</tr>
<tr>
<td>45–64 years</td>
<td>26</td>
</tr>
<tr>
<td>65+ years</td>
<td>36</td>
</tr>
</tbody>
</table>

5.2.3 Breast and torso shape measurements

Each participant’s breasts and upper torso were scanned using two hand-held three-dimensional scanners (Artec™ Eva 3D Scanner, Artec Group, San Jose), while the
participants were topless and assumed two different positions. In the first scanning position the participants stood upright, on a custom-made turntable, looking forward with their arms in slight abduction and their hands resting on hand rails for stability and sway prevention (Lee, Hong and Kim 2004; Moyer et al. 2008; Veitch et al. 2012; Figure 14A). The turntable was used to rotate the participants 360 degrees in order to capture their entire upper torso, with each scan lasting approximately 20 seconds in duration. The second scanning position was the same prone scanning position that was described in Chapter 2, Section 2.2.2 and is shown in Figure 14B. Participants were instructed to stay as still as possible during scanning with talking prohibited. One scan was taken of each participant in each scanning position and visually inspected immediately after capture to ensure all landmarks were visible and the scan was of a quality sufficient for analysis. If any problems were detected with the scan, the procedure was repeated with one scan per position for each participant subsequently imported into Geomagic Studio® software for analysis (Version 12; 3DSystems, South Carolina, USA). Within this software four breast measurements were calculated in order to characterise each participant’s left and right breast. The measurements derived from each scan are described in Table 12 and relevant measurement steps are visually depicted in Figure 15. In addition to the procedures described above, and in order to assess torso size, an under-bust chest circumference (UBCC) measurement (described in Table 12), was taken for each participant. This measure was chosen as it has previously been shown to increase with increasing BMI (Coltman, Steele and McGhee, 2017b). The same experienced investigator (CEC) performed all UBCC measurements and was shown to be highly reliable taking these measurements (ICC = 0.980; n = 7; three measurements performed on three consecutive days).
5.2.4 Statistical analysis

A two-step cluster analysis was applied to the data set in order to determine whether we could classify each participant’s breasts into different breast shape groups based on the five measurements described in Table 12. These measures were selected in order to reduce the effects of co-variance, as they are measures that are independent of one another. The number of clusters generated was fixed within the model to four and age and BMI were specified as evaluation fields displayed in the model as cluster descriptors. The distance measure was set to log-likelihood, the clustering criteria were set to Schwarz’s Bayesian Criterion and no outlier treatment was set. Each of the breast shape clusters consisted of breasts that had similar measurements to other breasts within that same cluster. This was confirmed by visual inspection of each scan by the primary investigator. Descriptive statistics (means and standard deviations) were then calculated for all breast and torso measurements per shape cluster. Chi-squared analyses were performed on data within each breast shape cluster to determine whether age and BMI were significantly \( p < 0.05 \) different for each shape cluster. All statistical calculations
were conducted using the Statistical Package for the Social Sciences (Version 21.0; SPSS Inc., Chicago, IL).

**Table 12:** A description of the five breast and torso measurements, as well as the scanning position from which they were taken.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Scanning position</th>
<th>Description of how each measurement was derived</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breast volume</td>
<td>Prone</td>
<td>From each participant’s prone scan a three-dimensional model of each breast was created by tracing around the border of the breast, removing the breast from the chest wall and attaching it to a posterior chest wall (created to match the curvature of the superficial surface of the pectoralis major muscle, which the posterior wall of the breast lies upon) to form one closed three-dimensional breast model (Coltman, McGhee and Steele, 2017). The volume (mL) of this three-dimensional breast model was calculated using the compute volume function of the Geomagic® software to represent breast volume.</td>
</tr>
<tr>
<td>Breast surface area</td>
<td>Prone</td>
<td>Surface area (cm²) of the breast was calculated as the total surface area of the closed three-dimensional breast model, described above for breast volume. It was calculated using the compute area function of the Geomagic® software.</td>
</tr>
<tr>
<td>Sternal notch-to-nipple distance</td>
<td>Standing</td>
<td>The point-to-point distance (cm) from the sternal notch to the nipple of each breast in the vertical plane was calculated using the measure distance function of the Geomagic® software. This distance is a measure of breast ptosis, whereby the greater the distance between the nipples and the sternal notch, the greater the ptosis (sagging).</td>
</tr>
<tr>
<td>Nipple-to-nipple distance</td>
<td>Standing</td>
<td>The point-to-point horizontal distance (cm) measured from the centre of the left nipple to the centre of the right nipple was derived using the measure distance function of the Geomagic® software. This distance is a measure of how far each breast deviates laterally from the midline of the torso. The greater the nipple-to-nipple distance (cm), the wider the breasts are splayed.</td>
</tr>
<tr>
<td>Under-bust chest circumference</td>
<td>Prone</td>
<td>UBCC is a measure of the horizontal girth of the chest just below the breast and inframammary fold. This measurement was performed directly on each participant using an anthropometric measuring tape (Birch Analog Quilt Tape Measure Yellow 300 cm; EC Birch Pty Ltd., Victoria, Australia) while participants were standing upright and breathing normally. The tape was held level in the horizontal plane, with minimal soft tissue compression and the mean of three measurements was recorded in centimetres (cm).</td>
</tr>
</tbody>
</table>
Breast shape

Figure 15: All images depict various stages of measuring each participant’s breasts and torso using Geomagic® software. Images (A)-(F) show how a three-dimensional model of the breast was created from the three-dimensional scan of each participant, obtained in the prone scanning position. From this three-dimensional model, breast volume and breast surface area were calculated. (A) Borders of the breasts were defined, (B) the breasts were removed from the trunk, (C) a posterior breast wall was created, (D) the posterior breast wall shown from the side, (E) and (F) the closed three-dimensional breast model shown from the side (E) and front (F). Image (G)-(H) show how point-to-point measures were taken from the standing scan. (G) sternal notch-to-nipple distance (depicted by the diagonal line) and (H) nipple-to-nipple distance (depicted by the horizontal line).

5.3 Results

5.3.1 Breast shape clusters

Overall, the quality of the cluster analysis was fair (average silhouette 0.4). From the cluster analysis, four breast shape clusters were identified based on the measurements
and ratios described in Table 12. Of the measurements imputed into the cluster analysis, sternal notch-to-nipple distance, breast surface area and breast volume were the most important predictors of cluster. The median and interquartile range for each breast shape cluster for each of the five measurements obtained are shown in Figure 16, and compared to the median and interquartile range for the total participant cohort (n = 345; Figure 16). We subsequently named the four breast shape clusters based on the characteristics of each cluster, which are described below. A typical example of each breast shape cluster is shown in Figure 17.

**Cluster 1: X-large, Very-ptotic & Splayed** (n = 42; 12% of the participant cohort)

This cluster was characterised by the largest breast volume, surface area and torso size (UBCC). Participants within this group had the largest sternal notch-to-nipple distance, representative of very ptotic breasts and the most splayed breasts, evident by the largest nipple-to-nipple distance.

**Cluster 2: Large, Ptotic & Splayed** (n = 96; 28% of the participant cohort)

This cluster was characterised by a large breast volume, a large breast surface area and a large torso size, but these values were smaller in comparison to Cluster 1. Participants within this group also had a large sternal notch-to-nipple distance, which is also representative of ptotic breasts, and widely splayed breasts, as evident by their large nipple-to-nipple distance, but again these values were less than Cluster 1.

**Cluster 3: Medium & Mildly-ptotic** (n = 116; 34% of the participant cohort)

This cluster was characterised by a medium breast volume, a smaller surface area than both Clusters 1 and 2 and a torsos size that was consistent with the median values of the entire cohort. Participants within this cluster also had a sternal notch-to-nipple distance that was smaller than Clusters 1 and 2 and breasts that were not splayed, evidenced by a
small median nipple-to-nipple distance, also consistent with the median values of the entire cohort.

**Cluster 4: Small & Non-ptotic** (n = 91; 26% of the participant cohort)

This cluster was characterised by the smallest breast volume, the smallest breast surface area and the smallest torso sizes. Participants within this cluster had the smallest sternal notch-to-nipple distance, which is representative of non-ptotic or pert breasts and their breasts were the least splayed, evident by the smallest median nipple-to-nipple distance.

* Figure caption on next page
Box and whisker plots of the median and interquartile range are shown for the four breast characteristic clusters for each measurement of the left and right breast and torso. Data depicting the median and interquartile range for the total participant cohort (n = 345) are also plotted on each of the respective graphs for comparison.

Note: For ease of presentation on the x-axis of each graph, the breast shape cluster names have been shortened to include only the first word of the name.
Breast shape

Cluster 1: X-large, Very-ptotic & Splayed
Cluster 2: Large, Ptotic & Splayed
Cluster 3: Medium & Mildly-ptotic
Cluster 4: Small & Non-ptotic

Figure 17: A typical example of each of the four breast shape clusters identified by the cluster analysis.

5.3.2 Effects of age and body mass index on breast shape

The average age and BMI of participants within each of the four breast shape clusters are show in Table 13. The distribution of each cluster group with respect to age and BMI category are shown in Figure 18. There was a significant effect of age ($\chi^2 (9, n = 345) = 47.82, p < 0.001$) on breast shape cluster such that women with Large, Ptotic &
Splayed breast shapes were more likely to be 65+ years \( (p < 0.01) \) and less likely to be 18 – 24 years \( (p < 0.05) \), compared to women in the other clusters. Women who had Small & Non-ptotic breast shapes were less likely to be 65+ years \( (p < 0.001) \). There was also a significant effect of BMI \( (\chi^2 (6, n = 345) = 245.4, p < 0.001) \) on breast shape cluster such that women with X-large, Very-ptotic & Splayed and Large, Ptotic & Splayed breasts were more likely to be obese \( (p < 0.001) \) or overweight \( (p < 0.05; \text{Large, Ptotic \& Splayed cluster only}) \) and less likely to have a normal BMI \( (p < 0.001) \) than women in the other two breast characteristic clusters. Conversely, women with Medium & Mildly-ptotic breasts were more likely to have an overweight BMI \( (p < 0.05) \) and less likely to have an obese BMI \( (p < 0.001) \) and women with Small & Non-ptotic breasts were more likely to have a normal BMI \( (p < 0.001) \) and less likely to have an overweight or obese BMI \( (p < 0.001; \text{Figure 18B}) \).

Table 13: Mean (range) age and BMI for participants within the four breast shape clusters \( (n = 345) \).

<table>
<thead>
<tr>
<th>Breast shape cluster</th>
<th>N</th>
<th>Age (years)</th>
<th>BMI (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster 1: X-large, Very-ptotic &amp; Splayed</td>
<td>42</td>
<td>52 (20 – 77)</td>
<td>37 (25 – 55)</td>
</tr>
<tr>
<td>Cluster 2: Large, Ptotic &amp; Splayed</td>
<td>96</td>
<td>53 (19 – 79)</td>
<td>31 (23 – 41)</td>
</tr>
<tr>
<td>Cluster 4: Small &amp; Non-ptotic</td>
<td>91</td>
<td>34 (18 – 84)</td>
<td>22 (19 – 26)</td>
</tr>
</tbody>
</table>
5.4 Discussion

This is the first study to systematically classify the shape of the breasts of a relatively large cohort of women based on objective measurements of both the breasts and torso of these women. Four different breast shapes were identified within the study cohort: (i) X-large, Very-ptotic & Splayed, (ii) Large, Ptotic & Splayed, (iii) Medium & Mildly-ptotic and (iv) Small & Non-ptotic. These breast shape clusters provide a more
Breast shape
c
comprehensive understanding of breast morphology among the general population of
genre and over than has previously been reported. The implications of
cclusters, and the effects of age and BMI on breast shape, are discussed below.

Participants who were identified as having X-large, Very-ptotic & Splayed
breast characteristics (12% of the participant cohort) had breast volumes that were
consistent with hypertrophic breast volumes previously reported in the literature
(Benditte-Klepko et al. 2007; Coltman, McGhee and Steele 2017; Coltman, Steele and
McGhee 2017b; Ikander et al. 2014; Kerrigan et al. 2001; refer to Chapter 4, Section
4.4). These women also had sternal notch-to-nipple distances similar to that reported
previously for women with large, ptotic breasts and breast reduction candidates (current
study range: 27.3 – 39.0 cm; previous research range: 21 – 54 cm; Coltman, Steele and
McGhee 2017b; Kececi and Sir 2014; Portincasa et al. 2017; Steele et al. 2017; Stevens
et al. 2008). Furthermore, 55% of women in this shape cluster had sternal notch-to-
nipple distances classified as severly ptotic (sternal notch-to-nipple distances > 32 cm;
Portincasa et al. 2017). As a consequence of the ptotic breasts and hypertrophic
volumes, these women had the largest breast surface areas, with this study being the
first to present such large breast surface area data. The wide splay of the breasts from
the midline of the torso of women in this cluster are thought to be related to the
downward and outward splaying of hypertrophic and ptotic breasts (Brown et al. 1999;
Pandarum et al. 2011). The nipple-to-nipple distances of women in this cluster,
however, were less than the same measurement reported for breast reduction candidates
(mean left: 44.7 ± 19.2 cm; mean right: 44.8 ± 20.1 cm; Chetty and Ndobe 2016),
whereby the breast reduction candidates also had substantially larger breast volumes
(mean resected volume: 1835 g) than participants in the current study. The large UBCC
measurement for women in this cluster confirmed that these women had large torsos, which is consistent with the BMI distribution for participants in this cluster.

At the other end of the breast size and shape spectrum were participants who were classified into the Small & Non-ptotic breast shape (26% of the participant cohort). These women had breast volumes classified as Small (Brown and Scurr 2016; Brown et al. 2012; Coltman, Steele and McGhee 2017b; Ikander et al. 2014; Pamplona and De Abreu Alvim 2004) and had surface areas in the range of those reported previously among women with small breast volumes (Eder et al., 2011; Thomson et al. 2009). Unsurprisingly, the sternal notch-to-nipple distances and nipple-to-nipple distances were consistent with those considered aesthetically perfect (17–23 cm; Liu and Thomson 2011; Penn 1954; Smith et al. 1986; Westreich 1995). These women also had the smallest UBCC measurement, which indicates a small torso size, consistent with the BMI distribution for participants in this cluster.

Interestingly, most study participants fell between these two extreme ends of the breast size shape spectrum, being clustered around what has been subsequently classified as Large, Ptotic & Splayed (28% of study cohort) and Medium & Mildly-ptotic (34% of study cohort) breast shapes. Before this study, no data had been presented on these breast shapes despite the high prevalence of these shapes among women within the community. The breast volumes of these two clusters were considered Large and Medium, respectively (Benditte-Klepetko et al. 2007; Brown and Scurr 2016; Brown et al. 2012; Coltman, McGhee and Steele 2017; Coltman, Steele and McGhee 2017b; Ikander et al. 2014; Kerrigan et al. 2001; McGhee and Steele 2011; McGhee et al. 2013; Pamplona and De Abreu Alvim 2004). Although the median sternal notch-to-nipple distance for women with Large, Ptotic & Splayed breasts was similar to distances reported among women with large, ptotic breasts (n = 50, mean:
Breast shape

28.5 range: 20.8 – 35.2 cm; Coltman, McGhee and Steele 2017), the median sternal notch-to-nipple distance for women with Medium & Mildly-ptotic breast shapes was slightly longer than what would be considered aesthetically perfect and could be considered mildly ptotic. Similarly, nipple-to-nipple distances of the Medium & Mildly-ptotic breasts were only slightly greater than what is considered aesthetically perfect (Liu and Thomson 2011; Penn 1954; Portincasa et al. 2017; Smith et al. 1986; Westreich 1995). Torso size, represented by the UBCC measurement, was similar to the average for the total cohort for the Medium & Mildly-ptotic cluster but slightly higher for the Large, Ptotic & Splayed breast cluster. This is reflective of the BMI distribution data for participants in these clusters.

A significant effect of age on breast characteristic cluster was identified within the study cohort (Figure 18A), such that women with Small & Non-ptotic breast characteristics were significantly less likely to be 65 + years of age. Instead, a greater percentage of women with Small & Non-ptotic and Medium & Mildly-ptotic breast characteristics were aged 18 – 24 years and 25 – 44 years. Unexpectedly, a large percentage of women with X-large, Very-ptotic & Splayed breast characteristics were also aged 25 – 44 years (40%; n = 17). As sternal notch-to-nipple distance, breast surface area and breast volume were the most important predictor of breast shape within the model, this finding has been attributed to the large values for these three predictors of participants within this cluster (X-large, Very-ptotic & Splayed) and age category (25 – 44 years). That is, of participants with X-large, Very-ptotic & Splayed breasts who were aged 25 – 44 years, 10 participants recorded sternal notch-to-nipple distances greater than 32 cm, three participants recorded breast surface areas in excess of 1000 cm², two participants recorded breast volumes in excess of 2500 mL per breast and 12 participants recorded breast volumes in excess of 1500 mL per breast. Furthermore,
Breast shape

60% of women within this cluster (X-large, Very-ptotic & Splayed) and age category (25 – 44 years) were over 30 years of age (mean age: 33 years) and on average reported to have gained 11 kg since they were 30 years of age. Therefore, the effects of body mass on breast size and breast shape (described later in this manuscript) are likely to further explain this high representation of women aged 25 – 44 years in the X-large, Very-ptotic & Splayed shape cluster.

Women aged 45 – 64 years had relatively equal representation across all four shape clusters (Figure 18A), and a greater percentage of women aged 65+ had X-large, Very-ptotic & Splayed or Large, Ptotic & Splayed breast characteristics compared to the other two clusters. Although this was only significant for the Large, Ptotic & Splayed group, this is likely due to the sample size difference between groups. That is, the smaller sample size of the X-large, Very-ptotic & Splayed group (n = 42) may have masked a significant effect being detected despite similar percentage data depicted in Figure 18A. These age effects indicate the progression from Small & Non-ptotic breast shapes to X-large, Very-ptotic & Splayed breast shapes with increasing age. Given that breast volume and BMI are positively correlated, and BMI increases with age (Coltman, Steele and McGhee 2017b; Den Tonkelaar et al. 2004; refer to Chapter 4, Section 4.3.2), this effect is likely to explain part of the breast shape progression observed with increasing age. In fact, the average age of women in the X-large, Very-ptotic & Splayed and the Large, Ptotic & Splayed clusters were 52 years and 53 years, respectively compared to 39 years for the Medium & Mildly-ptotic and 34 years for the Small & Non-ptotic shape clusters. In addition to breast volume, breast surface area and sternal notch-to-nipple distance were the most important predictors of cluster type in the current model. This highlights not only the importance of breast size, as a function of volume and surface area (Thomson, 2009), to cluster type but also breast ptosis, the
Breast shape

drooping or sagging of breasts. In fact, previous research has shown that breast skin thickness and elasticity change with increasing age (Coltman et al., 2017a; Ulger et al., 2003; refer to Chapter 3, Section 3.3), such that the greatest reductions in breast skin thickness and elasticity occur in the medial and superior aspects of the breast (Coltman et al., 2017a). We postulate that these age related changes to the skin of the breasts are likely to contribute to the differences in ptosis and amount of breast splay observed among the clusters. That is, reduced anatomical support (Coltman, Steele and McGhee 2017a; Gefen and Dilmoney 2007) in these medial and superior regions of the breast could explain the downward (ptotic breast) and outward (increased nipple-to-nipple distance) migration of the breasts (Elsahy 1990; Machida and Nakadate 2015; McGhee and Steele 2006) that was observed to the greatest extent among women in the X-large, Very-ptotic & Splayed and Large, Ptotic & Splayed breast shape clusters, who were also most likely to represent older women (65+ years).

A significant effect of BMI on breast shape cluster highlighted that women who had a normal BMI were most likely to have breast shape characteristics of the Small & Non-ptotic (Figure 18B). Conversely, overweight women were most likely to have breast shape characteristics of the Medium & Mildly-ptotic or Large, Ptotic & Splayed breast types (Figure 18B), and obese women were most likely to have breast shape characteristics of the X-large, Very-ptotic & Splayed or Large, Ptotic & Splayed clusters. In fact only 9% of obese women had Medium & Mildly-ptotic breast shapes and no obese women had Small & Non-ptotic breast shapes (Figure 18B). The high representation of overweight and obese women in the X-large, Very-ptotic & Splayed or Large, Ptotic & Splayed breast shape clusters is thought to be related to the large breast volumes that are associated with large body masses (Coltman, Steele and McGhee 2017b; refer to Chapter 4, Section 4.3.2) and large sternal notch-to-nipple distances.
Breast shape

(Coltman, McGhee and Steele, 2015; refer to Chapter 2, Section 2.3). This notion is reinforced with the importance of breast volume and sternal notch-to-nipple distance in the model. The median BMI of the X-large, Very-ptotic & Splayed and Large, Ptotic & Splayed clusters were 37 kg/m² and 31 kg/m², respectively (both classified as obese; Australian Institute of Health and Welfare 2012) compared to the median BMI of 25 kg/m² and 22 kg/m², respectively, for the Medium & Mildly-ptotic and Small & Non-ptotic breast shape clusters (both classified as normal; Australian Institute of Health and Welfare 2012). These results indicate that as BMI increases, breast shape changes to become more ptotic and splay further away from the midline of the torso, with a larger surface area. Given the high prevalence of overweight and obese women within Australia and globally (Australian Institute of Health and Welfare 2012; World Health Organisation 2016), breast shapes among the population are likely to become increasingly more representative of the X-large, Very-ptotic & Splayed and Large, Ptotic & Splayed clusters.

Our results have identified and classified the wide variation in breast shape observed in a large cohort of women within the community and the effects of age and BMI on breast morphology. We recommend clothing designers and manufacturers incorporate these data into bra designs that are specific to each breast cluster to better accommodate for differences in breast shape of women living in the community, and to cater for changes to breast shape with advancing age and increasing BMI. Basing future bra designs on evidenced-based shape clusters will better ensure that all women, irrespective of age and BMI, can be correctly fitted into bras that are designed to match their breast shape. These breast shape clusters could also be incorporated into a new bra sizing system, which properly represents the breast shapes of women living within the community.
The findings of this study are not without limitation. The cluster analysis assigned each participant to a cluster based on those variables that were deemed to be of the highest importance to the cluster determination (in this case, sternal notch-to-nipple distance, breast surface area and breast volume). Therefore, the authors acknowledge that breast shape variation may extend beyond the four breast shapes identified in this study (e.g. women with Small and Ptotic breast shapes). Further, the small representation of obese women aged 18 – 24 years (n = 15) and women with a normal body mass aged 65+ (n =17) might have impacted on the average age and body mass of the four clusters.

5.5 Conclusion

This is the first study to systematically classify the breast shapes of women within the community based on comprehensive, objective measurements of their breasts and torso. Within the study cohort, four breast shapes were identified (X-large, Very-ptotic & Splayed; Large, Ptotic & Splayed; Medium & Mildly-ptotic; and Small & Non-ptotic), with the difference in shape between clusters demonstrating the wide variation in breast shape among the general population of women. Breast shape was significantly influenced by age and BMI with a tendency for older and larger women to have breast shapes more characteristic of X-large, Very-ptotic & Splayed and Large, Ptotic & Splayed breast shapes, whereas younger and slimmer women were more likely to have breast shapes characteristic of Medium & Mildly-ptotic and Small & Non-ptotic breast shapes. These findings highlight the need for clothing designers and manufacturers to base future bra designs and sizing systems upon these fundamental differences in breast shape, which could help improve the way bras fit women’s breasts.
Part III

Why are we catering for these women?
Chapter 6

Can breast characteristics predict upper torso musculoskeletal pain?


Abstract

Several studies have associated a large breast size with an increased prevalence and severity of musculoskeletal pain, particularly pain in the upper torso. Despite this evidence, no research has explored whether breast size or related characteristics are risk factors for upper torso musculoskeletal pain. A backward multiple regression analysis was performed to identify whether characteristics of the breasts and upper torso, as well as physical factors known to be associated with musculoskeletal pain, could predict musculoskeletal pain among a cohort of 378 Australian women aged 18 years and over who had a wide range of breast sizes. The model identified that breast volume, age and nipple-to-nipple distance predicted 23% of the variance in upper torso musculoskeletal pain reported by the participants. Women with a larger breast volume, lower age and a greater nipple-to-nipple distance were predicted to report a higher upper torso musculoskeletal pain score.
6.1 Introduction

Musculoskeletal pain is widespread among adults and is acknowledged to be multifactorial in origin (Leroux et al. 2005; McBeth and Jones 2007; Picavet and Schouten 2003). Several risk factors for musculoskeletal pain have been identified including female gender (Leveille et al. 2005; Rollman and Lautenbacher 2001), older age (Goh et al. 1999), obesity (Hinman 2004), and level of physical activity (Vuori 1995). Although the notion of breast size as a physical risk factor for musculoskeletal pain has not been previously explored in the literature, several studies have associated a large breast size with an increased prevalence and severity of musculoskeletal pain, particularly pain in the upper torso (BeLieu 1994; Coltman et al. 2013; Glatt et al. 1999; Gonzalez 1993; Greenbaum et al. 2003; Kaye 1972; McGhee et al. 2018; Raispis et al. 1995; Spencer and Briffa 2013). These studies, however have been limited to either breast reduction candidates whereby the experience of musculoskeletal pain has been compared before and after the women have had breast tissue removed (Glatt et al. 1999; Gonzalez 1993; Greenbaum et al. 2003; Raispis et al. 1995), qualitative research (BeLieu 1994; Kaye 1972) or studies conducted with small participant numbers (n = 22 Coltman et al. 2013; n = 53 McGhee et al. 2018; n = 51 Spencer and Briffa 2013). Subsequently, previous research has either reported musculoskeletal pain among women with large breast sizes (Glatt et al. 1999; Gonzalez 1993; Raispis et al. 1995) or, compared differences in musculoskeletal pain between women with large and small breast sizes (Coltman et al. 2013; McGhee et al. 2018; Spencer and Briffa 2013). No research has explored the prevalence of musculoskeletal pain across the breast size spectrum (small, medium, large and hypertrophic; Table 10; Coltman, McGhee and Steele 2017) in a large group of community-based women.
As the structure and function of the musculoskeletal system are inter-related, it is thought that increased musculoskeletal pain among women with large breasts reflects compromised function caused by structural changes to the musculoskeletal system. These structural changes are thought to occur primarily in the vertebral column (Findikcioglu et al. 2007; Findikcioglu et al. 2013; McGhee et al. 2013; McGhee et al. 2018; Letterman and Schurter 1980) and are proposed to be a consequence of the weight of large breasts on the anterior torso shifting the centre of gravity of the breasts, and in turn the torso, forward (McGhee et al., 2018). This forward displacement of the torso centre of gravity is thought to result in an increased thoracic flexion torque and an increase in the thoracic kyphosis angle, which in turn lead to secondary changes in the cervical lordosis angle, increased tension in the neck extensor muscles and an altered scapulae position (Findikcioglu et al. 2007; Findikcioglu et al. 2013; Letterman and Schurter 1980; McGhee et al. 2013; McGhee et al. 2018; Schinkel-Ivy and Drake 2016).

Radiological images have shown that women with large breasts (D cup bra size; n = 19) have a significantly greater thoracic kyphosis angle than women with small breasts (A cup bra size; n = 25; Findikcioglu et al. 2007). Thoracic kyphosis angle has also been found to significantly decrease post-operatively in women after breast reduction surgery when at least 1000 g of breast tissue has been removed (Findikcioglu et al. 2013). Similarly, McGhee et al. (2018) reported that community-based women with large breasts (mean bilateral breast volume: 2448 mL ± 849 mL, mean age: 45.9 years ± 9.9 years, n = 27, not currently seeking breast reduction surgery) had a greater thoracic kyphosis angle than women with small breasts (mean bilateral breast volume: 453 mL ± 151 mL, mean age: 43.8 years ± 10.9 years, n = 26), as well as greater upper torso musculoskeletal pain. Other researchers have compared women with small and large breasts who were either older (post-menopausal; 50 – 84 years; Spencer & Biffa,
Upper torso musculoskeletal pain

2013) or younger (18 – 35 years; Coltman et al., 2013) than participants in the McGhee et al. (2018) study. These researchers found that participants with large breasts had greater thoracic pain than participants with small breasts, despite no difference in thoracic kyphosis angle (Coltman et al., 2013; Spencer & Biffa, 2013). The difference in findings among these studies is likely to be due to the region of pain assessed (thoracic versus upper torso), as well as confounding variables such as osteoporosis, which was not screened for by Spencer and Biffa (2013). However, another study of young women (18 – 26 years) found no association between thoracic pain and breast size when measured across a size spectrum (Wood et al., 2008). Therefore, although there is some evidence to suggest that an increased breast size can result in changes to the structure (thoracic kyphosis) and function (musculoskeletal pain) of the upper torso, further research is warranted to examine this relationship on a large cohort of women, across a range of ages and breast sizes, who are not currently seeking breast reduction surgery.

Increased thoracic kyphosis has also been found to limit the range-of-motion (ROM) of the shoulder complex (Crawford and Jull 1993; Griegel-Morris et al. 1992; McGhee et al. 2018). Poor mobility in the upper thoracic spine has also been shown to be a predictor of neck and shoulder pain (Norlander and Nordgren 1998; Perriman et al. 2012). It is therefore possible that the musculoskeletal pain suffered by women with large breasts is related to decreased mobility in the shoulder complex secondary to increased thoracic kyphosis (McGhee et al. 2018). Although the findings of the McGhee et al. (2018) study support this notion, the sample size was small (n = 53). Therefore, further research on a larger sample size is required to confirm these findings.

Breast shape and the relative location of the breasts on the trunk are also factors likely to be associated with musculoskeletal pain because these factors will affect
loading on the chest wall (Spencer & Briffa, 2013). Both breasts shape and breast position can be affected by age related declines in the mechanical properties of skin covering the breasts, such as skin thickness and elasticity (Coltman, Steele and McGhee 2017a; Chapter 3). Breast ptosis has also been found to increase with increasing age and BMI and broader breasts have been found in women with a higher BMI (Brown et al., 1999). The effects of different breast shapes and breast positions on musculoskeletal pain, however, are yet to be investigated. It is important to understand which variables predict the experience of musculoskeletal pain in the upper torso because this knowledge can be used to develop evidence-based treatment and preventive strategies in order to minimise the musculoskeletal pain experienced by women, regardless of their breast size.

The purpose of this study was to identify whether physical factors associated with breast and upper torso structure and function, as well as physical factors previously shown to be associated with musculoskeletal pain (such as age, BMI and physical activity level; Goh et al., 1999; Hinman, 2004; Vuori, 1995) predict upper torso musculoskeletal pain among women across the breast size spectrum. Breast and torso structure and function were characterised by breast volume, breast shape, breast skin properties, thoracic kyphosis angle and shoulder range of motion. It was hypothesised that the experience of upper torso musculoskeletal pain would be predicted by a large breast volume, a large breast ptosis, broad breasts, decreased skin thickness and elasticity, an increased degree of thoracic kyphosis, a decreased shoulder range of motion, older age, a high BMI and a decreased level of physical activity.
6.2 Materials and methods

6.2.2 Participants

The recruitment and study approval procedures were the same as those listed in Chapter 4, Section 4.2.1. Participants were the same as those reported in Section 4.2.1, although further exclusion criteria were applied when selecting data to be analysed (see Figure 19). Participants’ data were excluded from analysis in this study if the participant: (i) had any breast surgery which may affect their breast volume or shoulder range of motion (ii) if they reported having osteoporosis which may affect their thoracic kyphosis angle (Crawford and Jull 1993; Goh et al. 1999; Hinman 2004; Puche et al. 1995) or (iii) if they reported any pre-existing musculoskeletal injury that would have adversely affected their self-report musculoskeletal pain. Of the initial 378 volunteers, data for 300 women were included in the current study. These women (age range: 18 – 82 years, mean: 40.1 ± 18.6 years; BMI range: 19 – 55 kg/m², mean: 27.2 ± 6.0 kg/m²) were deemed representative of Australian women living in the community (Chapter 4, Table 9; Coltman, Steele and McGhee 2017b). Each participant’s age on the day of testing was recorded in years. Their height (m) and body mass (kg) was measured using the same procedures described in Chapter 4, Section 4.2.2. A power analysis was conducted using G*power 3.1.3 and revealed that for a conservative medium effect (0.15; Cohen, 1988) with 10 predictor variables (see Section 6.2.4 for predictor variables), a minimum sample size of 118 participants was required to achieve statistical power of at least 80% (with a significance level of \( P < 0.05 \)). Therefore, the present study sample (n = 300) exceeded the number of participants required to achieve sufficient statistical power.
Australian women aged 18 years and older were recruited to participate in this study via advertisements at the University of Wollongong, in local media or at participating Women’s Health Centre’s throughout New South Wales, Australia.

Excluded:
- Pregnant or breastfeeding
- Epilepsy
- Inability to assume scanning position

378 women attended one, 1 hr test session to measure each participant’s breast and upper torso characteristics

Excluded:
- Breast surgery (n = 32)
- Osteoporosis (n = 24)
- Musculoskeletal Injury (n = 22)

Final musculoskeletal analysis (n = 300)

Figure 19: Flow of participants through the present study and the exclusion criteria.

6.2.3 Upper torso musculoskeletal pain (dependent variable)

The self-report severity and frequency of musculoskeletal pain experienced by participants were recorded on a graded colour coded body chart for seven regions of the upper torso (neck, shoulders, arms, upper back, lower back, breasts and head (headache)). Within this chart, severity of pain was graded using a visual analogue scale (VAS; 0 = no pain; 10 = worst pain) and frequency was scaled from 1 – 3 (1 = rarely, ≤ 1 time per month; 2 = occasionally, ≤ 3 time per month; 3 = frequently ≥ 1 – 3 times per week; Griegel-Morris et al. 1992; McGhee et al. 2018). Visual analogue scales have been shown to be valid and reliable measurement tools to assess self-report pain severity (Downie et al. 1978; Price et al. 1983). The severity grade and frequency score were multiplied for each region (maximum score 30 at each region) and then summed.
across the seven regions to provide a total upper torso musculoskeletal pain score out of 210 (McGhee et al. 2018), which was used at the dependent variable.

6.2.4 Predictors of upper torso musculoskeletal pain (independent variable)

6.2.4.1 Breast volume
Breast volume was calculated from a three-dimensional scan of each participant’s breasts in a prone scanning position as shown in Figure 2C and described in detail in Chapter 2, Section 2.2.2. Breast volume was quantified due to the positive association between increased prevalence and severity of musculoskeletal pain in the upper torso and large breast sizes (BeLieu 1994; Greenbaum et al. 2003; Kaye 1972; Ryan 2000; McGhee et al. 2008; McGhee et al. 2018; Spencer and Briffa 2013).

6.2.4.2 Breast shape
The breast shape parameters sternal-notch-to-nipple distance (measure of breast ptosis; Westreich 1997) and nipple-to-nipple distance (measure of breast broadness; Westreich 1997) were assessed using the same procedures for these measurements that are described in detail in Chapter 5, Section 5.2.3 (also see Table 12 and Figure 15 G and H). These measures were quantified to assess the impact of breast shape on upper torso musculoskeletal pain (Spencer and Briffa 2013). These two measures were chosen as they are commonly used within the literature to characterise breast shape (Brown et al. 1999; Coltman, McGhee and Steele 2017; Liu and Thomson 2011; Penn 1954; Smith et al. 1986; Westreich 1995) and previous research has associated increased age and body mass with changes in these variables (Brown et al. 1999).

6.2.4.3 Breast skin thickness and elasticity
The protocol used to quantify breast skin thickness and elasticity are the same as those described in Chapter 3, Section 3.2.2 (skin thickness) and Section 3.2.3 (skin elasticity). The mean data collected at each of the four quadrants of the left breast (superior,
inferior, medial and lateral) was summed and averaged to obtain one breast skin thickness value (mm) and one breast skin elasticity (%) value. These measures were assessed to quantify the effect of the breast skin on upper torso musculoskeletal pain.

6.2.4.4 Thoracic kyphosis angle

A Flexicurve ruler (Faber-Castell, Germany; Greendale et al. 2011; McGhee et al. 2018; Spencer and Briffa 2013) was moulded to the posterior surface of each participant’s vertebral column, with its ends aligned with C7 and the L5-S1 intervertebral space. The moulded Flexicurve ruler was then placed on grid paper where it was traced. From the tracing a thoracic kyphosis angle was calculated (as described in Figure 20). Thoracic kyphosis was assessed as an increased degree of thoracic kyphosis has been associated with poor mobility in the thoracic spine (Crawford and Jull 1993; Griegel-Morris et al. 1992). Poor thoracic spinal mobility has, in turn, been associated with increased musculoskeletal pain (Norlander and Nordgren 1998; McGhee et al. 2018, Perriman et al. 2012).

**Figure 20:** The thoracic kyphosis angle calculation. The landmarks of C7, T12 and the apex of the thoracic spine are labelled as B, C and A, respectively, on the image. A straight line (TL) was drawn between B and C and a line (TW) was then drawn from A to meet BC at a right angle. TL was divided into TL1 and TL2 based on where TL intersects with TW and the kyphosis angle was calculated by the formula \( \theta = [\arctan(TW/TL1) + \arctan(TW/TL2)] \times 1.53 \) (Greendale et al. 2011).
6.2.4.5 Shoulder joint flexion range of motion

The forward flexion range of motion of the right glenohumeral (shoulder) joint was measured (degrees) while participants stood upright with their knees slightly flexed, their pelvis posteriorly tilted and their lumbar spine stabilised (McGhee et al. 2018). Participants were asked to raise their upper limb as high as possible and hold this position for approximately 5 seconds during which time the centre of a goniometer was aligned with the axis of the glenohumeral joint. The stationary arm of the goniometer was positioned parallel to the midline of the trunk and the moveable arm of the goniometer was positioned parallel to the midline of the humerus. The mean of three measures was calculated to represent flexion of the glenohumeral (shoulder) joint because poor mobility in the upper thoracic spine (which includes the shoulder complex) has been shown to be a predictor of neck and shoulder pain (Crawford and Jull 1993; Norlander and Nordgren 1998). Flexion of the shoulder joint has also previously been related to increased thoracic kyphosis and musculoskeletal pain in women with large breasts (McGhee et al. 2018).

6.2.4.6 Physical activity

All participants completed the Active Australia Survey to record the amount and type of physical activity performed in the week preceding survey completion. From this survey total time in physical activity (minutes) per week was calculated following the analysis guidelines (Australian Institute of Health and Welfare 2003). This variable was assessed as increased physical activity participation has been associated with reduced musculoskeletal pain in the upper torso (low back, neck and shoulder; Vuori 1995).

6.2.4.7 Reliability in measurement

The primary investigator, who performed all measurements, was deemed to have high intra-rater reliability in performing the measurements related to the methodology for
Upper torso musculoskeletal pain

this study. Specifically, the primary investigator had high reliability in scanning and analysing the breast volume and breast shape parameters (all Cronbach’s $\alpha \geq 0.95$). Similarly, high intra-rater reliability was established for skin thickness measurements ($ICC = 0.96; p < 0.001; n = 12$), skin elasticity measurements ($ICC = 0.83; p < 0.001; n = 7$), thoracic kyphosis angle measurement ($ICC = 0.78; p < 0.05; n = 6$) and shoulder ROM measurements ($ICC = 0.82; p < 0.05; n = 6$). The ICC values obtained by the primary investigator for all measures described above are similar to those reported in previous research (Greendale et al. 2011; McGhee et al. 2018; Mickle et al. 2013; Spencer and Briffa 2013) and indicate good or excellent reliability in measurement (Koo and Li 2016; Portney and Watkins 2000).

6.2.4 Statistical analysis

Descriptive statistics for total upper torso musculoskeletal pain score, as well as the musculoskeletal pain score reported at each of the seven regions of the upper torso, were calculated. To determine whether any of the independent variables described above were predictors of total upper torso musculoskeletal pain (dependent variable), a backward multiple regression analysis was conducted. The mean and standard deviation data for all independent variables that were used to predict total upper torso musculoskeletal pain are shown for the entire participant cohort ($n = 300$) in Table 14. Variance inflation factors (VIF) were assessed to ensure that the predictor variables imputed into the regression model were not highly correlated to one another (all VIF’s for independent variables within the model were < 2.7). The overall model and variable significance was set at an alpha of 0.05 and performed using the Statistical Package for the Social Sciences (Version 21.0; SPSS Inc., Chicago, IL).
Table 14: Mean ± SD and range values for each of the independent variables used to predict total upper torso musculoskeletal pain score (dependent variable) for all participants (n = 300).

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>41 ± 19</td>
<td>18 - 82</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>27 ± 6</td>
<td>19 - 55</td>
</tr>
<tr>
<td>Breast volume (mL)</td>
<td>644 ± 487</td>
<td>48 - 3100</td>
</tr>
<tr>
<td>Sternal notch-to-nipple distance (cm)</td>
<td>25 ± 4</td>
<td>17 - 39</td>
</tr>
<tr>
<td>Nipple-to-nipple distance (cm)</td>
<td>23 ± 3</td>
<td>16 - 35</td>
</tr>
<tr>
<td>Skin thickness (mm)</td>
<td>1.79 ± 0.25</td>
<td>1.12 - 2.87</td>
</tr>
<tr>
<td>Skin elasticity (%)</td>
<td>83 ± 6</td>
<td>58 - 93</td>
</tr>
<tr>
<td>Kyphosis angle (°)</td>
<td>31 ± 9</td>
<td>6 - 56</td>
</tr>
<tr>
<td>Shoulder ROM (°)</td>
<td>150 ± 10</td>
<td>122 - 175</td>
</tr>
<tr>
<td>Total time physical activity (min)</td>
<td>588 ± 533</td>
<td>0 - 3360</td>
</tr>
</tbody>
</table>

6.3 Results

Participants in the current study reported total upper torso musculoskeletal pain scores ranging from 0 – 192 (mean: 41.46 ± 35.38), out of a maximum possible score of 210 (Figure 21).

Figure 21: The total upper torso musculoskeletal pain score distribution of all participants measured in this study (n = 300).

The multiple regression analyses revealed that the strongest predictor model was able to estimate and predict 23% ($F_{3,298} = 29.453, p < 0.001$) of the total upper torso musculoskeletal pain score. This was predicted by interactions among the independent
variables of breast volume, age and nipple-to-nipple distance (Table 15). The regression coefficient was positive for breast volume and nipple-to-nipple distance, indicating that increased breast volume and increased nipple-to-nipple distance were associated with increased total upper torso musculoskeletal pain score. In contrast, the regression coefficient was negative for age, indicating that increased age was associated with a decrease in the reported total upper torso musculoskeletal pain score. The direct relationship between musculoskeletal pain score and the independent variables of breast volume, age and nipple-to-nipple distance are shown in Figure 22.

Table 15: Multiple regression analysis of independent variables effect on total upper torso musculoskeletal pain.

| Predictor variables           | Unstandardized coefficients | Standardized Coefficient |  |  |  |  |
|------------------------------|-----------------------------|--------------------------|  |  |  |  |
| (R² = 0.230)                 |                             |                          |  |  |  |  |
| Breast volume                | 0.024                       | 0.005                    | 0.333 | 4.760 | 0.000 |
| Age                          | -0.521                      | 0.099                    | -0.277 | -5.245 | 0.000 |
| Nipple-to-nipple distance    | 1.933                       | 0.773                    | 0.171 | 2.501 | 0.013 |

Figure 22: The direct relationship is shown between upper torso musculoskeletal pain score and breast volume (A), age (B) and nipple-to-nipple distance (C).
6.4 Discussion

This is the first study to explore whether physical factors associated with breast and upper torso structure and function, as well as physical factors known to be associated with musculoskeletal pain, can predict upper torso musculoskeletal pain among a large sample of women across a wide breast volume, age and BMI spectrum. Based on the predictive model we have identified that the variables of breast volume, age and nipple-to-nipple distance, in combination, are the best predictors of musculoskeletal pain in the upper torso. Combined, these variables explain 23% of the variance in upper torso musculoskeletal pain score, leaving 77% of this pain score unexplained. The implications of these findings are discussed below.

The average musculoskeletal pain scores (/210) reported by the participants in the current study were within the ranges reported in previous research (McGhee et al. 2018). Breast volume was the strongest predictor of upper torso musculoskeletal pain within the model, indicated by the highest absolute value standardised coefficient (Table 15). According to the regression predictor model, across the breast volume spectrum of study participants (48 – 3,100 mL), women are predicted to report experiencing an increase in upper torso musculoskeletal pain score from 0 – 73 units (35% increase; from the participant with the smallest to largest breast volume). Participants with the greatest upper torso musculoskeletal pain in the current study (pain scores > 100; n = 18; Figure 21), had an average breast volume of 1262 mL per breast (classified as hypertrophic; Table 10; Coltman, Steele and McGhee 2017b) and the participant with the largest breast volume of the entire cohort (3100 mL) reported the highest musculoskeletal pain score (score: 192; Figure 22A).

Considering 34% of the study cohort had breast volumes classified as large (breast volumes between 700 – 1200 mL; Table 10) or hypertrophic (breast volumes >
Upper torso musculoskeletal pain

1200 mL; Table 10; Coltman, Steele and McGhee 2017b), solutions to mitigate the negative symptoms in these women are needed. This could be achieved by decreasing the flexion torque of the thoracic spine by decreasing breast mass through breast reduction surgery, which has been shown to alleviate symptoms experienced by women with large breasts (Gonzalez 1993; Greenbaum et al. 2003; Letterman and Schurter 1980; Miller et al. 1995). There are, however, costs and risks associated with any form of surgical intervention (Atterhem et al. 2000). The symptoms could therefore also be addressed by increasing the level of breast support provided to women with large breasts with a high support and well-fitted bra (Abdel Hadi 2000; Greenbaum et al. 2003; McGhee et al. 2013; McGhee et al. 2018) or by increasing the trunk’s ability to counteract the flexion torque generated by the breasts by increasing thoracic extensor strength (McGhee et al. 2018).

Of the previous research that has compared upper torso musculoskeletal pain in women with large and small breasts, all have controlled for the effects of age by recruiting women of similar ages (e.g. young women, middle-aged women or post-menopausal women; Coltman et al. 2013; McGhee et al. 2018; Spencer and Biffa 2013). Therefore, this is the first study to present data on upper torso musculoskeletal pain across the age spectrum. In contrast to our hypothesis, there was a 34 unit decrease in upper torso musculoskeletal pain score across the age spectrum (i.e. from 18 to 84 years of age). Previous research that has observed musculoskeletal pain to decrease with increasing age (Brattberg et al. 1997; Gao et al. 2013) has suggested that this may be linked to lifestyle changes, such as retirement and decreased work-related strain (Brattberg et al. 1997). It is also speculated that cultural attitudes, as well as life experiences (e.g. childbirth), may influence pain tolerance, subsequently impacting upon the reporting of pain within the study population, with the lowest pain scores
Upper torso musculoskeletal pain

reported by participants aged 65+ years (Beigi et al. 2010; Honeyman and Jacobs 1996; Zborowski 1952). However, as younger women within the study cohort were predicted to report increased musculoskeletal pain in the upper torso, particularly those with large breast volumes and large nipple-to-nipple distances, improved breast support options are recommended as a treatment strategy for these women.

An increased nipple-to-nipple distance (measure of breast breadth) also predicted upper torso musculoskeletal pain score in the current model. According to the regression model, increased breast breadth led to an increased upper torso musculoskeletal pain score by 0 – 37 units (narrowest (16 cm) to broadest (35 cm) breasts). This finding is consistent with previous research in which the position of breast mass on the trunk has been proposed to be implicated in musculoskeletal pain (Spencer and Briffa 2013; Valtonen et al. 2014). We speculate that a large distance between each breast indicates that the breasts are splaying outwards from the midline of the body. This is likely to affect the force created by the breasts on the trunk, as well as have implications for how the breasts should be supported, highlighting the importance of breast shape to breast support and bra design (as discussed in Chapter 5). It is important to note, however, that the study cohort comprised only a small number of women with large nipple-to-nipple distances (Figure 22C). Therefore, further research is warranted to investigate the effect of large nipple-to-nipple distances on upper torso structure and function. This will confirm whether the relationship detected by the regression model applied in the current study holds true among this population of women.

Interestingly, despite previous research showing associations between increased breast size and negative outcomes in thoracic kyphosis and shoulder ROM (Findikcioglu et al 2013; Findikcioglu et al 2007; McGhee et al 2018), these latter two variables were not found to be predictors of upper torso musculoskeletal pain in the
present study. Although it is thought that these variables are inter-related (Crawford and Jull 1993; Griegel-Morris et al. 1992; McGhee et al. 2018), the previous research that has associated large breasts with either increased thoracic kyphosis, decreased shoulder range of motion or increased musculoskeletal pain have only examined women within a narrow age range (Coltman et al. 2013; McGhee et al. 2018; Spencer and Biffa 2013; Wood et al. 2008). We therefore suggest that future research investigate the structure and function of the upper torso among women with large breast across the age spectrum and better control for confounding factors such as osteoporosis.

Other variables related to breast shape and the position of the breasts on the torso, as well as physical activity and BMI, were also not found to be predictors of upper torso musculoskeletal pain. This indicates that these variables provide no additional explanatory effect on musculoskeletal pain beyond those variables identified by the model (Table 15). However, as the regression model was only able to predict 23% of the upper torso musculoskeletal pain score, 77% of this pain was unexplained, highlighting the complexity of musculoskeletal pain. As this study assessed only physical characteristics related to upper torso musculoskeletal pain, it is likely that psychosocial factors (personal and work related) further predict the experience of upper torso musculoskeletal pain among women. Work postures and roles, emotional stress, financial status and educational status should therefore be included in future research that explores factors that affect upper torso musculoskeletal in women (Leroux et al. 2005; Portenoy et al. 2004; Réthelyi et al. 2004; Roth et al. 2001; Van Der Windt et al. 2000; Wood et al. 2008). Furthermore, given that breast volume was found to be a predictor of musculoskeletal pain and breast hypertrophy is known to be associated with negative psychosocial consequences (Pérez-Panzano et al. 2017), exploring the impact
of both physical and psychosocial factors on musculoskeletal pain across the breast size spectrum is recommended.

As with any research, we acknowledge that this study has limitations, which must be considered when interpreting the data. Limitations of this study include the self-report nature of the prevalence and severity of musculoskeletal pain (dependent variable), with accuracy in participant responses susceptible to recall bias, as well as under or over-reporting (Spencer and Briffa 2013). Although participants were excluded if they reported having osteoporosis, the likelihood of women with undiagnosed osteoporosis participating in this study cannot be ignored.

6.5 Conclusion

Of the variables assessed within the current study, a larger breast volume, a younger age and an increased nipple-to-nipple distance were found to be the best predictors of women reporting a higher upper torso musculoskeletal pain score. However, as the model predicted only 23% of the variance in upper torso musculoskeletal pain, further research incorporating both physical and psychosocial factors related to musculoskeletal pain is recommended.
Part IV

Are these women being catered for?
Chapter 7

Which bra components contribute to incorrect bra fit in women across a range of breast sizes?


Abstract

The purpose of this study was to investigate whether different components of encapsulation style bras contributed to incorrect bra fit among women and whether this was influenced by breast size. The fit of five key bra components of 309 women’s own encapsulation bras was assessed using professional bra fit criteria among four breast size categories. Overall, incorrect fit prevalence was greatest among the cups, front band and strap components of the bra. Although no significant difference was observed in overall bra fit between the four breast size categories, a significant difference was observed between groups for the front band, underwire and strap components of the bra. Individual components of encapsulation style bras are associated with incorrect bra fit and these vary with breast size. Incorporating three-dimensional breast volume/shape and torso dimension data into bra component design could improve bra fit and breast support for women across the size spectrum.
7.1 Introduction

A poorly fitted bra can lead to numerous negative health outcomes, including poor posture, headaches and back ache (BeLieu 1994; Greenbaum et al. 2003; Kaye 1972; Ryan 2000). The symptoms associated with poor bra fit can be so severe as to lead women to seek reduction mammoplasty (BeLieu 1994; Greenbaum et al. 2003; Ryan 2000), as well as inhibit some women, particularly those with large breasts, from participating in physical activity (Lorentzen and Lawson 1987; Mason et al. 1999; McGhee et al. 2013; Scurr et al. 2010). Therefore, incorrect bra fit is an important women’s health issue. Although a high prevalence of incorrect bra fit has been reported in women across a range of bra sizes (Greenbaum et al. 2003; McGhee and Steele 2011; McGhee and Steele 2010a; McGhee et al. 2010; Wood et al. 2008), the consequences of insufficient breast support have been reported to be much greater for women with large breasts (Findikcioglu et al. 2007; Greenbaum et al. 1980; McGhee et al. 2013; Ryan 2009).

Several factors have been identified as contributing to the high prevalence of incorrect bra fit. These factors include insufficient knowledge of bra fit because of a lack of education on how to correctly fit a bra (McGhee and Steele 2010a; McGhee et al. 2010), a lack of standardisation in bra sizes among manufacturers (Fechter 1998; Kanhai et al. 1999; McGhee and Steele 2006), as well as a lack of use of professional bra fitting services (Brown et al. 2014; McGhee and Steele 2010a; White and Scurr 2012). Because incorrect bra fit can negatively impact women’s health, several strategies have been established to try and resolve this problem. These strategies have included the development of educational resources to educate women on how to correctly fit their bra (McGhee et al. 2008; McGhee et al. 2012) and recommendations for women to use professional bra fitting services (McGhee et al. 2010). Women are,
however, reluctant to use such services. In fact, 75% of adolescent females have reported that they had never used professional bra fitting services and 66% of women reported choosing to independently fit and purchase their own bras (McGhee and Steele 2010a; White and Scurr 2012). Therefore, it is imperative that factors that might impede women from selecting a correctly fitted bra are minimised.

One factor that is likely to contribute to the high prevalence of poor bra fit is how a bra is designed. Bras are most commonly designed in one of two ways: (a) as a compression style bra or (b) as an encapsulation style bra (Figure 23). Women can wear either compression style bras or encapsulation style bras (or a combination of both) when they participate in physical activity. The function of the two bra styles, however, is different (Zhou et al. 2013). Compression style bras are designed to compress both breasts against the chest wall as a single unit to limit breast motion, whereas encapsulation style bras are comprised of numerous individual components that are pieced together to form bras that support each breast individually in separate, structured cups (Loeher 2013; Yu and Zhou 2016; Zhou et al. 2013). Encapsulation bras can be designed to be worn for daily use and/or physical activity. These bras are the focus of the current study.

The main components of an encapsulation bra include the cups, front band, underwire, back band, and straps (Figure 23; Bowles and Steele 2013; Chen et al. 2011; Cummings 1987; McGhee and Steele 2010a; Page and Steele 2011; Pandarum et al. 2011; Yu and Zhou 2016). Given the unique function that each component of an encapsulation style bra is designed to perform, it is important to understand how these different components affect overall bra fit. Furthermore, considering the wide range of breast sizes that bras must support (Coltman, Steele and McGhee 2017b; refer to Chapter 4; Section 4.3), it is also important to determine whether the fit of these
different components differs with respect to breast size. For example, for a bra to fit properly the size of a bra cup must match the volume of the breast that it is to contain (Chen et al. 2011; Lee et al. 2004; Pandarum et al. 2011). Only McGhee and Steele (2011) have related breast volume data (n = 107; volume range: 125 mL – 1900 mL, per breast) to the participants’ professionally-fitted bra sizes (in the one style and make of bra). McGhee and Steele (2011) found that a range of breast volumes corresponded to the same professionally-fitted bra cup size. Furthermore, the range of breast volumes corresponding to the same bra cup size was greater for women with large breasts (defined as volumes > 500 mL; McGhee and Steele 2011). Based on the results of these studies, it appears that selecting the correct bra cup size could be confusing, particularly for women with large breasts, possibly contributing to incorrect bra size selection. Thus far no study has established which components of encapsulation bras are associated with poor bra fit.

The aim of this study was to determine which components of encapsulation style bras were associated with incorrect bra fit in women across a range of breast sizes. The following research questions were formulated:

1. What is the prevalence of incorrect bra fit in an encapsulation style bra among women of different breast sizes?

2. Does the frequency of incorrect fit of different bra components differ with respect to breast size?
Incorrectly fitting bra components

**Figure 23:** The two main styles of bras: (a) compression and (b) encapsulation (Loeher 2013; diagrams adapted from Zhou et al. 2013).

<table>
<thead>
<tr>
<th>Compression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compresses the breast against the chest wall as a single unit to minimise breast motion</td>
</tr>
<tr>
<td></td>
<td><strong>Components</strong></td>
</tr>
<tr>
<td>Front:</td>
<td>Commonly an elastic material that is designed to flatten, not separate the breasts against the chest as a unit</td>
</tr>
<tr>
<td>Back:</td>
<td>The back of the bra is most commonly a racer back style or T-bar design, which is used to provide firm support to compress the breasts and to prevent straps from slipping off the shoulders</td>
</tr>
<tr>
<td>Band:</td>
<td>Usually designed as an elastic component that wraps around the entire torso to firmly hold the bra in place</td>
</tr>
<tr>
<td>Straps:</td>
<td>Commonly designed wide (sometimes padded) for comfort to prevent digging into the shoulders</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Encapsulation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supports each breast individually in separate, structured cups</td>
</tr>
<tr>
<td></td>
<td><strong>Components</strong></td>
</tr>
<tr>
<td>Cups:</td>
<td>Designed to enclose and support each breast individually, while providing shape to the breasts. Cups can be rigid or soft with different levels of coverage</td>
</tr>
<tr>
<td>Front band:</td>
<td>Designed to sit flush against the sternum, helping to separate the breasts for positioning into the bra cups</td>
</tr>
<tr>
<td>Underwire:</td>
<td>A U-shaped hard component (usually wire), which is designed to provide shape and transfer the downward pressure from the weight of the breasts to the bra band</td>
</tr>
<tr>
<td>Back band:</td>
<td>Positioned in the horizontal plane, the band expands around the body and is designed to keep the bra firmly in place. The bra band acts as the primary support structure to the bra cups in supporting the weight of the breasts</td>
</tr>
<tr>
<td>Straps:</td>
<td>Designed to keep the bra in the correct vertical position on the body and provide secondary support to the bra cups</td>
</tr>
</tbody>
</table>

### 7.2 Materials and methods

#### 7.2.1 Participants

The recruitment and study approval procedures were the same as those listed in Chapter 4, Section 4.2.1. Prior to attending the test session participants were informed that they would be involved in several different tests, which would quantify their breast
characteristics and bra size and how this information would ultimately be used to improve breast support. The participants were given no specific instructions as to the style of breast support they should wear to the test session and they were not told that the fit of their bra would be assessed during the test session. This enabled demographic profiling of the type of breast support worn by women in the community and ensured that the participants did not change their bra wearing habits in anticipation of being assessed. The type of breast support worn by the women who participated in this study is shown in Table 16.

The published criteria used to assess bra fit were designed for encapsulation-style bras (McGhee & Steele, 2010). Therefore, participants who wore any form of unstructured bra (e.g., compression style bra, non-compression style breast support such as the Ahh bra, no bra or a singlet; n = 37; 11%), rather than an encapsulation style of bra, were excluded from analysis. In addition, participants who had undergone breast surgery (e.g., lumpectomy and mastectomy) were excluded (n = 32) from analysis as breast asymmetry, which is a common consequence of breast surgery, was considered to be a confounding variable that would affect bra fit (as bras are symmetrical). This reduced the analysed study sample size to n = 309 (age range: 18.1 – 83.7 years, mean: 43.5 ± 19.6 years; BMI range: 19.0 – 55.0 kg/m², mean: 27.6 ± 6.1 kg/m²). Participant height (m) and body mass (kg) were measured using the same procedures described in Chapter 4, Section 4.2.2.

Table 16: The style of bra worn by the participants who attended the testing session (n = 378).

<table>
<thead>
<tr>
<th>Bra style worn</th>
<th>Number of participants</th>
<th>Age (years; mean ± SD)</th>
<th>BMI (kg/m²; mean ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encapsulation</td>
<td>309</td>
<td>45 ± 20</td>
<td>28 ± 6</td>
</tr>
<tr>
<td>Compression</td>
<td>23</td>
<td>31 ± 13</td>
<td>24 ± 4</td>
</tr>
<tr>
<td>Non-compression/unstructured (e.g. ahh bra)</td>
<td>10</td>
<td>60 ± 16</td>
<td>32 ± 8</td>
</tr>
<tr>
<td>No bra or singlet top</td>
<td>7</td>
<td>50 ± 7</td>
<td>26 ± 4</td>
</tr>
</tbody>
</table>
7.2.2 *Breast Volume Measurement*

The size of each participant’s breasts was quantified by directly measuring the volume from a three-dimensional scan of each participant’s breasts in a prone scanning position as shown in Figure 2C and described in detail in Chapter 2, Section 2.2.2. Participants were divided into four breast size categories: those women with (a) small, (b) medium, (c) large, and (d) hypertrophic breasts (as per those described in Table 10). Participant characteristics for the four breast size categories are shown in Table 17.

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Breast volume (median ± IQR*; mL)</th>
<th>Age (years; mean ± SD)</th>
<th>BMI (kg/m²; mean ± SD)</th>
<th>Bra cup size** range</th>
<th>Bra band size** range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small (breast volume &lt;350 mL)</td>
<td>96</td>
<td>222 ± 81</td>
<td>229 ± 72</td>
<td>35 ± 16</td>
<td>22 ± 3</td>
<td>A-DD</td>
</tr>
<tr>
<td>Medium (breast volume 350-700 mL)</td>
<td>130</td>
<td>500 ± 130</td>
<td>503 ± 130</td>
<td>41 ± 20</td>
<td>26 ± 4</td>
<td>B - G</td>
</tr>
<tr>
<td>Large (breast volume 701-1200 mL)</td>
<td>83</td>
<td>909 ± 188</td>
<td>921 ± 144</td>
<td>52 ± 20</td>
<td>31 ± 5</td>
<td>C - J</td>
</tr>
<tr>
<td>Hypertrophic (breast volume &gt;1200 mL)</td>
<td>37</td>
<td>1669 ± 498</td>
<td>1665 ± 437</td>
<td>51 ± 16</td>
<td>35 ± 7</td>
<td>DD - K</td>
</tr>
</tbody>
</table>

*IQR = interquartile range

**Bra sizes were measured using the Australian sizing system (for international sizing conversions see Appendix A).

7.2.3 *Bra Fit Assessment*

The fit of the bra of all participants who wore an encapsulation style bra to the test session was assessed, once, using professional bra fit criteria (McGhee and Steele 2010a; Table 18), which have been developed to assess the fit of key components of encapsulation bras (cups, front band, underwire, back band, and straps). These criteria enabled the primary investigator [CEC], who performed all assessments, to determine whether each component of the participant’s own encapsulation bra fitted them...
incorrectly or incorrectly. The primary investigator received extensive one-on-one training over a 6-month period in assessing bra fit by the expert who developed the professional bra fit criteria. Data collection only commenced when the expert deemed the primary investigator to be highly proficient and consistent in performing the validated bra fit assessment. If all five bra components fitted the participants correctly, they were awarded an overall pass for the bra fit assessment. However, if any one or more bra component was rated as fitting incorrectly, the participant was awarded an overall fail for the bra fit assessment, and no adjustments to fit were made by the assessor. The frequency with which each bra component was rated as fitting correctly and incorrectly, as well as the number of components that failed and the frequency of overall passes or fails being awarded for the bra fit assessment, were recorded.

Table 18: The professional bra fit criteria used in this study to assess the fit of each participant’s own bra (McGhee and Steele 2010a).

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

7.2.4 **Statistical Analysis**

The frequency of incorrect fit of each of the five bra components and the overall bra fit assessment result (pass or fail) were calculated for every participant and then grouped
according to the four breast size categories (small, medium, large, and hypertrophic). Chi-squared analyzes were performed on the bra fit data recorded for the four breast size categories to determine whether breast size (small, medium, large, and hypertrophic) significantly \( p < 0.05 \) affected the frequency of correct and incorrect results for overall bra fit, as well as the fit of each of the five bra components. All statistical calculations were conducted using the Statistical Package for the Social Sciences (Version 21.0; SPSS Inc., Chicago, IL).

### 7.3 Results

#### 7.3.1 Bra Fit Assessment

Of those women wearing encapsulation style bras (n =309), 6 did not have straps (strapless) and 22 did not have underwire (wire free), reducing the number of participants who were assessed for the fit of these bra components. The women who wore strapless bras had an average age of 29 years (range: 20 – 46 years) and an average BMI of 24 kg/m² (normal; range: 20 – 28 kg/m²), whereas the women who wore wire free bras had an average age of 65 years (range: 28 – 83 years) and an average BMI of 32 kg/m² (obese; range: 20 – 48 kg/m²). Only 10% of the women who were wearing an encapsulation style bra (n = 309) wore a bra that was rated overall as fitting correctly. When examined by breast size category, 9% of women with small breasts, 12% of women with medium breasts, 7% of women with large breasts, and 15% of women with hypertrophic breasts wore a bra that was rated overall as fitting correctly (Table 19). The number of incorrectly fitting components, on average, of the encapsulation style bras that the participants wore to the test session is shown in Table 19.
Table 19: The number and percentage (in parentheses) of incorrectly fitting components of the participants’ encapsulation bras are shown for each breast size category (small, medium, large, and hypertrophic) and for the total cohort (n = 309).

<table>
<thead>
<tr>
<th>Number of features incorrectly fitting</th>
<th>Small (%) n = 77</th>
<th>Medium (%) n = 119</th>
<th>Large (%) n = 79</th>
<th>Hypertrophic (%) n = 34</th>
<th>Total (%) n = 309</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failed on zero components</td>
<td>7 (9)</td>
<td>14 (12)</td>
<td>5 (7)</td>
<td>5 (15)</td>
<td>31 (10)</td>
</tr>
<tr>
<td>Failed on 1 component</td>
<td>16 (21)</td>
<td>17 (14)</td>
<td>9 (11)</td>
<td>2 (6)</td>
<td>44 (14)</td>
</tr>
<tr>
<td>Failed on 2 components</td>
<td>25 (32)</td>
<td>27 (23)</td>
<td>15 (19)</td>
<td>9 (26)</td>
<td>76 (24)</td>
</tr>
<tr>
<td>Failed on 3 components</td>
<td>9 (12)</td>
<td>30 (25)</td>
<td>19 (24)</td>
<td>6 (18)</td>
<td>64 (21)</td>
</tr>
<tr>
<td>Failed on 4 components</td>
<td>9 (12)</td>
<td>22 (19)</td>
<td>12 (15)</td>
<td>8 (23)</td>
<td>51 (17)</td>
</tr>
<tr>
<td>Failed on 5 components</td>
<td>11 (14)</td>
<td>9 (7)</td>
<td>19 (24)</td>
<td>4 (12)</td>
<td>43 (14)</td>
</tr>
</tbody>
</table>

There was no significant difference in the percentage of women rated as wearing an incorrectly fitting encapsulation bra between the four breast size categories ($\chi^2 (3, n = 309) = 2.63, p > 0.05$; Figure 24). In contrast, when rating the fit of individual bra components, women with medium, large and hypertrophic breasts were more likely to have an incorrectly fitting front band ($\chi^2 (3, n = 309) = 35.29, p < 0.05$) and underwire ($\chi^2 (3, n = 287) = 17.45, p < 0.05$), whereas women with small breasts were more likely to have incorrectly fitting bra straps ($\chi^2 (3, n = 303) = 23.16, p < 0.05$; Figure 24). Although no significant difference was found in the fit of the back band or bra cups between the four breast size categories, the prevalence of incorrect fit of these components was high across all categories (Figure 24).
Incorrectly fitting bra components

Figure 24: The percentage of overall incorrect encapsulation style bra fit (n = 309) for the four breast size categories and for the five bra components (cups, n = 309; front band, n = 309; underwire, n = 287; back band, n = 309; and straps, n = 303). * indicates a significant difference between breast size categories (p < 0.05).
7.4 Discussion

The components of encapsulation-style bras that are associated with incorrect bra fit have been identified. The prevalence of incorrect fit was shown to vary across both component type and across breast size category. The implications of these findings in terms of bra fit and bra design are discussed below.

The high percentage of participants who were found to be wearing an ill-fitting encapsulation style bra (90% of cohort) was consistent with the findings of previous researchers (Greenbaum et al. 2003; McGhee and Steele 2010a; McGhee et al. 2010; White and Scurr 2012). Interestingly, it was discovered that most participants failed on more than one component of the bra fit assessment (Table 19), suggesting that women have difficulty fitting several components of their bra or, the fit of these components are inter-related, although this notion warrants further investigation. This finding has implications for the level of breast support that these women are receiving on a daily basis given the role that each individual component of an encapsulation style bra plays in supporting the weight of breasts (Figure 23). If one or more components of the bra are not correctly fitted the wearer will receive a reduced level of breast support, which can be uncomfortable and can lead to the development of musculoskeletal pain (Findikcioglu et al. 2007; Greenbaum et al. 2003; Letterman and Schurter 1980; McGhee et al. 2008; McGhee and Steele 2011; McGhee et al. 2013; Ryan 2009).

Although no significant difference was found between breast size categories in terms of whether their bra fitted correctly or not overall, the specific bra components that did not fit differed significantly between the four breast size categories. Compared to the women with small breasts, a significantly higher percentage of women with medium, large and hypertrophic breasts had incorrectly fitting front bands and underwire (Figure 24). Conversely, a significantly higher percentage of women with
Incorrectly fitting bra components

small breasts had incorrectly fitting bra straps compared to women with medium, large and hypertrophic breasts (Figure 24). Although the fit of the bra cups was not significantly different between categories, there was a trend for a higher percentage of incorrect fit of the bra cup with increased breast size (increasing from 49% among women with small breasts through to 66% among women with hypertrophic breasts; Figure 24). The high percentage of incorrect fit related to the bra cups that was observed across the four breast size categories, however, highlights that there is a problem with the fit of bra cups across all breast sizes, not just medium, large and hypertrophic sizes (Figure 24). According to professional bra fitting criteria, a fail in the fit of the bra cup resulted when the bra cup was either “too big” or “too small” (Table 18). The researchers observed that women with large and hypertrophic breast sizes tended to wear bra cups that were too small, whereas women with small breasts tended to wear bra cups that were too big. Although not part of the bra cup fitting criteria, we speculate that differences in breast shape across the breast size (volume) spectrum may have influenced the fit of breasts into the bra cup, resulting in the poor prevalence of incorrect bra cup fit among all four breast size categories. The health consequences of insufficient breast support due to poor cup fit, however, are acknowledged to be much greater for women with large breasts than for women with small breasts (Findikcioglu et al. 2007; Greenbaum et al. 2003; Letterman and Schurter 1980; McGhee et al. 2008; McGhee and Steele 2011; McGhee et al. 2013; Ryan 2009).

The high prevalence of incorrect fit among the underwire (31 – 61%) and front band (28 – 71%) components, which are related to the bra cup (Figure 23), was found to be significantly worse among women with medium, large and hypertrophic breast sizes compared to women with small breasts (Figure 24). This finding is likely to be related to the shape of the breast with previous researchers suggesting that as breast volume
Incorrectly fitting bra components

increases the shape of breasts change, which will influence how the breast fits into a bra cup (McGhee and Steele 2011; refer to Chapter 5; Section 5.4). It is therefore suggested that the anthropometric dimensions used to design and size current front bands, underwire and, by association, bra cups are not matching the true volume and shape of the breasts of women with medium, large and hypertrophic breasts. To improve bra fit for these women, bra designers and manufacturers need to base the design of these components of a bra on realistic breast volume and shape data of women who are likely to purchase their bras. Improving the design and fit of the bra front band and underwire, as well as the bra cups could, in turn, also improve the long-term health of these women. This is particularly important for those women with large and hypertrophic breasts because these women commonly experience higher levels of musculoskeletal pain and discomfort than women with small breasts (BeLieu 1994; Greenbaum et al. 2003; Kaye 1972; Ryan 2000; Spencer and Briffa 2013; refer to Chapter 6; Section 6.3).

The prevalence of incorrectly fitting bra straps was found to be significantly greater in women with small breasts (77%) compared to women with medium (63%), large (41%), and hypertrophic breasts (38%). To fit correctly bra straps must match the dimensions of a woman’s torso and the position of her breasts relative to her torso (Bowles and Steele 2013; Coltman et al. 2015). The length of the straps on most encapsulation bras can be adjusted, although some bra straps are a set length and cannot be adjusted. Although bra strap designs incorporating a wide, non-elastic padded region aim to reduce pressure (force per unit area) at the strap-shoulder interface, this strap design can limit the length over which a strap can be adjusted (Bowles and Steele 2013; Coltman et al. 2015). Furthermore, convertible straps, which allow different bra strap orientations, sometimes have insufficient length range when set in the cross-over orientation compared to a vertical orientation. This lack of length causes the straps to be
too tight, increasing the downward force and, subsequently, the pressure experienced at the bra strap-shoulder interface at the crest of the shoulder. Bra strap pressures in previous studies have been found to range from 6.2-13.8 kPa in vertical bra strap orientation and 5.7-14.9 kPa in crossover bra strap orientation (Bowles and Steele 2013; Coltman et al. 2015).

The range of encapsulation style bras that the participants wore to the test session included bras with adjustable and set-length straps, convertible straps and straps with shoulder pads. If bra straps are too long and cannot be shortened sufficiently, they will be too loose, which will affect the support offered by the bra as straps provide secondary breast support (Bowles and Steele 2013). When bra straps are too short and cannot be adjusted to fit correctly, the straps will be too tight, increasing the strap-shoulder interface pressure making them uncomfortable to wear (Bowles and Steele 2013). In fact, previous research has found that straps are the most disliked feature of sports bras due to the tendency for them to slip off or cut into the shoulders as a consequence of them being too loose or too tight, respectively (Bowles et al. 2012).

Considering that varying torso dimensions and bra strap orientation (vertical versus cross over) will affect the strap length requirements (Coltman et al. 2015), bra designers and manufacturers could improve bra fit and breast support for women by basing strap dimensions on torso and breast height dimensions.

There was no significant difference between the four breast size categories in terms of the fit of the back band. Despite this, the fit of this component was poor across all breast size categories (43 – 58% incorrect fit). Given that a bra is a close fitting garment, measurements of not only the breasts, but also the torso must be highly accurate. Despite the anatomical variation in torso shape that is observed among women, the circumference of the back band must match the breadth of the woman’s
Incorrectly fitting bra components

torso. This is particularly important because the back band is the primary structure assisting the bra cups in supporting the weight of the breasts (Figure 23). A back band that is too loose will reduce the level of breast support afforded by the bra, whereas a back band that is too tight will cause discomfort. Therefore, this measurement needs to be accurate across all breast sizes in order to ensure correct bra fit and, subsequently, sufficient breast support.

As with all research, the results of the current study must be interpreted in light of the study limitations. The professional bra fit criteria used were for encapsulation-style bras. Consequently, the breast support of 11% of the cohort was not assessed because these women wore compression style crop tops, singlet tops or no bra to the test session. The development of professional bra fit criteria for this unstructured bra style is recommended for future research. Furthermore, two components of encapsulation style bras, the back band, and the straps, have the ability to be adjusted. However, for purposes of the current study the bra fit assessment procedure did not assess whether adjusting these components would enable correct bra fit. Therefore, the incorrect fit prevalence of these two components of the encapsulation style bra was potentially overestimated, and we are unsure as to whether the incorrect fit was too big or too small. Finally, given that the bra fit assessment was performed at one point in time, more frequent assessment over a greater duration of time is likely to increase the accuracy of the prevalence of incorrect bra fit of each component and, subsequently, the conclusions drawn. We recommend future researchers assess bra fit in a large cohort of women who are followed longitudinally to confirm whether the bra fit habits of women vary over time.
7.5 Conclusion

Given that bras are typically worn during activities of daily living for long durations (12 – 14 hours per day) over a lifetime (up to 60 or 70 years) it is important to ensure they fit properly. The front band and underwire components of the participants’ own bras failed to fit significantly more women with medium, large, and hypertrophic breasts, whereas the bra strap design component failed to fit significantly more women with small breasts. The fit of the bra cup and back band were poor, irrespective of breast size. It is recommended that bra designers and manufacturers incorporate three-dimensional breast volume/shape and torso dimension data obtained for women across the breast size spectrum into their bra designs to improve the bra fit, breast support and, in turn, the long-term health of women. It is also recommended that women use professional bra fit services or educational resources/tools designed to assist women to fit their bras correctly.
Summary and recommendations for improved bra designs

8.1 Summary

Improvements to current bra designs are urgently needed to enhance bra fit and breast support for women. In order to develop superior bra designs, research quantifying the breast characteristics of women of different ages, body sizes and breast sizes is needed. This thesis aimed to systematically investigate the characteristics of the breasts of Australian women across the breast size spectrum in order to develop evidence-based bra design recommendations. The thesis aim was achieved through two studies, which were presented in four thesis parts. Part I aimed to establish a valid and reliable method of quantifying breast volume, using three-dimensional scanning, in women with large ptotic breasts. Part II aimed to gain a greater understanding of the women we should be catering for in terms of improved bra designs through comprehensively characterising the breasts of Australia women. Part III aimed to further our understanding of why it is necessary to improve bra designs for women across the breast size spectrum by determining whether factors related to the breasts and upper torso could predict musculoskeletal pain in the upper torso. Finally, Part IV aimed to determine whether women are currently being catered for by identifying the components of encapsulation style bras that are associated with incorrect bra fit across the range of breast sizes.

In Chapter 2 the breast volumes calculated from scanning the large ptotic breasts of women while they were standing upright relative to when lying prone were compared. This was necessary as three-dimensional scanning for a breast volume measurement is commonly performed in a standing position, although errors have been associated with measuring the breast volumes of women with large ptotic breasts in this
standing position. It was hypothesised that scanning large ptotic breasts in the prone scanning position would allow complete visualisation of the breasts and, in turn, a greater breast volume compared to a scan of the same breasts in a standing position. It was found that full visualisation of both breasts occurred in 100% of participants when they were scanned in the prone position, compared to only 5% of participants when they were scanned in a standing position. As a result of the entire breast being visualised by the scanner, breast volume was calculated to be significantly greater when women were scanned in the prone position compared to when standing. The percentage that breast volume was underestimated from the standing scanning position was found to increase as breast volume increased. This study demonstrated that the most accurate and reliable measure of breast volume using three-dimensional scanning is achieved when the breasts are scanned while participants are in a prone position. As such, this scanning position is recommended for future breast volume measurement and was subsequently used to assess breast volume in the rest of the thesis. As scanning in a prone position may not always be practical, it is recommended that when scanning the breasts of women in a standing position, errors associated with a breast volume measurement obtained in this position (3% for small breast volumes; 7 – 11% for large breast volumes) be taken into consideration.

The effect of age on breast skin thickness and elasticity at four quadrants of the breast (superior, lateral, inferior and medial) was systematically determined in Chapter 3. This was important because the skin overlying the breast plays an important role in supporting the weight of the breasts. However, given that ageing is associated with declines in skin structure and function, determining the effects of ageing on breast skin and across various regions of the breast has implications for external breast support. That is, if the anatomical breast supports decline with age and to varied extents across
different regions of the breast, then greater external breast support will be required from the bra in these regions. In support of the hypotheses, breast skin thickness and elasticity were found to be significantly reduced in older compared to younger women. Age-related declines in breast skin thickness and skin elasticity were observed to begin between 45 – 64 years of age and between 25 – 44 years of age, respectively. Regional variation was also observed, with the elasticity decline most evident in the superior and medial aspects of the breasts. These changes in skin elasticity are thought to contribute to the shift in breast mass downwards and outwards, which is evident with increasing age (Elsahy 1990; Machida and Nakadate 2015; McGhee and Steele 2006). Although this chapter provides evidence of the decline in support provided to the breasts by the skin with increasing age, the fascia within the breast, including the Cooper’s ligaments, are also thought to play a role in anatomically supporting the breasts. Therefore, future research should quantify the intrinsic mechanical properties of these other anatomical support structures in order to better understand the ability of these structures to provide support to the breasts.

Normative breast volume data for women of varying ages, body masses and breast sizes was established in Chapter 4 in order to provide evidence upon which bra cups can be designed to support the range of breast sizes exhibited by Australian women. Additionally, this chapter aimed to determine the effect of age and BMI on breast volume and the interaction of these variables. This was important to determine given the changing demographics of the Australian female population. Breast volume for an individual breast was found to range from 48 – 3100 mL. Although breast volume was not influenced by age, it was significantly affected by BMI, with the breast volume of overweight and obese women being 2 – 3 times greater than women with normal BMI’s. As these data are specific to Australian women, it is recommended that
Summary and recommendations

Future research expand on the breast volume data collected in this thesis to include global populations to understand differences in breast size internationally. This will better enable bra companies to apply these data to develop bras that meet the support needs of the global population of women.

The purpose of Chapter 5 was to systematically classify the breasts of women into different breast shape categories based on comprehensive and objective measurement of their breasts and torsos, and to determine the effect of age and BMI on the prevalence of these breast shapes. Despite the recognised importance of breast shape to bra design, limited research has quantified variation in breast shape among women. Within the study cohort, four breast shapes were identified; X-large, Very-ptotic & Splayed; Large, Ptotic & Splayed; Medium & Mildly-ptotic; and Small & Non-ptotic. The results indicate that breast shape is significantly influenced by age and BMI. Older women with higher BMI’s were more likely to have X-large, Very-ptotic & Splayed or Large, Ptotic & Splayed breast shapes, whereas younger women with a lower BMI were more likely to have Medium & Mildly-ptotic and Small & Non-ptotic clusters breast shapes. Although it is acknowledged that breast shape variation may extend beyond the four breast shapes identified in this study, the findings highlight the need for bra designers and manufacturers to base future bra designs upon these fundamental differences in breast shape. Future research should expand on this dataset with global populations to develop further shape classifications that match the breast shapes of women around the world.

The purpose of Chapter 6 was to identify whether factors associated with the breasts and upper torso of women could predict musculoskeletal pain among women across the breast size spectrum. Although several physical risk factors have been identified as contributing to musculoskeletal pain, the notion of breast characteristics as
a risk factor for musculoskeletal pain in the upper torso has not previously been explored. This is despite research that has associated large breast sizes with structural and functional changes to the upper torso, including an increased prevalence and severity of musculoskeletal pain. Based on the predictive model developed in this chapter, larger breast volumes, younger age and broader breasts were the best predictors of upper torso musculoskeletal pain. Therefore, improved breast support is recommended as an important strategy in preventing and minimising the negative side effects of large and broad breasts, including increased upper torso musculoskeletal pain. However, as this model explained only 23% of the variance in the upper torso musculoskeletal pain score, it is acknowledged that musculoskeletal pain is complex and multifactorial. Future research should therefore explore the impact of psychosocial (personal and work related) factors, as well as physical factors implicated with musculoskeletal pain in the upper torso across the breast size spectrum.

In order to examine problems with components of current encapsulation style sports bras, the aim of Chapter 7 was to determine whether the prevalence of incorrect bra fit in an encapsulation style bra differed among women of different bra sizes, and whether the frequency of incorrect fit of individual bra components differed with respect to breast size. No significant differences were found between the four breast volume groups in the percentage of women wearing an incorrect fitting bra. However, when rating the fit of individual bra components, significant between-group differences were observed. The front band and underwire components of the participants’ own bras failed to fit significantly more women who had medium, large, and hypertrophic breasts, whereas the bra strap design component failed to fit significantly more women who had small breasts. The fit of the bra cup and back band were poor, irrespective of breast size. These study findings provide support to the notion that bra designers and
manufacturers should incorporate three-dimensional breast volume/shape and torso dimension data, such as those presented in this thesis, into bra designs for women across the breast size spectrum in order to improve the fit of bra components.

8.2 Evidence-based recommendations for improved bra designs

Based on the results of this thesis, the following evidence-based recommendations are made to improve bra designs for Australian women:

1. In order to counteract the age-related decline in anatomical breast support from the breast skin, increased external breast support from a bra is recommended for women aged in their mid 20’s onwards. In particular, increased breast support is required inferiorly and laterally to alleviate the strain medially and superiorly on the breast skin as women age. This can be achieved by designing bra cups that provide greater structural support inferiorly and laterally, for example, through the use of panels (McGhee and Steele 2010b; Worldwide Patent no.102348, 2010).

2. Three-dimensional breast volume data, such as those presented in Chapter 4, should be incorporated into the design of bra cups to ensure bra cups match the magnitude of the volume of breasts they are required to support. Within the general population of Australian women, unilateral breast volumes of between 48 – 3100 mL need to be accommodated. It is recommended that bra cups are designed specific to breast size (volume) with components of the bra adjusted accordingly to provide sufficient breast support. For example, for women with small breast volumes (volumes < 350 mL) compression style garments are a suitable breast support choice because these women usually require the least breast support (Hindle 1991; Stamford 1996). Women with medium (breast volumes between 350 – 700 mL), large (breast volumes between 701 – 1200
mL) and hypertrophic (breast volumes > 1200 mL) breast volumes will require a progressively increased level of breast support compared to their counterparts with small breast volumes (Hindle 1991; McGhee et al 2008; Stamford 1996). This increased level of breast support can be achieved with an encapsulation style bra (Mason et al 1999), which has been recommended in the literature as the style of breast support that is best at reducing breast motion and the associated breast discomfort (Breast Research Australia 2017; Lorenzten and Lawson 1987; McGhee et al 2010a; Stamford 1996). Encapsulation style bras for these women should incorporate a wide and firm back band and wide bra straps in order to support and distribute the load generated by the weight of large breasts (Bowles and Steele 2013; Breast Research Australia 2017; Coltman et al 2015; Loeher 2013). It is also recommended that these bras contain a strong underwire component to further aid in supporting the breast mass and transferring the weight of the breasts to the bra brand, where it is better distributed (Loeher 2013). For physical activity women with large and hypertrophic breast sizes would benefit from wearing an encapsulation style bra, which incorporates the features described above, but with a compression garment over the top (Breast Research Australia 2017). This will aid in simultaneously encapsulating and compressing the breasts, which has been found to reduce breast and bra discomfort, as well as breast movement during activity in women with large breasts (McGhee and Steele 2010b).

3. It is recommended that the four breast shape types (X-large, Very-ptotic & Splayed; Large, Ptotic & Splayed; Medium & Mildly-ptotic; and Small & Non-ptotic) identified in Chapter 5 be incorporated into bra designs and sizing for Australian women. That is, bras should be designed to cater for the varying
types of breast shape. Although it is acknowledged that the breast is deformable, and bras function to lift the breast and present a more youthful and pert breast shape (Risius et al 2012), incorporating bra components specific to each shape type could enable an improved cup fit. For example, women with Small & Non- ptotic breast shapes will benefit from a more symmetrical bra cup and underwire design, whereas women with Medium & Mildly- ptotic breast shapes will require a bra cup design that comprises a fuller lower cup combined with a smaller upper cup that contours to the breast. This will avoid gapping at the top of the bra cup. Women with Large, Ptotic & Splayed and X-Large, Very- ptotic & Splayed breast shapes will benefit from a bra cup designed with increased width and depth that incorporates a broader underwire to match the shape of the breast (Lee and Hong 2007). This will enable the breast to comfortably fit into the bra cup and may prevent issues such as the underwire cutting up into the breast tissue laterally, causing pain and discomfort.

4. Considering the changing demographics of the Australian and global female population, the effect of age and BMI on three-dimensional breast volume and breast shape should also be considered by bra designers and manufacturers when designing breast support garments. This should involve designing bras specific to certain age groups or body sizes. For example, older women and women with larger BMI’s are more likely to have Very- ptotic & Splayed or Large, Ptotic & Splayed breast shapes. Furthermore, women with larger BMI’s are also more likely to have large breast volumes, requiring bras with enhanced support structures. Bra designers should also take into consideration differences in style, fit and colour preferences with increasing age (Liang 2008; Risius et al 2014; Sukumar 2007) and BMI.
5. In order to minimise the effects of large and broad breasts on musculoskeletal pain, it is recommended that improved breast support form part of the prevention and treatment strategy for women who report upper torso musculoskeletal pain across the breast size spectrum. In order to improve breast support, it is recommended that bra designers and manufacturers incorporate the three-dimensional breast volume and shape dimension data presented in this thesis, and more specifically, Recommendations 1 – 4, into bra designs for women across the breast size spectrum.

6. Based on the results of Chapter 7 it is evident that improvements to the fit of the underwire and front band in encapsulation style bras are needed for women with large breasts. Furthermore, improvements to the bra straps of encapsulation style bras are needed for women with small breasts. Three-dimensional breast volume, shape and torso dimension data (see Chapter 4 and 5) can be applied to the design of these components to improve the fit of these bra components.

7. Although not examined in this thesis, the materials used to construct breast support garments are a fundamental aspect of bra design. In particular, it is recommended that sports bras be made from strong yet flexible materials that work to minimise breast motion (McGhee and Steele 2010b). These materials must also be breathable and moisture-wicking to enhance comfort during physical activity (Ayres et al 2013).

These evidence-based recommendations are made in order to guide bra designers and manufacturers in improving bra designs. Incorporating such evidence-based recommendations in bra design could substantially improve the fit of breast support garments and, therefore, the ability of these garments to properly support the breasts of
Summary and recommendations

women. Improving bra design and bra fit will, in turn, enable women to participate in physical activity in comfort.
References


References


References


and their association with pain in two age groups of healthy subjects. *Physical Therapy, 72* (6), 425-431.


References


Liang, X., 2008. *An investigation into the pressures and sensations caused by wearing a bra and the influence of these on bra fitting*. Doctoral Dissertation, De Montfort University, UK.


Appendix A

International bra sizing

<table>
<thead>
<tr>
<th>International bra band sizes</th>
<th>Australia</th>
<th>USA</th>
<th>UK</th>
<th>France</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>28</td>
<td>28</td>
<td>75</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>30</td>
<td>80</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>32</td>
<td>32</td>
<td>85</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>34</td>
<td>34</td>
<td>90</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>36</td>
<td>36</td>
<td>95</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>38</td>
<td>38</td>
<td>100</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>40</td>
<td>40</td>
<td>105</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>42</td>
<td>42</td>
<td>110</td>
<td>95</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>International bra cup sizes</th>
<th>Australia</th>
<th>USA</th>
<th>UK</th>
<th>France</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>DD</td>
<td>DD or E</td>
<td>DD</td>
<td>E</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>DDD or F</td>
<td>E</td>
<td>F</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>G</td>
<td>F</td>
<td>G</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td>H</td>
<td>FF</td>
<td>H</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>I</td>
<td>G</td>
<td>J</td>
<td>J</td>
<td></td>
</tr>
<tr>
<td>GG</td>
<td>J</td>
<td>GG</td>
<td>K</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>K</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>HH</td>
<td>L</td>
<td>HH</td>
<td>M</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>M</td>
<td>J</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Musculoskeletal pain body chart

The next questions are about any musculoskeletal pain you may experience during day to day living. On the following diagram of the Front View and Back View of the body, please circle the severity and frequency of your pain for each of the seven body regions. To determine the rating value, please refer to the information below in the diagram.

Front View

Back View

Rate the severity of your pain between 0 and 10 where:

<table>
<thead>
<tr>
<th>No Pain</th>
<th>Moderate Pain</th>
<th>Worst Pain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

Rate the frequency of this pain by circling F, O or R, where:

R = rarely (1 time per month or less),
O = occasionally (2-3 times per month) and
F = frequently (1-3 times per week or more).
## Appendix C

### Active Australia survey

The next questions are about any physical activities that you may have done in the last week:

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. In the last week, how many times have you walked continuously, for at least 10 minutes, for recreation, exercise or to get to or from places?</td>
<td></td>
</tr>
<tr>
<td>2. What do you estimate was the total time that you spent walking in this way in the last week? <strong>In hours and/or minutes</strong></td>
<td></td>
</tr>
<tr>
<td>3. In the last week, how many times did you do any vigorous gardening or heavy work around the yard, which made you breathe harder or puff and pant?</td>
<td></td>
</tr>
<tr>
<td>4. What do you estimate was the total time that you spent doing vigorous gardening or heavy work around the yard in the last week? <strong>In hours and/or minutes</strong></td>
<td></td>
</tr>
</tbody>
</table>

The next questions exclude household chores, gardening or yardwork:

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. In the last week, how many times did you do any vigorous physical activity which made you breathe harder or puff and pant? (e.g. jogging, cycling, aerobics, competitive tennis)</td>
<td></td>
</tr>
<tr>
<td>6. What do you estimate was the total time that you spent doing this vigorous physical activity in the last week? <strong>In hours and/or minutes</strong></td>
<td></td>
</tr>
<tr>
<td>7. In the last week, how many times did you do any other more moderate physical activities that you have not already mentioned? (e.g. gentle swimming, social tennis, golf)</td>
<td></td>
</tr>
<tr>
<td>8. What do you estimate was the total time that you spent doing these activities in the last week? <strong>In hours and/or minutes</strong></td>
<td></td>
</tr>
</tbody>
</table>
The next questions are about the time you spend sitting during EACH DAY while at home, at work and while getting from place to place or during your spare time:

<table>
<thead>
<tr>
<th>9. How many hours EACH DAY do you typically spend sitting down while doing things like visiting friends, driving, reading, watching television or working at a desk or computer?</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) On a usual WEEK DAY [ ] hours</td>
</tr>
<tr>
<td>b) On a usual WEEKEND DAY [ ] hours</td>
</tr>
</tbody>
</table>

The next question asks about your physical activity in your main job (this could be paid work, unpaid work, caring etc – whatever you spend most of your “working day” doing):

10. On a usual working day, how often do you do each of the following while you are at work? (Mark one on each line)

<table>
<thead>
<tr>
<th></th>
<th>All of the time</th>
<th>Most of the time</th>
<th>Some of the time</th>
<th>A little of the time</th>
<th>None of the time</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Sitting</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>b) Standing</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>c) Walking</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>d) Heavy labour or physically demanding work</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
</tbody>
</table>
To what extent do you agree or disagree with the following statements about physical activity and health?

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>11. Taking the stairs at work or generally being more active for at least 30 minutes each day is enough to improve your health.</td>
<td>strongly disagree</td>
<td>disagree</td>
<td>neither agree nor disagree</td>
<td>agree</td>
</tr>
<tr>
<td>12. Half an hour of brisk walking on most days is enough to improve your health.</td>
<td>strongly disagree</td>
<td>disagree</td>
<td>neither agree nor disagree</td>
<td>agree</td>
</tr>
<tr>
<td>13. To improve your health it is essential for you to do vigorous exercise for at least 20 minutes each time, three times a week.</td>
<td>strongly disagree</td>
<td>disagree</td>
<td>neither agree nor disagree</td>
<td>agree</td>
</tr>
<tr>
<td>14. Exercise doesn’t have to be done all at one time—blocks of 10 minutes are okay.</td>
<td>strongly disagree</td>
<td>disagree</td>
<td>neither agree nor disagree</td>
<td>agree</td>
</tr>
<tr>
<td>15. Moderate exercise that increases your heart rate slightly can improve your health.</td>
<td>strongly disagree</td>
<td>disagree</td>
<td>neither agree nor disagree</td>
<td>agree</td>
</tr>
</tbody>
</table>