ERGONOMIC DESIGN OF SUPPORTIVE MOULDED BRAS

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CERTIFICATE OF ORIGINALITY

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____ (Signed)

________ Lee Cheuk Wing ______ (Name of student)

ABSTRACT

Breasts are mainly composed of soft tissues, which allow them to move freely over the pectoral fascia. Bras are a key external form of support for breasts. Without the adequate support of bras, excessive body movement results in large forces onto the breast skin, thus leading to the over-stretching of the breast tissues and related breast pain, and even an increase in sagging in the breast area. Permanent deformation of the breast structure could even be a possibility because of repeated high loads on the breasts. As compared against traditional cut-and-sewn bras, the smoothly moulded bras provide better shape, comfort, handfeel and support. However, there has been limited knowledge about the support features of moulded bras with differences in the material of shoulder straps, bra band and underwires, as well as the combined effect of bra components towards the bra support and bra-skin pressure. In this study, the overall aim is to evaluate the support features of moulded bras and the corresponding pressure comfort to improve the ergonomic design of moulded bras.

To fill the knowledge gaps in the traditional bra design process, the bra-skin pressure and the support function of moulded bras in term of vertical breast displacement were investigated. The effects of bra cup material, bra strap, underband and underwires on bra-skin pressure and breast displacement were systematically assessed by using the NOVEL Pliance-X® pressure system and the VICON motion capture system respectively. Bra conditions were examined with the change in length or material of shoulder strap and bra band, cup materials and underwire insertion. To minimize the discrepancies of human wear trials, a soft manikin with 75D and 75B breasts sizes was adopted to model the vertical dynamic movement of the breasts. A pneumatic system was designed with an auxiliary mechanical device that the manikin can move up and

down in a continuous repeatable motion, which corresponds to the heel strike in a gait cycle.

In pressure evaluation of bras, a changeable wired bra design that allows adjustment of tension or replacement of the bra components such as changing the shoulder straps, removing the underwire in a flexible manner was used. Significant pressure differences were found between various bra conditions, particularly at middle of underbreast underwire curve, shoulder and back of underband. Results indicated that high stress-strain behaviour of the shoulder strap, and bra band and flexible bra cup materials resulted in high bra-manikin pressure due to increase in the compression and tension forces. To enhance bra comfort, the elastic material properties of the shoulder strap and underband together with their corresponding lengths in pattern development should be well balanced for an optimum fit and pressure distribution.

In breast displacement evaluation, most of the donned bra conditions can effectively reduce the vertical breast displacement especially for the upward motion as compared to braless condition. Length of shoulder strap and underband, choice of low stress-strain property of shoulder strap and underband material, flexible cup material and underwire insertion not only affected the bra-skin pressures, but also associated with the control of vertical breast motion. Subject-specific empirical model was formulated to predict the breast motion behaviour. Independent variables of breast size, underband length, cup material modulus, shoulder strap and underband material modulus, underwire and gait speed were regarded as important variables in the prediction of vertical breast displacement. The soft manikin showed a satisfactory result validated by a subject wear trial, thus providing a reliable and objective approach for future bra studies.

To improve the support of breast, a new bra insert with aims of improving fit and control of breast displacement has been designed with reference to the natural curvature of the underbreast. It consists of an extended part from the curve to cover part of the breasts which helps to redistribute the weight of the breasts to the torso and therefore redistribute the impact during movement. Compared to conventional planar underwires, the newly designed bra insert exhibited a better performance in controlling breast motion. The insert design for ergonomic bras would provide a good reference to improve bra support, fit and comfort for women in daily activities.

PUBLICATIONS ARISING FROM THE THESIS

Journal articles

Lee, C. W., Yick, K. L., Ng, S. P. and Yip, J. Analysis of dynamic vertical breast displacement for the design of seamless moulded bras (Under revised for review by The Journal of the Textile Institute)

Lee, C. W., Yick, K. L., Ng, S. P. and Yip, J. Soft manikin as tool to evaluate bra features and pressure, *International Journal of Fashion Design, Technology and Education*, *13*(2), 204-212)

Conference paper

Yick, K. L., **Lee, C. W**., Ng, S. P. and Yip, J. The influence of bra features on wearing comfort and breast support of bras. The 91st Textile Institute World Conference, Leeds, United Kingdom, 23rd-26th Jul 2018 (pp.45)

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CHAPTER 1 INTRODUCTION

1.1 Background

Breasts subjected to excessive motion during physical activities can lead to the over-stretching of breast tissue. Therefore, bras were developed to protect the structure of the breasts, and provide external support to hold them (Wang & Chen, 2008). Over the past decades, a wide range of bra styles and features have been designed to fit the specific needs and expectations of customers, which provide different levels of support, softness and comfort. In particular, seamless bra cups have transformed the design concepts of bras in that they are moulded by using an entire sheet of material and therefore a one step process. In comparison to traditional cut-and-sewn bra cups, moulded foam cups provide better support and maintain a consistent shape after repeated washing and wearing. Since moulded bras entail no seams and use non-splicing applications, they are invisible when wearing tight-fitting or thin clothing. Moulded bras also provide a shaping effect which flatter and round the breast contours with different levels of support and softness. Today, the high demand for seamless moulded bras means that they dominate almost 80% to 90% of the bra market.

In bra moulding process, steel wires and pre-formed components are assembled and embedded into the foam cups. The level of support of a bra depends on the overall structure and material design. Different types of engineering processes and specialized technology are included in the highly complex design and production stages of moulded bras (Yu, Yeung & Harlock, 1995). The ergonomic design of moulded bras with suitable breast support and comfortable bra pressure depend on the structural features and materials of the shoulder straps, underband, cup design, coverage, and even embedded components. For example, a correct shoulder strap tension can effectively hold a bra in place, whilst fabric with a structure that has good extension and shape retention properties can minimize bra displacement during daily movement (Wu & Li, 2018; Sun, Chen, Yick, Yu, Lau & Jiao, 2019; Zhou & Yu, 2013). Nevertheless, there are few studies in the literature on objective and precise techniques that assess the bra features. In-depth evaluations and scientific studies on bra components and performance would help to advance ergonomic designs for bras to improve fit and comfort.

When designing a moulded bra, the biomechanical parameters of breast motion and perceived comfort should be taken into consideration. The structure of breasts means that they have little anatomic support. Discomfort, sagging, pain and structural damage are all associated with inadequate bra support for a long period of time (Starr, Branson, Shehab, Farr, Ownbey & Swinney, 2005). Study has been found that sport bras compress the breast to the body torso and helps to minimize breast movement (Chen, Gho, Wang & Steele, 2016; White, Scurr & Smith, 2009). However, too high compression force from bra may lead to increase bra-skin pressure and causing discomfort or pain especially for the large breasted-women (Burbage & Cameron, 2017). It is therefore important to optimize bra design in order to balance wear comfort and support function.

Breast elevation and compression is one of the factors that underlie support and bra comfort. The collected data on amount of breast displacement and bra pressure offer essential biomechanical information in bra design especially for large breasted women in daily life (McGhee & Steele, 2010; Sahari et al., 2016). Current studies have mainly investigated the effects of breast motion and bra-skin pressure with human subjects. However, biological variations are found, such as breast shape and volume for the same bra size (Figure 1.1). The subjects may also feel embarrassment during the braless condition when testing. The breathing rate and standing position may also have variation for each testing trials. Thus, all of these issues increase the difficulties in maintaining the testing conditions and reduce repeatability.

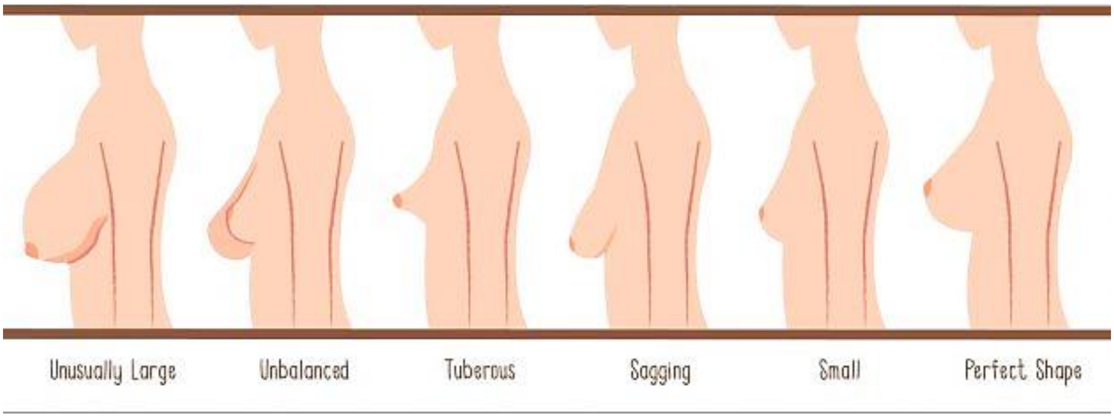


Figure 1.1 Examples of breast shape variations

Motion capture analysis systems and pressure sensing system have been frequently used to examine breast motion and bra comfort. For instance, effects of shoulder strap orientation on restricting breast motion by using markers attached to the nipples and trunk of their subjects (Scurr, White and Hedger, 2009; Kang, Choi & Oh, 2015). Moreover, previous studies examined the effects of the shoulder strap in terms of material physical properties and orientation for bra-skin pressure (Coltman, McGhee and Steele, 2015; Bowles & Steele, 2013) (Figure 1.2). Studies are mainly focused on studying single bra component. They did not examine the effects of the bra band and underwire. Therefore, researches on the impacts of materials or shape differences of bra bands and underwire on the functions of moulded bra is limited.

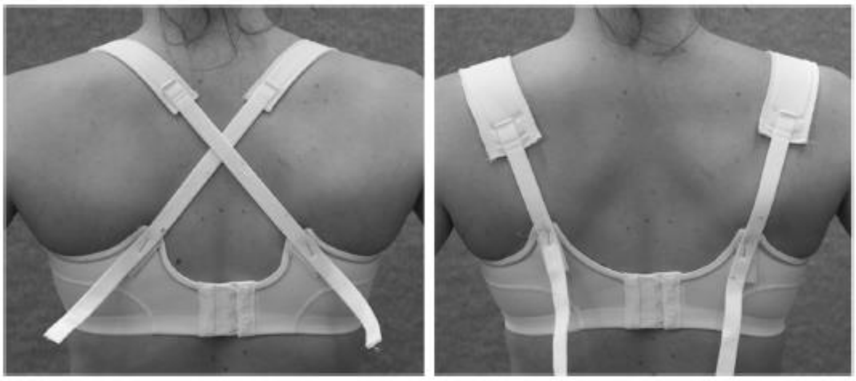
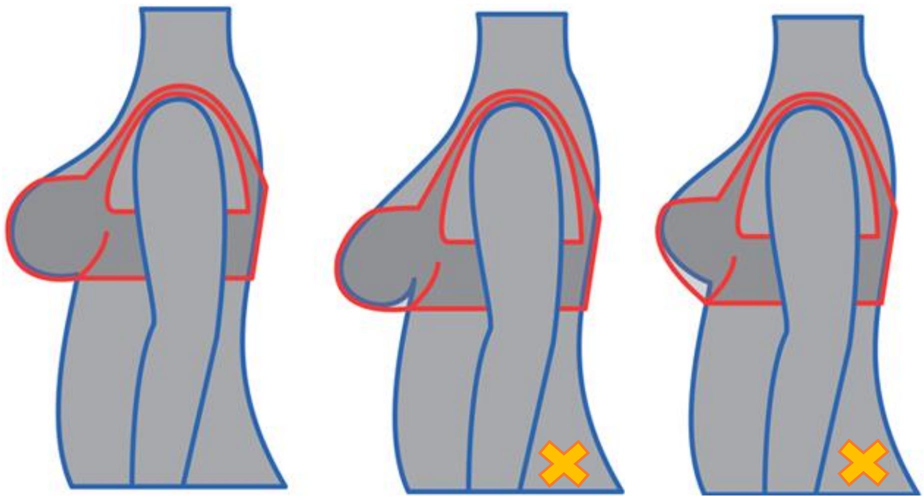


Figure 1.2 Effects of shoulder strap orientation on pressure and comfort

(Coltman et al, 2015)

On the other hand, wire related problems in fit and comfort are often reported, which adversely affect bra support performance and perceived comfort of bras. Despite these reports, a scientific and reliable method that assesses wire materials and their corresponding bra support performance has not been reported in the literature. The traditional planar underwire (typically pre-curved into a semi-circular shape) made of steel and/or plastic for shaping and supporting the lower periphery of bra cups would not be ideal for three-dimensional (3D) body contouring (Figure 1.3). However, it is anticipated that a proper design of a breast support insert with a slim 3D profile, together with appropriate fabrication materials that act like a spring-damper would reduce the load generated by breast motion and provide adequate breast support during daily activities (Deng, Davies & Bajaj, 2003). It is crucial to study the underwire properties and corresponding geometries on the breast to develop a bra support that improve the bra support and fitting problem.



(a) (b) (c)

Figure 1.3 Bra underwire fit

(a) correct fit and follows the breast contours, (b) and (c) incorrect fit

In this study, an ergonomic design for bras is achieved by combining optimal bra properties and support inserts to improve bra support and perceived comfort. The project aims to develop an ergonomic design for the support insert, and evaluate the effects of the bra components in terms of their elasticity and physical properties. In addition, numerical prediction formula will be used to facilitate the selection of the fabrication materials and advance the design of the support features of moulded bras.

1.2 Aims and Objective

The aim of this study is to evaluate the support features of moulded bras with differences in the structural design and material of the shoulder straps, bra band and embedded components in terms of the ergonomic design characteristics. The bra-skin pressure and breast displacement are also examined.

The specific objectives are:

- To analyze the bra-skin pressure distribution in relation to the structural design and material of the shoulder straps, underband and embedded components, and formulate empirical prediction models to predict the bra-skin pressure in relation to the stress-strain properties of the fabric.
- To establish a novel and efficient approach to assess breast motion and vertical breast displacement, and formulate empirical models to stimulate the dynamic behavior of the breasts at different activity levels, and therefore optimize the design features and fabrication of moulded bras.
- To design and develop a stabilizer that prevents breast motion which is embedded into the bra cups. The mechanical properties of the materials and their corresponding geometries will be characterized.
- To carry out laboratory wear trials that validate the analysis and prediction models for an effective solution to optimize the design of the support features of moulded bras.

The stress-strain properties of the shoulder strap, underband, cup material and insertion of the embedded component were examined for their performance on controlling breast displacement and impact to the bra-skin pressure. Moreover, the bending rigidity of the underwire was also studied to compare their effects on breast geometries and support feature.

1.3 Problem statement

With the increasing popularity of moulded bras, it is now crucial to evaluate the bra design for its support function and comfort. Previous studies have studied the different levels of support of sport bras or variations in the orientation of the shoulder straps. Yet problems in selecting material and methods to optimize the support function and comfort still exist. This study therefore proposes a systematic approach to evaluate breast motion and breast displacement in order to investigate bra function with differentiated components. Besides, a bra insert that prevents breast motion is developed to improve the ergonomic design in the support features of moulded bras. The result will contribute to address the following knowledge gaps.

(1) Limited research work on support features of moulded bras and bra-skin pressure

In bra design research, sports bras are commonly used as the type of bra for evaluation. The support function and comfort during various degrees of exercise are often examined with compression and encapsulation bras for comparison purposes (Chen, Gho, Wang & Steele, 2016). The effect of sports bras on controlling breast motion have also been investigated. Studies also include mastectomy bras comfort assessment (Vithanage & Subodha, 2013). Although some studies cover daily use bras, few have focused on designing the support features of moulded bras.

Daily-use bras have moulded cups with embedded support inserts to provide a certain degree of rigidity to reduce breast motion. Ying, Wang, Liu and Zhang (2011) studied the material properties of moulded cups in relation to the manufacturing process. They also investigated the dimensions and shape of the moulded cups. Bowles, Steele and Munro (2012) examined the orientation of the shoulder straps and found that they have different degrees of support and comfort for the wearer. They concluded that a cross-over shoulder strap alleviates strap slippage. However, the addition of shoulder strap cushions does not effectively reduce pressure exerted onto the wearer. Besides, a significant reduction of static and dynamic mean peak pressure were detected by

Coltman et al (2015) with shoulder straps that are wider. For support from moulded bras, the shoulder strap, bra band and underwire contribute to provide the majority of breast support and motion control. However, studies on the material properties of the fabric for moulded cups and shoulder strap orientation seldom include consideration of the bra band and underwire. Thus, there is the need to evaluate the effects of the bra band and underwire along with the shoulder strap in order to obtain a more in-depth understanding of the support functions of moulded bras.

(2) Difficulties in evaluating breast motion

In previous research, human subjects are invited to take part in wear trials. The breast motion trials require them to demonstrate set movements, such as walking, running or jumping. The braless condition is used for comparison purposes to assess the effectiveness of the support provided by the bra. Since either donning a bra or the braless condition requires subjects to take off their outer garments, they may feel personal embarrassment. In addition, inadequate breast support may result in breast pain or the braless condition may result in injury (Scurr et al., 2011). To avoid these issues, the braless condition is sometimes restricted to only slow walking. Moreover, the sample size is usually small in which two to twenty subjects are recruited because of their reservations about the braless wear trial (White et al., 2009; Okabe & Kurokawa, 2006).

There are also other criteria in selecting subjects. Depending on the research area, healthy subjects or subjects who have had breast surgery might be invited (Turner & Dujon, 2005). Within the subjects, there are also natural structural differences in the breasts during their menstruation cycle and pregnancy (Page & Steele, 1999). Apart from health conditions, volume and shape differences are observed for women who are the same size (McGhee, Ramsay, Coltman, Gho & Steele, 2017). The subjects may vary in terms of body weight, fat proportion or gait. For bra design evaluation, it becomes more difficult to maintain consistent testing conditions which affects the outcomes and repeatability of the testing. Therefore, difficulties in inviting subjects and the natural differences in breast structure could be barriers and prevent assessment of breast motion.

(3) Need for evaluation of bra underwire and development of new embedded support insert

Traditionally, underwire is made with metal or plastic. The planar underwire is bent with the shoulder and bra band length to fit the breast contours. Breast contours are 3D in curvature but conventional underwire is planar and have a certain degree of rigidity. The underwire fitting problem creates greater possibility of discomfort (Kim, Lee & Hong, 2000). However, there is a lack of anthropometry information on the breast base and underwire curvature. Research on the physical properties of underwire affected by the overall length adjustment and its own bending rigidity are limited (Lee & Hong, 2007). Besides, only a few studies have included 3D support inserts as a substitute to improve bra support and comfort (Precision Toolmaker, 2001). Therefore, it is important to take a closer look at the current underwire design features and modify the existing designs by developing a new embedded support insert for better support and comfort performance.

1.4 Project significance and originality

As women are becoming more interested in achieving the ideal body image, bra design is no longer restricted to the function of providing adequate breast support. Cleavage is important for many women, so push up bras have increased in popularity which give the illusion of cleavage. Breasts are lifted up and the soft tissue is pushed forward without discomfort due to bra length adjustment. The bottom rim of the bra cup is sewn with rigid steel wires to achieve an aesthetic effect. Compared to the 3D ergonomic breast contours, it is easier to identify the associated problems with a semi-circular wire design. Poor fit is a major concern and would further extend to discomfort and excessive pressure onto the lymphatic system and cause pathological changes in the breasts.

In the intimate apparel industry, seamless moulded bras are a revolutionary invention. Entire sheets of material can be directly moulded by using an appropriate mould head design. The manufacturing process has been greatly reduced in complexity because of the simplification of the sewing process. Although the design process is complex, the moulded bra design allows the 3D ergonomic structure of the cups and improves the overall bra performance. Moreover, stiff fabric and rigid foams with tight shoulder straps are traditionally used to control breast motion. High compression pressure and discomfort are imposed. Improvements are therefore needed to address this problem. Empirical and theoretical studies in the literature have already provided reliable geometries of the breasts and consistent assessment methods on the bra support function and effects of material variations. Hence, the project originality here is to address the current knowledge gaps in the support features of moulded bra designs as well as contribute to the limited research work on the support features of moulded bras and bra-skin pressure, research difficulties of breast motion and development of a new embedded support insert.

In this study, the ergonomic features are incorporated into the moulded bra design by using a numerical prediction formula to accurately determine the most desirable features and fabrication materials for optimized bra support. A theoretical understanding of breast motion as related to breast size is obtained with materials scientific characterization and validated through systematic experiments. The ergonomic design of the support features of moulded bras and scientific guideline for related products are the outcomes of this project. The formulated numerical prediction formula will promote breast kinetics analysis and material selection to optimize moulded bra design. The significance is not only a reduced process for the traditional moulded bras and development of moulded bras but also increases the competitiveness of bra manufacturers' in the ever-changing bra market environment

1.5 Outline of the thesis

Figure 1.4 presents the structure and framework of the study. Six chapters are included in this thesis. The flow of each chapter in this thesis is presented below:

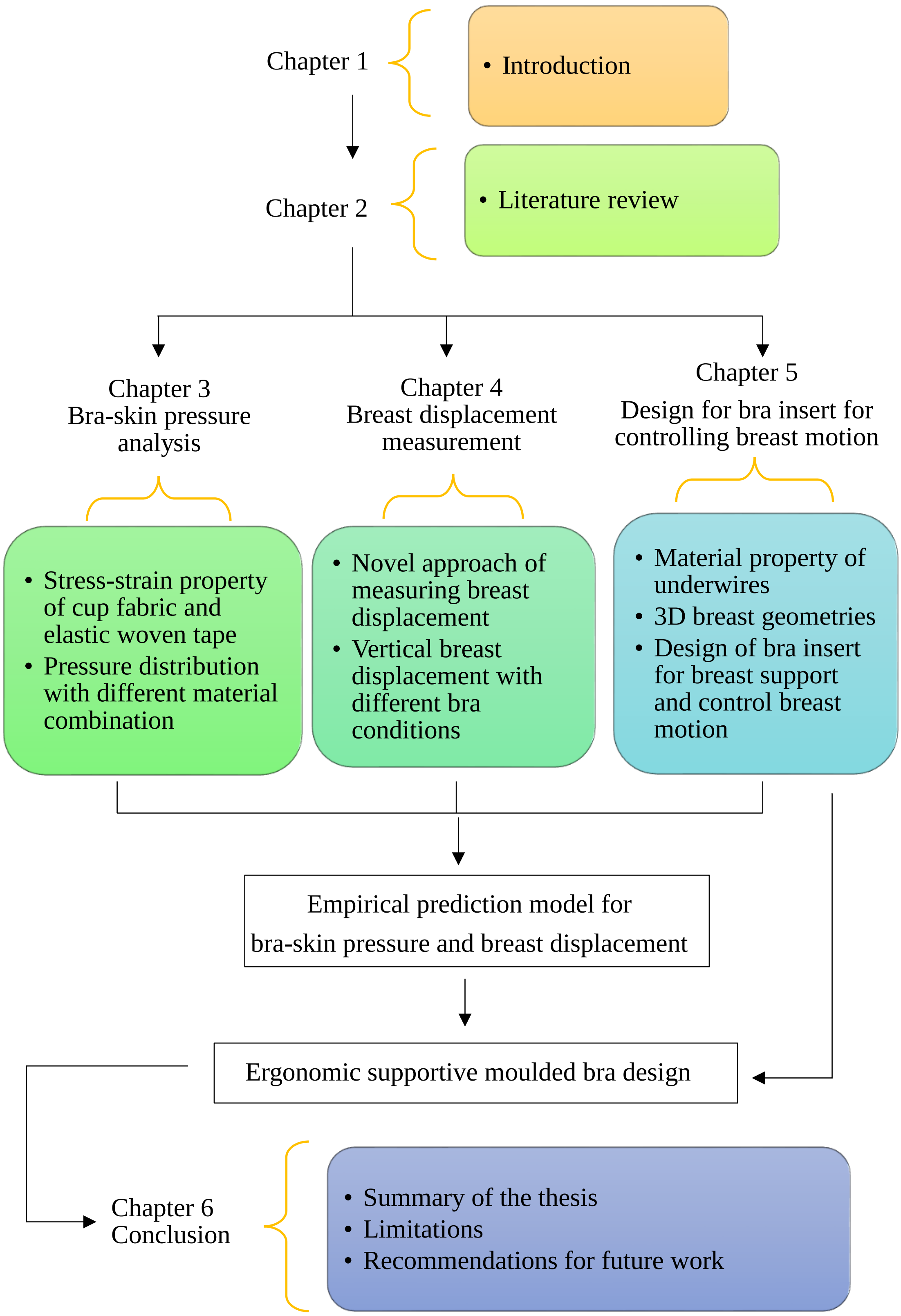


Figure 1.4 Thesis structure and framework

Chapter 1 provides the background information, concept and rationale, as well as project objectives, significance and originality. The features of existing bra designs, selection of bra materials and effect of excessive breast motion are discussed. Besides, the aims and scope of the study are described.

Chapter 2 is the literature review which provides a comprehensive understanding of the previous studies of moulded bra design, such as the structural characteristics and supportive components. It includes the limitations of the current moulded bra design. An introduction on the previous breast motion studies about the kinetics theory, impact of the excessive breast motion and the bra application towards the breast movement is given. Discussion on the method of measuring breast displacement, bra-skin pressure, breast shape geometry and bra fit and previous studies direction are also presented.

Chapter 3 reviews the analysis of bra-skin pressure and the corresponding wearing comfort. Equipment used and procedures for evaluating the bra-skin pressure under different bra conditions are presented. The stress-strain property of cup fabric and elastic woven material of the bra are assessed. This helps to evaluate the effect of the material property changes towards the bra-skin pressure. Bra design components such as cup fabric, shoulder strap, underband and underwire and their impacts on bra-skin pressures are systematically investigated by using the Novel Pliance-X pressure measuring system. Numerical prediction formula is formulated that the influence of changing bra design features and material parameters towards the bra-skin pressure can be predicted. The prediction model has been validated based on human wear trial, providing an effective approach for material selection and modifications in the bra design process.

In Chapter 4, a novel and objective approach of breast displacement evaluation is explored to reduce the human variations and inconsistency during data collection of human wear trials. A soft breast manikin has been designed to simulate the dynamic breast movement. By using VICON motion capture system, a new testing methods for measuring the vertical breast displacement is developed and reported in this chapter. The upward, downward and the overall breast displacement under various bra conditions (with different bra fabrications, properties and length adjustments) are measured and compared. A numerical predication model of vertical breast displacement is formulated to assist bra designers in identifying the breast motion control performance of bra designs so as to develop appropriate bras for different needs and daily activities. The findings propose a reference source to identify the key design factors to advance the design process with optimal breast support, fit and comfort.

Chapter 5 presents the new bra insert design for breast support by improving the fit and the breast displacement performance of bras. A three-dimensional (3D) handheld scanner was applied to record the 3D geometric changes of breast and underwires under different bra conditions. The collected data from the human subjects were deliberated with the soft breast manikin results. The traditional 2D planar underwire design and the 3D breast support insert are considered to act as reference for the new design of bra insert. The bending rigidity of the bra insert and traditional steel underwires were measured. With the development of new bra inserts, their corresponding performance of controlling breast displacement and bra-skin pressure were measured and compared with traditional underwire design. It is expected that the new design establishes an insight for breast movement control and hence improving the future design of supportive moulded bras.

In chapter 6, the conclusions will be summarized. Limitation of this study and recommendations for future studies are also included.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In this chapter, a literature review is provided which details the support offered by moulded bras, and the research gaps and limitations in current analyses on bra-skin pressure. Current studies rely on human wear trials which cannot be generalized; few studies are available on the support and comfort performance of 3D bra support inserts which have replaced or modified traditional underwires; and 3D printing technology which allows rapid prototyping of bras and technical skills is required for the general public to use. These are important issues that have led to the development of a process for prototyping a bra insert in this study.

To proceed, the background information on development of moulded bras is also elaborated, which include the type of materials used and functional design characteristics in which the key concerns for quality, design criteria and characteristics, as well as technical limitations of moulded bras are discussed. The literatures on measuring and evaluating breast displacement are reviewed. The use of 3D motion capturing systems to assess breast motion and displacement in relation to sports bra designs are first examined. Then pressure is considered, as the analysis of pressure can determine how different bra designs impact comfort. Therefore, pressure sensing equipment is used as an objective means of assessing bra comfort. Then, a supporting component of moulded bras, that is, the underwire, along with 3D printing technology, is discussed. Moreover, methods that evaluate the breast geometry and shape of bra underwires are reviewed to determine the possible solutions that would improve the fit and the corresponding support of the breasts with moulded bras.

2.2 Moulded bras

Breasts are composed of soft tissues with elastic ligaments. Daily movement, such as walking or exercising, causes different amounts of breast motion. Bras can be traced back to ancient Greece with the emergence of the modern bra in 1889. They have been designed not only to support the breasts but also offer different styles and special designs for aesthetic purposes. The structural design of bras offers different levels of support, minimizes breast displacement and improves breast stability. Information on breast displacement during daily movement with adjustments made to a supportive bra gives insights into advancing the ergonomic design of bra inserts for both support and comfort.

Bras are a close-fitting garment that covers the breast and provides external support for the soft tissues of the breasts. There have been many innovations in terms of the bra structure and design with different kinds of materials used. There are also an increasing variety of special bra designs and consumers can select the one that best fits their needs. Traditionally, bras were produced through a cut-and-sew process. With the advancement of technology, moulded bras have become very popular in the intimate apparel market. The manufacturing time for the cup is reduced because the cut -and-sew process is eliminated and the entire fabrication process can be completed in just one step. Demand for moulded bras is also continuously increasing because of the comfort and support that they provide.

Since the 3D bra cups of moulded bras offer better breast coverage, moulded bras provide a shaping effect that round the contours of the breasts. This provides both support and aesthetics when tight-fitting clothing is worn. The elimination of seams and use of 3D bra cups also allow for a better wear comfort. Support is also improved due to uniformity of compression of the breasts (Zheng, Yu & Fan, 2009). Moreover, bras are an undergarment that come into direct contact with the skin. Therefore, the material used should be comfortable. Elasticity of the material also needs to be taken into consideration because bras control breast movement. If rigid material is used without any elasticity, the breasts cannot move naturally. The proportion of stretchable and flexible materials also affects comfort and pressure (Zhuo, Sheng, Wei & Bin, 2011). The key components of moulded bras therefore include the bra cups, shoulder straps and bra band, and supporting components of moulded bras, as follows.

2.2.1 Bra cups of moulded bras

The components of bra cups are designed to cover the breasts and follow the natural curvature. A thin foam layer that is used for the bra cups eliminates the visibility of the nipples and also lifts the breasts. Both cups are held together with shoulder straps and an elastic bra band on the back (Calasibetta, 1986). The entire cup should enclose the breast (Luciani & Deal, 2009). This helps to gather the soft breast tissues and provide a push-up effect. The fabric for the cups could also include lace or other patterned fabric for aesthetics. Different cup designs are also available in the market which include full-, half, and three-quarter cups, and balconette and plunge bras, all of which are designed for different preferences.

The assembly of the pattern pieces of cut-and-sewn bra cups requires a skilled pattern maker and sewer. Moulded bra cups eliminate this complex stage of pattern drawing and cutting and sewing. Instead, they are formed through heating and moulding of synthetic or pre-made composites (Yu, Fan, Harlock & Ng, 2006). The moulding process is controlled through several parameters. In particular, the temperature, pressure and dwell times need to be well maintained to produce the expected results

(Mok & Kwong, 2002). Style, cup size and material physical properties, especially the thermal mechanical reactions, increase difficulties in shape conformity and quality optimization (Wu, Yick, Ng & Yip, 2012). The moulded cup contours therefore greatly depend on the design of the mould head (Figure 2.1). It is important to have a well-fitting mould head to optimize the resultant bra in order to provide adequate support and comfort.

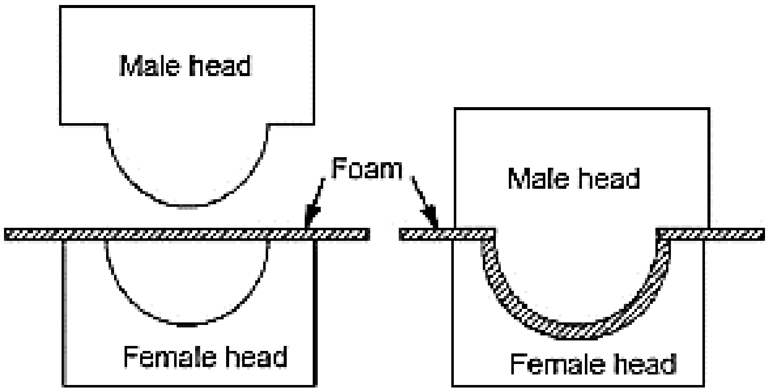


Figure 2.1 Contour moulding machine (Yick, Wu, Yip, Ng & Yu, 2011)

2.2.1.1 <u>Foam moulding process</u>

A single piece of foam material or pre-formed components are compressed between a pair of aluminum mould heads in the moulding process. The mould head is made of aluminum which can rapidly conduct heat. Among the different types of foams in the market, polyurethane foam is commonly used for moulded bra cups (Figure 2.2). This type of material is especially suitable for the intimate apparel industry because of its softness and flexibility (Yu, Yeung, Harlock & Leaf, 1998). Depending on the application, different thicknesses, hardness and densities can be used.

Figure 2.2 Different sized foam moulded cups

In the moulding process, foam and the properties of the laminated materials are the major factors that affect the cup height (Yick, Wu, Yip, Ng & Yu, 2010). However, more energy is needed to deform and heat-set fabric-laminated foams to obtain the desired shape. Besides, a larger bra cup for women with larger breasts also requires more energy to sufficiently soften and stretch the foam. Moreover, the elongation property of the fabric of the bra cup affects the measured pressure when the bra is worn. Less pressure and increased levels of comfort are found when materials with lower tensile strains are used for tight-fitting bras (Zhuo et al., 2011).

2.2.1.2 Fabric moulding process

Bra cups made of fabric are another option aside from polyurethane materials. Urethane and punctured sponge, as well as woven fabric are used as material for moulded cups in the market. Urethane sponge has excellent shape stability while woven fabric provides breathability (Jung & Na, 2016). Punctured sponge is another type of urethane sponge but has small holes which offer better breathability. However, it is relatively more expensive and cannot hold its shape as well as urethane sponge.

While polyurethane has a number of advantages, it also has poor moisture wicking ability and easily changes in colour. An alternative is 3D spacer fabrics. Since 3D spacer fabrics do not require lamination and have better moisture exchange, they can be used instead of polyurethane foam (Donaghy & Azuero, 1999; Schmirnoff & Weinrich, 2006). Spacer fabric is very porous which provides excellent breathability and shock absorption among the different kinds of lightweight composite materials (Doyen, Mues, Molenberghs & Cobben, 2010).

2.2.2 Shoulder straps and bra bands

The shoulder straps and bra band which are attached to the bra cups are designed to support the breasts. They maintain the bra position and increase the stability of the breasts. Shoulder straps can have different orientations, such as the traditional straight straps, cross-neck or double straps, or may not even be needed (strapless bras) to hold the breasts in position while the bra band is engineered to sustain the majority or 80% to 85% of the breast weight (Van Jonsson, 2013). Both the shoulder straps and bra band are made of elastic woven tape. However, strapless bras are not recommended for women with large breasts because of the negative impacts on posture (Findikcioglu, Findikcioglu, Ozmen, Guclu, 2007). Flexion torque of the thoracic spine would increase and lead to greater thoracic kyphosis compared to women with smaller breasts. Comparatively, the shoulder straps have less elasticity than the bra band. The elastic tape should have a certain amount of elasticity so that the wearer can breathe naturally, but also provide adequate control to contain vertical breast movement (Page & Steele, 1999).

Studies on the shoulder straps of bras have examined their design, pressure comfort and support performance. The shoulder straps and bra band are both bra components that can easily cause discomfort. This is especially true for larger breasted women, as the weight of the breasts causes a greater downward force with gravity and the shoulder straps and bra band both need to be stretched sufficiently to carry out their function. The shoulder straps contribute to 10% to 20% of the support while the bra band provides the remainder of the support. Different widths of both the shoulder straps and bra band can be used. A wider shoulder strap allows a more even pressure distribution due to a greater surface area for distributing the generated load between the shoulders and strap interface (Zhang, Li, Yeung & Kong, 2000) (Figure 2.3). Besides, the inclusion of cushioned padding helps to reduce discomfort and alleviate the problem of a slipping strap (Bowles, Steele & Munro, 2008). Cushioned padding also stabilizes the breasts more during motion (Bowles, Steele & Chaunchaiyakul, 2005).

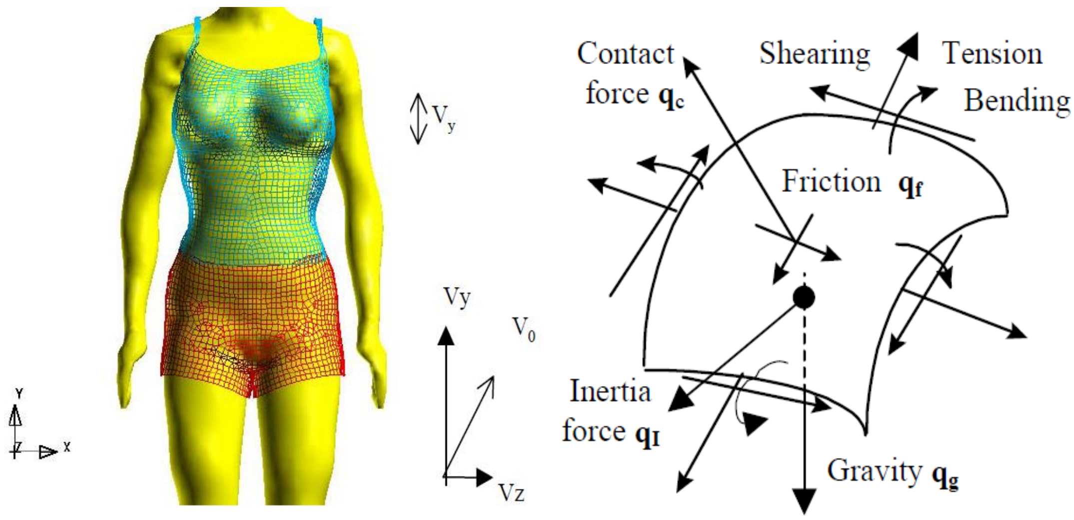


Figure 2.3 Mechanical analyses for additional cushion padding

(Zhang et al., 2000)

As for the strap orientation, the traditional straight straps are widely used with different orientations at the same time (Figure 2.4). Bowles and Steele (2013) investigated the bra-skin pressure with vertical and cross-back shoulder strap designs along with additional cushion padding (Figure 2.5). No significant difference between the tested conditions was found except that there is less pressure induced with cross-back straps. Incorporate cushioning material as the cross-back straps reduce scapular upward rotation (Kang, Choi & Oh, 2015). When considering dynamic conditions, straight straps show a better performance and the straps do not dig into the body or cause discomfort on the trapezius muscle based on a study by Coltman, McGhee and Steele (2015). They used a calibrated pressure sensor to measure the pressure that is one of the parameters to determine the discomfort of bra straps and found that straight shoulder straps lie along the shoulder bone and tolerate compressive forces between the strap and sensor surface. Better breast support is also found with conventional straight straps because the straps align with the direction of gravity (Zhou & Yu, 2013).

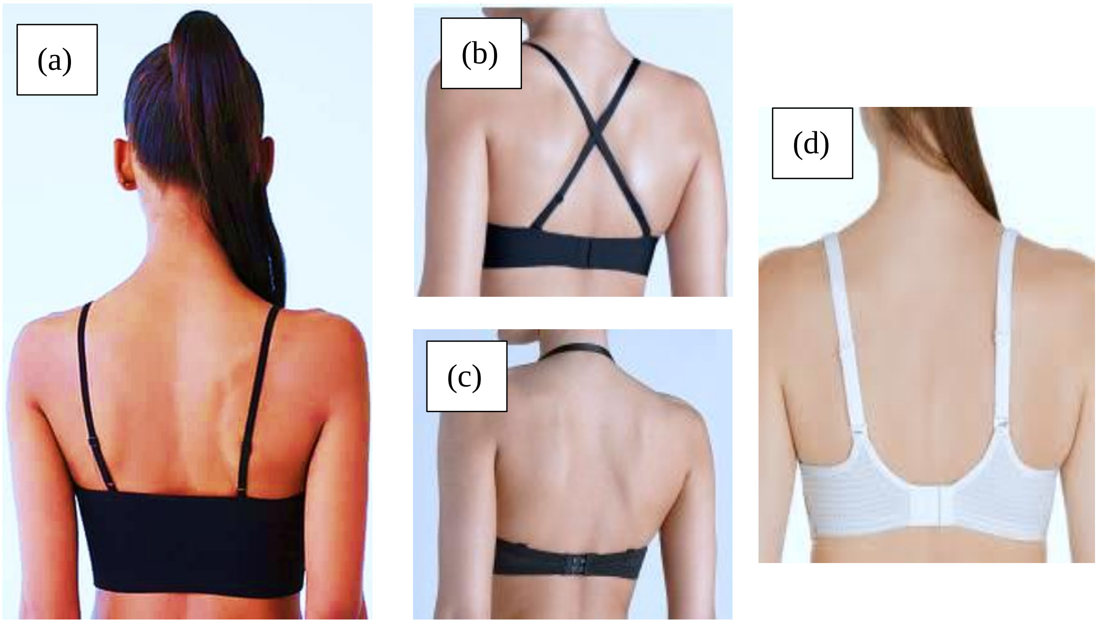


Figure 2.4 Different bra shoulder strap orientations:

(a) straight, (b) cross-back, (c) cross-neck and (d) U-back

Figure 2.5 Examples of use of additional cushion padding for shoulder straps

When a bra is worn on the body, the material of the shoulder straps or bra band is stretched to a certain degree. The amount of extension of the material is determined by the elastic modulus along the length of the strap or band (Yu, Yip, Yick, Luk & Ng, 2016). The shoulder straps are elastic with a certain degree of elongation. One of new developments in bras are dual elastic straps that have a low modulus of elasticity with high elongation for the front segment and high modulus of elasticity with low elongation for the back segment. A tubular structure is used with a wider and less elastic material for the first section and a narrower elastic material for the second section (Figure 2.6). For both the shoulder straps and bra band, a higher tensile modulus of the elastic woven tape means a higher amount of induced pressure (Zhuo et al., 2011). The tightness of the shoulder straps and bra band affects the soft tissues in the rib cage area, and the tissues around the torso section (not including the breasts) which may have indirect negative effects during breast movement (Mills, Loveridge, Milligan, Risius & Scurr, 2014). Therefore, the shoulder straps and bra band should have an appropriate amount of elongation and modulus of elasticity in contributing to providing support to the breasts as well as enhancing perceived comfort.

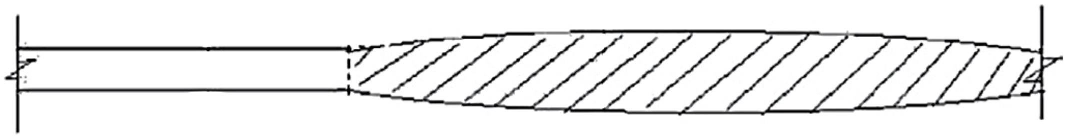


Figure 2.6 Example of shoulder strap structure (He, 2014)

Adjustment rings and sliders can also be attached onto the shoulder straps, and hooks and eyes on the bra band. They provide the appropriate tension to secure the bra in a consistent position and maintain support effectiveness. The back and shoulders are the areas that receive particularly high pressure and compression when a bra is overly tight fitting for the wearer (Miyatsuji, Matsumoto, Mitarai, Kotabe, Takeshima & Watanuki, 2002). Therefore, proper tension also allows the body to comfortably expand during natural respiration and tolerates an acceptable degree of pressure (Zheng et al., 2008). The tension should not restrict body movement (Shishoo, 2005). It is found in a study that the range of pressure exerted at the shoulder line that crosses the shoulder straps and bra band line is 24 mmHg and 11 to 16 mmHg, respectively (Makabe, Momota, Mitsuno & Udea, 1991). Therefore, the addition of strap cushioning can also reduce discomfort from the straps digging into the shoulders, such as gel straps but there is no difference in terms of reducing vertical breast displacement (Coltman et al., 2015). Moreover, Bowles and Steele (2013) concluded that shoulder strap cushions are not effective for reducing strap pressure. Therefore, the length of the shoulder straps and bra band should be adequate enough to accommodate the breasts and provide a good overall fit, such as no gapping between the cups.

2.2.3 Supporting components of moulded bras

2.2.3.1 Underwires

Underwires are inserted underneath bras. A wire channel or casing is used for the underwire insertion (Fildan, 1993). They increase the rigidity of the bra structure which improves support and lift. The cup shape is also better retained. With underwires, the desired breast shape is created along with meeting the 'golden proportions' (ratio of 1:1:618) of the body (Song & Yu, 2011). Sufficient flexibility of the planar underwire should be available to open the underwire to the appropriate extent and fit the breast contours. A good underwire is expected to be light in weight, supportive, and durable under repeated washings without damage (Figure 2.7). It should also enhance the body shape but not cause discomfort.

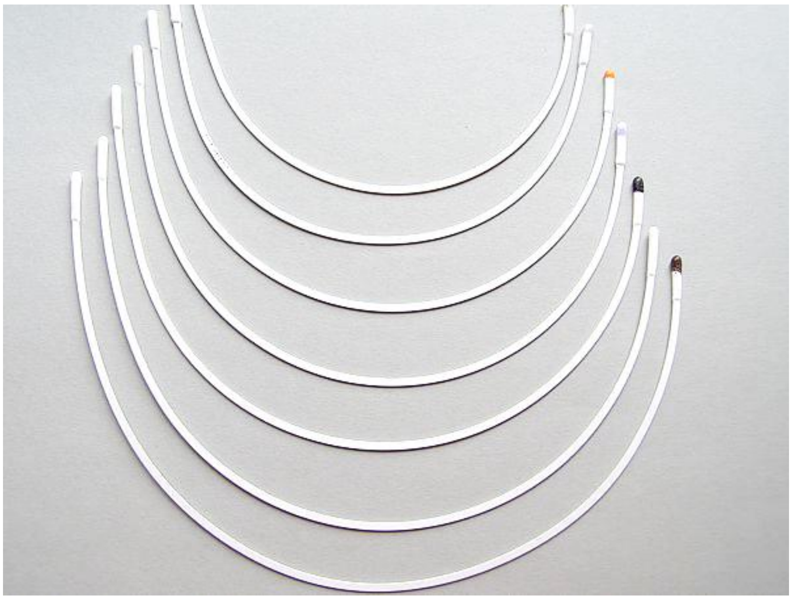


Figure 2.7 Underwire samples

Different underwire shapes are used to provide specific bra styles. The inner diameter equals to the distance of the gore to the end point of the wire, while the outside length refers to the total length of the underwire (Liang, Zhang & Shi, 2007). The differences in height between the gore and the end point are used to define different types of underwires. Underwires are planar which means that they are flat and can lie on a planar surface. A typical example is the U-shaped flat wire, which is attached to the bottom and sides of the bra cups through the wire channel (Shin, 2010). They can have an oval cross or flat section in the cross-sectional view. The two ends of the underwires have a tip cover that prevents the wire from penetrating out from the bra. S & S Industries which specializes in wire products patented a spring-loaded plastic cushion tip which was used to replace the traditional tips as they can poke through the bra (Figure 2.8). There are three categories of underwires, including underwires for high, medium or low impacts (Shin, 2010).

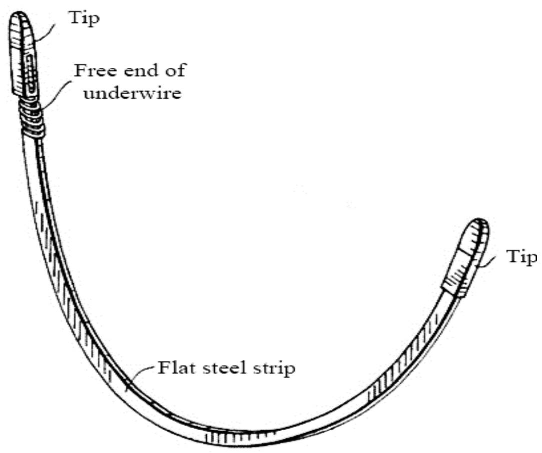


Figure 2.8 Underwire for bras (Thakur & Horta, 2002)

Underwires are generally made of metal, plastic or resin. Metal underwires are usually made of stainless steel or high-carbon steel. A coating is applied so that the wires do not easily distort or bend. Stability and flexibility are also improved with the application of the coating. Finally, the coating also minimizes contact with oxygen, and thus rusting of the metal wires can be prevented (Morris, 2014). Planar or semicircular shaped underwires require the tension of the shoulder straps and bra band to pull the underwire that is inserted in the wire channels in order to accommodate the breast contours.

Insufficient tension to open the underwire or improper underwire width and depth causes the end of the underwire to poke into the armpit or anterior midline. Difficulties in predicting the fit of a 2D planar underwire to the 3D geometry of the breasts means that the underwire usually has an inappropriate fit.

With increasing awareness those planar underwires may not provide optimal comfort for the wearer, underwires that take into consideration the 3D contours of the breasts have started to emerge in the market. Three-dimensional underwires aim to provide support through 3D bra cups. The design in Cheng (2011) aims to relieve the poor performance of the circular cross-section stainless steel wire due to the protruding ridge. A wide and flat section at the lower part of the underwire inclines inwardly and forms an inclined part for the upper edge to face outward and bend inward for the lower edge with the inclined angle of 30° to 85° in order to follow the breast contours (Figure 2.9). This also better ensures that the breast tissues are fully positioned within the cup. Figure 2.10 shows a modified design with a transition section that has a twist angle between the flat and inclined sections (Cheung, 2014). A better match and larger contact area between the underwire and the curve under the breasts can improve the overall breast support function of the underwire.

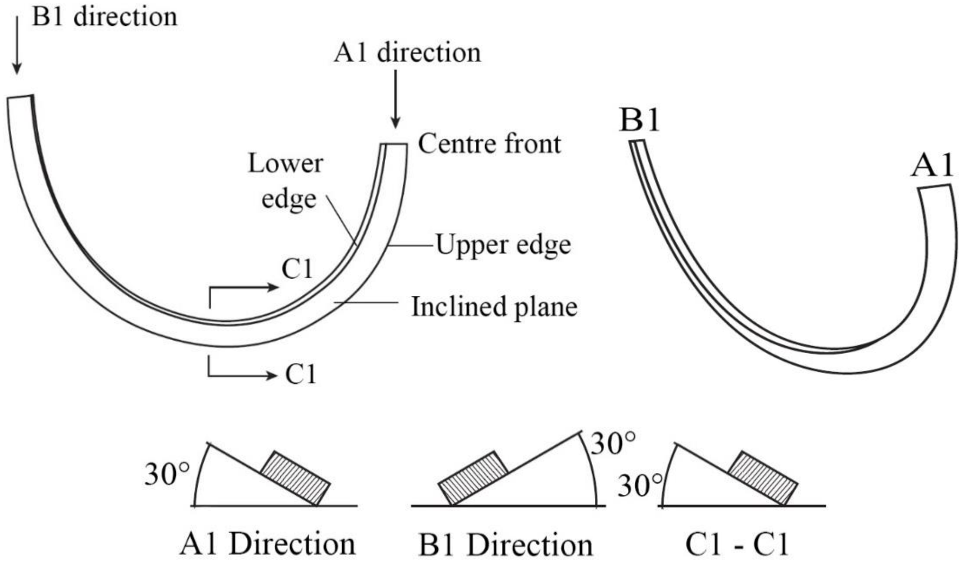


Figure 2.9 Three dimensional support ring for bra cup (Cheng, 2011)

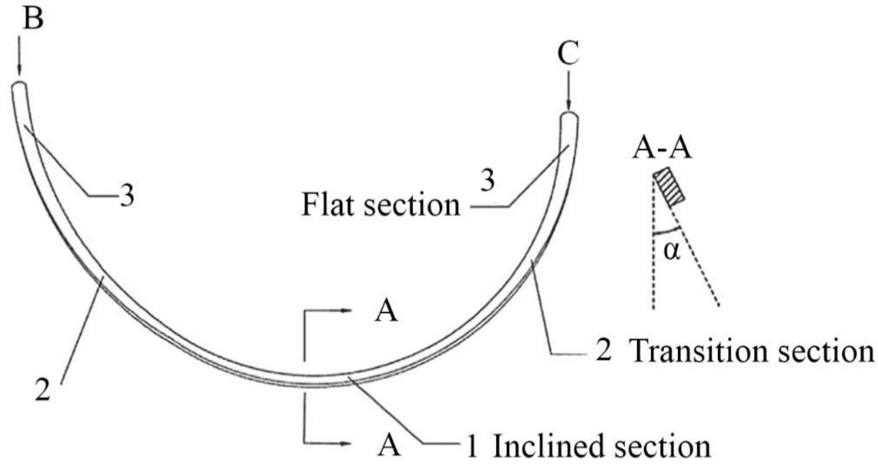


Figure 2.10 Three dimensional bra underwire (Cheung, 2014)

Moreover, underwires have been greatly advanced with the use of different types of materials and changes in their shape. These innovative modifications to underwires include for example, underwires that are 3D in shape, made of silicon, or are linked or padded. Silicon is used instead of the traditional stainless steel for a balance between support and comfort (Figure 2.11). The link elements in linked underwires allow wearers to self-adjust the length and pressure of the underwire (Liu, 2014a). The connected link elements move with the adjacent link element to accommodate the breast curvature (Figure 2.12). Changing the material of the link elements can provide different degrees of curvature. As for padded underwires, they are manufactured with a gel tip to ease any pressure that extends from the underwire (Martinet & Yip, 2013). The underwire comprises two layers of foam and set on the lower peripheral edge of the bra cup (Figure 2.13). This design helps to balance pressure and allow the bra to support the breasts.

Figure 2.11 Triumph Magic Wire bra (silicone underwire)

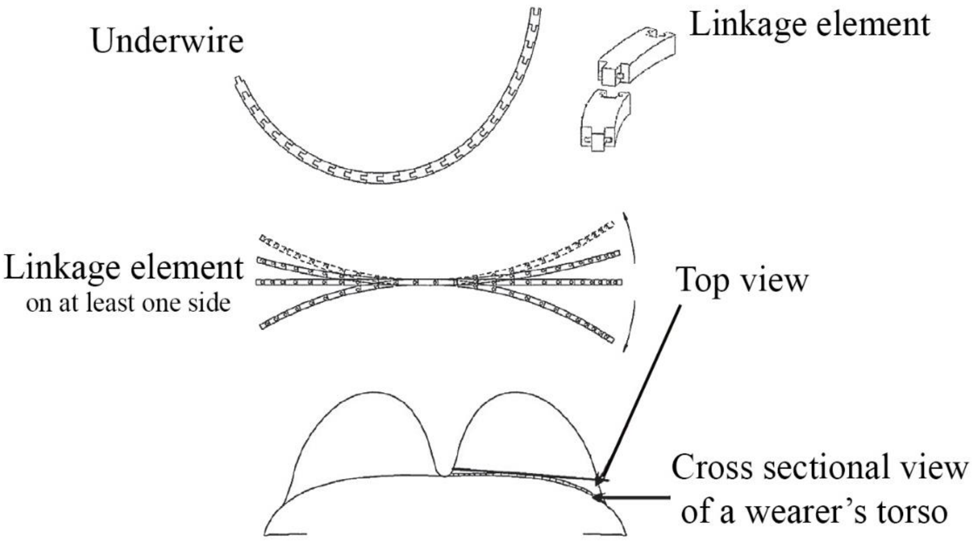


Figure 2.12 Underwire for brassiere (Liu, 2014a)

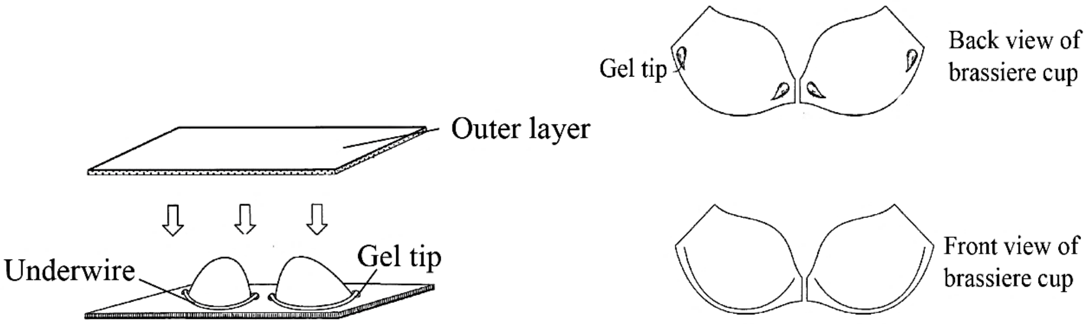


Figure 2.13 Brassiere cups with padded underwire

(Martinet & Yip, 2013)

Padded underwires, that is, underwires that are covered with cushioning material, for example, foam, are moulded into the bra cups (Zhang, 2013). They also offer 3D support through two layers of hard polymer that are wrapped around a conventional underwire and fit the lower peripheral edge of the bra cup (Figure 2.14). Aside from padded underwires that use cushioning material, polyurethane can also be used to provide extra support on planar underwires that are metal (Chen, 2014a).

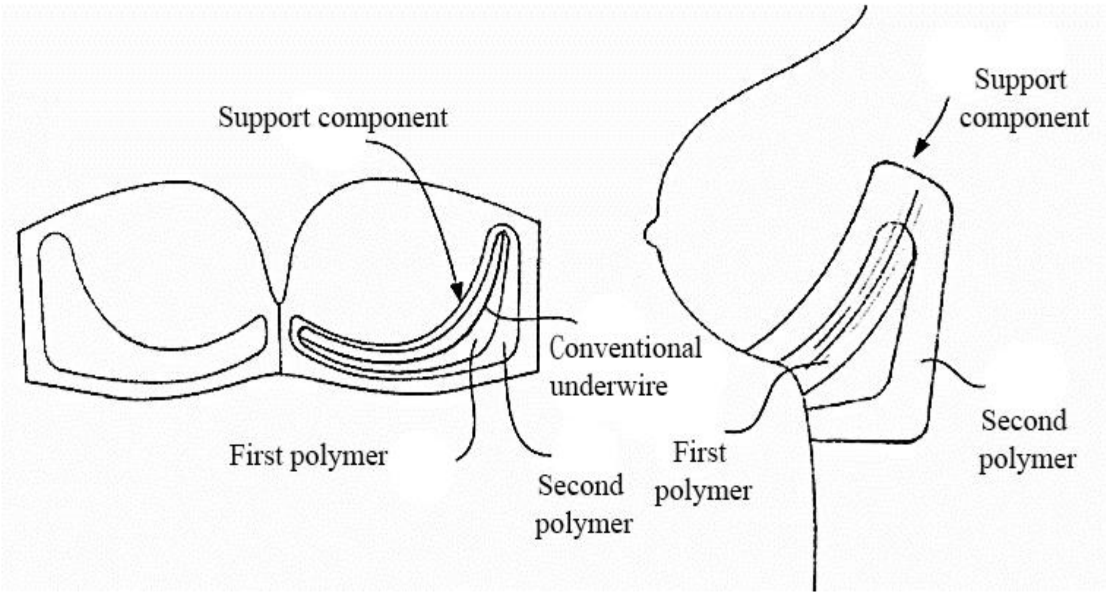


Figure 2.14 Three dimensional support structure of bra (Liu, 2014b)

Moreover, 3D underwires have also been developed with a variety of different materials to further improve the support of bras and perceived comfort of the wearer. For example, there are spoon shaped underwires that can swivel to accommodate the body contours and movements (Figure 2.15). Support insert designed by Chen (2013) includes underwire is placed underneath a silicone insert pad (Figure 2.16) which gives the wearer a comfortable wear experience because the soft texture of the underwire component. Underwires that accommodate the natural breast contours at the bottom part of the cup would enhance wear comfort as shown in Figure 2.17 (Braverman, 2017). Three-dimensional underwires have the same type of curvature and length as 2D underwires (Figure 2.18). However, 3D underwires lift the breasts more with less distance between the breasts. The breasts are also more gathered at the center of the front of the bra which provides better aesthetics.

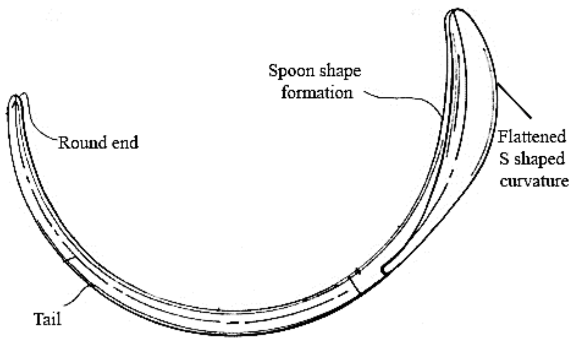


Figure 2.15 Spoon shaped underwire (Fildan & Wanzenböck, 2002)

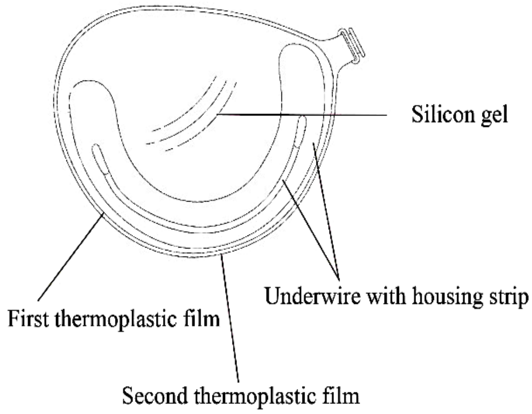


Figure 2.16 Breast form with underwire (Chen, 2014b)

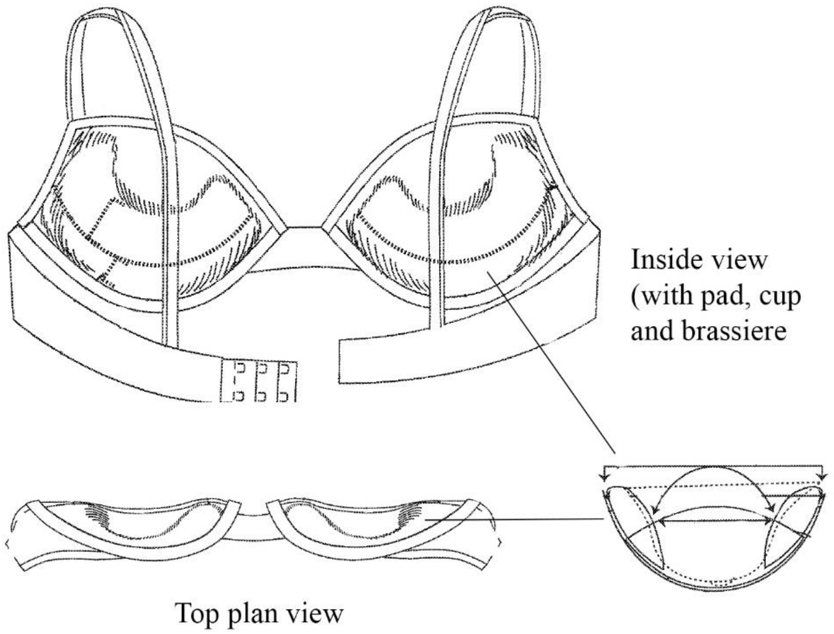
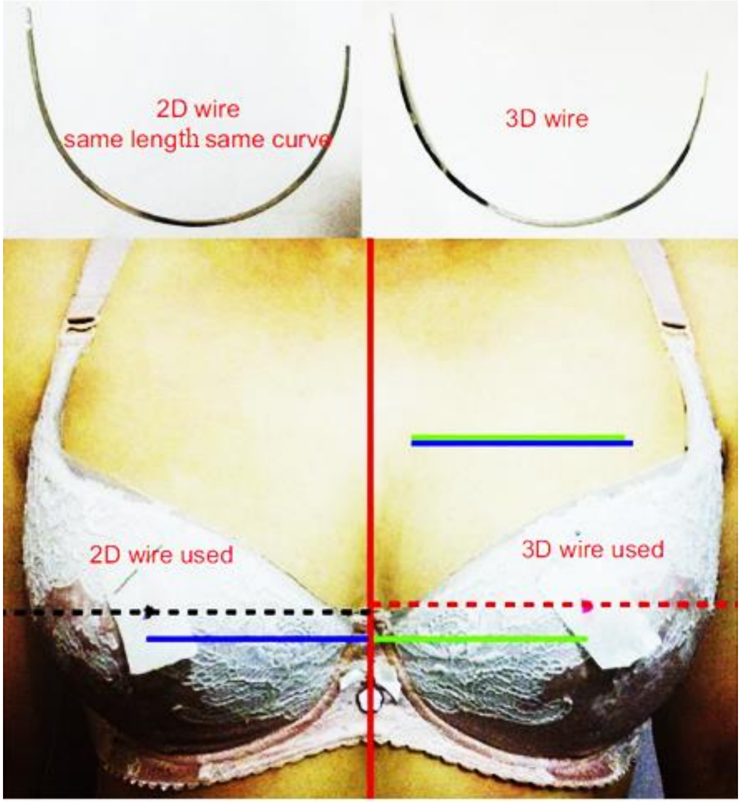


Figure 2.17 Bra support design that underwires that accommodates breast contours and enhances wear comfort (Braverman, 2017)



(a) (b)

Figure 2.18 Lifting up effect: (a) 2D underwire, (b) 3D underwire (Yu et al., 2016)

2.2.3.2 3D printing technology

Aside from the bra underwire, 3D printing technology is also used to provide supporting components of moulded bras. Three-dimensional printing technology helps to transform electronically scanned shapes into real products. The specified shape or size of a product can be produced with accurate dimensions by processing the scanned data through computer-aided design (CAD) modeling. This technology consists of several steps. First, a 3D model or digital data with a specified shape and appearance is created by using CAD software to ensure that the model is 3D printable by transforming the model into different file types such as .stl format. The software then processes the design, which is followed by layer by layer 3D printing of the modeled object (Valtas & Sun, 2016). The final product can be made of one type of material or a combination of materials. For example, thermoplastic polymers can be used in fused deposition modeling (FDM), which is one of the 3D printing technologies that produces products by melting thermoplastic polymers and extruding the polymer material through a nozzle based on the received file requirements (Yang, Chen, Wei & Li, 2016; Korger, Bergschneider, Lutz, Mahltig, Finsterbusch & Rabe, 2016) (Figure 2.19). The 3D appearance of the printed object can have different finishing, thickness, etc. (Partsch, Vassiliadis & Papageorgas, 2015).

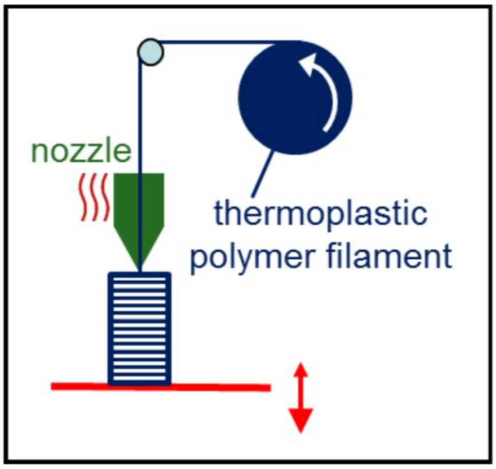


Figure 2.19 Fused deposition modelling technology

(Korger, Bergschneider, Lutz, Mahltig, Finsterbusch & Rabe, 2016)

Three-dimensional printing is not only used to print rigid 3D objects, but can also produce items with different softness or material properties (Figure 2.20). In the textile industry, use of fibrous materials, as a pre-treatment of textile materials, or printing on the textile surface are some examples of previous applications of 3D printing technology (Hudson, 2014, Novakova-Marcincinova, 2012; Richter, Schmülling, Ehrmann & Finsterbusch, 2016). The technology has now developed to the point of producing parts of a garment or even a complete piece that is ready-to-wear (Figure 2.21). This will reduce the pattern making and sewing time along with less material waste which was previously the case with the cut-and-sew process (Valtas & Sun, 2016).

Figure 2.20 Example of 3D printing technology in textile industry - 3D printed teddy bear (Hudson, 2014)

(a)

(b)

Figure 2.21 (a) Top panel design of garment ready for 3D printing and (b) Printed product

This technology is also known as additive manufacturing, and useful for producing products with a complex 3D geometry and facilitating the options for production processes because of the variety of options for size, colour or shape of the resultant printed product (d'Aveni, 2015). In this case, 3D printed wearable bra designs can accommodate the needs of the wearer (Aggarwal et al., 2017; Park, Lee, Seong & Kim, 2019). This 3D printed bras provide an enhanced corrective effect, comfort and functionality (Figure 2.22). Therefore, 3D printing technology enhance the functional properties of textile materials thus eliminating the shortcomings of conventional textile fabric (Melnikova, Ehrmann & Finsterbusch, 2014). This technology can also help to produce more ergonomically fitting bra components, for example, the cups or supportive underwire, so that they accommodate the breast contours. Three-dimensional printing can also provide a solution for a quicker turnaround time for prototyping and facilitating the design process (Vanderploeg, Lee & Mamp, 2017).

Figure 2.22 Example of 3D printed bra

2.2.4 Limitations of moulded bra designs

While 3D printing is an innovative and new way of addressing the production of new types of bras and bra components to accommodate the needs of the wearer, the design and manufacturing processes to produce bras are still complex. The downward forces generated from gravity during different activities and activity intensity, as well as different breast size mean that the support function of bras is very important. Besides, wear comfort is also an important issue because bras are worn for long hours next to the body.

The best way to wear a bra that fully takes advantage of the supporting components is that first, the breasts should completely fill the cup. There should be no excessive fabric and the breasts should not spill out of the cup (Elam, 1997). Another common issue that results in a poor fit is incorrect shoulder strap or bra band length. The bra band should stay in place after inserting two fingers under the hooks (Figure 2.23). An overly tight bra band may cause the back muscles to bulge and breathing difficulties. The correct amount of tension means that the bra band should lie flat across the back instead of squeezing the flesh or moving freely (Bowles et al., 2008). The tension should be enough to prevent the shoulder straps from falling or digging into the shoulders (Starr, Branson, Shehab, Farr, Ownbey & Swinney, 2005) (Figure 2.24). If the bra band has inadequate tension with overly tight shoulder straps, the straps may dig into the skin (Thomas, 1995), which would cause pain and irritate the skin because the weight of the breasts is excessively transferred from the bra band to the shoulder straps.

Figure 2.23 Incorrect vs correct amount of length

Figure 2.24 Overly tight shoulder

straps – digging marks

Underwires are also associated with ill-fitting bras. Traditional underwire designs are planar and have different gore heights and wire gauges to support the bra cup. Since the structure of the breasts is 3D, it is difficult for a planar surface to directly fit all breast shapes and mimic the shape of the breast roots (Figure 2.25). The opening length or underwire shape may not be able to accommodate the breast volume or the curve under the breasts. There may be a gap between the underwire and breasts, which may lead to reduced support or wear comfort.

Although measurements may indicate that the breasts have the same size, there is still variation in the breast volume, which may lead to discomfort from the underwire. Sizing standards are usually generalized to accommodate the mass population, so they do not take into consideration that the breast volume may vary, only the size of the breasts. For instance, the American wire gauge system is a sizing standard that classifies breasts as small or large. Therefore, the wrong wire gauge size may lead to digging (Yu, 2011) (Figure 2.26). While there is now new development of a 3D support insert that replaces the current planar underwire, research on the applied materials and the design of the shape of the insert are still in its early stages.

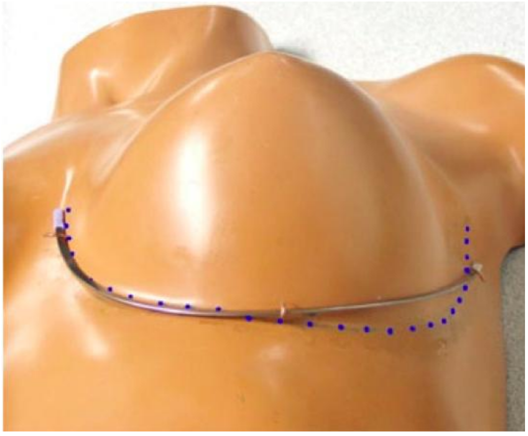


Figure 2.25 Underwire fit problem

Figure 2.26 Digging of underwire

(Morris, 2014)

Wear trials are conventionally used to evaluate different bra designs, especially the pressure between the bra and body/skin or breast displacement. However, as stated earlier, the breast shape or weight may vary even within the same breast size range. For example, bra-skin pressure measurements are taken during static or dynamic conditions. The peak pressure is determined based on breathing patterns of inhaling and exhaling. However, the respiratory rate may vary and combined with possible changes in the shape or weight of the breasts, could lead to differences in the measured bra-skin pressure even within individuals with the same breast size (Yu et al., 2016). It is also found that the breast mass variation of women with the same breast size results in different magnitude of breast motion due to the inferior migration of the nipples (Mills, Risius & Scurr, 2015).

To improve the consistency of experimental tests on breast measurements, a variety of different manikins are now available for use. For example, a smart manikin system with the standard physical dimensions of a female body is now commonly used to measure clothing pressure (Nayak & Padhye, 2017). The central line of the manikin can be transversely extended by 5 cm to take into consideration different body shapes (Figure

2.27) and sensors are distributed on the surface for measurement of pressure. A manikin with an artificial skeleton has also been developed to simulate the human torso for evaluating and testing garments (Yu, Fan, Li, Gu & Qian, 2006). Moreover, a sweating fabric manikin has been developed to advance the ergonomic design of textile products and design goods that respond to the actual completion of tasks or can be used in a specific location with a unique climate or environment (Fan & Chan, 2002). The manikin simulates different rates of perspiration and allows testing of the thermal insulation and moisture-vapor resistance of textile products.

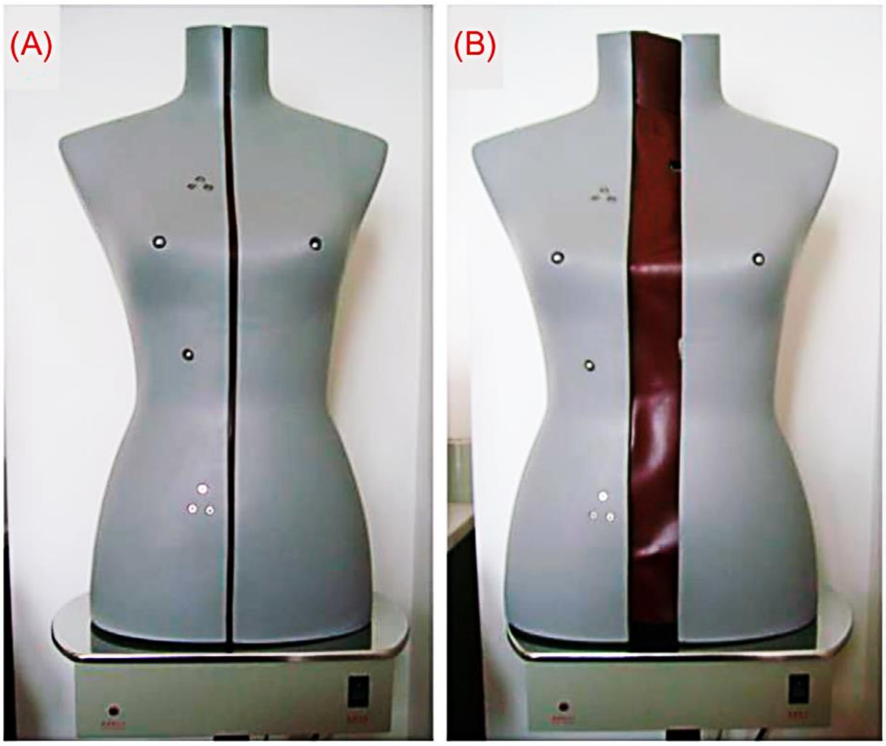


Figure 2.27 Smart manikin prototype (a) standard setting and (b) extended setting (Nayak & Padhye, 2017)

The “i-Dummy” robot is an innovative robotic manikin that accurately reflects the body dimensions for different sizes and races (Figure 2.28). Complicated mechanical engineered parts are constructed in the manikin to produce reliable and immediate responses for body measurements, which contribute to accelerating the garment design and development process. The manikin presents a direct image for customers as a part of their virtual try on experience and promotes online retailing. However, it is found that the manikin is lacking in terms of its rigid surface as it cannot approximate human tissues with fat nor can it accommodate different body sizes. This is particularly problematic for bra analyses, and so a soft breast structure needs to be added for better simulation of real breasts.

Figure 2.28 i-Dummy robot manikins

2.3 Breast motion

2.3.1 Breast motion kinetics

As stated above, breasts have a soft viscoelastic structure, with viscous damping properties and hyperelastic behaviors. The exterior of the breasts include skin, nipples and areolas. The thin layer of skin that covers the breasts is flexible and elastic.

Internally, the breasts contain Cooper's ligaments, which are fibrous connections that provide structure to the breasts, and extend to connect the fascial tissues in which the breasts lie. Breast support mainly depends on these ligaments, as well as the skin as the secondary supporting element. There are no muscles in the breast structure (Gehlsen & Stoner, 1987). Connective tissues in the stroma are responsible for bearing the entire weight of the breast structure. The fibrous ligament network or Cooper's ligaments maintain the breast shape during motion which only constitute thin fibrous bands in a sheet form and divides the lobules (gland the produces milk) in the breast structure (Hindle, 1991). The skin stretches when there is breast motion, and there is free movement of the breasts during torso movement (Bowles et al., 2008).

That is, breast motion is affected by trunk movement during dynamic movements (Haake & Scurr, 2010). The momentum of movement is transferred from the feet to the upper torso. That is due to ground reaction forces, which are the intensity and duration of stress exerted onto the body when the feet come into contact with the ground (McClay et al., 1994). Many factors affect the impact of these forces, including the body mass during deceleration, and the joint angle and stiffness (Nigg & Liu, 1999). Shock attenuation occurs during impact transmitted by the joints and muscles. When the lower torso muscles cannot absorb all of the shock, the additional force is absorbed by the breasts.

The breasts and trunk therefore move simultaneously together or there is only a small delay at different moving speeds or activity levels. When the trunk is ascending, the breasts are descending (McGhee, Steele, Zealey & Takacs, 2013). The net force is generated with the jarring effect of the breast and trunk movement. There is multiplanar movement of the breasts. Therefore, superior and inferior displacements are observed which exert the greatest magnitude in movement of the breasts (Scurr, White & Hedger, 2011). The force of the gravity exerted onto the breasts and trunk is however limited by the anatomical structure of the breasts. The vertical forces absorbed by the breasts include gravity, and trunk driven and restraining forces. However, mass and acceleration impact the force of gravity, and therefore the net force generated may be moderated. As a result, increased breast mass is associated with increased net force. Correspondingly, large breasted women should have more breast support in order to receive the same amount of support as their smaller breasted counterparts.

2.3.2 Excessive breast motion

The viscoelastic structure of breasts means that breast movement correlate with body movement. The momentum and displacement of the breasts due to motion are therefore influenced by walking or different kinds of activities and breast mass. Since repeated force is exerted onto the breasts, this aggravates the skin and connective tissues, and stretches them. Pain, sagging or other negative effects are the result if the soft tissues of the breasts are inadequately supported. The natural perkiness of breasts may be reduced as a result. This could cause embarrassment because the breasts are not positioned appropriately to move freely with the breast weight (Robbins, Pender & Kazanis, 2003). The gravity force and motion increase with greater breast weight. This means that vertical displacement of the breasts is therefore increased in larger breasted women, with more associated discomfort (McGhee et al., 2013). This may reduce the motivation of women to exercise which would lead to health problems (McGhee, Steele & Power, 2007).

Unfortunately, insufficient breast support also results in permanent appearance or health problems. Breast pain emerges with limited external breast support. When the breasts move away from a neutral position, this is known as excessive strain and one of the possible causes of breast pain (Knight, Wheat, Driscoll & Haake, 2014). Continual stretching can result in increased breast sagging and even injury (Shangold & Mirkin, 1985). Permanent deformation of the breast structure could even be a possibility because of repeated high loading on the breasts (Page & Steele, 1999). Increases in vertical breast motion also cause a great deal of discomfort (Starr et al., 2005). Thus, inadequate breast support should be addressed to prevent the consequences that come with excessive breast motion.

2.3.3 Bras that control breast motion

Excessive motion results in overstretching of the connective tissues and skin of breasts. The remedy are bras, which are used to protect the soft breasts from excessive motion. The external support provided by bras helps to minimize discomfort and the other negative impacts generated by the high intensity motions (Bowles et al., 2008). Sports bras and the effectiveness of sports bras are determined through comparisons with braless conditions. Studies on sports bra designs and breast motion also examine the strain and force (Haake & Scurr, 2011; Bowles et al., 2008; Milligan & Scurr, 2016; Yick, Wu, Yip, Ng & Yu, 2010). They conclude that the shoulder straps and bra band hold the breasts in place and act as the primary supporting elements. Other than maintaining the breast shape, underwires can reallocate the pressure downward to the bra band (Loehr, 2013).

While the effects of the shoulder strap orientation have also been investigated by Bowles and Steele, (2013), few studies have investigated the combined effects of shoulder strap and bra band length on the support function and comfort performance of bra designs. There are also lacks of studies that examine the role of the underwire in reallocating pressure, particularly the bending angle of the underwire with bra length adjustment. Besides, the supporting effects of different underwire designs have not yet been studied. Therefore, it is timely and important to investigate these areas to facilitate improvements in bra design.

2.4 Evaluation of breast motion and displacement

Breast motion is 3D movement. When electromaterials such as sensors are used for testing, the amplitude and frequency of breast motion vary with breast weight, the amount of support and activity level. Breast movement during walking or running is usually a repeated pattern. Therefore, quantified data on breast motion offers important information including the amount of breast movement and pattern of the movement. Through analyses of the information, researchers and designers can evaluate the current support and stability of bra designs. This is because excessive breast motion leads to breast pain, which is not only due to inadequate support and causes discomfort, but may result in long-term health problems. Breast support elevates the breasts which enhances bra comfort (Bowles et al., 2012). Finally, a reduction in breast displacement may improve the overall bra performance.

2.4.1 Motion capturing systems

Investigation of breast motion requires measurements that quantify the level of movement. Motion capturing systems have been popular in recording and evaluating breast movement. Older versions use a camera to extract 2D coordinates of markers in every captured image on film (Lorentzen & Lawson, 1987). To increase the accuracy of measuring movement, 3D coordinates obtained through 3D camera imaging are now used to provide the amplitude, velocity or acceleration of the movement. Motion analysis software is also used to analyze infrared reflected motion after the information is captured with an infrared camera (Fuseya & Matsumoto, 2006).

Advanced motion capture systems, such as the VICON motion capture camera, and infrared cameras such as the Oqus optoelectronic digital infrared cameras or ProReflex infrared cameras, have been developed and used to assess breast motion (see for e.g., White, Mills, Ball & Scurr, 2015; Lu, Qiu, Wang & Dai, 2016; White, Scurr & Smith, 2009) (Figure 2.29). The pre-calibrated and pre-configured process increases the convenience of extracting and evaluating data. Although such systems are popular, data accuracy is still limited by the collected frequency of the samples, number of cameras, and number and position of retro-reflective passive markers that are used to identify the object of motion capture.

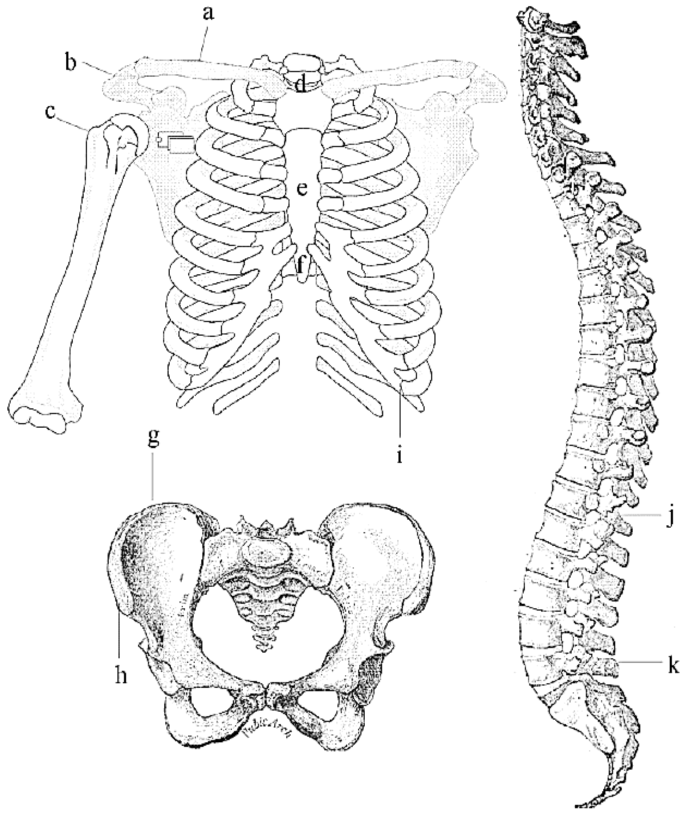
(a) (b)

Figure 2.29 (a) Oqus digital infrared camera and (b) VICON motion capture camera

2.4.2 References points for evaluation of breast motion

The time frame captured every second by infrared cameras and number of cameras can be varied depending on the equipment availability and the requirements of the study.

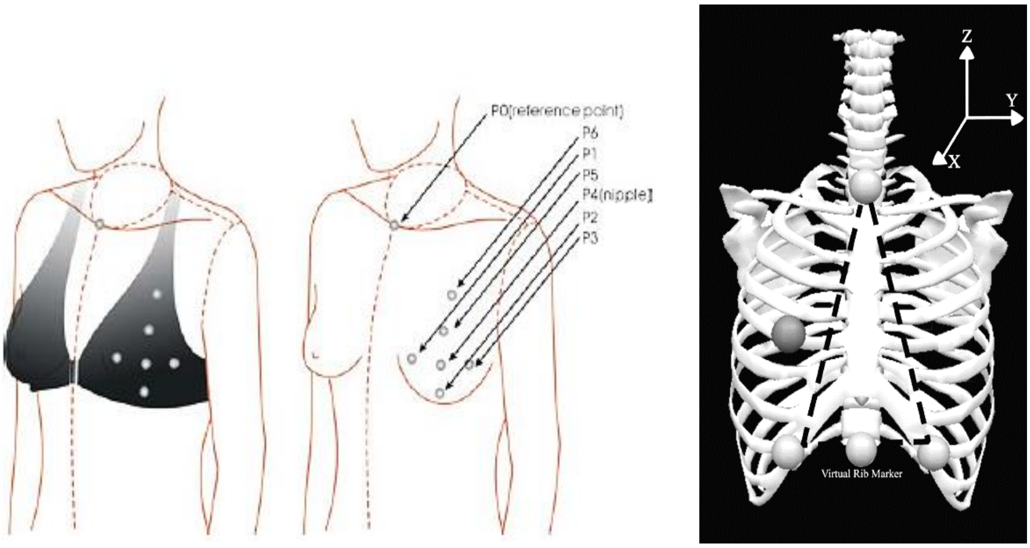
Marker position is also important and therefore it is suggested that the reference points can be easily located and repeated on any subject (Conti, Cristofolini, Juszczyk, Lwaedini & Vicoeconti, 2008). Markers placed on the skin surface above bones are easier to define (Veeger, Helm, Chadwick & Magermans, 2003) (Figure 2.30).



a: left clavicle center
b: lateral point of acromion processes
c: front arm point
d: suprasternal notch
e: sternum on the third rib level
f: lower sternum
g: iliac crests (ICs)
h: anterior superior iliac spines (ASISs)
i: anterior inferior aspect of the 10th rib
j: spinous process of the 12th thoracic

Figure 2.30 Reference positions on skin of body parts (Zhou, Yu & Ng, 2011)

In particular, markers placed on the reference points of the suprasternal notch for analyzing the displacement of nipples are commonly used in breast motion evaluation (Okabe & Kurokawa, 2004; Haake & Scurr, 2011). Some studies may attach more markers onto the breast to evaluate the motion of the entire breast or effects of the ability of a bra to stabilize movement (Figure 2.31(a)). Markers may also be placed onto the 7th cervical vertebrae and 10th thoracic vertebrae to indicate the upper back segment of the body while markers on the shoulders and ribs can show the upper front of the body (Figure 2.31(b)). If the studied area covers the effect of motion on gait cycle, lower torso markers are placed on the anterior and posterior superior iliac spines for the pelvis, leg and foot (Mills et al., 2015).



(a) (b)

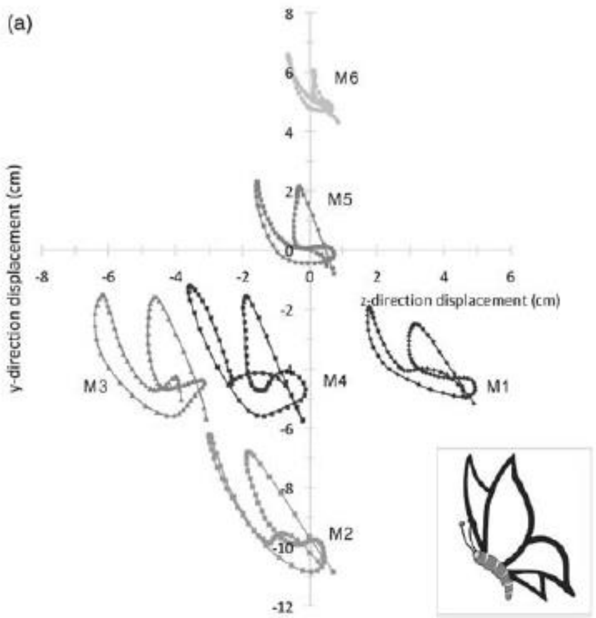
Figure 2.31 (a) Position of reflective markers for breast motion evaluation (Zhou, Yu, Ng & Hale, 2009), and

(b) Position of reflective markers to mark torso (Mills et al., 2014)

2.4.3 Quantification of breast motion

To examine breast motion, motion capture systems can capture the 3D position of the reflective markers and calculate the changes in displacement in the 3D plane. The amplitude of the displacement is primarily investigated. Since motion capture systems are able to collect data in a 3D plane, motion in multiple directions can be evaluated. The vertical direction is the most commonly applied vector in investigations on breast motion (Gehlsen & Albohm, 1980; Mason, Page & Fallon, 1999). The vertical displacement of the breasts is examined because breast weight has no support and the combined effects of gravity and motion displacement cause movement in this direction to be more significant.

Aside from examining the amplitude of the displacement of the breasts, velocity and acceleration may also be used as factors for analysis. Since velocity and acceleration are correlated with breast comfort, they can be used in related research work accordingly (McGhee & Steele, 2010). The velocity and acceleration of the breast movement trajectory affect the overall movement of the breasts. The non-linear viscoelasticity of the breast skin and suspensory ligaments also need to be taken into consideration so that the range of motion can be evaluated (Figure 2.32).



Marker M1, M2, M3, M5:
4 cm apart from the nipple along both horizontal and vertical directions
Marker M4: Nipple
Marker M6: 4 cm above M5

Figure 2.32 Breast movement trajectories (Zhou, Yu & Ng, 2012)

Quantifying breast motion has important uses aside from determining the amount of movement to design bras for comfort. Previous studies have quantified the motion to explore how bras can also effectively reduce breast displacement, which contributes to the determining the effectiveness of bras for support. Figure 2.33 shows the data collected for evaluating the effectiveness of bra support during walking, running and jumping with the VICON motion capture system. Breast displacement under different bra conditions with the donning of everyday, encapsulated and compression bras have also been compared to the braless condition (Figure 2.34). Encapsulated bras can better reduce breast movement as opposed to compression bras since they support each breast individually. The padded cups of these bras absorb some of the kinetic energy during motion, so that the tensile and compression energies are transferred through the materials used for the padding (Lu, Qiu, Wang & Dai, 2016). A higher bra neckline also helps to compress the breasts and is more effective for shock absorption (Zhou et al., 2009). With quantification of breast motion, it is now easier for the industry to assess the support function of current designs and develop a more well-rounded bra.

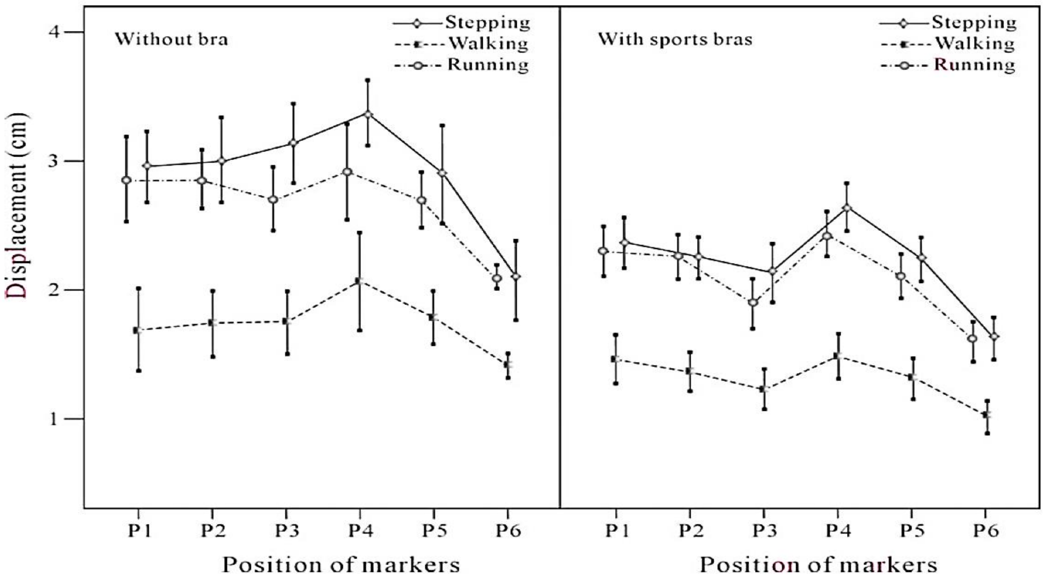


Figure 2.33 Peak vertical breast displacements under different speeds with braless and bra wearing conditions (Zhou et al., 2009)

Notes: P1: inner breast; P2: lower breast; P3: outer breast; P4: bust point; and P5: upper breast

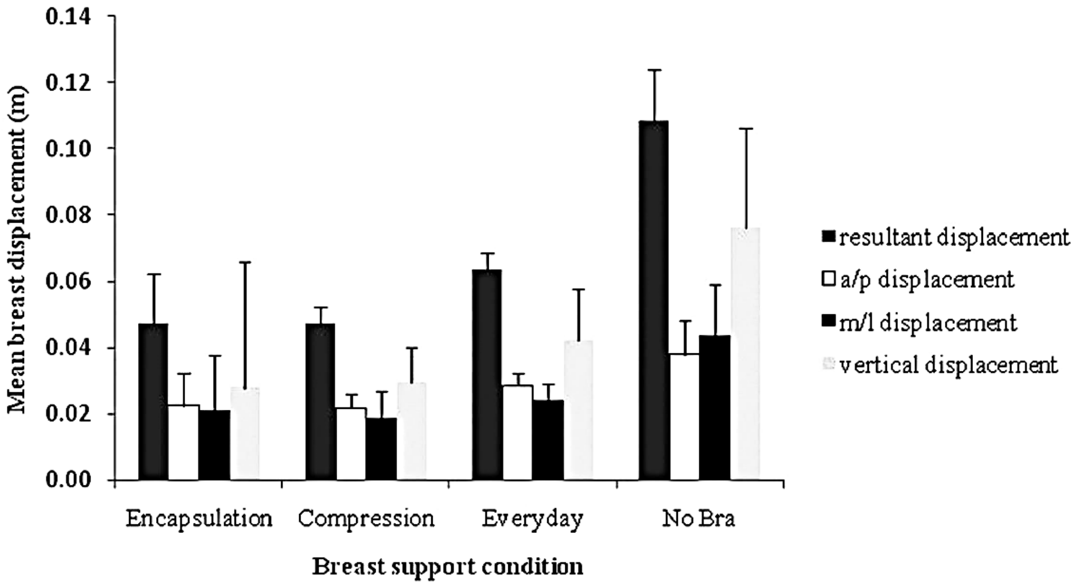


Figure 2.34 Breast displacements during running at 3 m/s in various breast support conditions (White, Scurr & Smith, 2009)

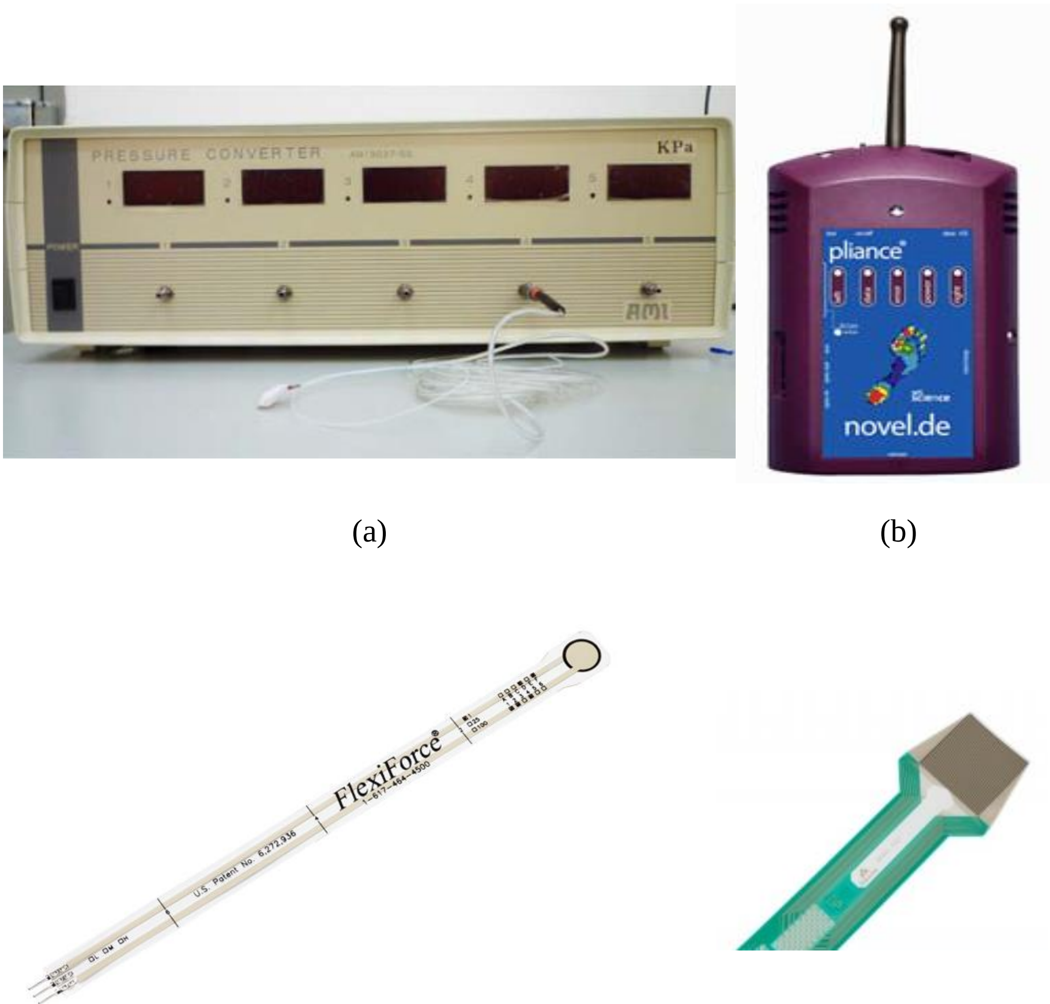
Note: a/p is anterioposterior; m/l is mediolateral

2.5 Evaluation of bra-skin pressure

The tightness and fit of garments directly influence the amount of induced pressure. When tight garments mechanically interact with the skin, the skin senses the compression. Some compression garments are used to prevent deep vein thrombosis. Other examples are knee or elbow braces that athletes use to reduce muscle movement reduction and increase strength and control (Song, 2001). However, garments with excessive compression cause chafing or rashes during daily life or exercise, which creates discomfort. Since bras are a tight-fitting garment and come into direct contact with the skin, excessive pressure may cause discomfort (Nayak & Padhye, 2017). That is, too much compression may result in excessive pressure on the body and affect use of the products. Bras, which are used for support, exert a certain amount of pressure onto the shoulders, breasts and back of the body (Haruko, Hiroko, Tamaki & Kazuo, 1991). Women therefore place high expectations on the wear comfort of their bra. This also affects whether consumers are willing to buy and use a certain bra.

To enhance comfort, ergonomic designs can be applied which would allow protection and thermal comfort, such as in sporting activities and for medical purposes. Ergonomic designs need to consider the interaction of materials and actual application itself (Li, 2001). For example, ergonomic designs can incorporate stretch materials, so that garments can stretch and allow body movement. However, perceived comfort is an individual feeling so that individuals may experience different levels of comfort even under the same environmental conditions. Such subjectivity of comfort might be determined in studies through the use of questionnaires based on a scale (Kilinc-Balci & Elmogahzy, 2008). Since there is an increasing demand for compression or tightly fitting garments, it is important to measure the amount of induced pressure to conduct a more scientific and systematic analysis that would evaluate the pressure comfort of various products, including bras.

The amount of compression induced by a garment can be measured by using pressure sensors. These are now available in the market and widely used to assess the pressure of tightly fitting garments on the body. They can also be used to examine the interfacial pressure between the skin and a garment which is a preferred method of evaluation. There are different ways of doing so. First, there is pneumatic pressure sensing. By placing an air cushion between the clothes and the skin, and then inflating the cushion, the pneumatic pressure inside the air cushion is recorded which shows the clothing pressure. Then there is the hydrostatic method which inserts a liquid filled sensor that is connected to a manometer and measures the hydrostatic pressure variations of a garment (Morooka, Fukuda, Nakahashi, Morooka & Sasaki, 2005; Mitsuno, Makabe, Momota & Ueda, 1991). There is also electrical pressure measurement equipment, including AMI3037 S-5, which is a pressure measuring device, NOVEL Pliance-X® strip sensors which measure pressure on the hands, FlexiForce® which has the capability of measuring force between any two surfaces, and I-scan systems which are flexible and thin sensors that measure the interface pressure between two surfaces (Liu, Chen, Wei & Pan, 2013; Steele, 2013) (Figure 2.35). These sensors are very precise (Macintyre, 2011)



(a) (b)

(c) (d)

Figure 2.35 (a) AMI3037 S-5, (b) NOVEL Pliance-X® strip sensor, (c) Flexiforce® and (d) I-scan sensor

The diameter of a single strip sensor of the NOVEL Pliance-X® pressure sensing system is 10 mm and its surface area is 78.54 mm^2. The thickness of the circular surface is 0.95 mm. The system has been validated as a reliable pressure measurement system with a low interface pressure that can be used to test static conditions (Lai & Li-Tsang, 2009). The strip sensor can be extended to use a non-sensing conductive strip which is more convenient for inserting the sensor into the desired measured points. The sensor can measure a pressure that ranges from 0.5 to 60 kPa with an error within 0.13 kPa. The measured outputs have good repeatability in which the coefficients of variation are less than 0.1. It should be noted that the limitation of this sensor is the need for measurements to be carried out on a flat surface for sensing accuracy.

To measure the bra-skin pressure, the conditions need to be controlled during the respiratory cycle or during walking and running. The points to be measured vary with the focus of the study. Shoulder straps, underwire mid-point and the bra band are in general, critical for measuring the pressure (Makabe, Momota & Mitsuno, 1991). While there are studies that have measured multiple pressure points, some of them have also chosen to use a single point such as the shoulders (Coltman et al., 2015). Figure 2.36 shows the selected points for bra-skin pressure measurements in Peterson and Suh (2016). The average peak pressure (kPa) is usually measured. For sport bras that do not have padded cups, a static pressure of 1.25 kPa at 5 cm below the nipple has been measured in a study by Lu, Qiu, Wang and Dai (2016). Therefore, during higher impact activities such as jumping, the bra may actually induce extra pressure.

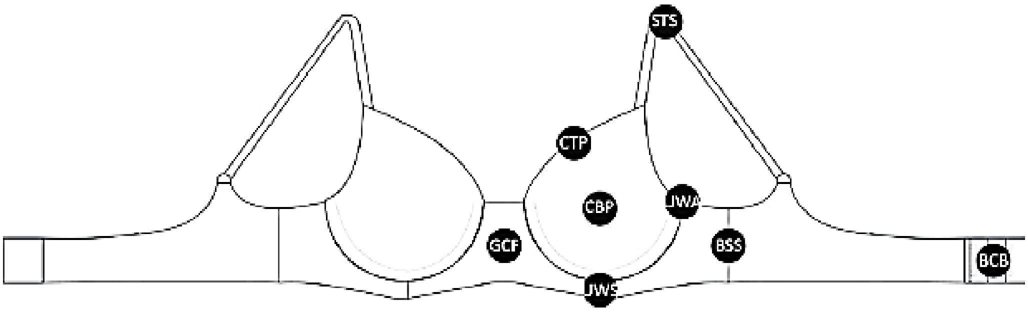


Figure 2.36 Measured points for bra-skin pressure (Peterson & Suh, 2016)

Notes: GCF: Center front gore; UWS: underwire at seam; UWA: underwire at armpit; CTP: top of cup; CBP: cup at breast apex; STS: shoulder strap; BSS: band at side seam; and BCB: band at center back

2.6 Evaluation of geometry of breasts and bra fit

2.6.1 Breast geometry

Since breasts are soft and elastic, it is difficult to find a bra that can exactly fit them because the challenge lies in designing cups that will accommodate all breast shapes (Figure 2.37). Breasts have a diverse physiognomy which means that it is difficult to carry out accurate and repeatable measurements (Westreich, 1997). The development of 3D scanning is therefore advantageous because the technique allows the 3D analysis of the breast shape. However, there are no specific standardized parameters or mathematical equations that apply to all breast size and shapes. Accurate data however would contribute to selecting the correct bra size (McGhee, Ramsay, Coltman, Gho & Steele, 2017).

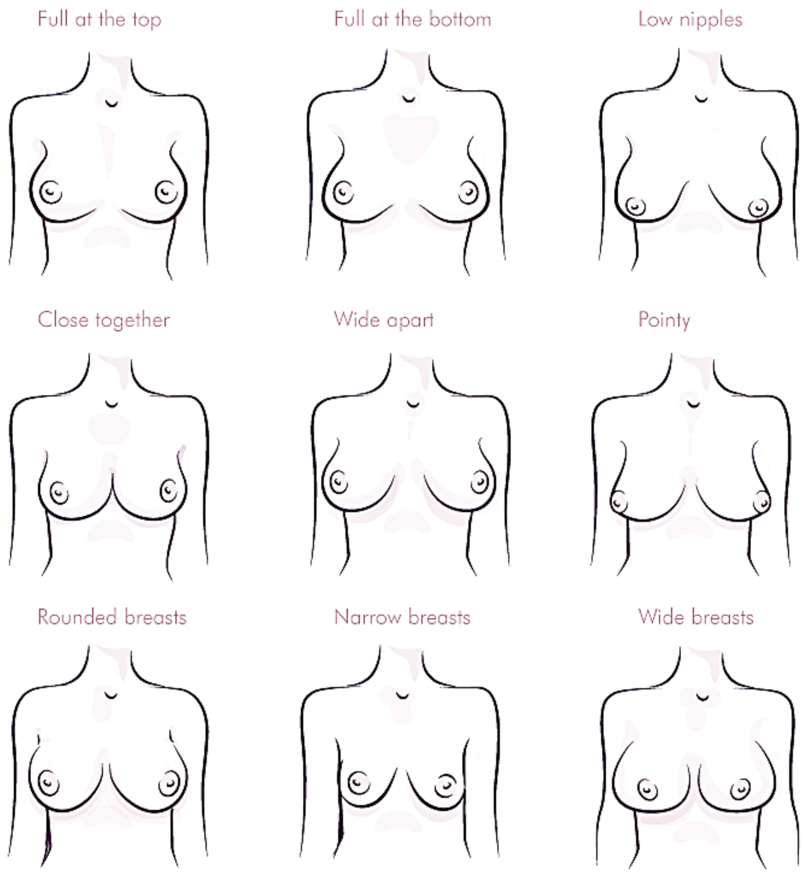


Figure 2.37 Breast shape variations

The curve under the breasts is one of the factors that especially affect bra comfort. The measurement of the curve provides quantified information for bra designs (Daanen & Ter Haar, 2013). However, the definition of the curve under the breasts varies in extracting the breast shape. As well, the boundaries of the breasts affect the accuracy of measuring the breast parts with software (Yip, Mouratova, Jeffery, Veitch, Woodman & Dean, 2012). Besides, scanning of sagging breasts may obscure the bottom line of the breasts which would not be acceptable for underwire design (Lee, Hong & Kim, 2004).

2.6.2 Evaluation methods of breast shape

During the scanning process, it is important that the breasts maintain the same static motion in order to obtain clear images. To identify the outline of the breasts, upward and inward pushing of the breasts may be necessary (Figure 2.38). The same breast may result in different measured volumes due to differences in calculation methods or definition of breast outline. Consequently, the lack of standards in studies on breast shape may lead to difficulties in improving bra designs such as due to the prevalence of bunching (Xing, Ying, Zhang & Lu, 2014). However, breast shape identification and measurements are based on bra sizing and pattern development (Probst, Chopping, Wheat, Harrison & Goyal, 2015). Therefore, a better understanding of the breast shape will allow the intimate apparel industry to modify current designs or use materials that will increase the perceived comfort and support function of bras.

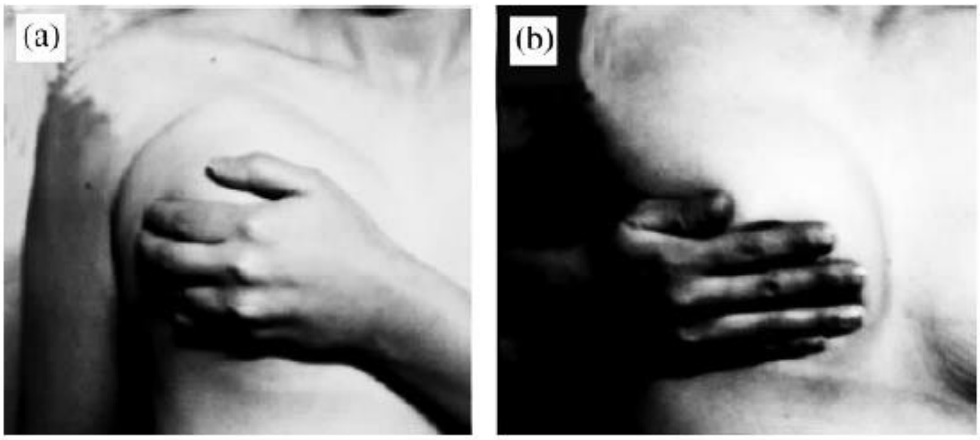


Figure 2.38 Methods for defining breast outline (Lee et al., 2004)

(a) Upward pushing and (b) Inward pushing

The anthropometric method for defining body measurements requires landmarks to be set to calculate the length, volume or dimension in 3D scanning. The placement of these landmarks may vary in different studies (Miyoshi, 2001). Some of the studies place a series of landmarks along the base margin of the breasts with the chest wall or abdominal wall as the line for separating the breasts and body (Yip et al, 2012). The volume is then extracted with a contoured cut plane that involves the real curves of the body shape. In McGhee et al. (2017), the breasts were digitally removed by software, so that only the torso remained with the underbust circumference (Figure 2.39).

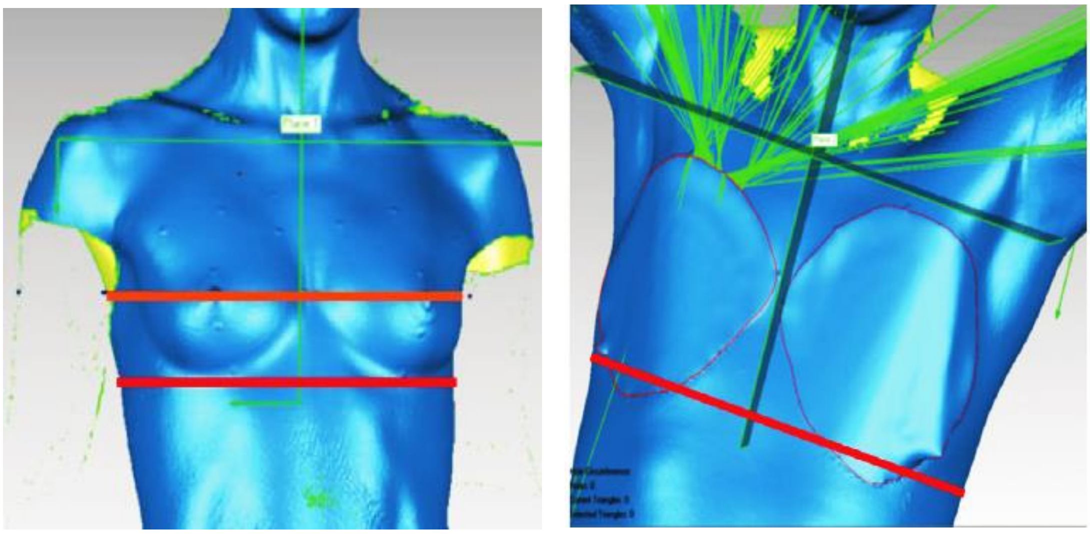


Figure 2.39 Extraction of breast structure from upper torso in 3D scanned diagram (McGhee et al., 2017)

Depending on the research focus, the reference point for the entire breast or line of the curve under the breasts may vary. For breast volume analysis, the reference points may cover the front of the neck, shoulders, upper breast, inner breast, bust, outer bust, bottom of the breast, etc. (Figure 2.40). While there have been many studies that have calculated the breast volume and offer a wide range of breast evaluation results, bra fitting has been comparatively less investigated with the anthropometric method to assess bra design. It is recommended that this method can contribute to future analyses and enhance ergonomic bra designs.

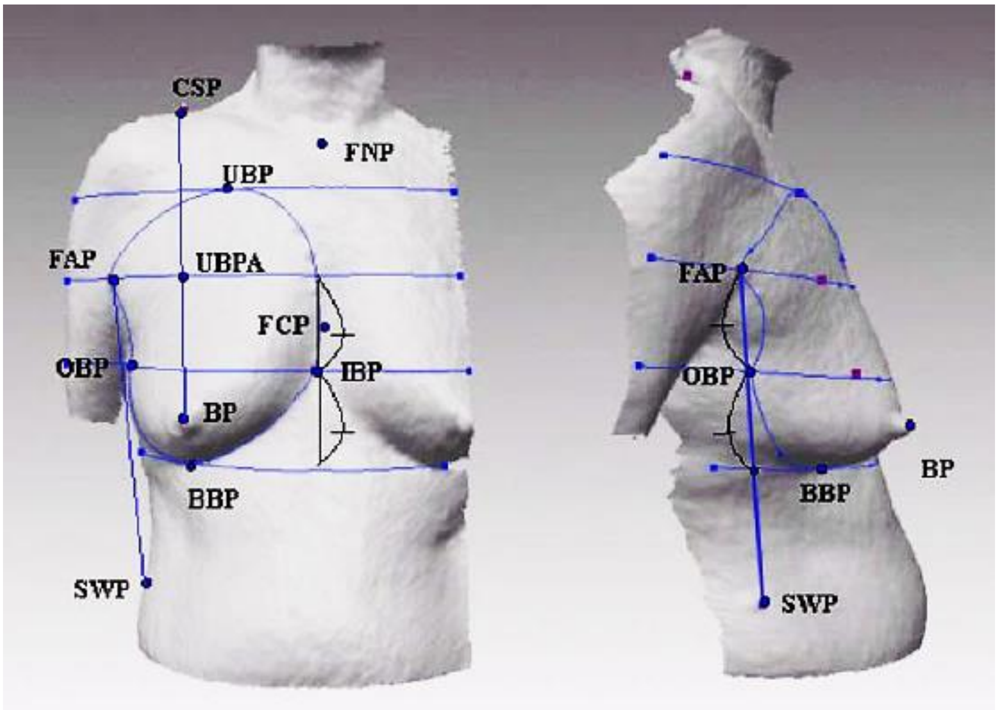


Figure 2.40 Examples of reference points in 3D scanned image of breast structure (Lee et al., 2004)

2.6.3 3D scanning equipment

The geometry of the breasts can be used to increase current understanding on the body contours and improve bra size selection. Three-dimensional scanning also helps to modify the bra cup and underwire designs (Liu, Istook, Li & Wang, 2018; Wu, Yick, Ng, Yip & Kong, 2012). However, breast volume is also important for a good fitting bra cup. Three techniques are commonly used to measure the breast volume: indirect visualization through imaging means such as magnetic resonance imaging (Caruso, Guillot, Nguyen & Greenway, 2006), water displacement, moulding, and anthropometric measurements. Indirect visualization techniques consist of emitted light that is projected onto the breasts and mathematical algorithms applied to compute the breast volume (Sigurdson & Kirkland, 2006). The magnetic resonance imaging measurement completed by sweeping wand around the object and the accuracy is about 1 mm (Yu, Ng & Yan, 2001). Water displacement requires the subject to place her breasts into a container of water and the breast volume is determined by the displacement of the water. Moulding is the use of moulding materials to produce a negative cast of the subject and then water is used to fill the cast to measure the breast volume. However, there are limitations in the breast size that can be measured and the method is difficult to use (Bulstrode, Bellamy & Shrotia, 2001).

Anthropometric measurements are the most recent means of measuring the volume and shape of different breasts. Three dimensional scanning is one of the popular anthropometric methods of data collection to determine the breast volume and evaluate bra fit. The 3D scanner provides accuracy of measuring breast volume with 2.27±0.99% measurement precision with a mean deviation (percentage of mean breast volume) (Kovacs et al., 2007). This technology does not expose the subject to ionizing radiation. Therefore, it is regarded as a quick and safe method for acquiring the breast volume and shape, and more commonly used for breast shape analysis and bra design development. The advantage of using 3D scanners is that it is a rapid means of obtaining consistent and accurate measurements.

Three-dimensional scanners are typically either fixed or handheld devices. The size of the former is relatively large with more mechanical parts while the latter is transportable. Examples of fixed 3D scanners and their processing software include Cyberware WBX scanner with CySlice software (Yip et al., 2012), VITUS smart scanner with ScanWorks XTM software (Chen, LaBat & Bye, 2010), and Cyberware WBX scanner, (Figure 2.41). These capture the full body with coloured images. Full body scanning is mainly used for mass customization and evaluating the fit for the entire body (Fan, Yu & Hunter, 2004). The VITUS scanning system allows visualization with a mesh of up to 16 million triangles but needs to be carried out in dark conditions. The 3D scanned output can undergo further processing to develop products that are an ergonomic fit.

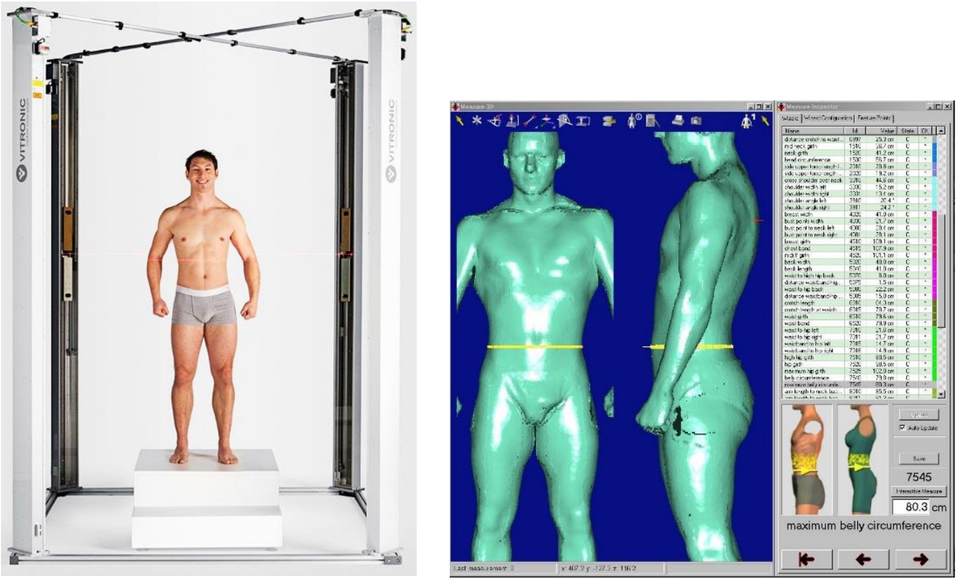


Figure 2.41 VITUS scanning system and software

An example of a handheld scanner is FastScan Artec™ Eva with Geomagic Studio® (Coltman, Steele & McGhee, 2018) or RapidForm software (Lee & Hong, 2007). It is smaller in size and transportable so it can be used in different places for scanning. Scanning does not need to be carried out in the dark because the 3D handheld scanner works by computing scanned data from projected laser light patterns (Fan, Yu & Hunter, 2004). A relatively focused evaluation of small parts of the body with a high resolution can be obtained. The handheld scanning system has also been used for breast related research work (Coltman, McGhee & Steele, 2017; McGhee, Ramsay, Coltman, Gho & Steele, 2017) (Figure 2.42) and the results are preferable on applying to bra designs development. However, the measurements need to be further processed with software with handheld scanners while the fixed scanning system can directly provide basic body measurements right after scanning. Besides, 3D handheld scanners require skill to maintain scanning quality while fixed scanners only require computer knowledge to operate the device.

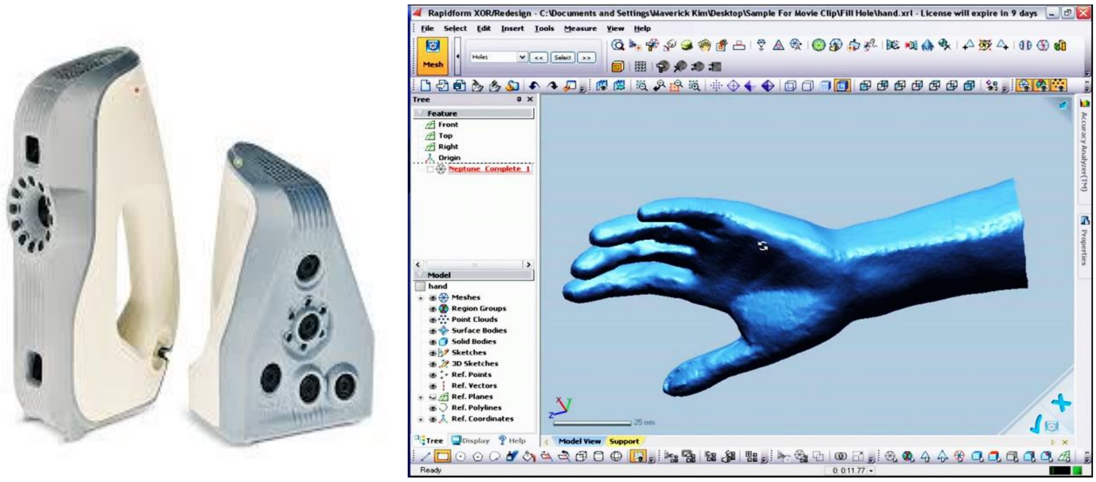


Figure 2.42 Three-dimensional handheld scanner Artec™ Eva with Rapidform software

2.7 Chapter summary

Breasts comprise soft tissues with viscous damping properties. In considering the physical properties of breasts, moulded bras are the most ideal for women in terms of obtaining the best fit, comfort and support function. The literature has shown that bras are a form of external support to reduce breast displacement and provide wear comfort. Therefore, background information on moulded bras and their components has been discussed in this chapter. A brief introduction of 3D printing technology has also been provided to discuss the production method for bra components with an ergonomic design.

Breast motion causes stretching of the connective tissues and skin of the breasts. These could possibly lead to overstretching of the breasts when there is inadequate support and therefore increase discomfort or cause negative health problems. Also, evaluating breast motion, measuring bra-skin pressure and determining the breast geometry have also been elaborated.

The literature review shows that there are research gaps in the support provided by moulded bras and limitations in current analyses on bra-skin pressure. First, current studies on breast motion evaluation rely on human wear trials which cannot be generalized due to variations of subjects. Second, although 3D bra support inserts have replaced or modified traditional underwires to some extent, there are few studies on their support and comfort performance. Third, 3D printing technology may offer a means for rapid prototyping of bras and provide another choice for the bra insert manufacturing. It is therefore crucial to address the effects of bra components in balancing support and comfort. Therefore, a breast motion simulation device is used to test bra functions in this study. The bra components, including the shoulder straps, bra band and underwire, are evaluated. The purpose of embedded support elements is to improve support and level of comfort. The new bra insert prototyping process uses 3D printing technology. In addition, a 3D motion capture system and pressure sensing system are used to assess breast displacement and bra-skin pressure for different bra conditions. It is expected that the formulation of a numerical prediction model can determine the related factors that address the support and comfort performance of bras and advance the ergonomic design of moulded bras. In addition, an innovative new design for a bra insert is also provided to contribute to the development of bra inserts

CHAPTER 3 BRA-SKIN PRESSURE ANALYSIS

3.1 Introduction

Since bras are a closely fitting garment on the body, comfort is one of the major consideration of wearers. However, comfort is relatively subjective when evaluating a bra and its functions. One of the ways that wear comfort can be objectively quantified is to examine the bra-skin (/manikin) pressure. According to van Josson, (2013) and Reilly (2013), the shoulder straps should provide 10-20% of the support to the breasts, with the remaining support provided by the underband. However, inappropriate adjustment of the length of the shoulder straps and underband or different bra components may result in an ill-fitting bra and discomfort. Therefore, pressure measured at critical points on the breasts, shoulders and back will provide a better understanding on the effects of different lengths or bra features. Pressure can also be used to determine the areas that are particularly affected by the bra design features and fabrication materials, such as the shoulder straps, underband, bra cups, etc. Therefore, pressure measurements could very well address the issues around the length adjustment of bras and further contribute to improving bra designs or material selection for bras.

Changeable bras (Luk, Yu, Liu & Suh, 2015) allows the bra components such as shoulder straps, underband and cup material to be easily changed or adjusted. They have been used to evaluate the effects of breast shape, hence reducing the time and potential discrepancies during wear trials (Sun, Yick, Yu, Chen, Lau & Jiao, 2018). To eliminate the inconsistencies that are produced in studies due to human wear trials, such as the different proportions of breast fatty tissues, a soft manikin with breasts and artificial skin is used in this study for bra-manikin pressure measurements. Since the NOVEL Pliance-X® system is commonly used to measure bra-skin (/manikin) pressure, it will be used in this study. This chapter also presents a bra-manikin pressure analysis as well as formulation and validation of a numerical formula to address the project objectives accordingly. Details on the experiment and use of equipment are also discussed here.

3.2 Experimental work

3.2.1 Changeable bra design

In this study, the design of the bra components such as the shoulder straps, bra band, underwire and cup material and their impacts on bra-manikin pressure and breast support were examined. A changeable bra design that allows adjustment of length or replacement of the components in a flexible manner was used (Luk et al., 2015). The shoulder straps, bra band and cup material are attached with metal hooks. This design allows the various components to be changed or adjusted during the experiment and allows the effect of different material properties on bra-manikin pressure and breast support to be evaluated (Figure 3.1). The inter-cup distance was maintained as 10 mm while the width of the shoulder straps (with a straight orientation) and underband was fixed at 1.2 cm in all of the tested conditions.

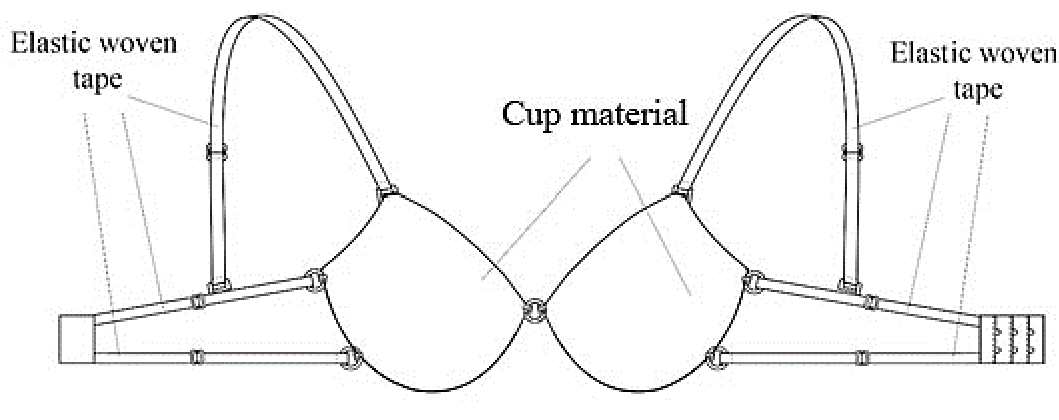


Figure 3.1 Changeable bra

3.2.1.1 Stress-strain of elastic woven tapes

The stress-strain of the elastic woven tapes for fabricating the shoulder straps and bra band was first examined by measuring the Young’s modulus with an Instron 4411 tensile strength tester (Norwood, MA, USA) (Figure 3.2). Two types of elastic woven tapes: EW1 (control) and EW2 were examined and their specifications are listed in Table 3.1. Based on the Standard Test Method for Tension and Elongation of Elastic Fabrics (ASTM D4964), the narrow elastic samples were sewn into a looped shape (ASTM International, 2016). Loads at 30%, 50% and 70% tension strains were measured and used for the calculation of the Young’s modulus of the material.

Table 3.1 Materials specification of tested elastic woven tape samples

Elastic woven tape	Content	Structure	Width	Thickness
EW1 (Control)	Polyester	Woven	1.2 cm	2.5 mm
EW2	Nylon tricot			

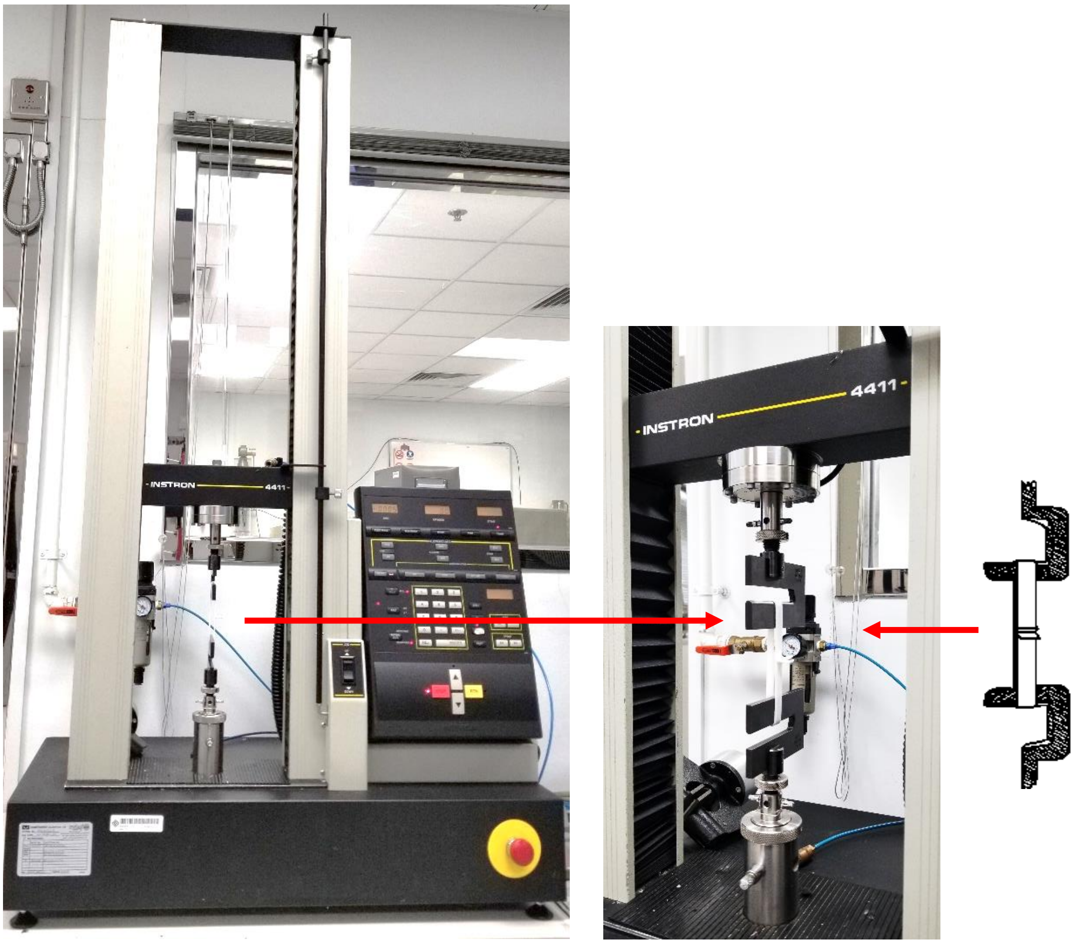
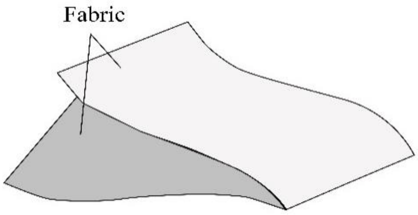
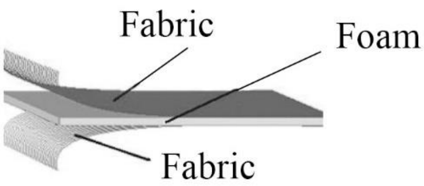


Figure 3.2 Equipment for testing stress-strain of elastic woven tape

3.2.1.2 Stress-strain of cup materials

The cup material of a bra covers and wraps the breasts. In traditional compression bras, rigid bra cups along with tight shoulder straps are used to control excessive breast movement. To assess the effect of the properties of the cup materials on bra-manikin pressure and support performance, the Standard Test Method for Stretch Properties of Textile Fabrics- CRE Method (ASTM D6614) was applied along with the Instron 4411 tensile strength tester (Norwood, MA, USA) (Figure 3.3). As shown in Table 3.2, two types of cup materials including a warp knitted lace fabric (CM1) and a fabric-foam laminated polyurethane (PU) material typically used for moulded bras were sourced for this study.

Table 3.2 Material specifications of tested cup materials

Cup material	Material structure	Thickness	Weight
CM1 (Control)	Warp knitted lace fabric 	0.83 mm	90.48 g/m^2
CM2	Fabric-foam laminated PU material 	4.25 mm	287.04 g/m^2

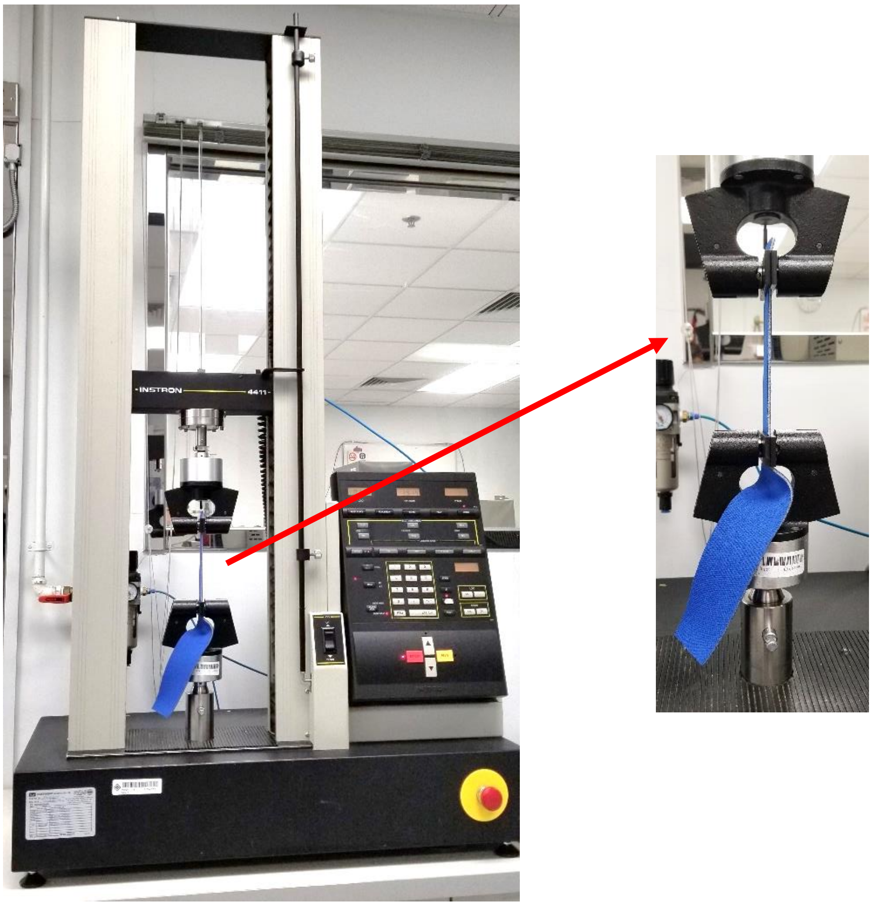


Figure 3.3 Equipment for testing stress-strain of cup material

3.2.2 Soft manikin with breasts

A soft manikin torso with a layer of artificial skin made of silicon was used in this study. Traditional manikins are relatively rigid and do not have an elastic surface. The soft layer of artificial skin therefore provides some flexibility and softness which can simulate human skin. A breast prosthesis could be inserted which can be used to mimic the natural damping motion of the breasts (Figure 3.4). Extended rigid shoulders were attached onto the manikin as the clavicle that serves as the strut between the shoulder blade and the breastbone.

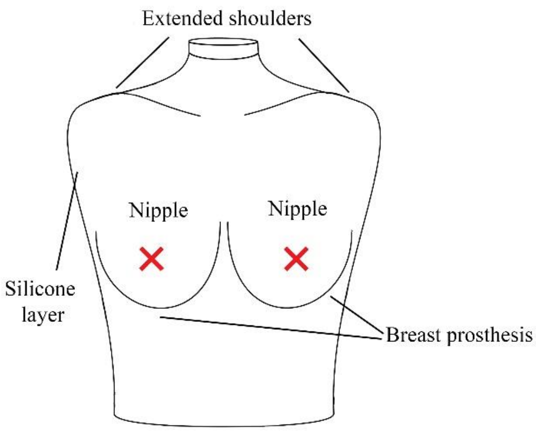
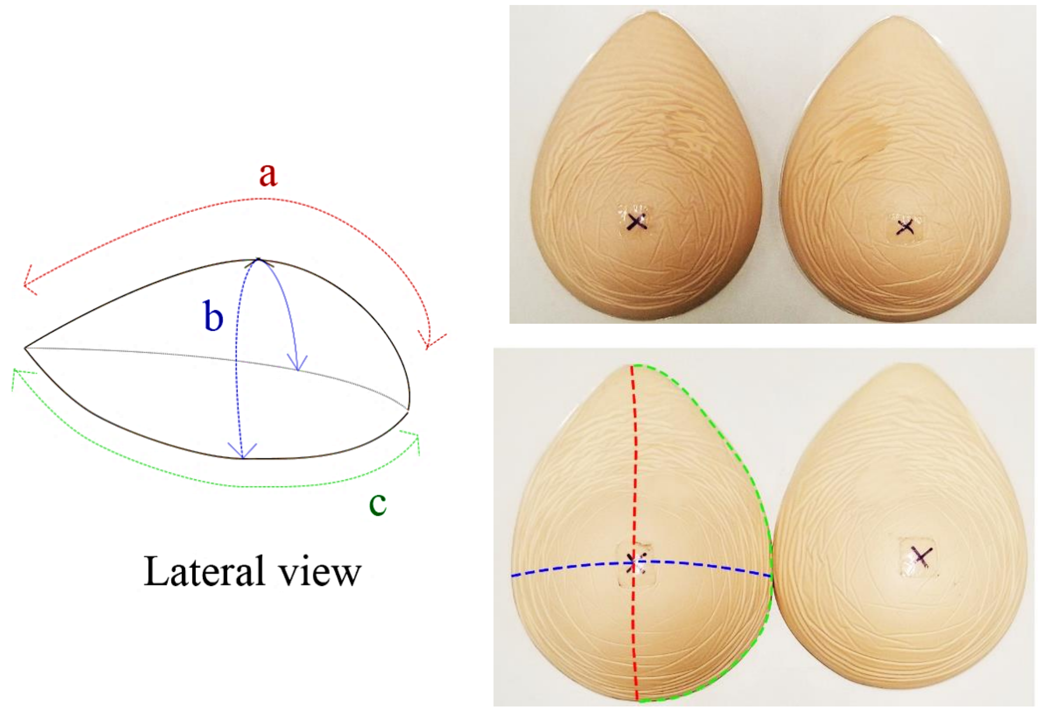


Figure 3.4 Illustration of soft manikin with breasts used in experiment

Breast prostheses with a bra size of 75B (standard size) and 75D (large size) were sourced from Trulife Breastcare (a clinical breast form company) to systematically evaluate the bra-manikin pressure and breast displacement in different bra conditions. The nipples of the breast prostheses (the highest point) were marked (Figure 3.5). The weight and dimensions of the breast prostheses are listed in Table 3.3.



(a) (b)

Figure 3.5 (a) Lateral view of breast prostheses, and

(b) breast prostheses: 75B (top) and 75D (bottom)

Table 3.3 Weight and dimensions of breast prostheses

		Size	
		75B	75D
Weight		206.35 g	357.75 g
Length	a	19 cm	22 cm
	b	15 cm	18 cm
	c	22 cm	24.5 cm

3.2.3 Bra-skin (/manikin) pressure measurement

3.2.3.1 Equipment - NOVEL Pliance-X® pressure system

The NOVEL Pliance-X® pressure system is a highly accurate device. The good repeatability of pressure sensor measurements also helps to obtain accurate bra-manikin pressure values for evaluating bra designs because tension due to tight shoulder straps and underband may result in the straps and band digging into the shoulders and back respectively while increasing the bra-manikin pressure. On the other hand, inadequate tension may lead to falling shoulder straps, an underband that rides up the back, and a bra that provides inadequate support. In this study, the NOVEL Pliance-X® pressure system is used to measure the bra-skin pressure (Bowles & Steele, 2013) (Figure 3.6). This pressure system has been often used to measure the interface pressure between the next-to-skin apparel and the body (Ng, Au and Yu, 2008; Zhang, Yeung & Li, 2002; Zheng, Yu, & Fan, 2009). The flexibility of the sensors allows the sensors to conform to highly contoured sites without wrinkling which is useful for bra-skin pressure analyses (Lim, Ng, Yu, & Fan, 2014).

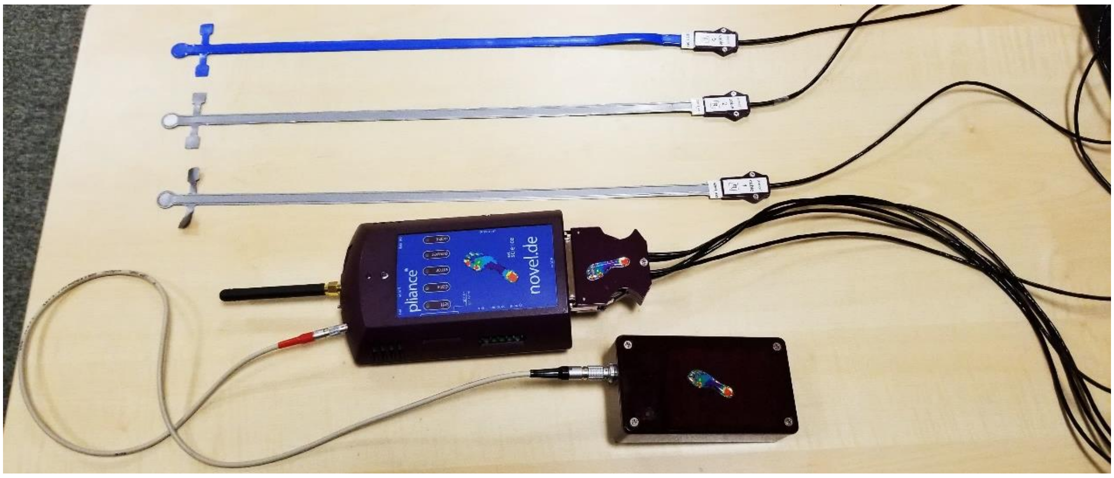


Figure 3.6 NOVEL Pliance-X® pressure system

While bras provide external support and lift the breasts upwards with different components, the design may have areas that induce a greater amount of pressure and therefore affect wear comfort. Six pressure measurement locations were therefore examined in this study, including the gore, start, middle and end of the underbreast / underwire curve, shoulders, and back of the underband (Chan, Yu & Newton, 2001; Peterson & Suh, 2016) (Figure 3.7). A strip sensor with a diameter of 10 mm and area of 78.54 mm^2 was placed between the bra and surface of the soft manikin to obtain the corresponding peak pressure. This capacitive sensor can measure a pressure range of 0.5 kPa to 60 kPa with a measurement error of less than 0.13 kPa (Lai & Li Tsang, 2009). The pressure sensor also had good repeatability with less than 0.1 coefficient of variation. Each condition was continually collected data for five 10 seconds periods and five average peak pressures were recorded.

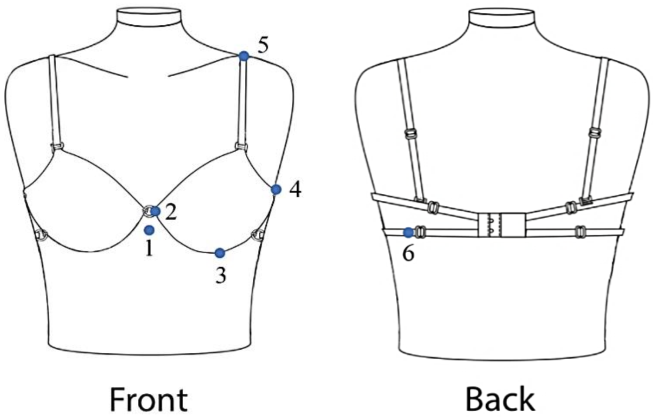


Figure 3.7 Points of bra-skin pressure measured on soft manikin with breasts (1: gore; 2: start of underbreast / underwire curve; 3: middle of underbreast / underwire curve; 4: end of underbreast / underwire curve; 5: shoulders; and 6: back of underband.

3.2.3.2 Testing conditions

The testing conditions of the bra-manikin pressure are described as Experiments A and B, as follows.

(1) Experiment A: Changes in length of shoulder straps and underband

Experiment A aims to evaluate the structural changes of the shoulder straps and underband on the bra-manikin pressure. A total of 15 bra conditions that comprised three lengths of shoulder straps and five lengths of underbands were established (Table 3.4). The shoulder straps were then set to lengths of 38 cm (tightest), 40 cm (best fit) and 42 cm (loosest). Although the underbust girth is 75 cm for both bra sizes of 75B and 75D, a 10 to 15 cm adjustment should be taken into consideration to allow for the best fit of the underband for the soft manikin (Shin, 2007). Thus, the length of the underband could be adjusted from 65 cm (best fit) to 81 cm (loose fit) at 4 cm intervals, in which 4 cm refers to each side of the underband relaxed for 2 cm. A reduction factor was used to identify the range of the adjustment of the underband length of the underbust girth. Based on the recommendations of a bra fitting expert who has been working in the intimate apparel industry for over 6 years, a length of 40 cm of shoulder strap and 65 cm of the underband length was considered to provide the optimal bra adjustment for the soft manikin used in this study based on a fitting trial test from McGhee & Steele's study (2010). An electronic caliper was used to ensure there is no material deterioration of the elastic shoulder straps and underband. Landmarks at 1cm intervals were made on the straps and the underband.

Table 3.4 Bra conditions of various shoulder strap and underband lengths

	Shoulder strap		
Underband [reduction factor]	I (38 cm)	II (40 cm) – best fit	III (42 cm)
A (65 cm) – best fit [-10 cm]	IA	IIA	IIIA
B (69 cm) [-6 cm]	IB	IIB	IIIB
C (73 cm) [-2 cm]	IC	IIC	IIIC
D (77 cm) [+2 cm]	ID	IID	IIID
E (81 cm) [+6 cm]	IE	IIE	IIIE

(2) Experiment B: Material properties of bra components

Experiment B aims to investigate the effects of the material properties of the bra components on bra-manikin pressure and breast motion. As shown in Table 3.5, three additional bra conditions (Bra Conditions X, Y and Z, for 75B and 75D respectively) are used. The components of the bras, including shoulder strap/underband, cup material and underbreast support (underwire) are varied. The bra-manikin pressure obtained from Bra Conditions X, Y and Z was measured and compared with the control.

Table 3.5 Bra conditions with variations in material properties

Bra Condition	**Shoulder strap and underband**	**Underwire**	**Cup material**	
			Wale direction	Course direction
Control	0 (EW1)	0 (Yes)	0 (CM1)	0 (CM1)
X	1 (EW2)	0 (Yes)	0 (CM1)	0 (CM1)
Y	0 (EW1)	0 (Yes)	1 (CM2)	1 (CM2)
Z	0 (EW1)	1 (No)	0 (CM1)	0 (CM1)

Notes: "0" represents the material or condition used in control. "1" represents materials or condition different from control. Yellow highlighted box indicates that bra component has changed for that sample compared to control

3.3 Result and discussion

3.3.1 Bra-manikin pressure distribution

3.3.1.1 Experiment A: Length changes of shoulder strap and underband

Bra-manikin pressure measurements were carried out for bra sizes of 75B and 75D. Tables 3.6 and 3.7 show the bra-manikin pressure measurements for the different shoulder strap and underband lengths of bra sizes 75B and 75D and the control sample. Both bra sizes can be observed to induce different amounts of pressure onto the skin among the tested bra conditions at Points 3 (middle of underwire), 5 (shoulders) and 6 (back of underband).

Table 3.6 Bra-manikin pressure of 75B (control sample)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2. Underwire (start)	0.8	0.5	0.6	0.7	0.6	0.5	0.6	0.5	0.5	0.3	0.3	0.2	0.3	0.2	0.2
3. Underwire (middle)	10.6	10.6	10.5	10.3	10.1	10	9.5	7.6	7.2	7.8	7.5	6.4	6.4	5.9	5.4
4. Underwire (end)	0.7	0.6	0.6	0.6	0.5	0.4	0.5	0.4	0.4	0.5	0.4	0.3	0.4	0.3	0.3
5. Shoulder	8.0	6.3	5.1	6.6	5.7	4.9	6.8	5.9	4.6	6.2	4	3.2	5.1	3.4	2.3
6. Back of the underband	7.0	6.1	5.8	5.0	4.9	5.2	4.1	3.9	3.5	1.5	1.6	1.5	0.5	0.5	0.4

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively.

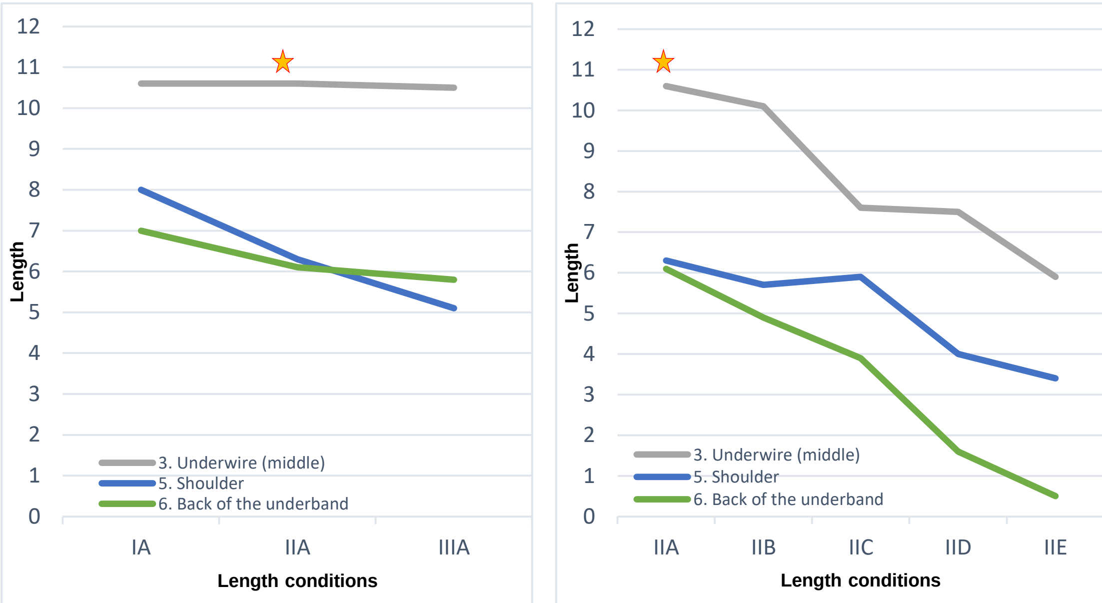
Table 3.7 Bra-manikin pressure of 75D (control sample)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2. Underwire (start)	1.1	0.6	0.8	0.8	0.8	0.6	0.8	0.8	0.6	0.4	0.3	0.2	0.3	0.2	0.2
3. Underwire (middle)	10.6	10.6	10.6	10.4	10.4	10.3	9.8	7.9	7.5	8.2	7.6	6.8	7.3	7.1	5.9
4. Underwire (end)	0.9	0.8	0.5	0.6	0.6	0.4	0.7	0.6	0.3	0.7	0.6	0.4	0.5	0.5	0.4
5. Shoulder	8.0	6.6	5.4	6.8	5.9	5.3	7.1	6.3	4.8	6.5	4.4	3.3	5.5	3.7	2.6
6. Back of the underband	7.3	6.5	6.2	5.3	5.2	5.5	4.4	4.3	3.8	1.7	1.7	1.6	0.6	0.6	0.5

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively.

Figures 3.8 and 3.9 show the effects of the shoulder straps and underband in terms of the pressure exerted onto the skin with bra sizes of 75B and 75D respectively and the control sample. With changes in the shoulder strap length, the greatest amount of reduction in pressure on the shoulders is found among the three selected positions of measurement; i.e., middle of the underwire, shoulders and back of the underband.

While pressure induced on shoulders is reduced from 8 kPa to 5.1 kPa, the bra-manikin pressure at the back of the band is reduced from 6.1 kPa to 0.5 kPa. It should also be noted that the pressure from the underwire (middle) is also reduced from 10.6 kPa to 5.9 kPa. A similar trend of the effects of the shoulder straps and underband was found for bra size 75B with differences in the level of pressure. There is a declining trend in pressure for the increasing underband length.

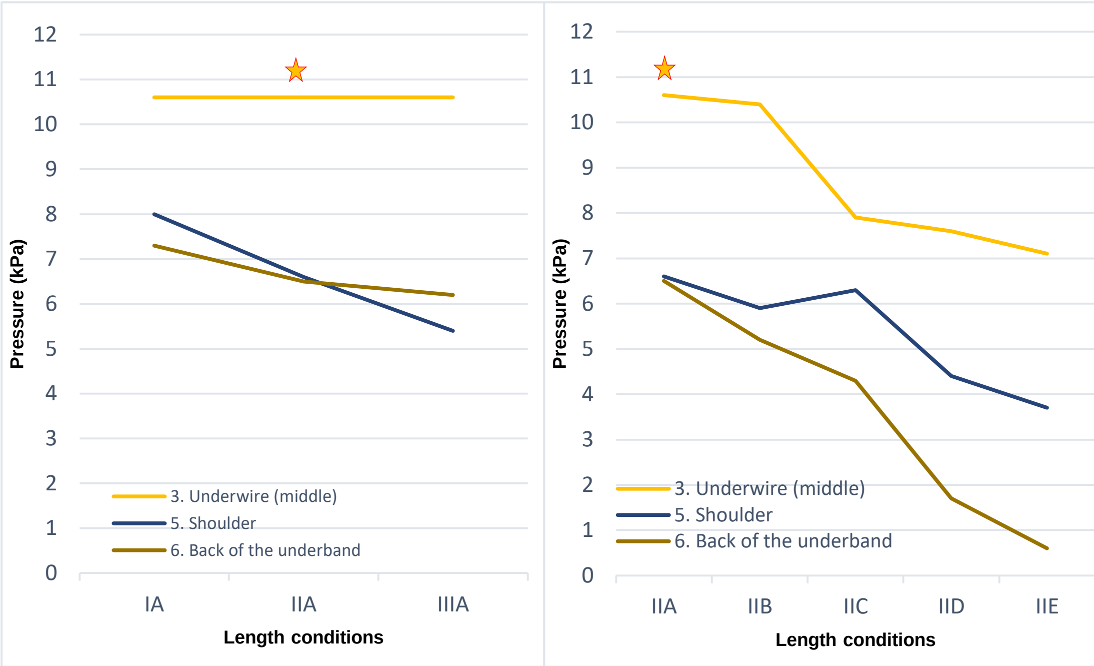


(a) (b)

Figure 3.8 Bra-manikin pressure for 75B with changes in length of (a) shoulder strap and (b) underband obtained from the control sample

Notes: IA, IIA and IIIA refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm respectively with underband length of 65 cm. IIA, IIB, IIC, IID and IIE refer to underband lengths of 65 cm, 73 cm, 77 cm and 81 cm respectively with shoulder strap length of 40 cm.

☆ refers to the best fit with shoulder strap and underband length (IIA)



(a) (b)

Figure 3.9 Bra-manikin pressure for breast size 75D with changes in length of (a) shoulder strap and (b) underband obtained from the control sample

Notes: IA, IIA and IIIA refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm respectively with underband length of 65 cm. IIA, IIB, IIC, IID and IIE refer to underband lengths of 65 cm, 73 cm, 77 cm and 81 cm respectively with shoulder strap length of 40 cm.

☆ refers to the best fit with shoulder strap and underband length (IIA)

The length of the shoulder straps and underband has major effects on the bra-manikin pressure. The results are in agreement with those in Bowles and Steele (2013) who conducted a study with a group of women who have a bra size of 70C and 80D, in that a high range of pressure (5.2 kPa to 10.6 kPa) can be induced by the shoulder straps. In this study, the middle of the underwire induces an exceedingly high amount of pressure for both bra sizes, which ranges from 5.9 kPa to 10.6 kPa. This may be due to the insufficient breast support from the shoulder straps and underband. The forces induced by the weight of the breasts are therefore transferred to the middle of the underwire. A high pressure value was also found for the tighter shoulder strap and underband combinations. Reducing the length of the shoulder straps and the underband in turn reduces bra gapping. However, in doing so, this may affect the original fit of the bra and cause discomfort.

The pressure reduction with shorten underband length may cause increased pressure on shoulder straps or underwire (middle) because the shoulders and underwire now become the primary elements that support the weight of the breasts. For the obtained range of pressure induced on shoulders of the soft manikin with breasts, it was found to approximate the result of a previous study by Coltman, McGhee and Steele (2015) which was 6.2 kPa to 13.8 kPa for a vertical shoulder strap.

When the length of the shoulder strap or underband is reduced, the bra is loosening. There may be a gap between the layer of the skin and the bra of soft manikin with breasts when the length is too long. Inappropriate length adjustment may lead to the problem of a poor fit. This would then lead to grooves on the shoulders, upper body pain and intertrigo (Netsche, Meade, Goodman, Brehm, Friedman & Trornby, 2000). Thus, it is important to have an appropriate amount of length adjustment that takes into consideration the bra component materials or bra design in order to optimize bra support but is also comfortable to the wearer.

Comfort is relatively subjective and therefore problematic when evaluating the bra design to determine the level of comfort. Therefore, the bra-manikin pressure allows comfort to be objectively assessed. Liu, Chen, Wi and Pan (2013) found that the range of pressure induced onto the breasts that does not cause discomfort is 0.96 to 1.35 kPa.

In this study, the measured pressure among the different areas of bra length (Points 3, 5 and 6) is 5.7 ± 5 kPa. Therefore, the bra features in this study do not facilitate length adjustment for a range of pressure that would allow the wearer to feel more comfortable.

3.3.1.2 Experiment B: Material properties of bra components

(1) Stress-strain of elastic woven tapes and cup materials

The initial modulus of a material is the initial part of a stress-strain curve and useful for measuring the resistance when there is a small degree of extension (Hearle & Morton, 2008). The bra-manikin pressure for Bra Conditions X and Y was measured and compared with that of the control. The stress-strain behavior of the elastic woven tapes and cup materials are shown in Figures 3.10 and 3.11 respectively.

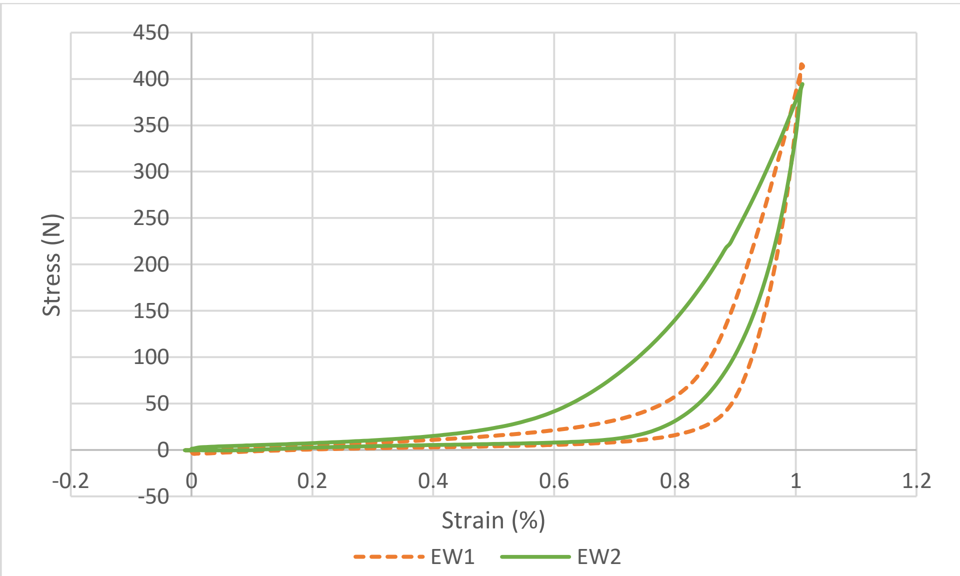
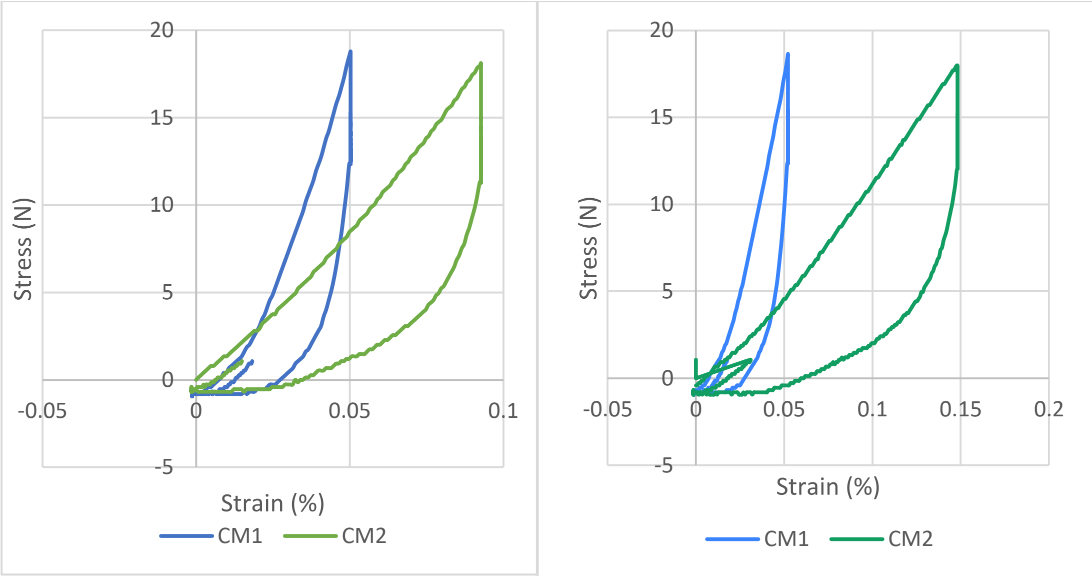


Figure 3.10 Stress vs. strain of elastic woven tapes (EW1 and EW2)



(a) (b)

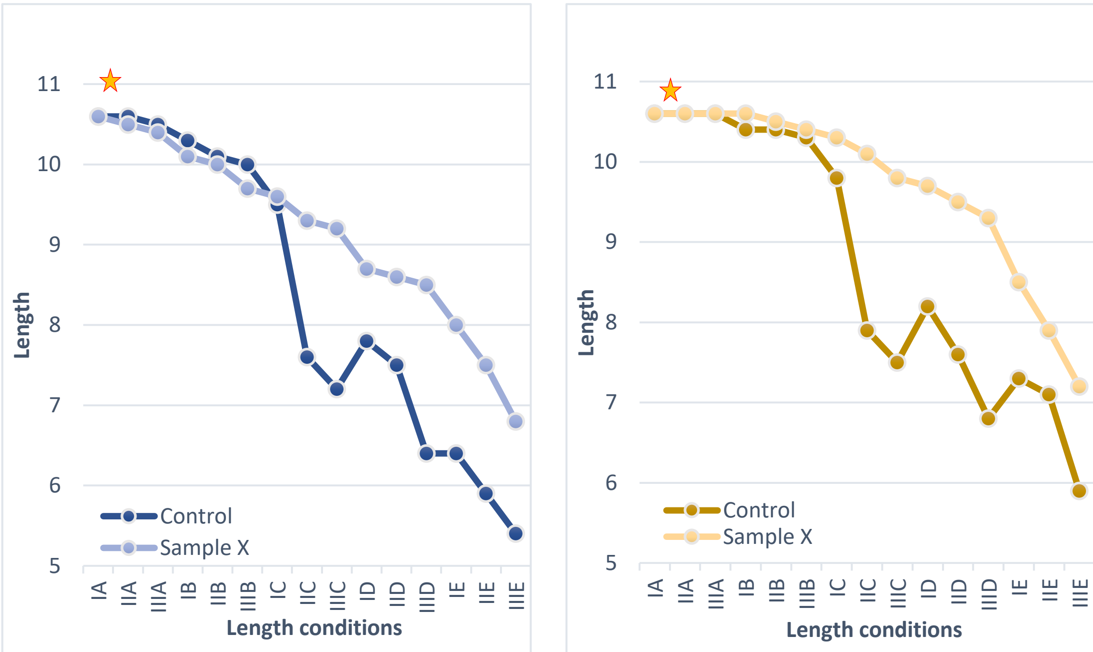
Figure 3.11 Stress vs. strain of cup materials (CM1 and CM2)

(a) wale direction and (b) course direction

As shown, EW2 (Bra Condition X) has a higher Young's modulus of 15.58 MPa with a stiff handfeel as compared to EW1 (control bra) which has a lower modulus of 9.86 MPa and softer handfeel. CM2 (Bra Condition Y) has a Young's modulus of 28.40 N/cm^2 in the wale direction and 18.28 N/cm^2 in the course direction. Compared to Bra Condition Y, the cup panel of the control sample fabricated with CM1 is relatively more rigid with a higher modulus in both the wale (33.36 N/cm^2) and course directions 33.06 N/cm^2). The influence of the material behavior on bra-manikin pressure was then further investigated.

(2) Shoulder strap and underband material

In Experiment A, large difference in the bra-manikin pressure was observed at Pressure Points 3 (middle of the underwire), 5 (shoulder) and 6 (back of the underband). To assess the bra-manikin pressure with different types of shoulder straps and underband materials, the control sample (low modulus elastic material) and Bra Condition X (high modulus elastic material) were evaluated. While the shoulder strap and bra band materials of the control sample has a Young's modulus of 9.86 MPa, the material used for Bra Condition X is 15.28 MPa. The bra-manikin pressure measured at Point 3 (middle of the underwire) of the control sample and Bra Condition X with changes in length is shown in Figure 3.12.

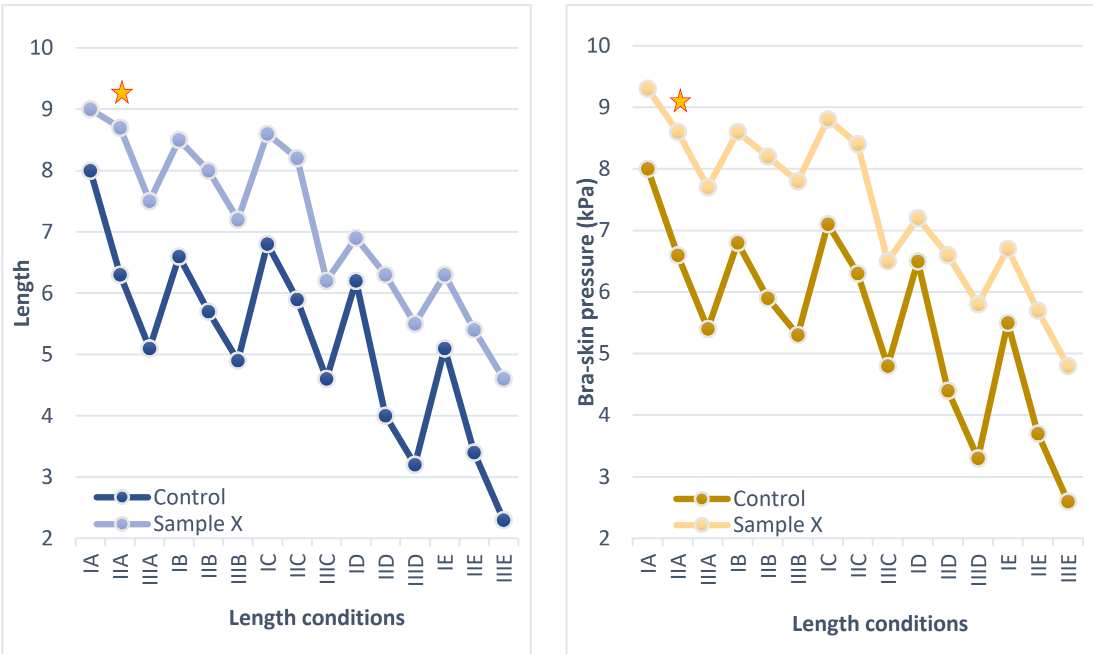


(a) (b)

Figure 3.12 Bra-manikin pressure of bra size (a) 75B and (b) 75D at middle of underwire with changes in length of shoulder strap and underband: control sample vs. Bra Condition X

☆ refers to the best fit with shoulder strap and underband length

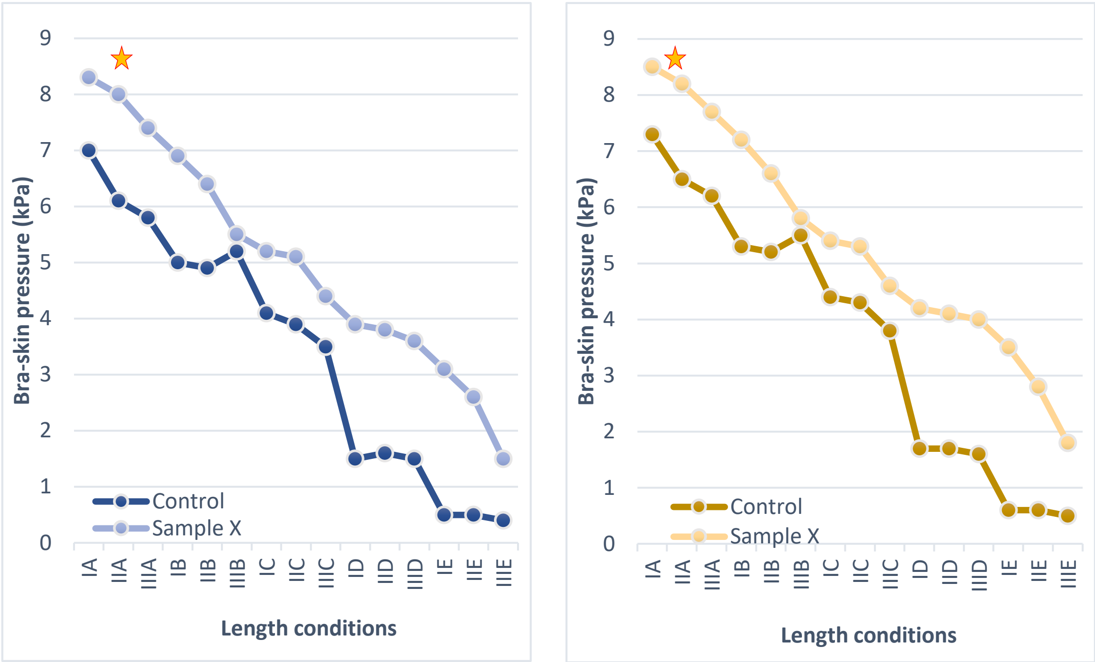
The bra-manikin pressure at the shoulders and underband of the control sample and Bra Condition X with changes in the length of the shoulder strap and underband is presented in Figures 3.13 and 3.14 respectively. As shown, Bra Condition X (a high modulus elastic woven tape) results higher pressure consistently on the shoulders and back of the underband as compared to the control sample, regardless of the length adjustments of both the shoulder strap and underband. The differences in pressure (percentage) between the braless condition of a bra size 75D range from 11% to 85% at Pressure Point 5 (shoulder) and 5% to 484% at Pressure Point 6 (back of the underband). The recorded differences (percentage) are more than 0% to 37% greater than that measured at Pressure Point 3 (middle of the underwire).



(a) (b)

Figure 3.13 Bra-manikin pressure for bra size (a) 75B and (b) 75D at shoulder with changes in length of shoulder strap and underband: control sample and Bra Condition X

☆ refers to the best fit with shoulder strap and underband length (IIA)



(a) (b)

Figure 3.14 Bra-manikin pressure for bra size (a) 75B and (b) 75D at underband at the back with changes in length of shoulder strap and underband: control sample and Bra Condition X

☆ refers to the best fit with shoulder strap and underband length (IIA)

In this study, the use of a high modulus elastic woven tape for the shoulder strap and underband (Bra Condition X) increases the bra-manikin pressure. For bra sizes of 75B and 75D, the magnitude of the bra-manikin pressure is increased by 0.5 kPa to 2 kPa with Bra Condition X as compared to the control sample. The rigid shoulder strap and bra band structure does not readily deform to fit the 3D body contours as opposed to the elastic woven tape used in the control sample which has a low modulus. Rigid materials that are used for sports bras compress the soft breast tissues, thus resulting in a high bra-skin pressure (Li, Zheng & Yeung, 2003). Note that the bra-manikin pressure at Pressure Point 3 (middle of the underwire), 5 (shoulder), and 6 (back of the underband) is consistently higher than the pressure range of 0.96 to 1.36 kPa which is considered to be a comfortable range of pressure as indicated by Liu, Chen, Wei and

Pan (2013), even though the length of the shoulder straps and underband is considered to provide the best fit.

To alleviate the discomfort that bras exert onto the body, particularly for women who have a larger breast size during vigorous exercising, materials with a high Young's modulus are recommended for the shoulder straps and underband. The high modulus could allow an appropriate amount of elasticity so that the chest can expand to take in air (Bowles, Steele & Munro, 2012). The materials may also need to withstand the heavier breast mass with less distortion of the bra band for better support of the breasts.

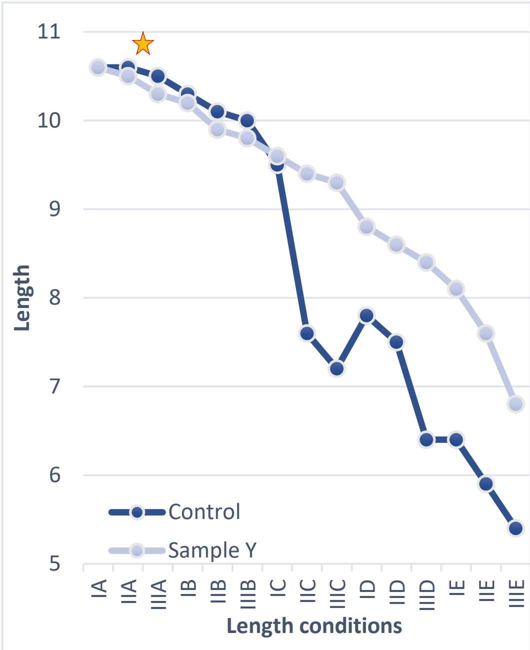
With reference to a study by Yu, Yip, Yick, Luk and Ng (2016), a bra strap could comprise two sections, with each having appropriate elongation and elastic modulus. The front section of the shoulder strap should be highly elongated with a low modulus to preserve comfort during movement. The back section should provide support to the breasts, made of less elongated materials with a high modulus. More recently, Pioneer Elastic (Hong Kong) Ltd invented the Flexi Stretch elastic tape which can stretch from 80 to 160 mm but maintain the same level of elastic modulus. This helps to improve the fit and comfort because the material elasticity is retained during adjustment of the strap length. A balance between comfort and strap function would then be possible.

The traditional straight shoulder strap orientation of bras shows more changes in the bra-skin pressure on the lateral part of the body compared to cross-back shoulder straps. Tension on the upper trapezius is increased with straight shoulder straps compared to cross-backs (Kang, Choi & Oh, 2015). This may cause pain in the upper trapezius (Ryan, 2000). Besides, a wider elastic tape can reduce the bra-skin pressure because the strap or bra band has a larger contact area and the force can be evenly distributed onto the shoulders or to the back (Yu et al., 2016).

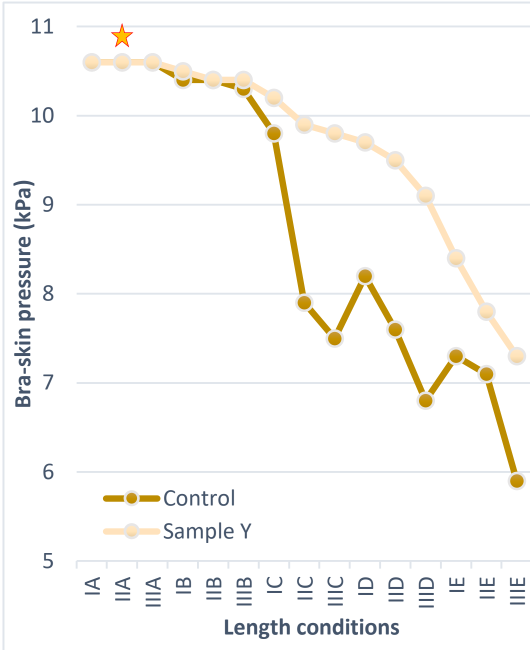
(3) Cup material

The effects of the cup material on bra-manikin pressure are further investigated. Bra Condition Y has a cup material made with a soft flexible fabric-foam laminate and has low stress-strain. The corresponding pressure induced at Pressure Points 3 (middle of the underwire), 5 (shoulder) and 6 (back of the underband) was recorded and compared against that of the control sample.

Figure 3.15 presents the bra-manikin pressure at Pressure Point 3 (middle of the underwire), of the control sample and Bra Condition Y under different lengths. At Pressure Point 3, Bra Condition Y which uses a flexible cup material shows a smaller reduction in the bra-manikin pressure of 3.8 kPa for 75B and 3.3 kPa for 75D when the length of both the shoulder strap and underband is 81 cm (E) versus 5.2 kPa and 4.7 kPa for 75B and 75D of the control sample. Similar pressure values are observed between the bra samples when the underband length is in the appropriate range of A (best fit of 65 cm) and B (69 cm). Compared to pressure measured at middle of underwire and back of the underband, the influence of different types of cup materials on the pressure exerted onto the shoulders is somewhat minimal, see Figure 3.16. In view of the underband pressure, the control shows a lower bra-manikin pressure at the back in comparison to Bra Condition Y (Figure 3.17).



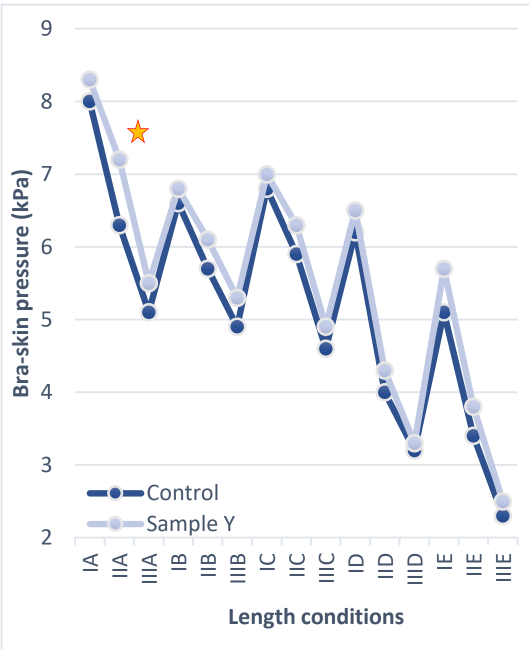
(a)



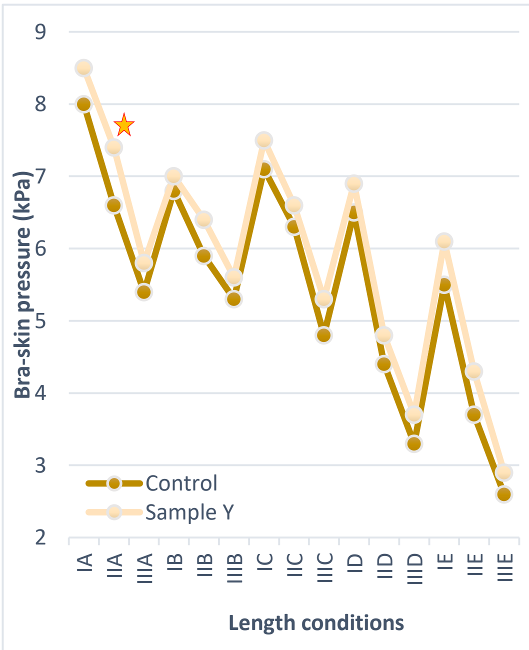
(b)

Figure 3.15 Bra-manikin pressure for bra size (a) 75B and (b) 75D at middle of the underwire of shoulder strap and underband with changes in length: control sample and Bra Condition Y

☆ refers to the best fit with shoulder strap and underband length (IIA)



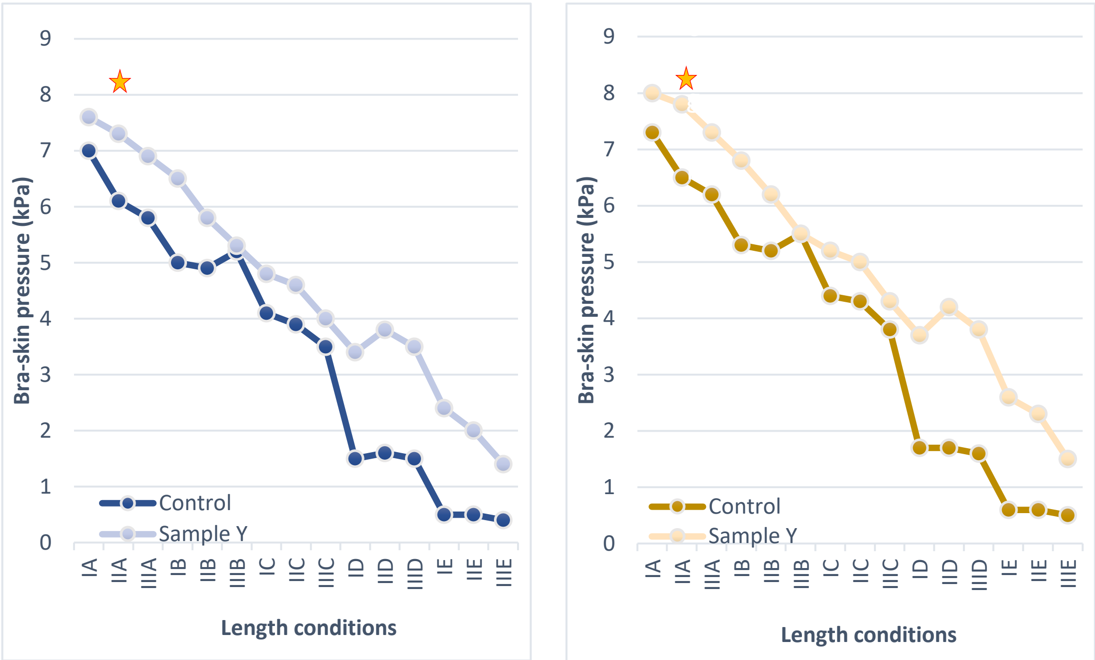
(a)



(b)

Figure 3.16 Bra-manikin pressure for bra size (a) 75B and (b) 75D at shoulders with changes in length of shoulder strap and underband: control sample and Bra Condition Y

☆ refers to the best fit with shoulder strap and underband length



(a) (b)

Figure 3.17 Bra-manikin pressure for bra size (a) 75B and (b) 75D at back of the underband with changes in length of shoulder strap and underband: control sample and Bra Condition Y

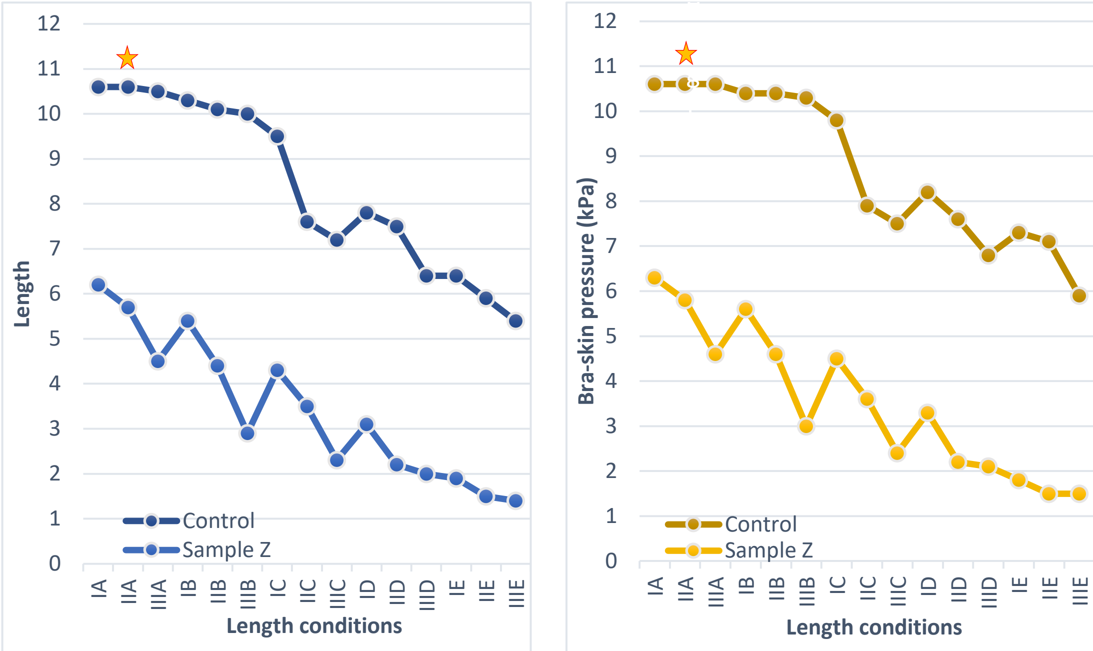
☆ refers to the best fit with shoulder strap and underband length (IIA)

The rigid lace cup exerts a lower bra-manikin pressure than the soft fabric-foam laminated cup regardless of the shoulder strap and underband length. Compared to the length of the shoulder strap and underband, the influence of the rigid cup material on bra-manikin pressure is more significant. As addressed by Haruko, Hiroko & Kazuo (1991), the bra-skin pressure obtained from the lateral top of a 3/4 cup may also be higher than that of a full cup. Since the bra-manikin pressure is greatly affected by human locomotion, more in-depth investigations on measuring dynamic bra-manikin pressure will be reported in the next chapter.

(4) Underwire

The underwire is one of the prevalently found bra components that is inserted into the bottom rim of the cup material and carries the weight of the breasts as well as help to lift up the breasts. However, different shoulder strap and underband lengths may cause ill-fitting problems with the underwire and increase discomfort. If the length is too high, the underwire may shift to an inappropriate position and dig into the chest of the wearer. When the length is reduced, the underwire may not be able to accommodate the contours underneath the breasts.

Figure 3.18 shows the bra-manikin pressure measurements of the control sample (with underwire) and Bra Condition Z (without underwire) with changes in the length of the shoulder strap and underband. The absence of the underwire in Bra Condition Z results in a substantial decrease of the bra-manikin pressure at the middle of the underbreast curve (Pressure Point 3) of 39% to 79% when the shoulder strap is loosened and underband length is reduced. With the tightest shoulder strap and highest underwire length (IA), the pressure is observed to be highest (10.6 kPa) in the control sample. The high pressure could be attributed to the digging of the underwire into the skin. Bra Condition Z has a lower pressure of only 6.2 kPa and 6.3 kPa with the 75B and 75D bra size respectively. There is still a measured pressure for Bra Condition Z even though there is no underwire because there is still contact between the bra wire channel and body.

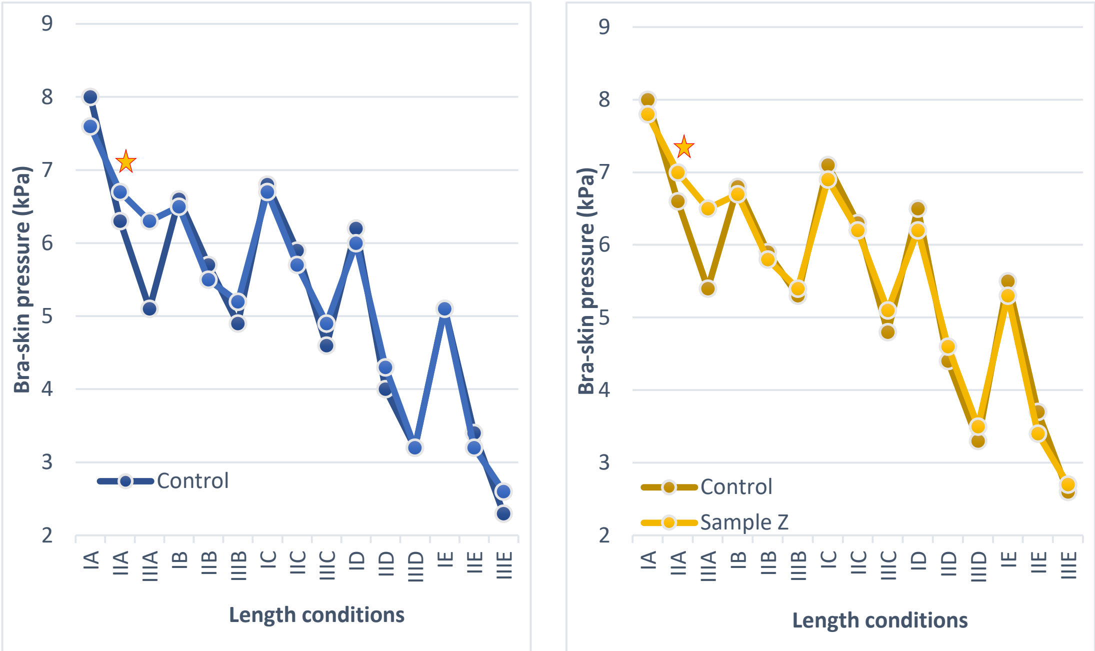


(a) (b)

Figure 3.18 Bra-manikin pressure for bra size (a) 75B and (b) 75D at middle of underbreast / underwire curve with changes in length of shoulder strap and underband: control sample and Bra Condition Z

☆ refers to the best fit with shoulder strap and underband length (IIA)

In Figures 3.19 and 3.20, the influence of the underwire on the measured points of pressure at the shoulders and underband is minimal. The length from the shoulder strap and bra band laterally and vertically bends the underwire to fit the rib cage and accommodate the curvature of the underbreast. The absence of the underwire would not improve the bra fit and reduce the bra-manikin pressure because the weight of the breasts cannot be accommodated by the underwire and redistributed to the body. Therefore, the bra-manikin pressure at the shoulders (Pressure Point 5) and back of the underband (Pressure Point 6) are similar to that on the control sample.



(a) (b)

Figure 3.19 Bra-manikin pressure for bra size (a) 75B and (b) 75D at shoulders with changes in length of shoulder strap and underband: control sample and Bra Condition Z

☆ refers to best fit with shoulder strap and underband length (IIA)

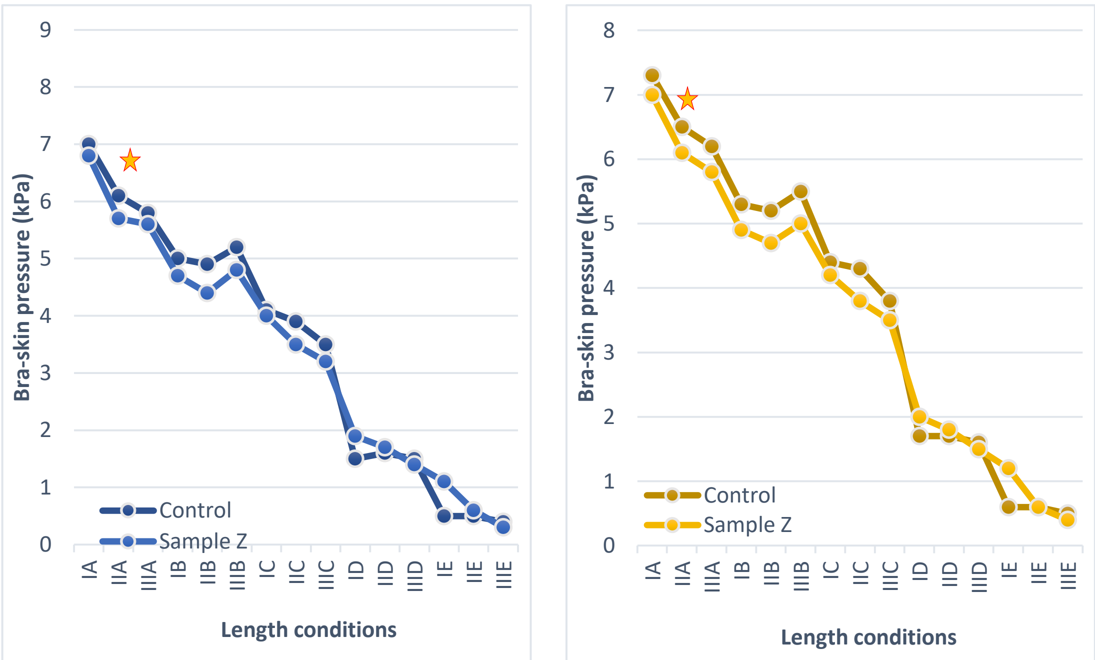


Figure 3.20 Bra-manikin pressure for bra size (a) 75B and (b) 75D at back of the

underband with changes in length of shoulder strap and underband: control sample and Bra Condition Z

☆ refers to the best fit with shoulder strap and underband length (IIA)

The use of an underwire increases the bra-manikin pressure. The function of underwire is to lift up and support the breasts by accommodating the weight of the breasts. In addition, low length of both the shoulder straps and underband would help to reduce the bra-manikin pressure. Nevertheless, when they are too loose, there might be a poor fit. The underwire also cannot transfer the weight of the breasts to the bra band when there is an inappropriate fit (Coltman, Steele & McGhee, 2017). Particularly, underwired bras are not recommended for pregnant women to prevent interfere with milk production because they are too rigid (Page & Steele, 1999). Bra components should be assessed therefore as a whole because they mutually influence each another in terms of the overall bra support and wear comfort (Peterson & Suh, 2016). Although the use of an underwire results in high bra-manikin pressure, the absence of the underwire may lead to poor breast support. To improve the wear comfort, steel underwires could be wrapped with multiple layers of fabric/foam materials in moulded bra designs. Soft plastic underwires are also available for a better fit and more comfort (Lee & Hong, 2007).

3.3.2 Empirical prediction model of pressure

This section discusses the formulation of a prediction model to determine the interface pressure between the bra and the body. IBM software program Statistical Package of Social Science (SPSS) was used for the statistical analysis. Statistical significance was set to a level of 0.05. Correlation analysis was completed to identify the factors that significant correlate with the bra-skin pressure before the formulation of the prediction model. A multiple linear regression analysis was carried out to provide the prediction model for the corresponding measured points with the most affected independent factors.

In the process of formulating the prediction model, the bra-skin pressure at particular points is the dependent variable. Six independent variables including bra size (X_1), shoulder strap length (X_2), underband length (X_3), stress-strain of cup material (X_4), stress-strain of shoulder strap and underband material (X_5) and underwire (X_6) were examined for their influence on predicting the bra-skin pressure. For ease of computation with the SPSS program, most of the length or physical property values of the independent variables were numerically transformed.

3.3.2.1 Formulation

(1) Underbreast / underwire pressure

Independent variable X_6 (r=0.861) shows a strong positive correlation with the bra-skin pressure at the middle of the underbreast / underwire curve, whilst independent variables X_3 (r=-0.433), X_4 (r=-0.345) and X_5 (r=0.347) are moderately correlated with the bra-skin pressure for the middle of the underbreast / underwire curve. The four selected variables above show a significant linear relationship with the underbreast pressure with a *p*-value smaller than 0.05. A relatively high coefficient of determination (r^2=0.943) was found. Over 94% of the variance in the bra-manikin pressure at the middle of the underbreast / underwire curve or Pressure Point 3 can be described by using the tested variables. The prediction equation for the pressure at Pressure Point 3 is as follows (Equation 3.1):

Bra-skin pressure at the middle of the underbreast / underwire curve (3.1)

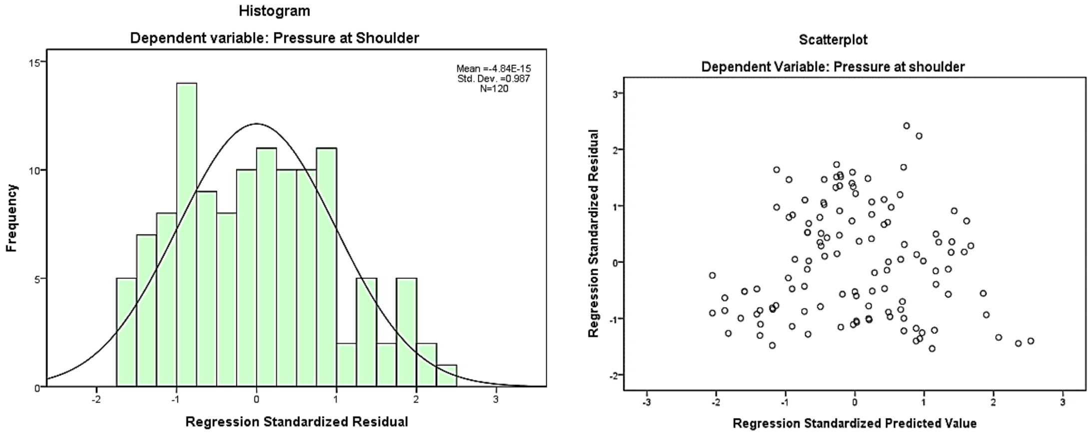
$$= 7.443 + (1.578)\ X_6 + (-0.218)\ X_3 + (0.163)\ X_5 + (-0.180)\ X_4$$

where X_3: underband length; X_4: stress-strain of cup material; X_5: stress-strain of shoulder strap and underband material; and X_6: underwire.

An overall significantly linear relationship of the bra-skin pressure is obtained with the independent variables with a *p*-value of 0.000 ($p<0.05$). The middle of the underbreast / underwire curve supports the majority of the weight of the breasts while the start and end of the underwire hold the underwire in position and help with the fit (Shin, 2007). This is a typical area where the underwire would have the largest correlation with the measured pressure. The insertion of underwire is an independent variable that can influence more than 70% of the pressure in a prediction formula. To further increase the accuracy of the prediction formula, other independent variables are added for a more representative formula.

(2) Shoulder pressure

A moderate correlation is found among the bra-skin pressure and the independent variables X_2 (r=-0.542), X_3 (r=-0.633), and X_5 (r=0.466) while the weak correlation is noted for variable X_6 (r=0.184). After conducting a linear regression model analysis with considering the correlated variable, normally distributed residual data sets of the bra-skin pressure at Pressure Point 5 (shoulder) were obtained. It is important to conduct a stepwise linear regression evaluation so that a prediction formula with the corresponding independent variables can be obtained. Figure 3.21 shows histogram and scatter diagrams that summarize the distributional assumptions and linearity of the dependent variable. There are no major outliers in the regression model.



(a) (b)

Figure 3.21 (a) Histogram and (b) scatter plot of residuals and predicted scores for bra-skin pressure at shoulders

The three independent variables that affect the bra-skin pressure at the shoulders are X_2, X_3 and X_5. They have a significantly linear relationship with the measured pressure with a *p*-value smaller than 0.05. These variables can explain for 91.0% of the bra-skin pressure at the shoulders (r^2=0.910). The prediction formula for the bra-skin pressure is presented as follows (Equation 3.2):

$$\text{Bra-skin pressure at shoulder} = 4.110 + (-0.182)\,X_3 + (-1.079)\,X_2 + (0.323)\,X_5 \qquad (3.2)$$

where X_2: shoulder strap length; X_3: underband length; and X_5: stress-strain of shoulder strap and underband material.

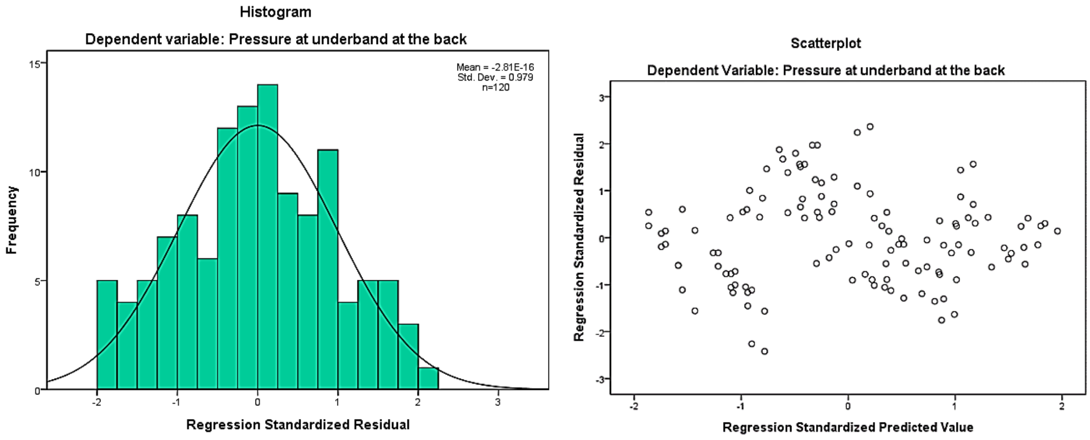
The overall linear relationship of the bra-skin pressure at shoulders is statistically significant (*p*-value < 0.05). There is direct influence on the bra-skin pressure at the shoulders when there the shoulder strap length and the material used are both changed.

The underband length also contributes to pressure changes at the shoulders probably because of the transfer of the weight of the breasts. When the underband does not have sufficient length to accommodate the weight of the breasts, it lowers the ability for underband to redistribute breast weight to the body back. In this case, maintaining the proper position of the bra and support of the breasts relies on the shoulder straps. This results in an increase of the bra-skin pressure at the shoulders.

The underband length, shoulder strap length, and stress-strain of the shoulder strap and underband material are investigated as they are the three most influential independent variables to determine the pressure with the prediction formula. From the model summary of the regression model computation, the coefficient of determination (r^2) is increased from 0.396 to 0.910 by including the shoulder strap length and stress-strain of shoulder strap and underband material. The shoulder strap length and its elasticity help with the upward lifting of the bra and maintain the bra position (Ryan, 2009). Besides, the traditional straight shoulder strap orientation causes scapular downward rotation and discomfort in the upper trapezius (Kang et al., 2015). The lower tensile resistance of the material has been found to reduce the garment pressure (Wang, Chen & Lin, 2011). Changes in the strap length and material properties may have corresponding effects on the downward force or restriction of the strap movement. Therefore, it is reasonable for these two variables to also have a significant impact on the pressure and taken into consideration in the prediction formula.

(3) <u>Underband pressure</u>

After conducting the correlation analysis, independent variable X_3 (r=-0.912) was found to be strongly correlated with the bra-skin pressure while the variable X_5 (r=0.252) and X_6 (r=0.219) showed less correlation with the measured bra-skin pressure. The correlated independent variables are used to formulate the prediction model for Pressure Point 6 (back of the underband) that specifically determines the comfort of the back of the wearer. The remaining data are normally distributed and the collected values are therefore applicable for the linear regression model analysis. The SPSS software generated two diagrams that showed no extreme data for the formulation of the prediction formula (Figure 3.22).



(a) (b)

Figure 3.22 (a) Histogram and (b) Scatter plot of the residuals and predicted scores for bra-skin pressure at shoulders

To assess the bra-skin pressure of the back of the underband, three independent variables X_3, X_5 and X_6 were used to evaluate the bra-skin pressure. A significant relationship was found among these independent variables and the measured pressure (*p*-value < 0.05). The coefficient of determination (r^2) is 0.914. This implies that over 90 % of the bra-skin pressure measured at the back of the underband can be explained by these independent variables. Equation 3.3 is the prediction formula for the bra-skin pressure measured at back of the underband.

Bra-skin pressure at back of the underband (3.3)

$$= 0.869 + (-0.350)\ X_3 + (0.187)\ X_5 + (0.236)\ X_6$$

where X_3: underband length; X_5: stress-strain of shoulder strap and underband material; and X_6: underwire

The prediction formula for the bra-skin pressure at the back of the underband has a significantly linear relationship with a *p*-value that is less than 0.05. The underband length is a typical factor that affects the pressure at the back. If single independent variable X_3 is included in the prediction model, 83.1% of bra-skin pressure can be explained. Almost 90% of the bra-skin pressure can be determined by independent variables X_3 and X_5. This means that the pressure exerted onto the back of the underband is mainly controlled by the material and the fit of the underband.

The bra band is used to link the bra cups and shoulder straps. Unless the bra has a backless design, the bra band is one of the crucial components of bras. Since the bra band helps to support the weight of the breasts and redistributes the downward forces to the back of the wearer, this results in pressure on the back. Thus, it is one of the bra components that easily causes discomfort (Chen, Gho, Wang & Steele, 2016). It is therefore crucial to control the underband length because it would otherwise induce a high amount of pressure onto the body. This may become more serious when the shoulder straps also do not fit well and weight of the breasts cannot be evenly distributed. An overly tight underband would also affect breathing, or cause itching or rashes (Chan et al., 2001). Therefore, it is important to consider the underband length and material properties when predicting the bra-skin pressure.

3.3.2.2 Validation

Two female subjects with a bra size of 75B and 75D were recruited to collect data on bra-skin pressure and the obtained information was used to validate the accuracy of the prediction formula. Both of the subjects have no prior history of breast surgery or injuries. The Human Subjects Ethics Sub-committee at the Hong Kong Polytechnic University approved the experiment. Before the wear trial was conducted, information with a brief introduction on the study and detailed test procedures or arrangements were provided to the two subjects. Written consent for the wear trial was obtained. Six points of measurement including the gore, start, middle and end of the underbreast / underwire curve, shoulders and back of the underband were measured in the wear trial. During measurement of pressure, subjects stood stationary and upright with natural breathing. Same as the manikin pressure measurement, five consecutive 10 seconds periods were recorded for each testing condition. Rest was provided for every 15 minutes.

To determine the relationship between the bra-skin pressures and bra-manikin pressures, a correlation analysis was used and calculated the root mean square error (RMSE) of the pressures measured at middle of underbreast (/underwire) midpoint, shoulder and back of the underband respectively. Pearson correlation coefficients was also examined to reflect the linear relationship strength between the bra-skin pressure and the bra-manikin pressures at the three selected measured points. The coefficient of determination (r^2) was applied to further evaluate the robustness of the data obtained with the soft manikin in the prediction formula to predict actual human conditions.

The correlation coefficients for the relationship between the bra-skin pressure and bra-manikin pressure on middle of underbreast / underwire curve (pressure point 3), shoulder (pressure point 5) and back of the underband (pressure point 6) are ranged from 0.872 to 0.956 (n=150, *p*-value < 0.01 (two-tailed)) respectively. This shows the bra-skin pressure and bra-manikin pressure are highly positively correlated. To further evaluate the discrepancies of the measurement from the soft breast manikin and human subjects, the root mean square error (RMSE) was calculated. The values of RMSE are satisfactory with 1.03 kPa, 0.79 kPa and 0.80 kPa for pressure Point 3, 5 and 6 respectively. The r^2 for the middle of the underbreast (/underwire) is determined to be 0.65. The r^2 for the shoulder is 0.75 and 0.73 to that of back of the underband. The soft manikin shows that approximately 65% to 75% of the bra-skin pressure can be predicted at this three measured points. Coefficient of variation (CV%) is generally less than 5%. The use of the soft breast manikin to measure the bra-manikin pressure is repeatable with consistent result.

The pressure measured at middle of underbreast / underwire curve are has larger differences amongst pressure point 3, 5 and 6 may due to the complex geometry of breast that would cause the variation from individuals and affect the underwire fit and corresponding bra-skin pressure. A reliable simulated pressure at the shoulders can be obtained because of the bony shoulder structure. The artificial skin layer of the upper torso also provides a consistent testing condition to measure the pressure at the back of the underband. Since the soft breast manikin results is used for generating the prediction model, satisfactory representativeness of the soft breast manikin results towards the actual pressure means the subject-specific empirical model are also reasonable for the analysis.

3.4 Chapter summary

In this chapter, an analysis of the bra-manikin pressure has been provided to mainly address two objectives of this study on the bra-skin pressure distribution with different bra features such as cup material, shoulder straps, underband and underwire. A soft manikin with breasts is used to obtain data on the pressure differences with changes in bra components under different lengths. The bra-skin pressure observed to have differences on the middle of the underbreast /underwire curve, shoulders and back of the underband varies with the bra condition. The shoulder strap and underband length, elasticity of the cup material and elastic woven tape, as well as the insertion of an underwire are found to induce interface pressure onto the body. A subject-specific empirical prediction model is then formulated to predict the bra-skin pressure based on six independent variables including the bra size, shoulder strap length, underband length, stress-strain of the cup material, stress-strain of the shoulder strap and underband material and underwire. The prediction formula established on the basis of the soft manikin has a satisfactory result for predicting the bra-skin pressure on human subjects. This support the future use of soft manikins with breasts for assessing bra comfort in bra research work.

CHAPTER 4 BREAST DISPLACEMENT EVALUATION

4.1 Introduction

The breasts have viscoelastic behavior so bras are worn as a form of external support to minimize breast motion and prevent breast injuries. The structure of bras or materials used should offer a balance between comfort and support. Breast displacement is one of the parameters used to quantify the support performance of bras. The displacement of the breasts in the vertical direction is a typically examined displacement direction for evaluating bra support. The support of the breasts is usually realized through the shoulder straps and underband of a bra. However, insufficient shoulder strap and underband length not only result in a poor fit, but also impair the support performance of bras. To quantify the effectiveness of various bra components during locomotion, the magnitude of the vertical breast displacement (including upward and downward directions) in relation to the length changes in the shoulder straps and/or underband, as well as the type of material used for the bra cups are investigated here.

The changeable bra used in Chapter 3 and the testing conditions developed in this study are also used in the breast displacement evaluation in this chapter. A manikin with soft breasts is affixed onto an auxiliary mechanical device to simulate the motion of the torso at slow (2.30 km/h) and fast (4.08 km/h) walking speeds. The use of a dynamic manikin with soft breasts eliminates inconsistencies and improves the testing repeatability for evaluating the support function of bras. A VICON motion capture system is used to capture images of breast movement under a braless condition or with a bra donned which includes several changes in the components. In this chapter, the details of the experimental process to evaluate breast displacement are presented. Breast displacement is systematically measured and analyzed. A numerical prediction formula and validation of the formula for realizing the objectives of this study are also discussed below.

4.2 Experiment work

4.2.1 Manikin with auxiliary device

A soft manikin with artificial skin and breast prostheses (bra sizes 75B and 75D) was used as the human torso in the experiment. An auxiliary mechanical device in a pneumatic system (Figure 4.1) was designed to mimic dynamic human movement (slow and fast walking). The vertical breast displacement under a rapid walking speed of 4 km/h has been analyzed by Haake and Scurr (2011). They concluded that during walking or running, a waveform pattern emerges which shows a range of different wave frequencies and amplitudes of breast displacement (Figure 4.2).

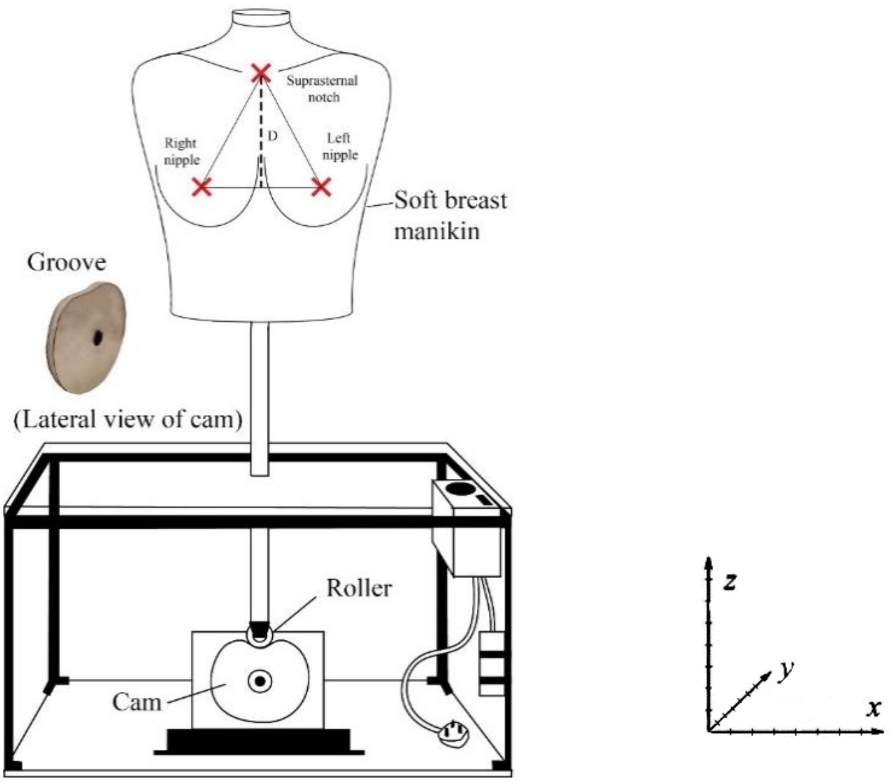


Figure 4.1 Manikin with soft breasts prostheses and torso on auxiliary mechanical device to simulate movement

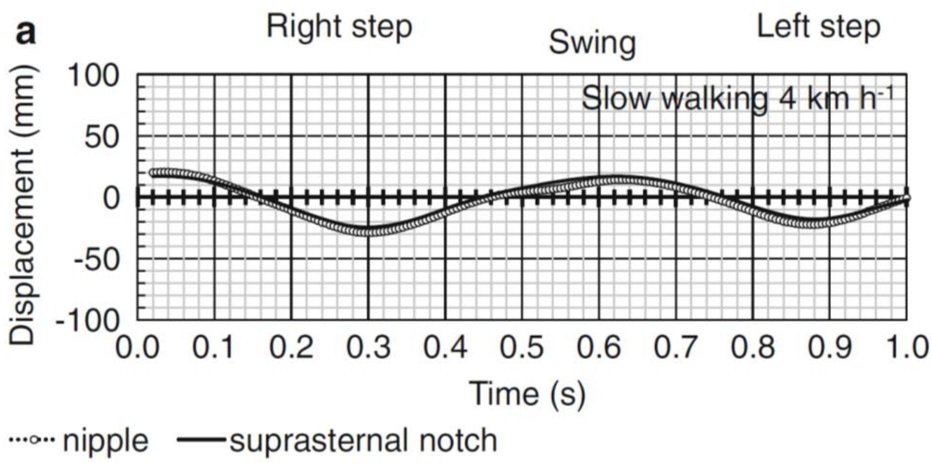


Figure 4.2 Vertical displacement vs. time of suprasternal notch and nipple of subject walking at 4 km/h (Haake & Scurr, 2011)

The displacement pattern can be obtained if the auxiliary mechanical device of the pneumatic system incorporates a cam that is placed below the soft breast manikin.

Using a 3D drawing software called SolidWorks, a circular shaped cam with a groove was created to replicate the breast movement pattern by simulating the movement of the human body. The movement of the cam was controlled by using a cam profile and based on the groove path. The manikin could move up and down continuously with the geometric shape of the cam that follows the groove path, thus corresponding to the heel strike in the gait cycle. Each step taken would be equivalent to 360° (Figure 4.3). The speed of the auxiliary mechanical device (rotation frequency) was controlled by using a motor. Each cycle of the cam movement is equal to half of the gait cycle. The displacement vs. time was plotted. Two maximum peaks in the plotted graph are defined as one completed gait cycle.

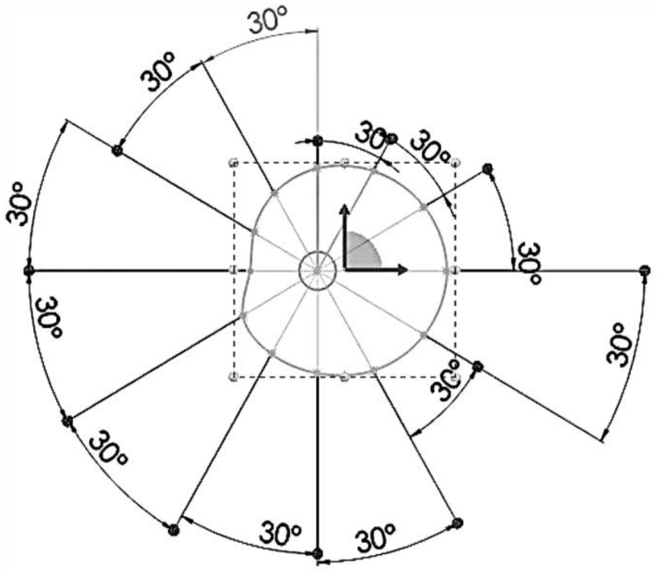


Figure 4.3 Cam design to simulate vertical breast movement

The groove and cam shapes were designed based on the braless condition. Haake and Scurr (2011) had a female subject walk at a speed of 4 km/h in their study and found a vertical breast displacement of 18 mm. When the speed of walking is increased to 7 km/h or more (running), the breast displacement increases to 35 mm. Therefore, the cam profile in this study is developed and designed by taking into consideration the human gait cycle and the corresponding rhythm of human motion. By adjusting the rotation frequency of the motor, walking speeds that range from 2.30 km/h to 4.08 km/h can be simulated. As the gait cycle and human motion considerably change during running (i.e. 7 km/h), a new cam profile would be required for better simulation of the actual breast movement.

4.2.2 Breast displacement measurement

A VICON motion capture system was used in this study to track breast motion and calculate the breast displacement of different bra conditions or activity levels. Eight VICON cameras were placed around a capture area (Lu, Qiu, Wang & Dai, 2016). The sampling frequency was 100 Hz, which means 100 frames were captured every second. The measured volume was calibrated so that the movement of the markers which were placed onto the manikin could be accurately recorded.

4.2.2.1 Marker locations

A total of 9 retro-reflective markers (with a diameter of 14 mm) were attached onto specific areas of the manikin, including the suprasternal notch, left and right nipples, both shoulders, both sides of the ribs, the 7th cervical vertebra (C7), and 10th thoracic vertebrae (T10), to measure the relative displacements of the breasts (Zhou, Yu & Ng, 2012; White, Scurr & Smith, 2009) (Figure 4.4). The nipples are considered to cause the most deviation of the breasts, and therefore the most representative marker position in calculating breast displacement is on the nipples (Milligan & Scurr, 2015).

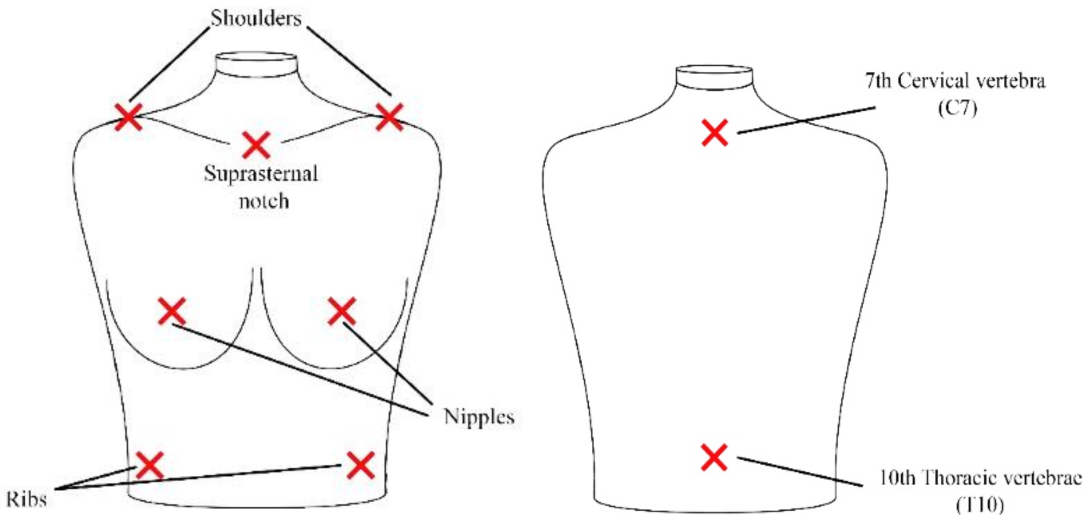


Figure 4.4 Front and back marker placement

4.2.2.2 Test conditions

The braless condition was first evaluated with changes in walking speed and bra size. Based on Section 3.2.3.2, the effects of the length changes in the shoulder straps and underband, and the stress-strain behavior of the shoulder strap and underband material, cup material and insertion of an underwire on controlling breast displacement during motion were systematically studied. A total of 15 testing conditions were designed for Experiment (A) (Table 4.1) on the basis of the control bra sample (which is high stress-strain property of shoulder strap and underband material, rigid cup material and insertion of underwire). In Experiment (B), 3 additional test conditions were taken into consideration. The dynamic manikin with soft breasts was set to move at a walking speed of 2.30 km/h or 4.08 km/h. A minimum of ten cycles were captured in one trial which would be considered a successful trial.

Table 4.1 Shoulder strap and underband length combinations

	Shoulder strap		
Underband [reduction factor]	I (38 cm)	II (40 cm) – best fit	III (42 cm)
A (65 cm) – best fit [-10 cm]	IA	IIA	IIIA
B (69 cm) [-6 cm]	IB	IIB	IIIB
C (73 cm) [-2 cm]	IC	IIC	IIIC
D (77 cm) [+2 cm]	ID	IID	IIID
E (81 cm) [+6 cm]	IE	IIE	IIIE

4.2.3 Breast displacement calculations and statistical analysis

Before recording motion in the different conditions, a series of calibrations needed to be completed to the VICON motion capture system. First, the focus of the 8 cameras was ensured, and the capture direction of the cameras was established with set marker positions. A wand wave was carried out by waving a T-wand. The positioning of the T-wand during the calibration process define the direction of the movement specified in three directions including up and down, left and right, and forward and backward. With both static and dynamic calibrations were conducted, the acquisition of data can be completed and the residuals data were maintained of less than 1 mm. Figure 4.5 shows how the T-ward defines the X (left and right), Y (forward and backward) and Z (up and down) coordinate planes. The corresponding vertical motion of the markers was defined with the Z coordinates of the exported data.

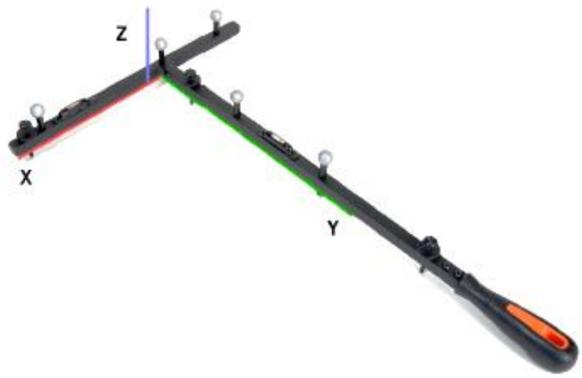


Figure 4.5 Three coordinate planes determined with T-wand

The net vertical displacement of the breasts is defined as the relative displacement between the nipples and the suprasternal notch (Equation 4.1). At time frame i, the change in vertical breast displacement (ΔD_i) is noted to be positive and this means that the nipples are moving away from the suprasternal notch and the breasts are moving downward. A negative (ΔD_i) indicates a reduced distance between these two reference points and the breasts are moving upward.

$$\Delta \mathrm{D_i} = \mathrm{D_i} - \mathrm{D_0} \tag{4.1}$$

ΔD_i- represents vertical breast displacement at time frame i

D_i – represents vertical distance between suprasternal notch and nipple at time frame i

D_0 – represents vertical distance between suprasternal notch and nipple in initial position

Microsoft Excel 2016 was used to generate the displacement-time graphs. The displacement was measured in mm. Statistical Package of Social Science (SPSS) software was used to examine the homogeneity of variance and normality. The significance in data differences between the tested conditions was acquired by using one-way repeated measures analysis of variance (ANOVA) for data evaluation.

4.3 Results and discussion

4.3.1 Breast displacement evaluation

4.3.1.1 Braless condition

The amount of breast motion in the vertical direction is represented by the total vertical breast displacement, and breast displacement in the vertical plane (upwards and downwards). The total breast displacement takes into consideration the vertical displacement and represents the overall breast movement. The vertical displacement of bra sizes 75B and 75D in the braless condition showed a significant difference between the two walking speeds of 2.30 km/h and 4.08 km/h (p-value smaller than 0.05). Figures 4.6 and 4.7 show the vertical breast displacement at 2.30 km/h and 4.08 km/h for both bra sizes. Both are observed to have higher repeating frequency at 4.08 km/h. The repeat of displacement is 0.5 sec and 0.7 sec at 4.08 km/h and 2.30 km/h respectively.

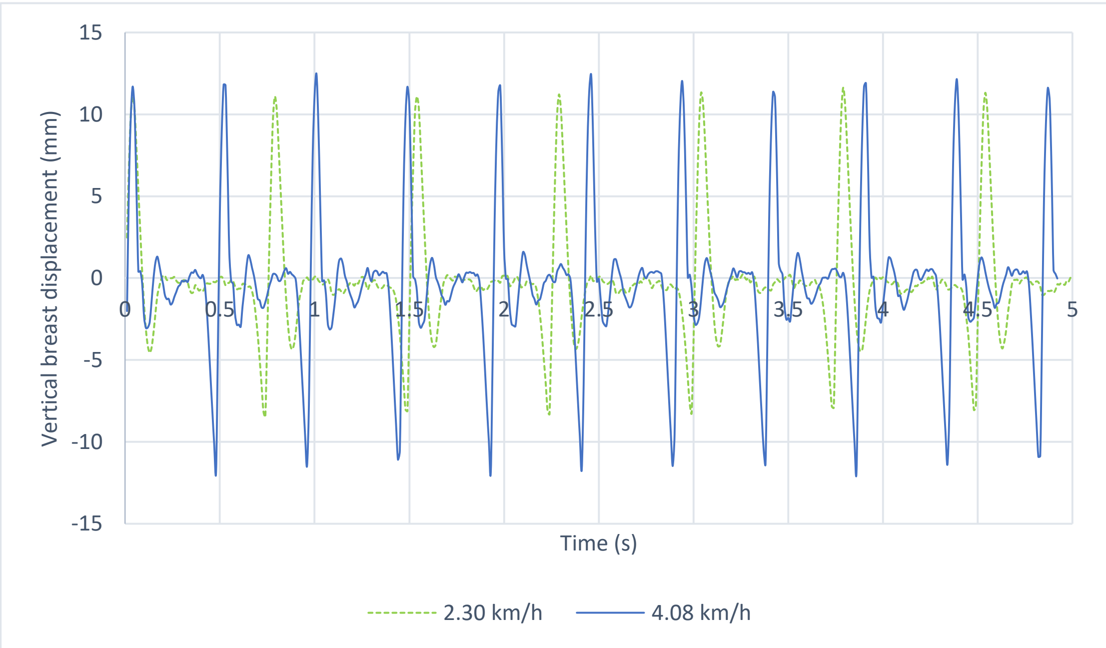


Figure 4.6 Vertical breast displacement vs. time under braless condition for 75B

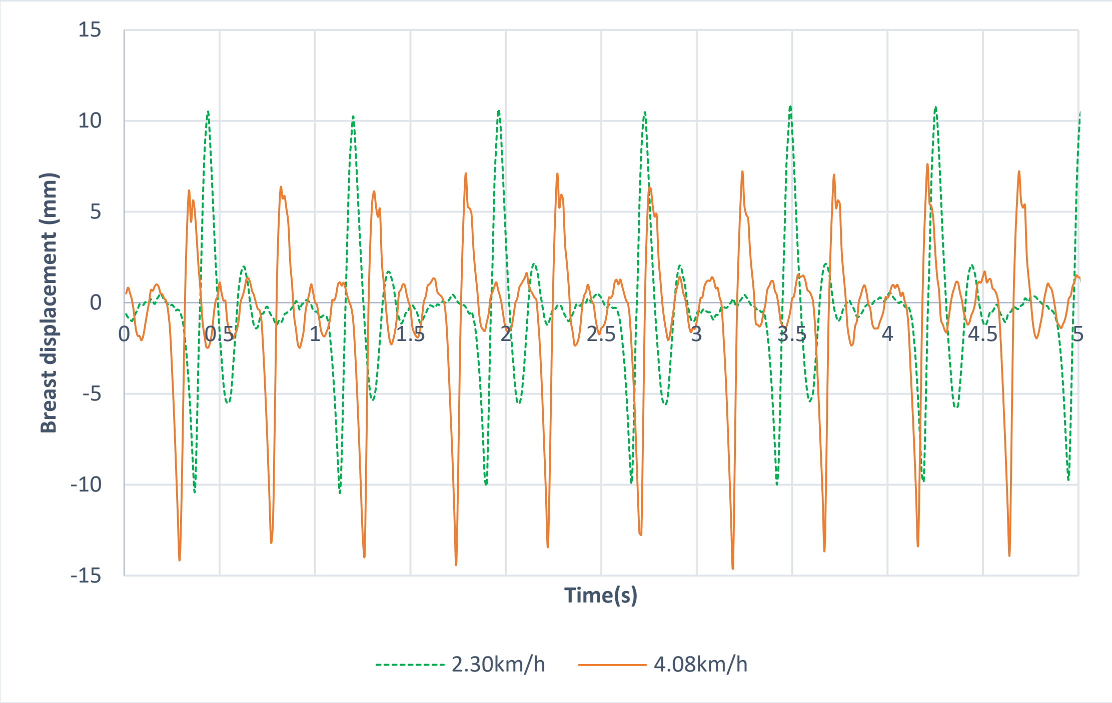


Figure 4.7 Vertical breast displacement vs. time under braless condition for 75D

The breast displacement was calculated in terms of the difference in the distance between the suprasternal notch and nipples. Negative values represent upward movement because there is reduced distance between the suprasternal notch and nipple than in the original position. It was specifically observed that a normal walking speed of 4.08 km/h creates more upward movement than slower walking at 2.30 km/h. The findings are consistent with a study by Mason, Page and Fallon (1999) on breast displacement during walking or running trials at different speeds. A comparable result is also found in Haake and Scurr (2011) for large breasted women who were walking at a speed of 4 km/h in their study, which indicates a vertical breast displacement of 18 mm. Besides, the minimum and maximum peaks in the breast displacement-time graph are in agreement with those of a previous study by Zhou et al. (2012). This shows that the manikin with soft breasts used in this study can simulate the actual breast movement of women.

Moreover, breast oscillations, which are linked to breast deformation, are evident in the displacement-time graph. At a walking speed of 4.08 km/h, there is greater oscillation. Oscillation, which is a constant back and forth movement, balances the forces exerted onto the breasts during faster movement and allows the breasts to revert back to their original state. Larger breasts absorb higher impact forces due to the breast weight and the effects of gravity (McGhee, Steele, Zealey & Takacus, 2012). Both upward displacement and the magnitude of oscillation are greater in comparison to a smaller breast size. Therefore, more external support should be provided for those with larger breasts.

4.3.1.2 Experiment (A): Length changes of shoulder straps and underband

Since the manikin with soft breasts can be used to determine vertical motion displacement, it was used to test different bra conditions so as to assess the effects of the bra components during slow and fast walking speeds. Tables 4.2 and 4.3 show the average vertical values of the total and vertical breast displacements for bra sizes 75B and 75D in comparison to the control sample respectively. Condition IIA which is highlighted in the tables, involves the length that provides the best fitting shoulder strap and underband (at lengths of 40 cm and 65 cm respectively), with the least total vertical breast displacement at 2.30 km/h and 4.08 km/h.

Compared to the braless condition, the total vertical breast displacement with the best fitting combination of shoulder straps and underband is reduced 24% to 33%, particularly in terms of upward breast movement (59% to 67%) for a bra size of 75D. The total vertical breast displacement is 22.31 mm to 15.85 ± 2 mm at 2.30 km/h for the different combinations of length, whilst the reductions in displacement at 4.08 km/h are comparatively less (20.11 mm ± 3 mm). Similar trends with greater reductions in breast displacement can be observed with the smaller bra size. The percentage of the reduction is more, with a reduction of 31% to 63% in the total vertical breast displacement for the two walking speeds.

Table 4.2 Vertical breast displacement for 75B braless condition vs. control sample

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.31 (0.8)	11.83 (1.39)	-8.48 (0.87)	20.82 (0.42)	11.16 (0.47)	-9.66 (0.36)
IA	7.65* (0.54)	6.01* (0.66)	-1.63* (0.75)	15.26* (0.75)	11.38 (0.84)	-3.88* (0.25)
IB	8.04* (0.35)	6.28* (0.5)	-1.76* (0.58)	14.60* (0.56)	11.78 (0.49)	-2.82* (0.34)
IC	8.90* (0.5)	7.08* (0.63)	-1.82* (0.38)	17.00* (0.62)	14.15* (0.67)	-2.85* (0.35)
ID	11.45* (0.38)	9.05* (0.49)	-2.40* (0.33)	17.27* (0.67)	14.32* (0.55)	-2.95* (0.24)
IE	11.07* (0.28)	8.52* (0.46)	-2.54* (0.42)	17.52* (0.92)	14.32* (0.47)	-3.20* (0.76)
IIA	7.55* (0.26)	6.04* (0.27)	-1.51* (0.27)	14.27* (0.67)	11.52 (1.11)	-2.76* (0.78)
IIB	8.96* (0.35)	7.39* (0.51)	-1.57* (0.34)	15.06* (0.58)	12.52* (0.53)	-2.55* (0.25)
IIC	9.28* (0.81)	7.21* (0.99)	-2.07* (0.41)	16.69* (0.61)	13.94* (0.61)	-2.75* (0.28)
IID	10.48* (0.28)	8.35* (0.43)	-2.13* (0.34)	16.58* (0.62)	13.56* (0.64)	-3.02* (0.31)
IIE	11.24* (0.52)	8.42* (1.18)	-2.81* (0.93)	17.64* (0.99)	14.04* (0.55)	-3.60* (0.85)
IIIA	7.72* (0.36)	6.08* (0.4)	-1.63* (0.45)	14.37* (0.7)	11.66 (0.56)	-2.71* (0.27)
IIIB	9.53* (0.41)	7.64* (0.74)	-1.88* (0.67)	15.82* (0.59)	13.17* (0.51)	-2.65* (0.21)
IIIC	10.22* (0.7)	8.11* (0.87)	-2.11* (0.37)	17.36* (0.86)	13.88* (0.71)	-3.48* (0.29)
IIID	10.40* (0.25)	8.41* (0.33)	-1.99* (0.3)	16.51* (0.67)	13.54* (0.66)	-2.97* (0.34)
IIIE	10.98* (0.36)	8.52* (0.38)	-2.47* (0.26)	17.58* (0.44)	13.93* (0.55)	-3.65* (0.37)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. *p-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

Table 4.3 Vertical breast displacement for 75D braless condition vs. Control sample

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.87 (0.28)	11.18 (0.41)	-9.69 (0.29)	22.31 (0.71)	8.6 (0.43)	-13.71 (0.6)
IA	15.70* (0.58)	11.23 (0.18)	-4.46* (0.58)	17.90* (0.37)	12.99* (0.56)	-4.91* (0.48)
IB	13.98* (0.33)	10.01* (0.28)	-3.97* (0.47)	19.54* (0.3)	13.43* (0.48)	-6.11* (0.46)
IC	15.70* (0.33)	11.23 (0.24)	-4.46* (0.42)	20.71* (0.34)	14.06* (0.65)	-6.65* (0.43)
ID	16.49* (0.49)	11.18 (0.27)	-5.31* (0.39)	20.63* (0.92)	12.85* (0.74)	-7.78* (0.83)
IE	17.94* (0.55)	11.70* (0.25)	-6.24* (0.54)	20.77* (0.42)	12.65* (0.55)	-8.12* (0.78)
IIA	13.98* (0.48)	9.97* (0.21)	-4.01* (0.43)	16.96* (0.39)	12.40* (0.46)	-4.56* (0.47)
IIB	14.51* (0.38)	9.90* (0.36)	-4.60* (0.61)	18.47* (0.28)	12.62* (0.35)	-5.85* (0.26)
IIC	15.23* (0.29)	10.76 (0.17)	-4.46* (0.36)	20.16* (0.3)	13.22* (1.11)	-6.94* (0.94)
IID	16.97* (0.42)	12.03* (0.24)	-4.94* (0.4)	24.30* (1.21)	14.96* (1.07)	-9.34* (0.47)
IIE	17.08* (0.48)	11.42 (0.18)	-5.66* (0.49)	22.31 (0.87)	13.36* (0.98)	-8.95* (1.01)
IIIA	14.39* (0.58)	10.02* (0.18)	-4.38* (0.58)	19.24* (0.92)	13.47* (0.32)	-5.77* (0.93)
IIIB	15.70* (0.39)	10.66* (0.35)	-5.05* (0.53)	19.46* (0.21)	12.78* (0.4)	-6.67* (0.42)
IIIC	13.84* (0.47)	9.71* (0.37)	-4.13* (0.37)	19.68* (0.23)	12.80* (0.33)	-6.87* (0.4)
IIID	17.72* (0.48)	11.60* (0.16)	-6.13* (0.41)	20.52* (0.4)	12.27* (0.73)	-8.26* (0.5)
IIIE	18.49* (1.03)	12.83* (1.14)	-5.65* (0.28)	20.94* (0.32)	12.43* (0.69)	-8.52* (0.73)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. *p-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

To investigate the effects of the shoulder straps and underband, the breast displacement of the two bra sizes at a normal walking speed of 4.08 km/h was further analyzed (Figures 4.8 and 4.9). The bra that provided the optimal shoulder strap and underband length (at lengths of 40 cm and 65 cm respectively) significantly reduces the upward and total breast displacement when compared to the braless condition (p -value < 0.05). Figures 4.10 and 4.11 show the effects of the underband length on vertical breast displacement. A significant reduction in controlling the breasts is found for the total, upward and downward displacements when there is shorten underband length (p-value < 0.05).

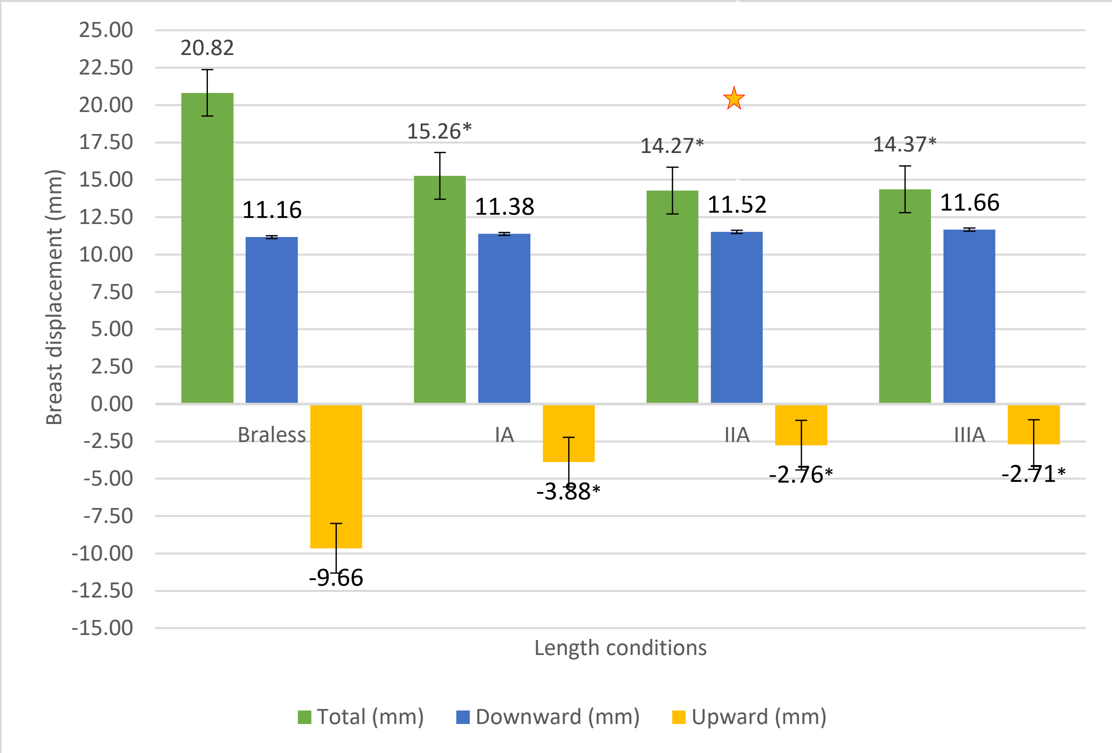


Figure 4.8 Vertical breast displacement with different lengths of shoulder straps during fast walking for 75B vs. control sample

Notes: IA, IIA and IIIA refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm respectively with underband length of 65 cm. * p -value < 0.05 as compared to IIA with optimal shoulder strap length (40 cm).

☆ refers to the best fitting shoulder strap and underband length condition (IIA)

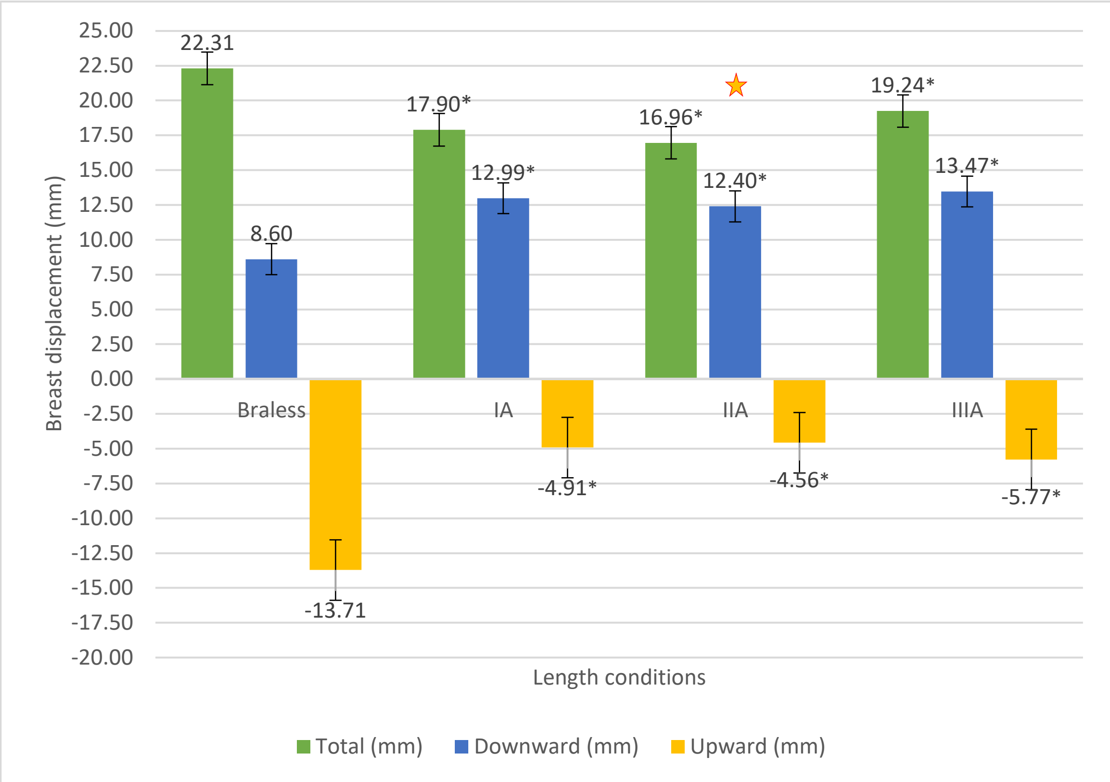


Figure 4.9 Vertical breast displacement with different lengths of shoulder straps during fast walking for 75D vs. control sample

Notes: IA, IIA and IIIA refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm respectively with best fit underband length of 65 cm. * *p* -value < 0.05 as compared to IIA with optimal shoulder strap length (40 cm)

☆ refers to best fitting shoulder strap and underband length condition (IIA)

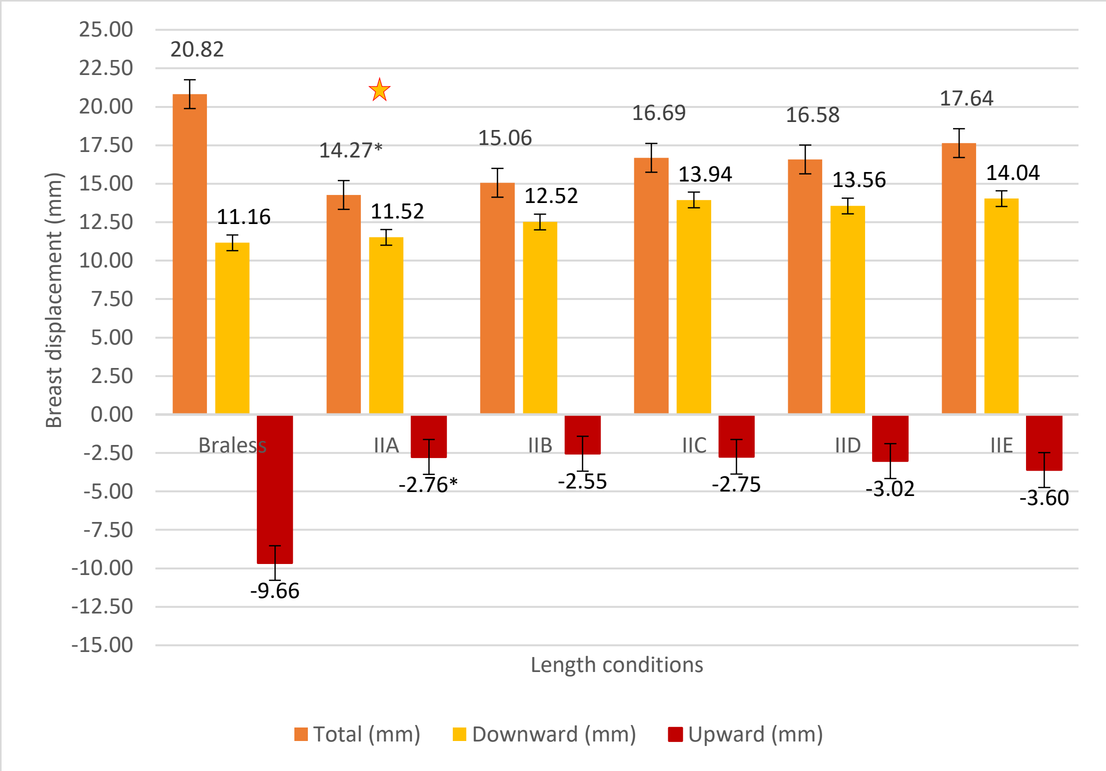


Figure 4.10 Vertical breast displacement with different underband lengths during fast walking for 75B vs. control sample

Notes: IIA, IIB, IIC, IID and IIE refer to underband lengths of 65 cm, 73 cm, 77 cm and 81 cm respectively with shoulder strap length of 40 cm. * *p*-value < 0.05 as compared to IIA with optimal strap length (40 cm)

☆ refers to best fitting shoulder strap and underband length condition (IIA)

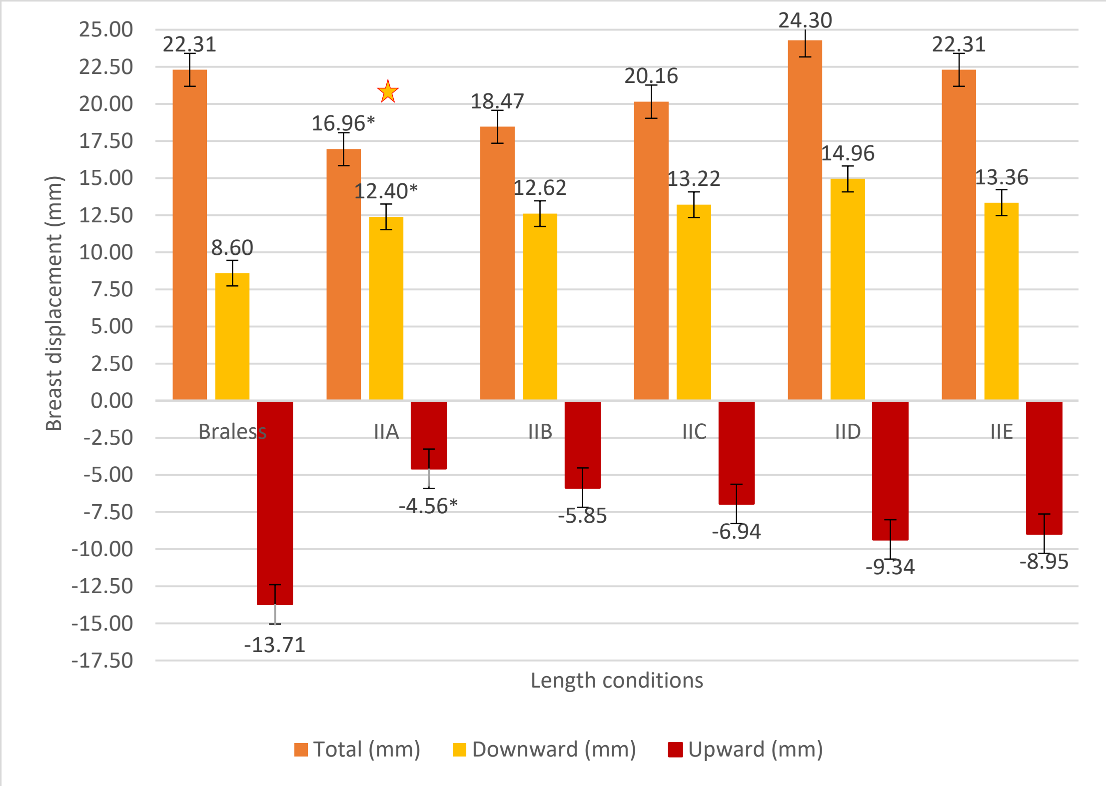


Figure 4.11 Vertical breast displacement with different underband lengths during fast walking for 75D vs. control sample

Notes: IIA, IIB, IIC, IID and IIE refer to underband lengths of 65 cm, 73 cm, 77 cm and 81 cm respectively with shoulder strap length of 40 cm. * p-value < 0.05 as compared to IIA with optimal strap length (40 cm).

☆ refers to best fitting shoulder strap and underband length condition (IIA)

It is critical to note that increases in the total breast displacement take place with higher length of the shoulder straps (IA). There was an increase in the compressive forces induced onto the breast structure. The nipples were elevated, but the momentum of movement could not be evenly distributed around the breast structure. Therefore, reducing the shoulder strap length offsets a reduction in displacement by the elevated breasts. However, the optimal shoulder strap length (40 cm) helps to absorb and convert the kinetic energy of the breasts into tensile energy of the fabric (Lu et al., 2016). Balance is achieved and the vertical displacement is reduced as a result.

The reduction of displacement with shorten underband length may be explained by the impacts of the breast weight and dynamic forces due to walking which are transferred to the shoulder straps. The original shoulder strap design and material did not take into consideration all of the breast loads. The impact forces are supposed to be distributed throughout the entire bra. When the shoulder straps fail to absorb all of the momentum from breast motion, significant increases in motion result in breast displacements in the vertical direction. Besides, both bra sizes have a larger change (percentage) in total vertical breast displacement when the underband length is adjusted as opposed to the shoulder strap. The underband has a relatively greater effect on the vertical breast displacement. This may be related to the function of the underband which is to share the weight of the breasts and accommodate the underwire for support.

The smaller bra size (75B) shows a reduction of total vertical breast displacement of 35% to 38% and 24% to 39% due to the shoulder strap and underband lengths respectively. Therefore, the ability of the shoulder straps and underband to control breast movement is evident. A similar effect of the shoulder straps and underband was observed for the larger bra size (75D). Therefore, the ability of bras to elevate the breasts is an area of improvement. Since the bra in this study provides insufficient support to elevate the breasts and absorb motion, there is an increasing downward displacement with the larger breasts even when a bra is worn. However, the ability of the bra to reduce the overall motion of larger breasts still ranges between 2% and 18%. Nevertheless, the current bra design should be further modified to provide better support.

4.3.1.3 Experiment (B): Material properties of bra components

(1) Shoulder strap and underband material

To investigate the effects of the shoulder strap and underband material on vertical breast displacement, the breast displacement values obtained from the control sample are compared with Bra Conditions X, Y and Z respectively. The differences in the total vertical breast displacement between the bra samples are shown in Figures 4.12 and 4.13 for bra sizes 75B and 75D at 4.08 km/h. In comparison to the control sample, Bra Condition X (shoulder strap and underband with high modulus) causes greater vertical breast displacement regardless of the bra size and walking speed.

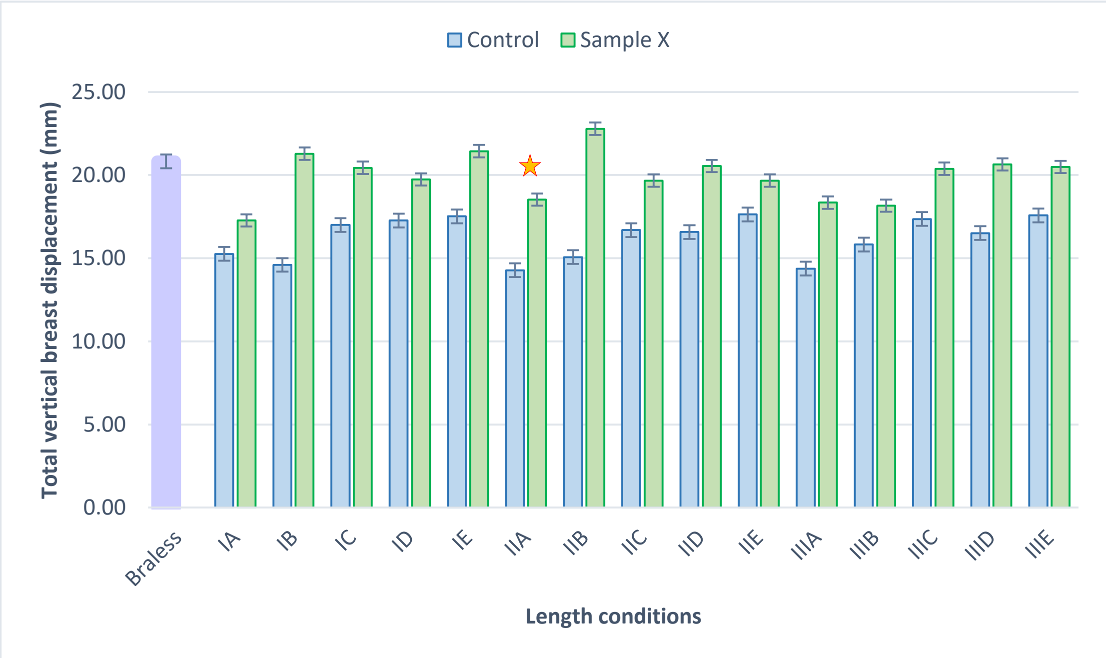


Figure 4.12 Total vertical breast displacement for 75B at 4.08 km/h with changes in lengths of shoulder strap and underband: control sample vs. Bra Condition X

☆ refers to best fitting shoulder strap and underband length condition (IIA)

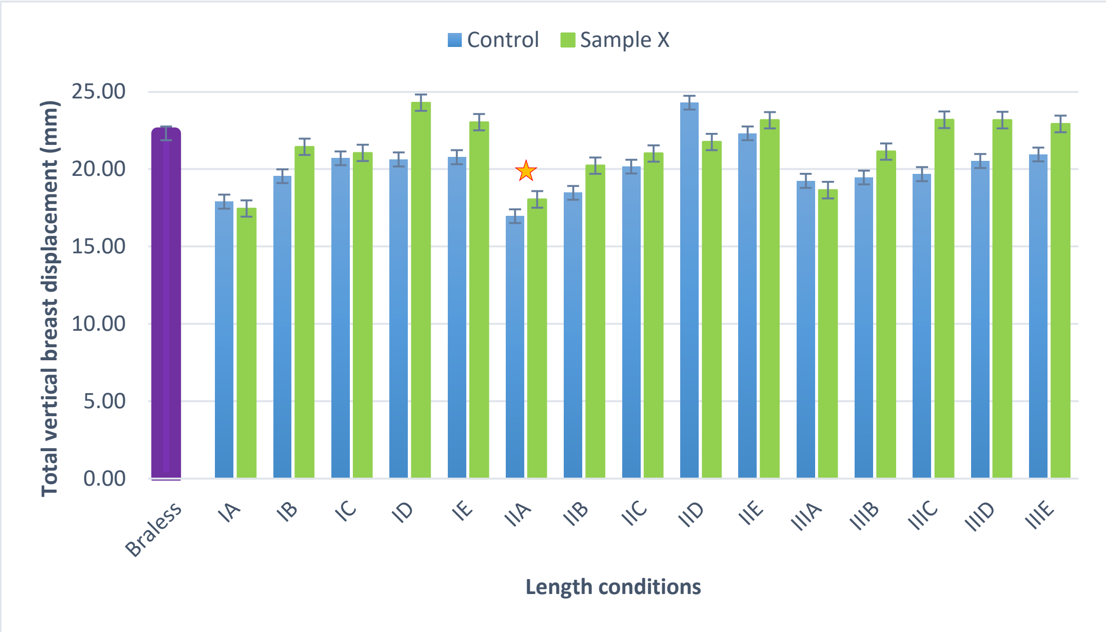


Figure 4.13 Total vertical breast displacement for 75D at 4.08 km/h with changes in lengths of shoulder strap and underband: control sample vs. Bra Condition X

☆ refers to best fitting shoulder strap and underband length condition (IIA)

The results indicate that the best fitting shoulder strap and underband length condition (IIA) offers the best control of the vertical breast movement of the control sample. However, the use of an elastic woven tape with high modulus (Bra Condition X) resulted in a considerable increase in the vertical breast displacement. To prevent the displacement, the length of the shoulder strap should be reduced. The total vertical breast displacement was subsequently reduced by 6% and 4% for 75B and 75D respectively.

A flexible and highly elongated shoulder strap and bra band material offers adequate elongation to reduce breast displacement and preserve comfort. However, materials may lose their elasticity due to prolonged use. Although reducing the strap length would help elastic material with high modulus to support the breasts, this would induce a higher bra-manikin pressure, and in this case, an increase from 8.6 kPa to 9.3 kPa. Besides, the shoulder straps digging into the skin or flesh bulging from the underband are frequently reported due to increased weight of the breast, particularly for large breasted women (Steele, 2013; Scurr, Brown, Smith, Brasher, Risius & Marczyk, 2016).

While the shoulder straps help the bra remain in position, the underband is responsible for the redistribution of the gravitational downward forces from the breasts to the back. Since breast motion is like a damping motion, there is oscillation of the breasts after movement from each step in the gait cycle (Haake & Scurr, 2010). The vertical ground reaction force measures the stress intensity and duration when the body comes into contact with the ground for each step taken (White et al., 2009; Shivitz, 2001). The high elasticity of the material used give the breasts to have room to reduce the oscillation and provide an acceptable wear experience. A rigid strap and bra band therefore provide less reduction of the total vertical displacement of 2 mm compared to the control sample which uses a low modulus material for the strap and underband.

(2) <u>Cup material</u>

As reported above, the length changes of the shoulder straps lead to an increase in total vertical breast displacement. The Young's modulus of the bra material is considered to be a key factor that influences the bra support performance particularly in reducing vertical breast displacement (McGhee & Steele, 2011). Bra samples with a cup made of warp knitted lace fabric (control sample) and fabric-foam laminated PU material (Bra Condition Y) were used to examine the effects of the cup material. The relationship between the cup material and the length of the shoulder strap and underband was investigated.

Figures 4.14 and 4.15 illustrate the total vertical breast displacement for bra sizes of 75B and 75D with various bra lengths during fast walking. The best fitting length condition (IIA) provides good support of the breast in that the total vertical displacement is 16.96 mm (control) and 15.59 mm (Bra Condition Y) respectively. Compared to the rigid material of the control sample (Bra Condition X), the use of soft flexible cup material (Bra Condition Y) resulted in a significant reduction of the total vertical breast displacement (p-value < 0.05). The reduction of the total vertical breast displacement obtained from 75B is slightly more than that of 75D.

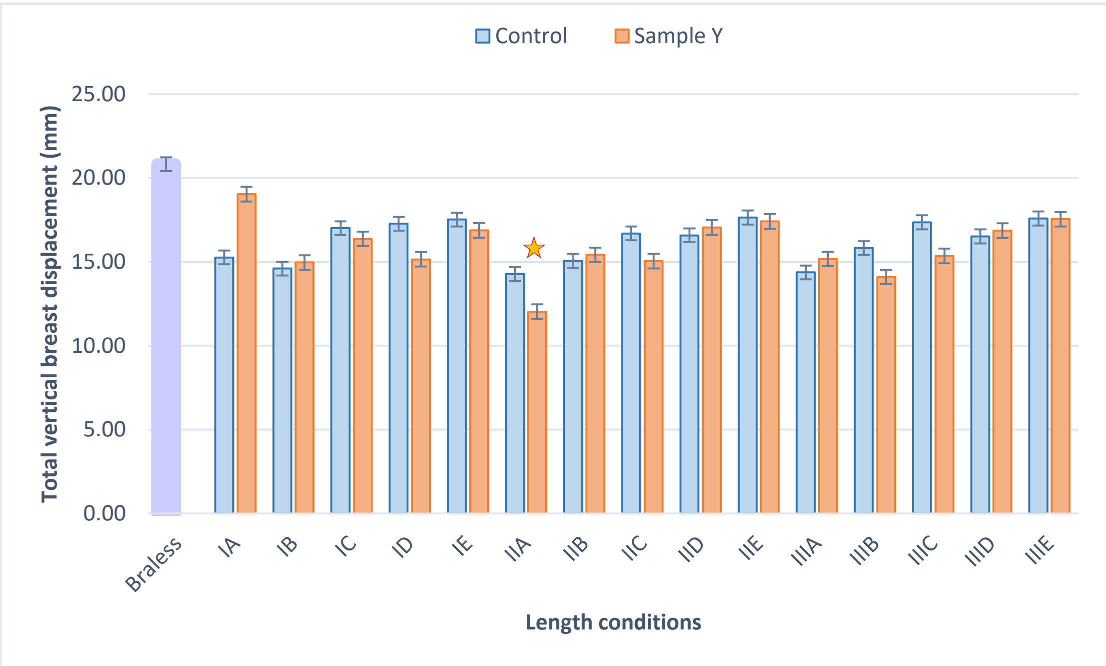


Figure 4.14 Total vertical breast displacement for 75B at 4.08 km/h with changes in lengths of shoulder strap and underband: control sample vs. Bra Condition Y

☆ refers to best fitting shoulder strap and underband length condition (IIA)

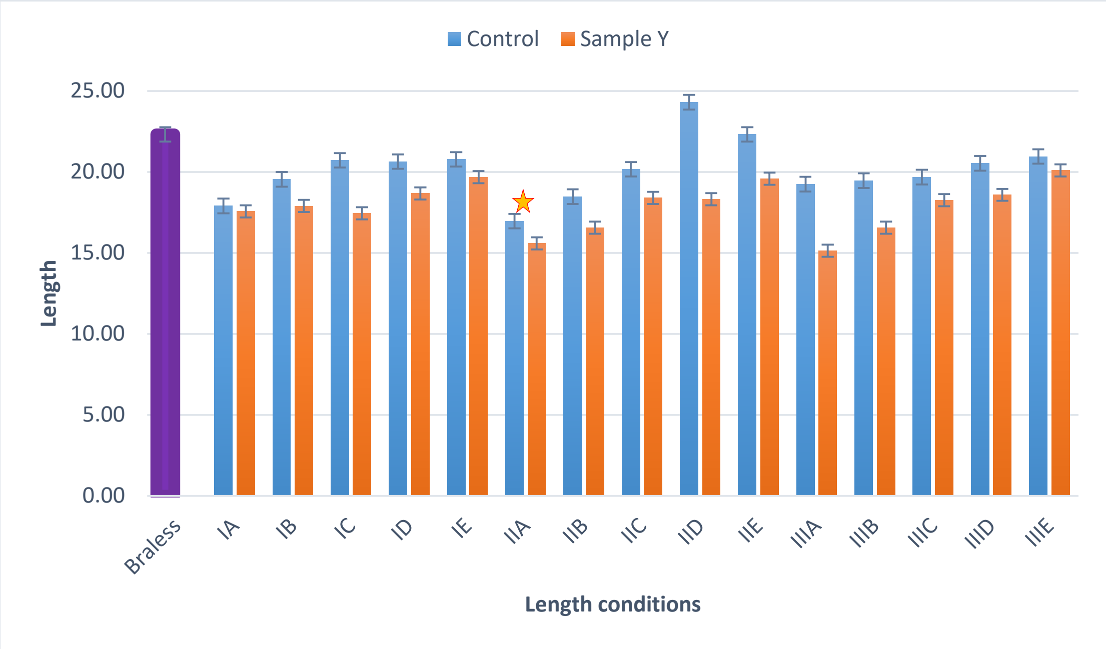


Figure 4.15 Total vertical breast displacement for 75D at 4.08 km/h with changes in lengths of shoulder strap and underband: control sample vs. Bra Condition Y

☆ refers to best fitting shoulder strap and underband length condition (IIA)

The finding above is different from previous findings on sports bra designs in which a cup material with a high modulus and rigid shoulder strap were used to control breast displacement (Krenzer, Starr & Branson; 2005; Lawson & Lorentzen, 1990). Such differences may be due to the variations in the tested condition at high running speeds (> 6 km/h) and the recruited subjects (age and bra size). Moreover, in sports bra designs, the breasts are compressed to the chest wall to restrict their natural movement (Chen, Gho, Wang & Steele, 2016). Apart from the elasticity of the cup materials (Krenzer et al., 2005), control of breast displacement is strongly associated with the elevation of the breasts. The use of a rigid material for the cups and high lengths may lead to overcompression of the breasts which could offset the positive effects of breast elevation, hence failing to control breast displacement during exercise. Thus, the findings in this study on the whole are in agreement with the findings in the human wear trials in McGhee and Steele (2010) who found the use of highly elastic material for bra cups could improve the support and comfort performance of the bra during exercise.

(3) Underwire

Underwires are used to improve the support performance of a bra. The vertical breast displacement for the control condition (with underwire) and Bra Condition Z (without underwire) was measured. The results are shown in Figures 4.16 and 4.17, through which it can be observed that vertical breast displacement significantly increases by 5% to 80% without an underwire as compared to the control sample which has an underwire for both bra sizes. With longer shoulder straps and underband, an increase in the total vertical displacement is noted compared to the braless condition.

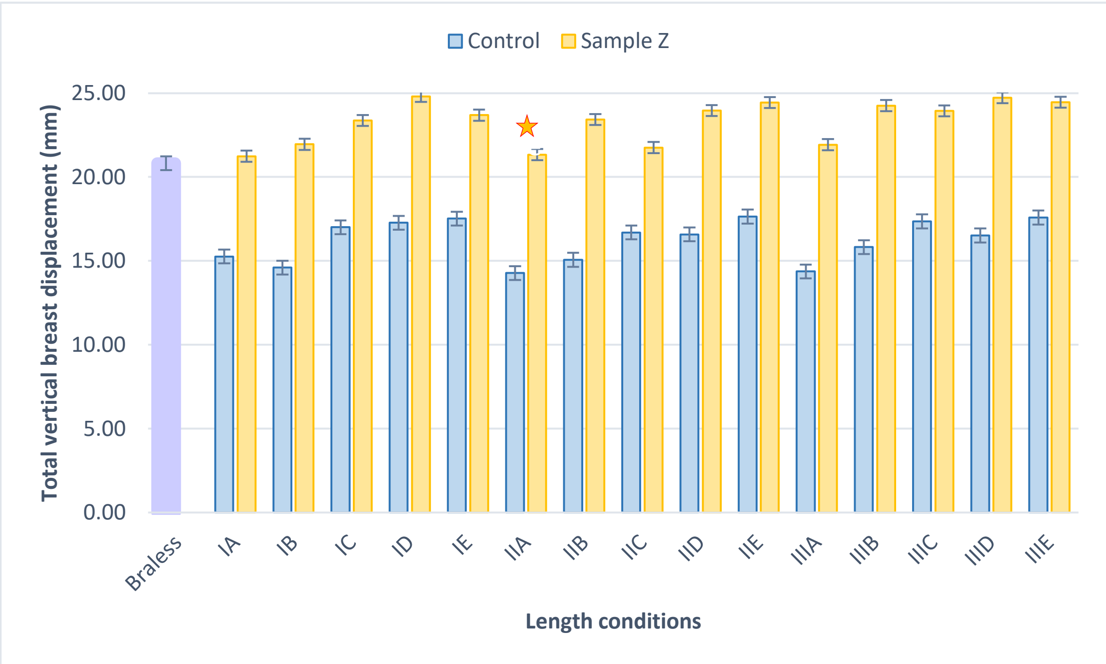


Figure 4.16 Total vertical breast displacement for 75B at 4.08 km/h with changes in lengths of shoulder strap and underband: control sample and Bra Condition Z

☆ refers to best fitting shoulder strap and underband length condition (IIA)

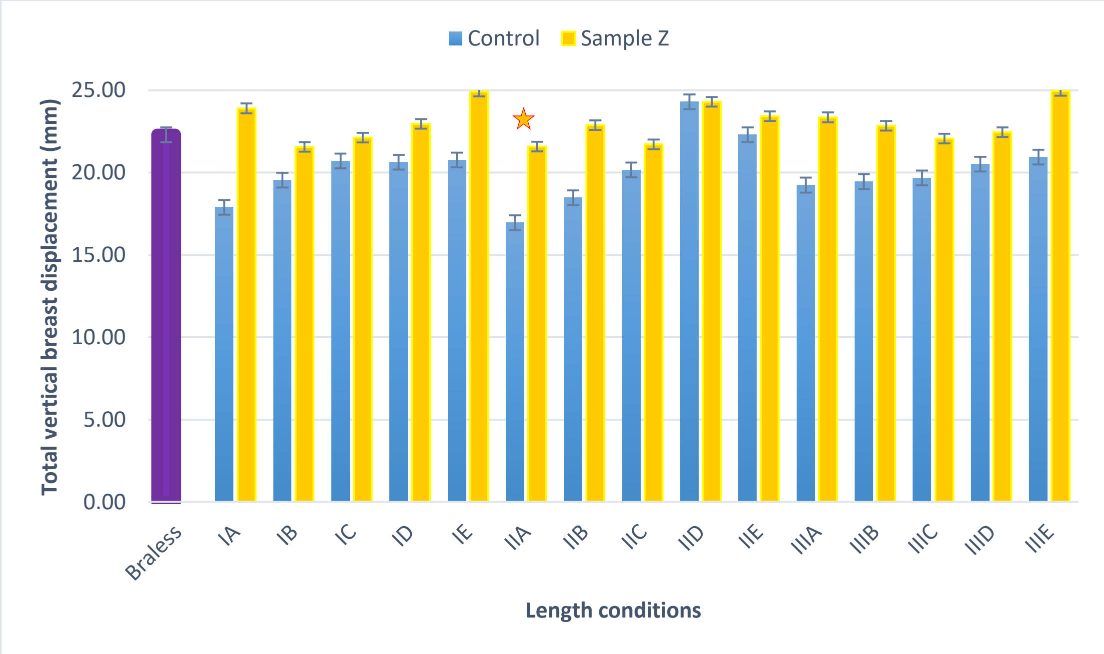


Figure 4.17 Total vertical breast displacement for 75D at 4.08 km/h with changes in lengths of shoulder strap and underband: control sample and Bra Condition Z

☆ refers to best fitting shoulder strap and underband length condition (IIA)

Underwires are inserted underneath the bra cups. Planar underwires are bent to accommodate the 3D shape of the underbreast curve. The underwires hold the weight of the breasts and redistribute dynamic impact forces to the underband during movement (Page & Steele, 1999). They shift the weight of the breasts to other bra components and reduce the vertical breast displacement (Zhang, Wang & Han, 2016). In addition, underwire material properties such as bending rigidity affect the springing open of the planar underwire to fit the ergonomics of the bra (Lee & Hong, 2006). While this is important, nevertheless, scientific studies on the length of the shoulder straps and underband, and the underwire material are scarce.

The bra-manikin pressure in Bra Condition Y (without underwire) is found to be much lower than that of the control sample (with underwire). Although a comfortable range of pressure is obtained without the use of an underwire, the removal of this supportive component is not recommended to avoid sacrificing the supporting function of the bra.

4.3.2 Empirical prediction model of breast motion

4.3.2.1 Formulation

The total vertical breast displacement discussed in the previous section gives an overall view of the performance evaluation of bras in how they affect breast motion or provide bra support. The corresponding changes in the amplitude of the displacement are found with changes in the selected variables. A statistical analysis was completed by using SPSS and a statistical significance level of 0.05 was used. The primary independent variables that affect the total vertical breast displacement were identified by using the numerical prediction formula with a multiple linear regression analysis, and may apply to future studies that predict breast displacement with various bra samples.

Before generating the linear regression model, correlation evaluation was carried out to identify the correlated independent variables into the prediction model. A moderate correlation is obtained when movement speed (r=0.606), underwire (r=0.456) and cup material (r=0.364) are tested with the correlation analysis for the total vertical breast displacement. Size (r=0.286), underband length (r=0.224) and strap and underband materials (r=0.073) have a weak correlation with the dependent variable. The independent variable of shoulder strap length is excluded with a *p*-value of 0.385 which is larger than 0.05 and this represents no significant influence towards total vertical breast displacement. This is consistent with Bowles and Steele (2013) in that the shoulder strap of a bra may be more designed to hold the bra in place rather than primarily provide support.

It is assumed that a linear regression model analysis used to predict total vertical breast displacement would have normally distributed data. This allows the continuation of the program to carry out the stepwise linear regression evaluation and shows the relationship between the factors that affect the total vertical breast displacement. The six tested independent variables that have correlation with the dependent variable are included in the numerical prediction formula for total vertical breast displacement. They are: movement speed, insertion of underwire, size, shoulder strap and underband material, and underband length and material stress-strain properties.

A significantly linear relationship was found between the independent variables and these six independent variables (*p*-value <0.05). The coefficient of determination (r^2) is 0.780 for the linear regression model, and 78% of the tested total vertical breast displacement can be predicted by considering the six independent variables The numerical prediction formula for the total vertical breast displacement is shown below (Equation 4.2).

$$\text{Total vertical breast displacement} = -5.166 + (3.330)\,Y_7 + (-5.124)\,Y_6 + (0.545)\,Y_1 + (0.362)\,Y_5 + (0.190)\,Y_3 + (0.112)\,Y_4 \quad (4.2)$$

where Y_1= bra size; Y_3= underband length; Y_4= stress-strain of cup material; Y_5= stress-strain of shoulder strap and underband materials; Y_6= underwire; and Y_7= speed

The formula for predicting total vertical breast displacement is statistically significant (*p*-value<0.05). The three independent variables of speed, underwire and size have major impacts on total vertical breast displacement with the use of the prediction formula. The representativeness of the prediction model is improved from 36.7% to

65.7% compared to the inclusion of single factors in the formula. By adding the remaining factors to the prediction formula that mainly affect the bra fitting performance, the r^2 is increased to 0.7.

An underwire and the stress-strain of the shoulder strap and underband materials and the cup material influence the supportive performance of bras. Walking more quickly and larger breasts increase the total breast displacement (Scurr, White & Hedger, 2011). Forces are exerted onto the breasts during motion increase with the breast mass (Monari, Desloovere, Bar-On, Molenaers, & Jaspers, 2012). Women who have larger breasts therefore should select a supportive bra to minimize breast motion when activity intensity is increased (McGhee et al., 2013).

The insertion of an underwire helps to share the weight of the breasts or impact momentum during motion. The material properties of the elastic components allow the bra fit to be adjusted and hold the bra into position. Besides, the shoulder strap and bra band frequently cause discomfort because of the insufficient support or improper fitting (Chen et al., 2016). The material properties of the bra components also influence the supporting performance of the bra in both static and dynamic conditions (Lu et al. 2016). The prediction formula shows that it is important to consider both bra component material and length of the shoulder straps and underband so as to offer the most effective breast support.

4.3.2.2 Validation

A female subject with a bra size of 75D who have no prior breast surgery or injuries history was invited to conduct an evaluation on breast displacement. The experiment was approved by the Human Subjects Ethics Sub-committee at the Hong Kong

Polytechnic University. Information with a brief introduction on the study and detailed test procedures or arrangements were provided to subject before the wear trial. Written consent for the wear trial was obtained. After subjects completed the treadmill warm-up, subject then undertook the walking trials with 2 km/h and 4 km/h walking speeds on the treadmill under braless, bra with different shoulder strap and underband length adjustment. Rest was provided for every 15 minutes.

To determine the relationship between the vertical beast displacement measured from the dynamic manikin with soft breasts and human subjects, correlation analysis was completed. Upon on examination, the Pearson correlation coefficients and root mean square error of the vertical breast displacement were computed to assess the strength of the linear relationship and discrepancies of the data. The values of coefficient of determination (r^2) explains the representativeness of the manikin result compare to that of subject. The larger of the r^2 value refers to better simulation result of the soft manikin.

After comparing the total vertical breast displacement results from the manikin with soft breasts and the human subject, the total vertical breast displacement showed a similar trend of changes with magnitude of length based on different length combinations of shoulder straps and underband but the total vertical breast displacement of the subject is consistently less than that of the manikin. In Figure 4.18, the total vertical breast displacement of the subjects under different testing conditions is plotted against the result from the manikin. To calculate the actual total vertical breast displacement by using the results of the manikin with soft breasts, a linear equation (4.3) is used to model the real life situation:

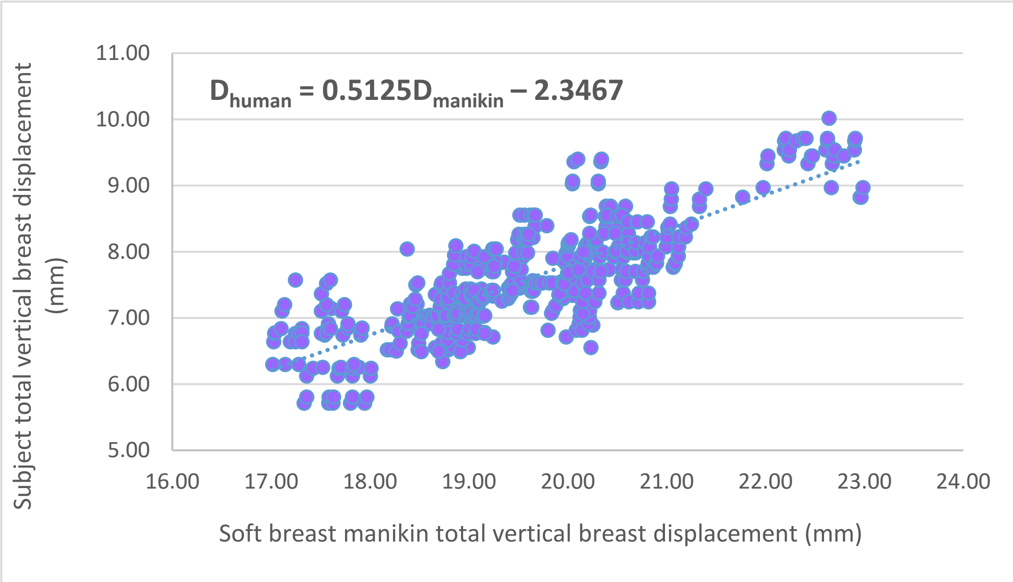


Figure 4.18 Scatter diagram of total vertical breast displacement: subject vs. manikin

$$D_{human} = (0.5125)D_{manikin} - 2.3467 \tag{4.3}$$

where D_{human} = the vertical breast displacement of the subject

$D_{manikin}$ = vertical breast displacement of the manikin with soft breasts

A high correlation coefficient for the relationship between vertical breast displacement of dynamic manikin with soft breasts and human subjects is found ($r = 0.81$, $n=480$, *p*-value < 0.01 (two-tailed)). The root mean square error (RMSE) is 12.01 mm. More than 77% of the variance of the vertical breast displacement can be explained with dynamic manikin with soft breasts ($r^2=0.78$).

The magnitude of the total vertical breast displacement the manikin is higher than that of the subjects. This could be related to the moving mechanism of the manikin. The cam design which controlled the manikin to simulate vertical movement determines the movement of the entire manikin rather than a single parameter or the breasts. The current design therefore simulates the vertical movement of the whole torso and the breast motion is both the movement of the breast prostheses and the entire manikin. Moreover, the breast prostheses may have variations from the actual highly complex breast structure because of the non-linear properties of the soft tissues. There may also be differences in the measured displacement values.

The use of a dynamic manikin with soft breasts for both walking speeds provides a consistent result for the bra evaluation process. The vertical breast displacement differences under various bra conditions are still acceptable due to the simulation consistencies and similar patterns of movement. The use of the manikin helps to eliminate personal embarrassment and allows for repeated wear trials unlike human subjects who become tired after a while. In spite of the differences in the magnitude of the total vertical breast displacement between the manikin and human subjects, one more step with the linear equation should be used to compute the actual magnitude. There may also be adjustment of the breast prostheses in order to improve the simulation result.

4.4 Chapter summary

This chapter focuses on a breast displacement evaluation. The specific objectives are to examine the amount of vertical breast displacement with different activity levels to optimize the design features and fabrication of a moulded bra by using a novel approach and numerical formula to predict the bra support performance. To minimize the potential inconsistencies with human subject wear trials or personal embarrassment, a dynamic manikin with soft breasts has been designed to simulate vertical breast motion during slow and fast walking. For the braless condition, it is observed that larger breasts and more intense activity level increase vertical breast displacement. The corresponding magnitude and frequency of the oscillation after each displacement peak also increase for larger breasts and more intense activity level. When a bra is worn, the majority of the bra samples and tested conditions significantly reduce the total vertical breast displacement particularly in terms of the upward movement. Better control of the vertical breast movement is found with optimal length of the shoulder straps and underband, along with low stress-strain of the shoulder strap and underband materials, soft and flexible cup material and use of an underwire for both slow and fast walking conditions. Six independent variables which are movement speed, insertion of an underwire, bra size, strap and underband material, underband length and stress-strain of the strap and underband material are selected as the factors that could affect the total vertical breast displacement to produce a prediction formula for the total vertical breast displacement. A satisfactory result is obtained with the dynamic manikin in simulating actual breast vertical motion which is validated with a wear trial. The breast displacement evaluation of the bra characteristics, and wear trials with the manikin contribute to an ergonomic moulded bra design that will be investigated for its support performance.

CHAPTER 5 BRA INSERT DESIGN TO CONTROL BREAST MOTION

5.1 Introduction

Bras are designed to provide support to the breasts while allowing a comfortable wear experience. As discussed in Chapters 3 and 4, the use of an underwire can successfully reduce the displacement of the breasts, but result in increased bra-manikin pressure. Underwires with a planar shape are traditionally made of steel which is bent (or "opened") to a 3D shape. By controlling the length of the shoulder straps and underband with appropriate underwire material, the bending angle of the underwire can be adjusted to fit the 3D contours of the underbreast curve. To improve the fit and comfort of an underwire bra, plastic underwires and 3D underwire designs have also been developed (see Braverman, 2017; Kim, Lee & Hong, 2000). Nevertheless, to date, the influence of the shape and bending behaviours of the underwire on controlling breast displacement have been somewhat uncertain.

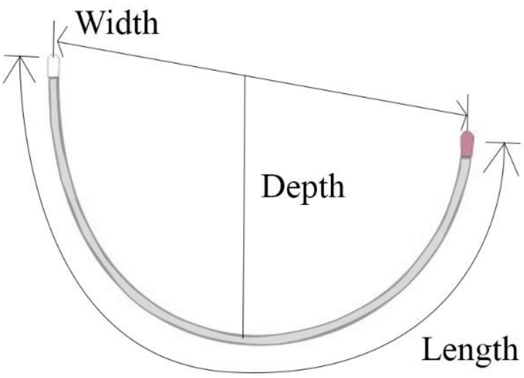
In this chapter, the bending performance of traditional steel underwires are first discussed (Lee & Hong, 2007). The geometric shape of the underbreast curve of fifteen subjects is obtained by using an Artec™ Eva handheld 3D scanner. Based on the shape of their underbreast curve, a novel 3D bra insert is developed and constructed by using 3D printing. The effects of the fit and lateral bending behaviour of the 3D bra insert on controlling breast displacement are subsequently evaluated.

5.2 Evaluation of bending performance of underwires

5.2.1 Samples

Three conventional planar underwires made of steel for bra sizes 75B and 75D were sourced and purchased from the market. Their lateral bending rigidity was first evaluated and the specifications are summarized in Table 5.1. As shown in the table, U1 is slightly shorter than the other two samples. In comparison to a bra size of 75B, the overall dimensions of the 75D samples are larger for better support of breasts that are larger in volume. Two additional underwires made of nylon 12 and polylactic acid (PLA) were also constructed by using 3D printing and their corresponding bending performance was assessed.

Table 5.1 Specifications of planar underwires

Underwire	**U1**		**U2**		**U3**	
Cup size	B cup	D cup	B cup	D cup	B cup	D cup
Dimensions						
Width	12.2 cm	12.8 cm	12.7 cm	13.7 cm	12.7 cm	13.7 cm
Depth	18 cm	19 cm	18.5 cm	20.5 cm	18.5 cm	20.5 cm
Length	5.4 cm	5.8 cm	5.8 cm	6.2 cm	5.8 cm	6.2 cm
Weight	1.93 g	2.05 g	2.21 g	2.60 g	2.36 g	2.45 g
Appearance	 (B cup)		 (B cup)		 (B cup)	
	 (D cup)		 (D cup)		 (D cup)	

5.2.2 Lateral bending of steel underwires

Bending a stiff planar underwire to fit the 3D curvature of the underbreast requires shoulder straps and an underband with a high amount of length. A soft underwire can be readily bent but may fail to offer an appropriate amount of support to the breasts during exercise. The lateral bending of underwires is therefore associated with the fit, length and the breast support of a bra. An underwire holder was designed to bend the underwire samples with reference to Lee and Hong (2007). The middle of the underwire was fixed by using a wire connector (Figure 5.1). Force was then applied onto the end of the tips of the sample. The lateral bending behavior of the three conventional planar underwires made of steel (U1, U2 and U3) and two 3D printed underwires (nylon 12 and PLA) was examined in the study.

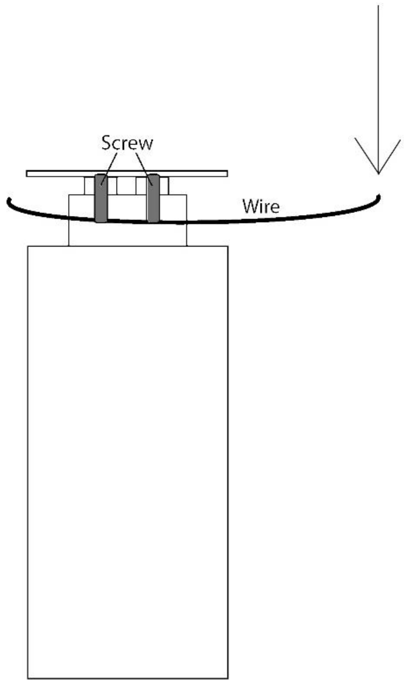


Figure 5.1 Underwire holder for bending rigidity test

The two-point bending method in the ISO 5628 Standard test method for determination of bending stiffness with paper and board was applied (International Organization of Standards, 2012) by using an Instron tensile strength tester, through which force was perpendicularly applied to bend the underwire to a maximum linear displacement of 30 mm (or the bending displacement with bra wear) (Figure 5.2) (Shin, 2007). The bending force for displacements of 10 mm, 15 mm, 20 mm, 25 mm and 30 mm was recorded (Figure 5.3) that the bending rigidity of the underwires could be calculated (Equation 5.1).

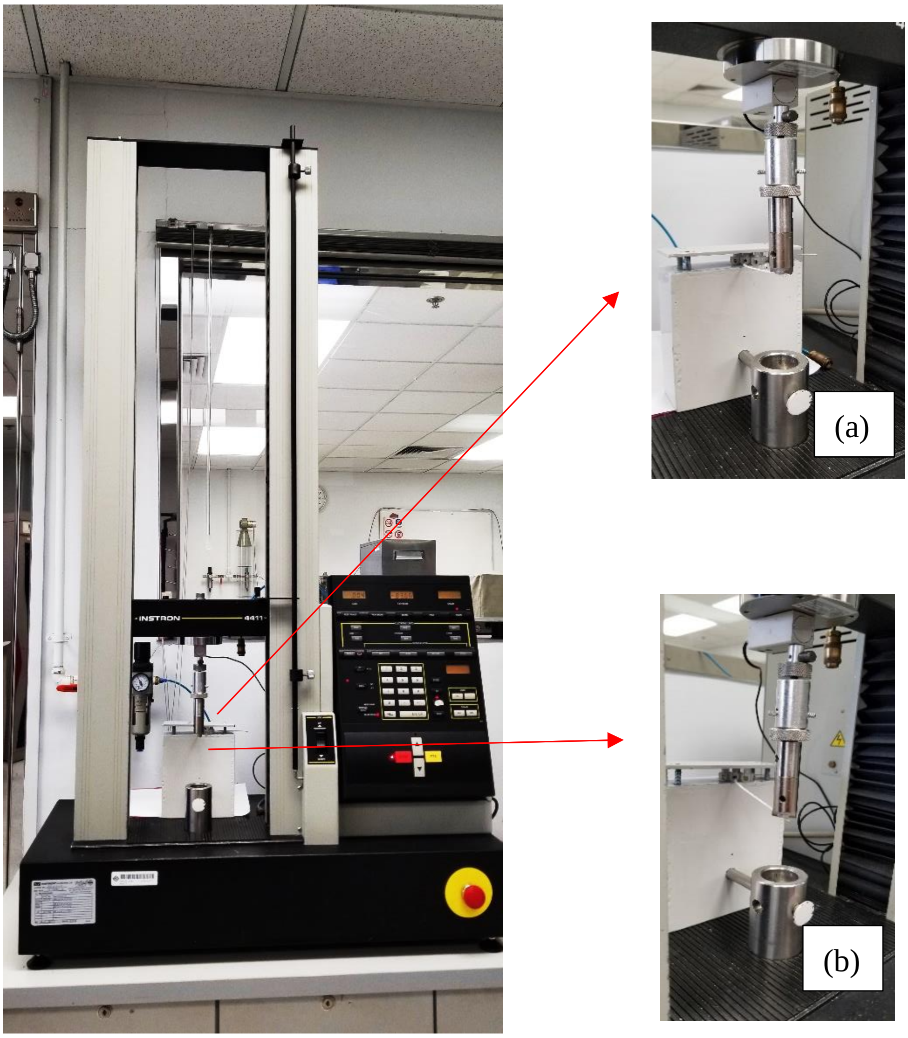


Figure 5.2 Instron tensile strength tester and underwire bending device

(a) Before bending and (b) After bending

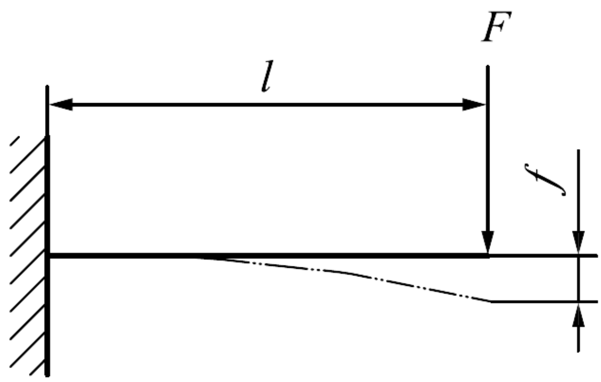


Figure 5.3 Two point method

F = Force (in newtons)

f = Linear deflection (in millimetres)

l = Bent length (in millimetres)

$$S_b = \frac{F}{f} \cdot \frac{l^3}{3b} \quad (5.1)$$

where S_b = bending stiffness

F = force

f = linear deflection

l = bent length

b = width of the tested sample bent in the direction of the bending axis

5.3 Characterization of curvature of underbreast

Since the curve of the underbreast is 3D, the 2D planar shape of conventionally used underwires may not be able to accommodate the diversity of breast shapes and curvatures. The bra length (shoulder straps and underband in particular) during wear could also affect the shape and ultimate fit of the underwire. A better understanding of the curvature of the underbreast can therefore improve the fit, comfort and even the support and control of bras. The natural 3D shape of the underbreast and the geometrical changes of the underwire under the force of length could therefore facilitate the ergonomic design of a bra insert that would control excessive displacement of the breasts during daily activities.

5.3.1 Subjects

Fifteen subjects were recruited to characterize and analyze the geometric shape of their underbreast for constructing a 3D ergonomic bra insert. Their demographic information is provided in Table 5.2, in which the subjects are divided into 2 groups based on their bra size. Amongst the 12 subjects with a bra size of 75B, the average age and body mass index (BMI) are 23 years old and 20.11 respectively. The average age and BMI of the 3 subjects with a bra size of 75D are 32 years old and 21.51, respectively.

Table 5.2 15 Demographic information of subjects in wear trial

Bra size	**75B**	**75D**
No. of subjects	12	3
Age (years old)	23±13	32±16
Weight (kg)	52±6 (3.02)	58±8 (6.43)
Height (m)	1.60±0.05 (0.03)	1.64±0.02 (0.01)
BMI	20.11±2 (0.97)	21.51±2 (2.06)

Note: numbers in parentheses refer to standard deviation

5.3.2 Evaluation of geometric shape of underbreast curve

To avoid the embarrassment caused by scanning of the naked breasts, the geometric shape of the underbreast curve was obtained by using a casting method (Figure 5.4). During the test, subjects were required to stand straight steady and keep natural breathing. An Orfit® Classic Soft thermoplastic film was used to cast the contours of the underbreast curvature under a braless condition. A standard underwire was first placed under the breast contours to define the start of the underwire (near the centre of the body) and the end of the underwire (near the armpit). Then, the softened thermoplastic film was wrapped around the bottom of the breasts onto the surface of the skin, and the natural curvature of the breasts was obtained in 30 seconds. An Artec™ Eva 3D handheld scanner was then used to capture the 3D geometric shape of the underbreast curvature, thus providing useful geometric information that is used to design the 3D bra inserts. The 3D images of the breasts can also be superimposed so that the angle between the coronal plane and the inclined plane (based on the natural baseline of the breasts in the braless condition) obtained from the casting of the breasts can be quantified. The bending angle of the three underwires during wear (U1, U2 and U3) can also be measured and compared.

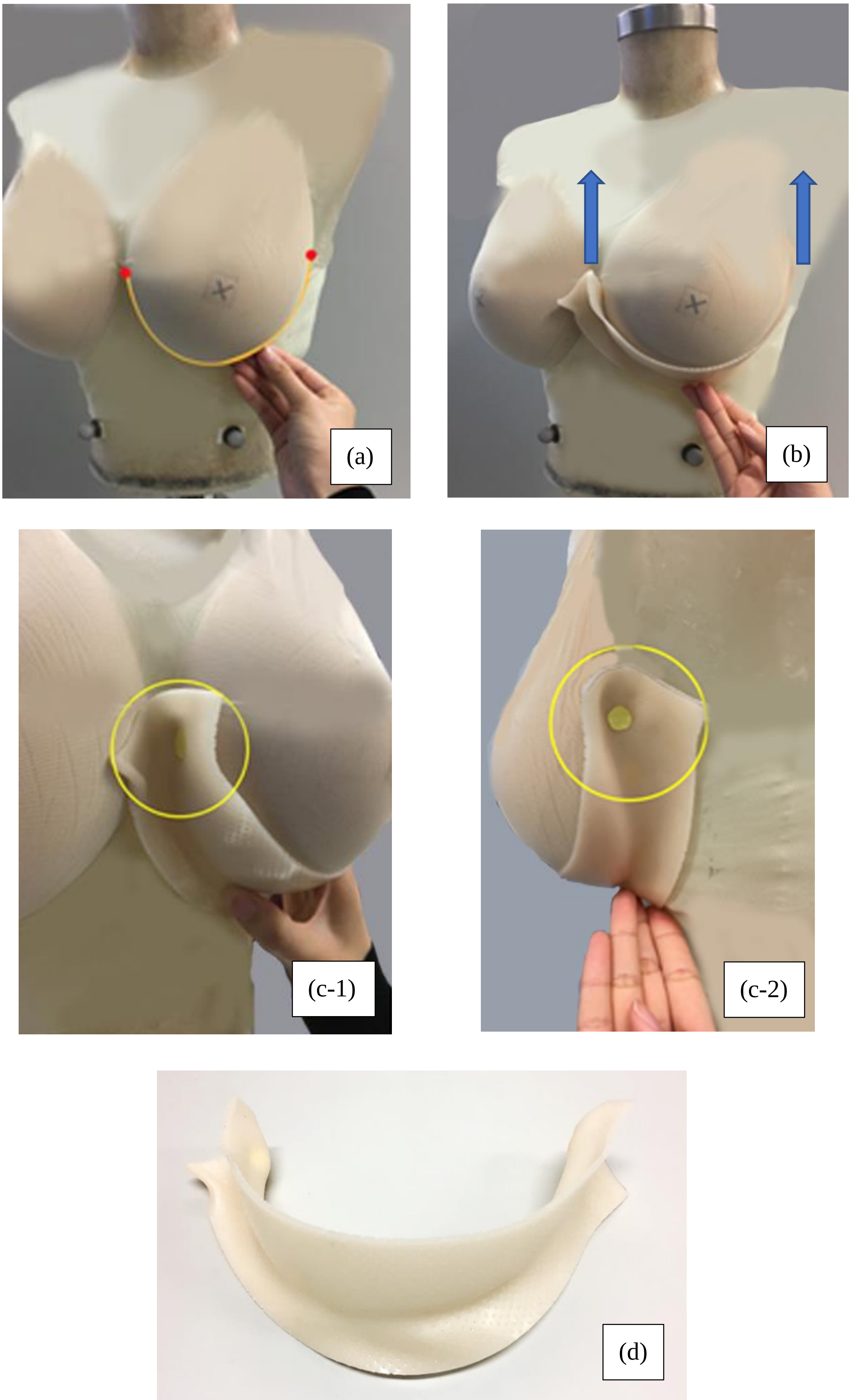

(a)
(b)
(c-1)
(c-2)
(d)

Figure 5.4 Casting process of breast contours

(a) Marking start and end of underwire

(b) Wrapping softened thermoplastic film around bottom of breasts to obtain contours

(c-1 and c-2) Remarking

(d) Final cast of breast root

5.3.3 Inclination angle of underwire

When wearing a bra, the length of the shoulder straps and bra band exerts a pulling force onto the 2D planar underwire towards the thoracic cavity of the wearer in order to accommodate the breast volume and provide support. However, the angle of the inclined plane of the underwire increases with increases in the length of the shoulder straps and underband. In this study, the angle of the underwire in relation to the length of the shoulder straps and underband is examined by using a soft manikin with breasts. Images are taken with 3D scanner and further processed with Rapidform XOR3 64 software (Figure 5.5). The corresponding angle of inclined plane can be compared and the angle of the underwire can be quantified by referring to the start (innermost point), middle and end (outermost point) of the underwire (Figure 5.6). With reference to the length conditions of the shoulder straps and underband in Chapters 3 and 4, the angle of the underwire in 9 conditions for examining bra length is recorded and then compared (Table 5.3).

(a) (b)

Figure 5.5 3D scanned image of (a) soft manikin with bra (b) planar underwire

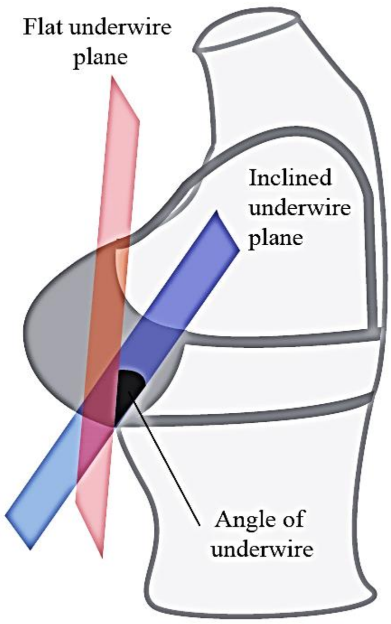


Figure 5.6 Measurement of angle of underwire between the flat and inclined plane of underwire

Table 5.3 Length of shoulder straps and underband

	Shoulder strap		
Underband [reduction factor]	I (38 cm)	II (40 cm) – best fit	III (42 cm)
A (65 cm) – best fit [-10 cm]	IA	IIA	IIIA
C (73 cm) [-2 cm]	IC	IIC	IIIC
E (81 cm) [6 cm]	IE	IIE	IIIE

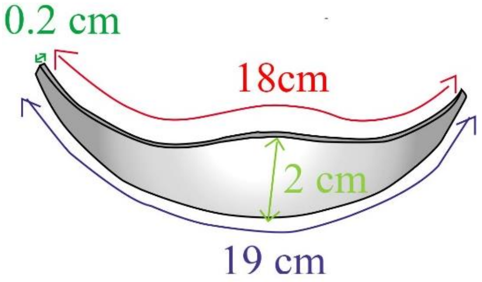
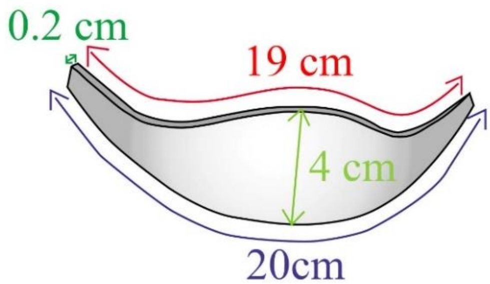
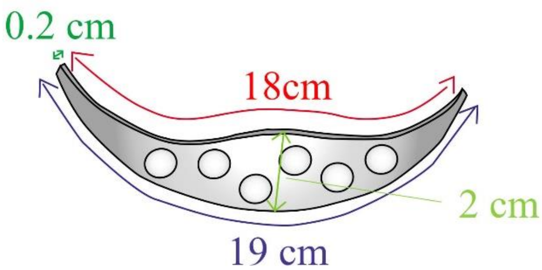
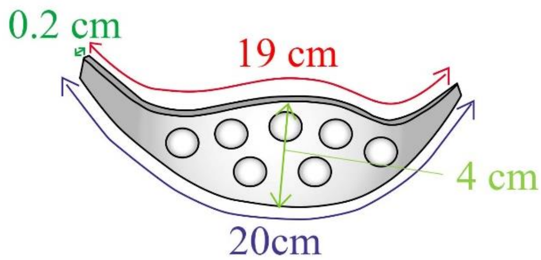
5.4 Ergonomic design of bra insert

5.4.1 3D design and prototype of bra insert

The design of the bra insert was inspired by the work in Huang (2008), Powell and Seymour (2002) and Gatto and Hayes (2002) in which there is a cantilever-like component at the middle or end of the underwire, thus providing an increased surface area for the breasts. It is anticipated that the 3D design of the bra insert could help to redistribute the weight of the breasts, and thus increase the support performance of the bra.

Table 5.4 provides the bra insert designs and dimensions. The bra insert in this study was based on the 3D geometric shape of the underbreast curve and fabricated by using a 3D printer. A total of 4 samples for bra sizes 75B and 75D (made of nylon 12 and PLA respectively) were prepared. An additional 4 samples with porous material were also printed. These porous bra inserts not only have increased air permeability and comfort, but their weight is also reduced by 20% to 25%.

Table 5.4 Bra insert design specifications

Bra insert design	
Non-porous material	
B cup	D cup
	
Porous material	
B cup	D cup
	

5.4.2 Evaluation of 3D bra insert

To evaluate the breast support performance of the 3D bra inserts, the bra insert samples were embedded into fabric-foam cups (Bra Condition Y in Chapter 4). The corresponding vertical breast displacement was measured by using a dynamic soft manikin with breasts.

5.5 Results and discussion

5.5.1 Lateral bending of steel underwires

Figures 5.7 and 5.8 show the bending force-displacement behaviour of the planar underwires made of steel (U1, U2 and U3) and 3D printed underwires (nylon 12 and PLA) for bra sizes 75B and 75D respectively. The bending force for a linear deflection of 30 mm ranges from 0.04 N (nylon 12) to 1.45 N (U3). U1, U2 and U3 all require a higher bending force than the 3D printed underwires (nylon 12 and PLA). The slope of the 3D printed material has a relatively constant value for both bra sizes. U1 has a linear bending performance with increased bending deflection but U2 and U3 are non-linear.

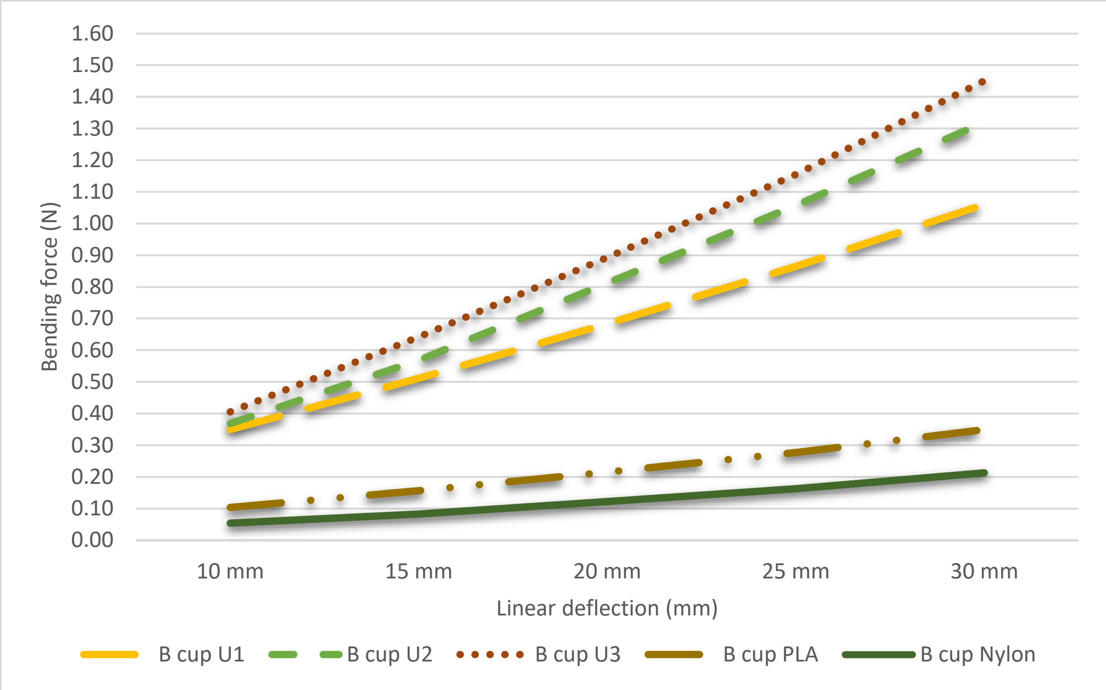


Figure 5.7 Bending of 75B underwire samples and bra insert design conditions

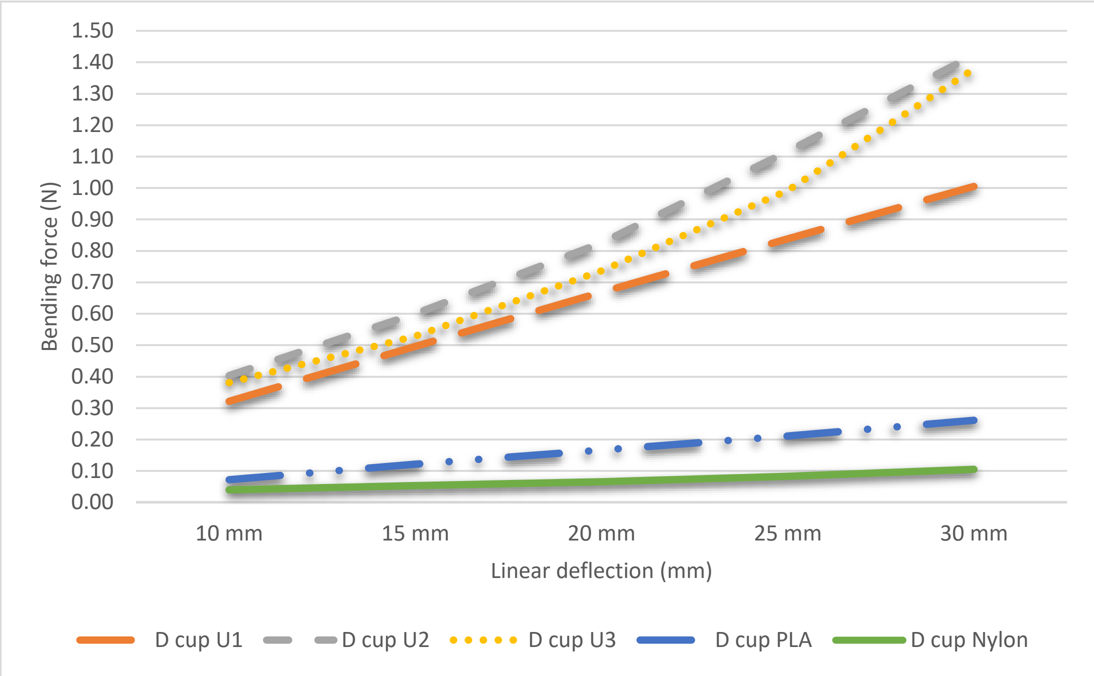


Figure 5.8 Bending of 75D underwire samples and bra insert design conditions

The amount of bending rigidity of the underwire samples for a linear deflection of 30 mm is listed in Table 5.5. U1 to U3 have a high bending rigidity that ranges from 3.20 Nm to 6.06 Nm so that a high length force is necessary to fully spring open the underwire. In comparison, the 3D printed underwires (nylon 12 and PLA) have greater flexibility with a bending rigidity of 0.34 Nm and 1.03 Nm. This is because steel is composed of carbon and iron which have a higher tensile strength while the 3D printed materials are malleable.

Table 5.5 Bending rigidity of underwire samples for linear deflection of 30 mm

Cup size	**U1**	**U2**	**U3**	**PLA**	**Nylon 12**
75B	3.24 Nm	6.05 Nm	6.06 Nm	1.03 Nm	0.63 Nm
75D	3.20 Nm	5.47 Nm	5.65 Nm	0.75 Nm	0.34 Nm

Note: highlighted numbers are lowest bending rigidity

Regardless of the material used, the smaller cup size (B cup) consistently has a higher bending rigidity than a larger cup size (D cup). The principle of leverage can be applied here, which means that the B cup samples have a shorter distance between the point of support of the underwire and the force of effort, thus necessitating a higher bending force as compared to the D cup samples.

5.5.2 Underbreast shape curve and 3D angle of underwire

Table 5.6 shows the 3D angles of U1, U2 and U3 during wear (5.65°, 4.06°, 3.35° respectively), which are consistently smaller than that of the natural breast curvature obtained in a braless condition. The angles of the underwires are significantly different (p-value< 0.05) among the different test conditions. The different bending properties of the steel materials result in changes in the angle of the underwire with the same length adjustments of the shoulder straps and underband. For both 75B and 75D, U1 tends to better accommodate the natural underbreast curvature in comparison to U2 and U3.

Table 5.6 Average angle between underwire and underbreast curve for different conditions

	Angle between underwire and underbreast curve			
Bra size	Braless	Bra Condition Y		
		U1	U2	U3
75B	**7.16**°±1°	**5.65**°±2° (1.51°)	**4.06**°±1° (3.10°)	**3.35**°±2° (3.81°)
75D	**7.18**°±2°	**5.25**°±1° (1.93°)	**3.36**°±0.5° (3.82°)	**2.95**°±1° (4.23°)

Note: Number in parentheses refers to the differences in the angle of underwire compared to braless condition

Figures 5.9 and 5.10 graphically present the angle between the planar underwire and different bra conditions which are based on a wear trial with the subjects who have a bra size of 75B or 75D respectively. The angle between the planar underwire and the tested bra conditions (braless, U1, U2 and U3) show a similar trend among the subjects. This means that there is still the problem of an underwire mismatch with the natural underbreast curvature which might be due to the planar underwire limitations in bras. Moreover, the measured angle of the underwire is consistent among the subjects and can be used for comparing the underwire effects.

Figure 5.9 Angle between planar underwire and different underwires – bra size 75B

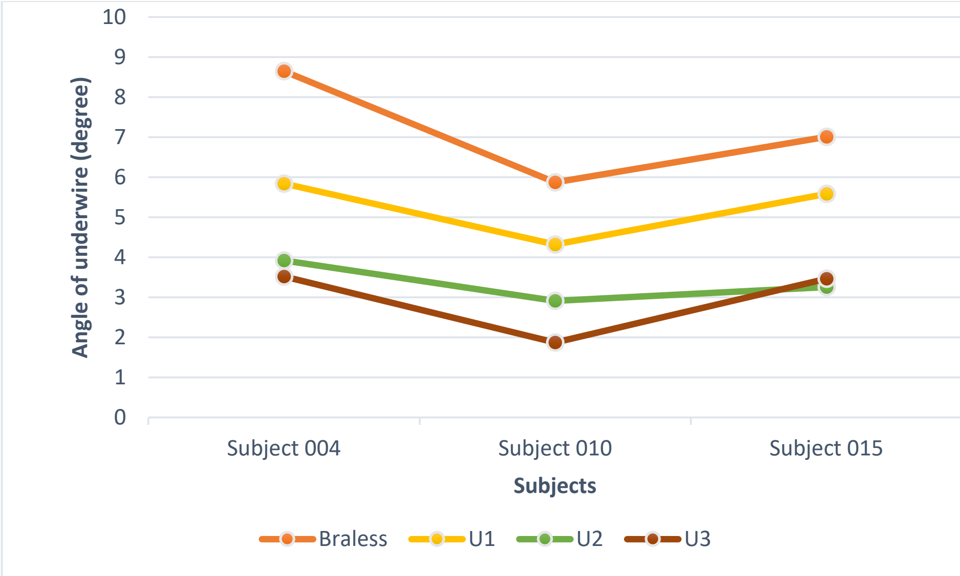


Figure 5.10 Angle between planar underwire and different underwires – bra size 75D

5.5.3 Inclination angle of underwire

By using the soft manikin with breasts, the angles of U1, U2 and U3 obtained with different adjustment of length are presented in Table 5.7. The 2D underwire of U1 shows the least amount of changes in the angle of the underwire compared to U2 and U3. Although the angle of the underwires shows no significant difference (p-value>0.05) for the lengths of the shoulder straps and underband, the effect on the angle of the underwire can still be addressed. The shoulder strap and underband with the highest length result in similar underwire angles for U2 and U3 but the variation in the angle in comparison to the braless condition is higher than that of U1 (21% to 31%). The bending rigidity results (as discussed in Section 5.5.1) are consistent with the angle of underwire results in that the flexible material can fit the underbreast curve with shorten length of the shoulder strap and underband.

Table 5.7 Angle of underwire with different lengths of shoulder strap and underband for 75B and 75D - soft manikin with breasts

	75B			75D		
Underwire sample	U1	U1	U2	U3	U2	U3
Braless		4.77°			4.81°	
IA	6.54°	6.78°	5.82°	6.24°	5.67°	6.23°
IIA	4.27°	5.24°	6.79°	6.50°	6.53°	6.56°
IIIA	5.34°	5.60°	7.32°	7.45°	7.16°	7.26°
IC	5.76°	5.79°	7.65°	7.00°	7.49°	7.34°
IIC	4.16°	4.27°	6.50°	6.45°	6.31°	6.23°
IIIC	4.22°	4.57°	6.26°	6.38°	5.87°	5.47°
IE	2.50°	2.61°	3.67°	3.23°	3.43°	3.36°
IIE	2.07°	2.25°	3.52°	3.13°	3.24°	3.11°
IIIE	1.16°	1.18°	2.67°	2.51°	2.41°	2.33°

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm. A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. Highlighted numbers are adjusted to the best fit with shoulder strap and underband length (IIA)

When there is a reduction in the length of the shoulder straps but that of the underband remains the same (IA, IIA and IIIA), the angle of the underwire compared to the braless condition is increased (Figure 5.11). The difference (percentage) in the angle of the underwire for 75B and 75D increase by 20% to 50% with shorten underband length. The release of the length of the shoulder straps reduces the pulling force for the cup fabric to open the planar underwire. In this case, the underwire cannot fully accommodate the breast volume and provide sufficient bra fit.

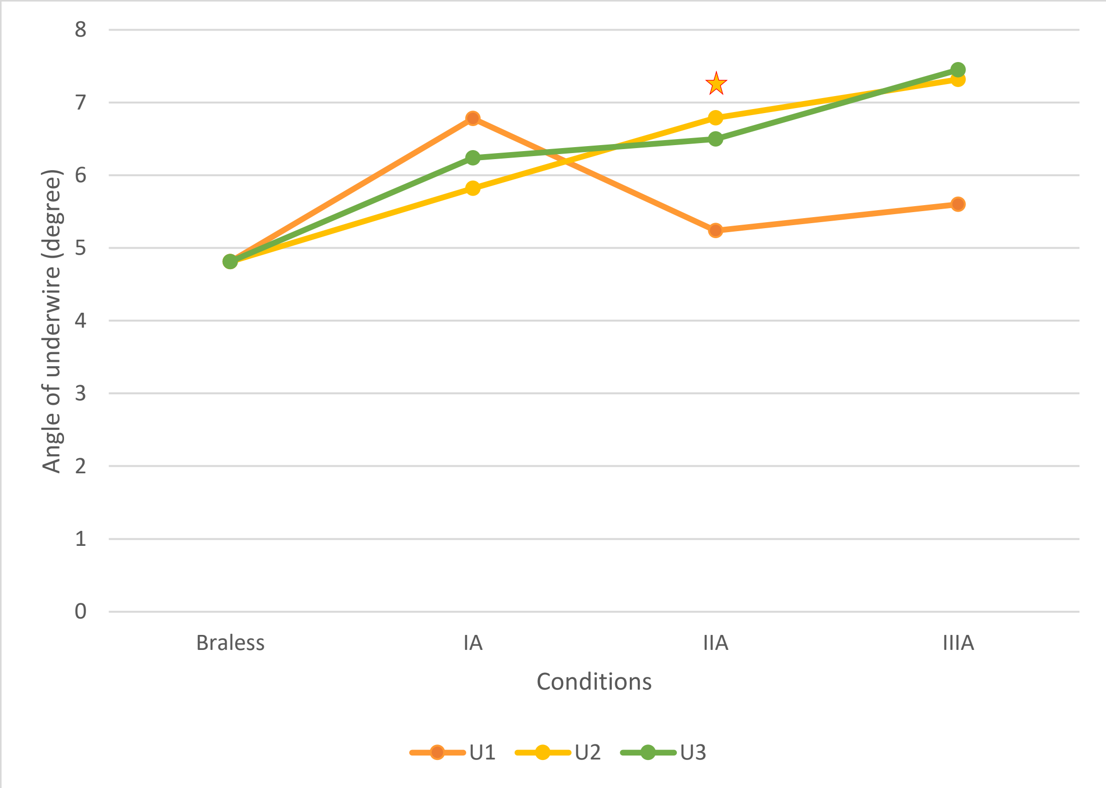


Figure 5.11 Angle of underwire with changes in length of shoulder strap (75D)

Notes: IA, IIA and IIIA refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm respectively with underband length of 65 cm.

☆ refers to best fitting shoulder strap and underband length (IIA)

Figure 5.12 shows the effects of underband length on the angle of the underwire. The angle of U1, U2 and U3 all show an increased difference compared to the braless condition with a reduction in the underband length. Figure 5.13 shows the angle of the underwire with an underband length that provides the best fit (A) and with the loosest underband length (E). The former follows the natural underbreast curve due to the appropriate amount of length adjustment while IIE causes a larger gap between the underwire and underbreast curve. Therefore, the underband length seems to be a key factor that affects the underwire angle during bra wear. A lower underband length does not allow the underwire to deform and bend, thus resulting in a poor-fitting bra.

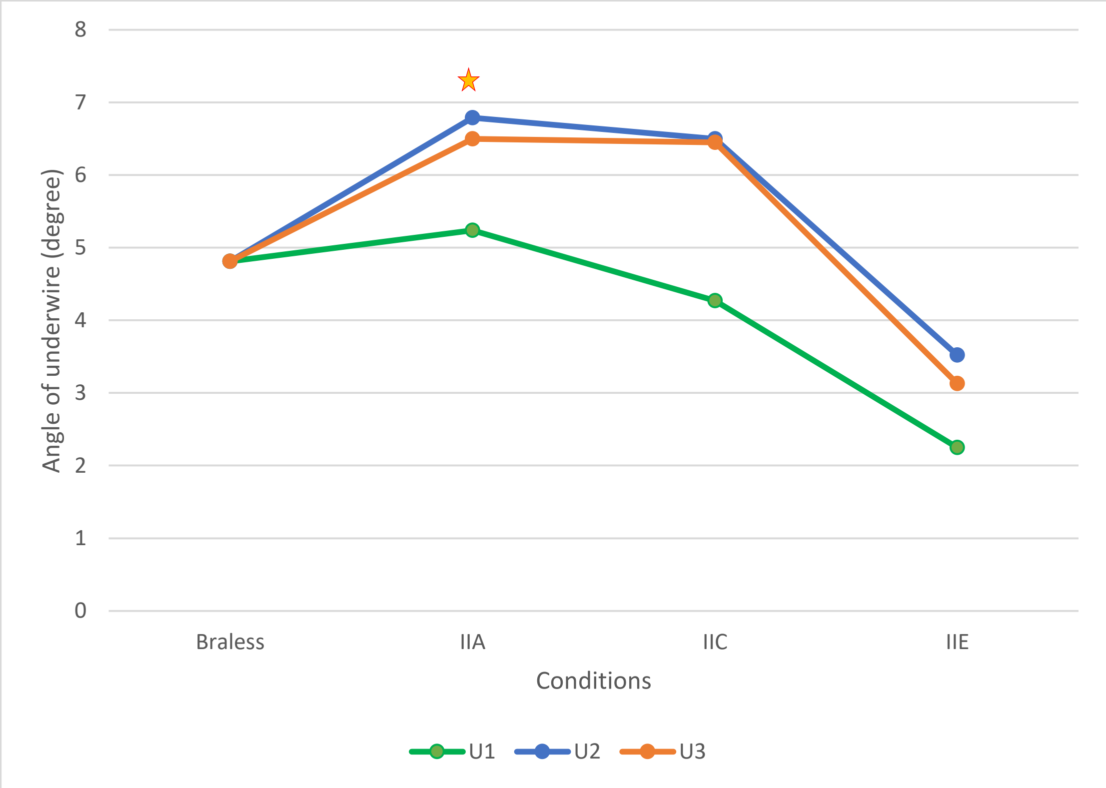


Figure 5.12 Angle of underwire with changes in length of underband (75D)

Note: IIA, IIC and IIE refer to underband lengths of 65 cm, 73 cm and 81 cm respectively with shoulder strap length of 40 cm

☆ refers to best fitting shoulder strap and underband length condition (IIA)

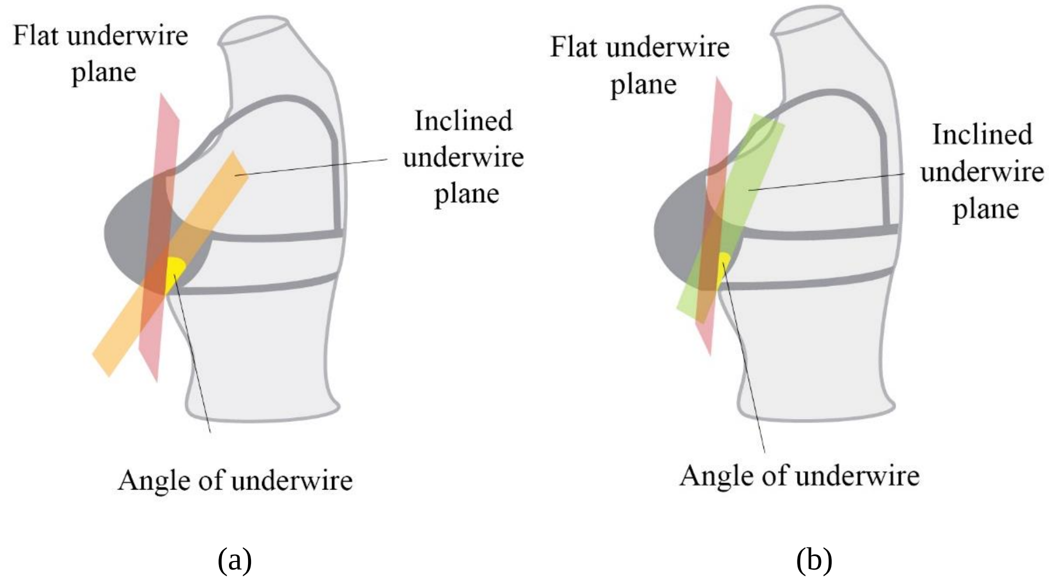


Figure 5.13 Angle of underwire: (a) IIA and (b) IIE condition

Note: IIA and IIE refer to underband lengths of 65 cm and 81 cm respectively with shoulder strap length of 40 cm

It is worth noting that the angles of the underwire obtained from the subjects and the soft manikin with breasts are similar. The soft manikin with breasts shows a significantly linear relationship with the coefficient of determination (p-value<0.05) which represents 77.9% of the actual angle of the underwire (Figure 5.14). The findings show that the soft manikin with breasts could be used as an alternative for evaluating bra fit, because it provides consistent results and not affected by the variations found with human subjects.

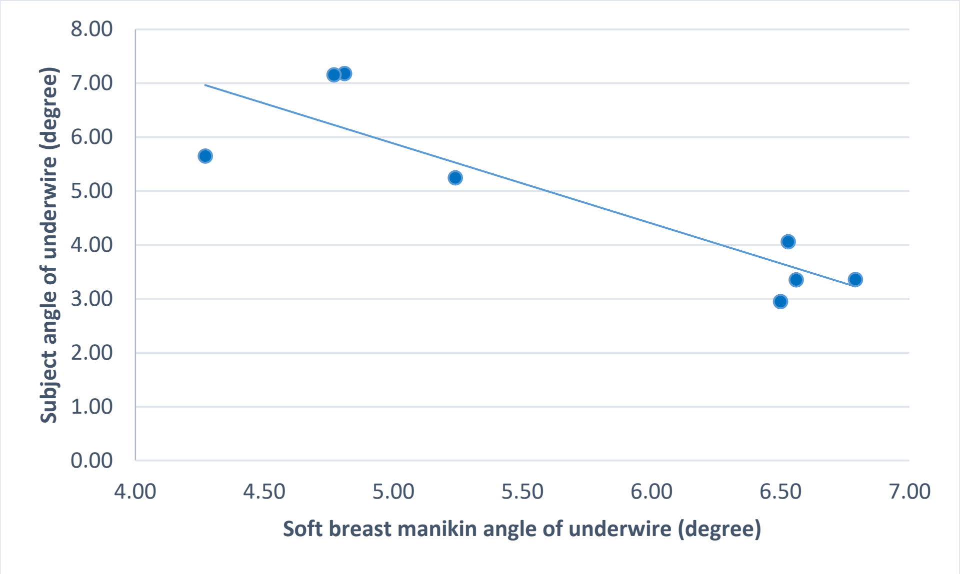


Figure 5.14 Scatter diagram of angle of underwire: subject vs. soft manikin with breasts

5.5.4 Evaluation of bra insert design

The angle of the underwire based on the different underwire/ bra insert designs is presented in Figure 5.15. It can be observed that the 3D bra insert better accommodates the natural shape of the underbreast curve. The smallest angle difference in underwire angle is obtained between the braless and 3D bra insert fabricated with nylon 12 (0.37° and 0.39°). In terms of the bending results (see Section 5.5.1), nylon 12 has the lowest bending rigidity. Although materials with a lower bending rigidity help with the bra fit, overly flexible underwire materials may result an easier deformation of the underwire or bra inserts from the length of the shoulder straps and underband. A certain amount of rigidity needs to be available in order to balance fit and support (Lee & Hong, 2007).

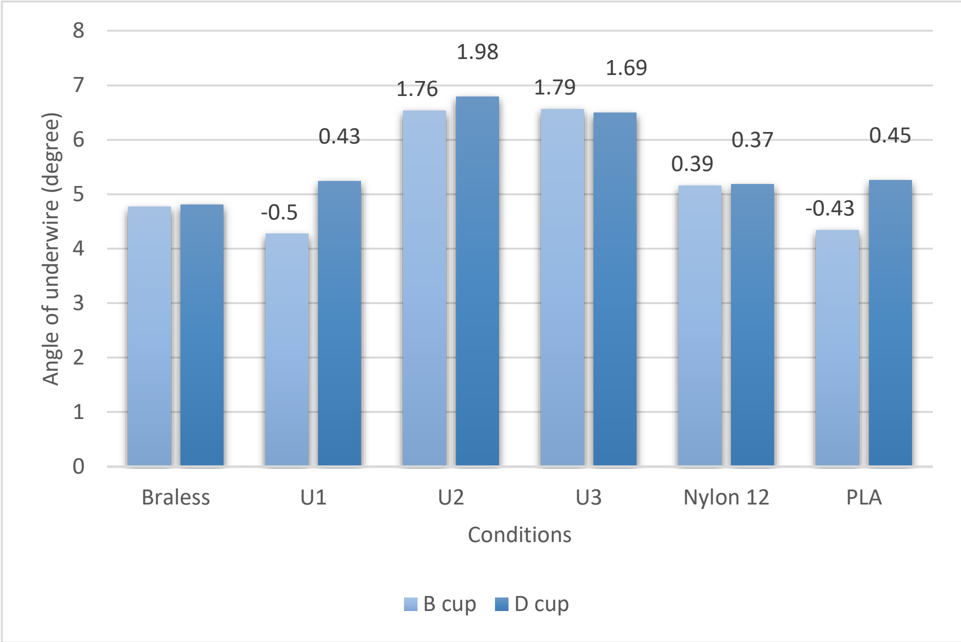


Figure 5.15 Angles of underwire with different underwire/ bra insert designs

Note: Number in parentheses refers to the angle of underwire differences between braless condition and with a bra worn

To examine the support of the different underwire samples (U1, U2 and U3) and bra inserts (nylon 12 and PLA), Figure 5.16 shows the total vertical breast displacement of the dynamic soft manikin with a bra size of 75D when walking at speeds of 2.30 km/h and 4.08 km/h with different support components. All of the underwire samples or bra insert designs provide significant decreases in the total vertical breast displacement compared to the braless condition under the two walking speeds and two bra sizes (*p*-value <0.05). A greater reduction in the total vertical breast displacement is found for a slower walking speed of 2.30 km/h and smaller bra size of 75B due to the lower impact force and gravity effect (McGhee, Steele, Zealey & Takacus, 2012). The results are consistent with the findings in Chapter 4.

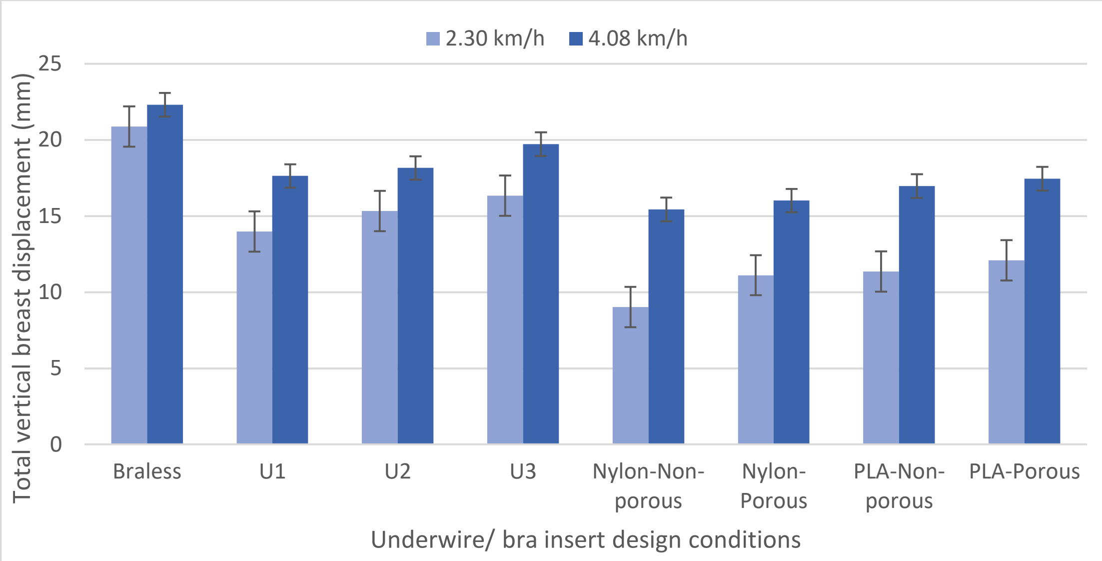


Figure 5.16 Total vertical breast displacement of soft manikin with breast size of 75D: walking speeds of 2.30 km/h and 4.08 km/h

Among the steel underwire samples, U1 provides better breast support than U2 and U3. The decrease (percentage) in the total vertical breast displacement with U1 is 21% to 59% while that with U2 and U3 ranges from 12% to 55% compared to the braless condition. For the 3D bra inserts, nylon 12 reduces the total vertical breast displacement of 30.83%% from 22.31 mm to and 15.43 mm at a faster walking speed of 4.08 km/h while PLA does not reduce the total vertical breast displacement as much with 23.98 % of about 6 mm.

Moreover, the 3D printed non-porous inserts show more effectiveness in restricting the breast motion, and reduces 31% of the total vertical breast displacement compared to the braless condition at a walking speed of 4.08 km/h. On the other hand, the 3D printed porous inserts reduces 28% of the total vertical breast displacement at the same walking speed. A larger percentage of decrease in the vertical breast displacement for a walking speed of 2.30 km/h is also obtained with the non-porous inserts (57%) as opposed to the porous inserts (47%). Therefore, the 3D printed non-porous inserts have a better performance in controlling breast motion than both of the 3D printed inserts which are porous for both bra sizes.

It is remarkable that the ergonomic bra inserts composed of flexible material better accommodate the natural curvature of the underbreast. A well-fitting bra helps to reduce breast displacement and provide better bra comfort (Bowles & Steele, 2013). The results of the vertical breast displacement are in line with the results of the breast geometry measurements. Besides, greater coverage of the breast volume would help to redistribute the weight of the breasts to the torso of the body. Since the bra inserts better control breast motion while moving, adverse effects of breast pain or injury would also be minimized (McGhee & Steele, 2010).

Although the 3D printed bra inserts in this study improve the bra fit and support performance, the weight of the bra insert should be closely examined. As the traditional steel underwires are around half of the weight of the 3D bra inserts, it is important to assess whether the increased weight would affect the bra comfort in the long term.

5.6 Chapter summary

In this chapter, newly designed bra inserts are proposed to control breast. The bending rigidity is examined because the length of the shoulder straps and underband would spring open the underwire so an overly rigid insert/underwire inhibits this function. The mechanical properties and corresponding geometric shape of the underwires and inserts have also been characterized. By measuring the angle of the underwire, the corresponding changes with different material properties or adjustments to the shoulder straps and underband are investigated. A material with a lower bending rigidity offers a better fit of the natural curvature of the underbreast with appropriate shoulder strap and underband length. Besides, the designed ergonomic 3D bra inserts have a better performance in controlling breast motion compared to the conventional planar underwire samples. Both bra fit and support function are also improved with the new inserts. The advantages of the 3D ergonomic bra inserts in controlling breast motion mean that it is worthwhile to pursue further related studies to balance comfort and support for commercialization of the inserts in the market in the future.

CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 Conclusions

The breasts are viscoelastic in nature and rely on the ligaments and skin for anatomic support. Bras are used to provide external support to the breasts, which include underwire, padded, and wireless bras. They protect the breast structure during movement. Moulded bras are gaining in popularity due to their aesthetically pleasing appearance and wear comfort. Nevertheless, their shortcomings such as excessive high length of the shoulder straps and underband could have substantial negative effects on wear comfort and the physical health of women. Therefore, a properly designed and well fitting bra helps to control excessive pressure induced by the bra and limit breast motion to prevent the connective tissues from over-stretching. However, previous research studies have mainly focused on the compression and motion control performance of sports bras, particularly on the design of the shoulder straps, influence of the shoulder strap orientation or cushioning of the bra-manikin pressure and controlling breast displacement. Scientific research work on moulded daily use bras has been limited. It has been concluded that increased length of the shoulder straps and underband could reduce the gap that causes breast movement, thus resulting in less breast motion and better support of the breasts. However, the breasts may be over-compressed which would cause issues such as pain or increase the breast displacement. Nevertheless, it is not clear how the use of an underwire and manipulating the length of the bra band would affect the support of the breasts.

The overall aim of this research work is to evaluate the supportive features of moulded bras by changing the properties of the shoulder straps, bra band and cup inserts. A dynamic manikin with soft breasts is used to evaluate the changes in the bra components that would affect the bra-manikin pressure and the vertical breast displacement. The objectives outlined in Chapter 1 have been achieved and the findings are summarized below.

(1) To analyze the bra-manikin pressure distribution with changes in the structural design and material of the bra, the NOVEL Pliance-X® pressure system is used to measure the pressure and pressure changes at the shoulder straps and underband and the material properties of the various bra components (shoulder strap and underband material, cup material and underwire). Six measured points including the gore, curve of the underbreast (/underwire) start, middle and end points of the underwire, shoulders and back of the underband have been tested for length changes under different bra conditions. Particularly, the pressure points of the middle of the underbreast (/underwire), shoulders and back of the underband are found to have more significant bra-manikin pressure changes among the various conditions. A high length of the shoulder straps and underband, high stress-strain of the shoulder strap and underband material, flexible cup material and insertion of an underwire are observed to produce a relatively higher bra-manikin pressure at those three points. Six independent variables including the underwire, underband length, stress-strain of the cup fabric, shoulder strap and bra band material, shoulder strap length and bra size are used in a subject-specific empirical prediction model to determine the bra-skin pressure. The testing with the manikin provides satisfactory results that validate the predicted results.

(2) To minimize personal embarrassment and inconsistencies with the use of human subjects when measuring breast motion, a novel approach of using a dynamic manikin is applied in this study. The manikin can be used to simulate vertical breast

displacement at slow (2.30 km/h) and fast (4.08 km/h) walking speeds. The VICON motion capture system is used to capture the motion through retro-reflective markers placed on the suprasternal notch and nipples and then the (total) vertical breast displacement and examined motion in the upward and downward directions are determined. Under the braless condition, the total vertical breast displacement for both the 75B and 75D bra sizes shows a significant difference for the two walking speeds. A higher repeating frequency with a greater magnitude of the vertical motion and oscillation after the displacement peak is reached for the faster walking speed are observed. The majority of the donned bra conditions show a significant reduction of the total vertical breast displacement especially in the upward direction. Although high levels of bra-manikin pressure are observed with the use of a bra that has shoulder straps and underband with low stress and strain, the soft flexible fabric-foam laminated cup material and the insertion of an underwire result in better control of the breast movement during both slow and fast walking. Similar changes in the total vertical displacement for bra sizes of 75B and 75D are found under the different testing conditions. The critical independent variable of movement speed is examined with the use of six independent variables in the subject-specific empirical prediction model of bra-manikin pressure to calculate the total vertical breast displacement. Laboratory wear trials are also conducted to validate the vertical breast motion of the dynamic manikin with the results from a human subject. Although the magnitude of the displacement of the manikin is consistently greater than that of the subject, a significant linear relationship can be obtained with a linear equation. Therefore, a dynamic manikin is another option that can be used to examine the vertical breast motion.

(3) To improve the ergonomic design and support function of the moulded bra, an investigation is carried out on the geometric shape of the breasts to gain a better understanding on the effect of the angle of conventional planar underwires. Similar results of the underbreast curvature with different underwires are obtained from the manikin and invited subjects with breast sizes of 75B and 75D. The appropriate shoulder strap and underband length then provide sufficient length to stretch the underwire material with lower bending rigidity into an angle that accommodates the curvature of the breasts without a bra. A new bra insert design is then developed on the basis of the natural curvature of the underbreast and consists of an extended part from the curve to cover part of the breasts. The primary ergonomic feature of the bra insert is that it provides a better fit with the natural curvature of the underbreast. A 3D bra insert made of nylon 12 is found to be the most flexible compared to steel and the more rigid PLA material. The support performance of the 3D bra inserts has also improved. Greater coverage of the breast volume by the supporting components helps to redistribute the weight of the breasts to the torso and therefore redistribute the impact during movement. Nylon 12 with a non-porous material as the bra insert provides the best support among the tested underwire samples and designed bra inserts. Therefore, the insert design for ergonomic bras should be studied in more depth because of its role in supporting the breasts.

6.2 Limitations of the study

This study has several limitations that might affect the generalizability of the results. They are as follows.

(1) A manikin is used throughout the entire study. The bra-manikin pressure is measured with the manikin in a static state. Therefore, dynamic activity is not considered or

the bra-manikin pressure under different activity levels are not taken into account because there are difficulties in ensuring that the flat surface of the pressure sensor would be in close contact with the pressure points on the breasts during motion. For both the bra-manikin pressure analysis (Chapter 3) and breast displacement evaluation (Chapter 4), the same manikin with two bra sizes is used. The breast prostheses and layer of skin applied to the manikin assume that the breasts and skin have a uniform structure with a single type of material. However, the composition of the breasts and skin layer have different proportions of fat, ligament linkages and fibro-glandular tissues. The differences in material properties such as elasticity may cause deviation of the behavior during motion. Besides, the bra cannot be fitted onto the manikin like on an actual human being. For example, some of the muscles near the armhole need to be pulled forward as the breast structure and fill the bra cup with tissue. The composition or structural differences of the manikin in comparison to human subjects may mean that the manikin cannot insufficiently reflect real life situations.

(2) Subject-specific empirical prediction formulas are calculated to determine the bra-skin pressure at selected pressure points and total vertical breast displacement in Chapters 3 and 4 respectively. Both are validated with one to two recruited subjects. Since there are difficulties in recruiting subjects for the braless or donned bra wear trials, the sample size is relatively small. Variations among the small number of invited subjects may also affect the accuracy of the validation process.

(3) Typical bra components that include the shoulder straps, underband, underwire and bra cup materials are examined for bra-manikin pressure, breast displacement and the corresponding geometric shape to assess the overall performance of a bra.

However, a complete bra design involves multiple components such as the wings or gore which are not taken into consideration here. Therefore, future studies should consider more design parameters.

6.3 Recommendations for future work

Based on the limitations in this study, recommendations are provided below for future work on the overall performance of bras. First, if future studies would like to use a manikin, it is recommended that they use multiple layers of materials with different hardness or materials that can be extended for the breast prostheses. A review of the properties of the breast components would help to select the materials for the breast prostheses. By incorporating the actual properties of the breasts, the experiments with the manikin can more reflect the actual situation. For the dynamic part of the manikin, the cam design of the mechanical device should be improved for more smooth movement and reflect the actual magnitude of breast displacement. More cam designs should be proposed to test walking or running speeds that are faster than 4.08 km/h. This extends the application of the dynamic manikin to sport bra related studies. To validate the accuracy of using the manikin, more subjects can be invited to enhance the representativeness of the results.

Future research work could also include different material properties such as friction or air permeability to explore the impact of the materials on bra comfort. Design features including cup material or underwire shape, shoulder strap orientation, and bra band width can also be included as test variables to understand their impacts on bras.

APPENDIX I BRA-SKIN PRESSURE RESULTS

Bra-skin pressure for bra size of 75B (Sample X)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Underwire (start)	2.6	2.3	1	2.4	1.8	1.7	2.6	1.9	1.4	1.5	1.1	0.7	1.1	0.6	0.5
3. Underwire (middle)	10.6	10.5	10.4	10.1	10	9.7	9.6	9.3	9.2	8.7	8.6	8.5	8	7.5	6.8
4. Underwire (end)	2.3	2.1	2.1	2.2	1.9	1.9	2	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.1
5. Shoulder	9	8.7	7.5	8.5	8	7.2	8.6	8.2	6.2	6.9	6.3	5.5	6.3	5.4	4.6
6. Back of the underband	8.3	8	7.4	6.9	6.4	5.5	5.2	5.1	4.4	3.9	3.8	3.6	3.1	2.6	1.5

Bra-skin pressure for bra size of 75B (Sample Y)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Underwire (start)	2.8	2.6	2.6	1.4	1.2	2.3	1.9	1.8	1	1	1	1.3	1.3	1	1
3. Underwire (middle)	10.6	10.2	9.6	8.8	8.1	10.5	9.9	9.4	8.6	7.6	10.3	9.8	9.3	8.4	6.8
4. Underwire (end)	1.9	1.7	1.5	1.4	1.2	1.8	1.6	1.5	1.3	1.1	1.6	1.3	1.1	1	0.9
5. Shoulder	8.3	6.8	7	6.5	5.7	7.2	6.1	6.3	4.3	3.8	5.5	5.3	4.9	3.3	2.5
6. Back of the underband	7.6	6.5	4.8	3.4	2.4	7.3	5.8	4.6	3.8	2	6.9	5.3	4	3.5	1.4

Bra-skin pressure for bra size of 75B (Sample Z)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Underwire (start)	0.4	0.3	0.2	0.3	0.2	0.1	0.1	0	0	0	0	0	0	0	0
3. Underwire (middle)	6.2	5.7	4.5	5.4	4.4	2.9	4.3	3.5	2.3	3.1	2.2	2	1.9	1.5	1.4
4. Underwire (end)	1.4	1.3	0.8	1.2	1	0.7	0.9	0.9	0.6	0.6	0.6	0.5	0.4	0.3	0.3
5. Shoulder	7.6	6.7	6.3	6.5	5.5	5.2	6.7	5.7	4.9	6	4.3	3.2	5.1	3.2	2.6
6. Back of the underband	6.8	5.7	5.6	4.7	4.4	4.8	4	3.5	3.2	1.9	1.7	1.4	1.1	0.6	0.3

Bra-skin pressure for bra size of 75D (Sample X)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Underwire (start)	2.8	2.3	1	2.6	1.9	1.3	2.6	1.8	1.3	1.4	1	1	1.2	1	1
3. Underwire (middle)	10.6	10.5	10.3	10.2	9.9	9.8	9.6	9.4	9.3	8.8	8.6	8.4	8.1	7.6	6.8
4. Underwire (end)	1.9	1.8	1.6	1.7	1.6	1.3	1.5	1.5	1.1	1.4	1.3	1	1.2	1.1	0.9
5. Shoulder	8.3	7.2	5.5	6.8	6.1	5.3	7	6.3	4.9	6.5	4.3	3.3	5.7	3.8	2.5
6. Back of the underband	7.6	7.3	6.9	6.5	5.8	5.3	4.8	4.6	4	3.4	3.8	3.5	2.4	2	1.4

Bra-skin pressure for bra size 75D (Sample Y)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Underwire (start)	2.8	2.4	1	2.5	1.9	1.7	2.7	2.1	1.4	1.6	1.2	0.8	1.2	0.7	0.5
3. Underwire (middle)	10.6	10.6	10.6	10.6	10.5	10.4	10.3	10.1	9.8	9.7	9.5	9.3	8.5	7.9	7.2
4. Underwire (end)	2.4	2.2	2.2	2.3	2	1.9	2.1	1.8	1.6	1.7	1.6	1.5	1.5	1.3	1.2
5. Shoulder	9.3	8.6	7.7	8.6	8.2	7.8	8.8	8.4	6.5	7.2	6.6	5.8	6.7	5.7	4.8
6. Back of the underband	8.5	8.2	7.7	7.2	6.6	5.8	5.4	5.3	4.6	4.2	4.1	4	3.5	2.8	1.8

Bra-skin pressure for bra size of 75D (Sample Z)

Pressure (kPa)	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
1. Gore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2. Underwire (start)	0.4	0.3	0.1	0	0	0.3	0.3	0	0	0	0.2	0.1	0	0	0
3. Underwire (middle)	6.3	5.6	4.5	3.3	1.8	5.8	4.6	3.6	2.2	1.5	4.6	3	2.4	2.1	1.5
4. Underwire (end)	1.4	1.3	1	0.7	0.5	1.2	1.2	1	0.6	0.4	0.8	0.8	0.7	0.5	0.3
5. Shoulder	7.8	6.7	6.9	6.2	5.3	7	5.8	6.2	4.6	3.4	6.5	5.4	5.1	3.5	2.7
6. Back of the underband	7	4.9	4.2	2	1.2	6.1	4.7	3.8	1.8	0.6	5.8	5	3.5	1.5	0.4

APPENDIX II VERTICAL BREAST DISPLACEMENT RESULTS

Vertical breast displacement for 75B braless condition vs. Bra condition X

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.31 (0.8)	11.83 (1.39)	-8.48 (0.87)	20.82 (0.42)	11.16 (0.47)	-9.66 (0.36)
IA	9.16* (0.25)	7.20* (0.27)	-1.96* (0.14)	17.27* (0.68)	13.69 (0.7)	-3.58* (0.33)
IB	12.67* (0.44)	9.54* (0.44)	-3.13* (0.27)	21.29* (1.23)	15.02* (0.71)	-6.27 (0.61)
IC	11.66* (0.37)	8.71* (0.2)	-2.95* (0.23)	20.44* (1)	14.82* (0.7)	-5.62 (0.48)
ID	11.16* (0.27)	8.37* (0.17)	-2.78* (0.14)	19.74* (0.74)	14.41* (0.75)	-5.34 (0.22)
IE	10.98* (0.23)	8.14* (0.18)	-2.84* (0.14)	21.44* (1.02)	15.14* (0.62)	-6.30* (0.54)
IIA	9.76* (0.18)	7.81* (0.2)	-1.95* (0.17)	18.53 (0.58)	14.42* (0.78)	-4.11* (0.47)
IIB	11.20* (0.25)	8.64* (0.25)	-2.56* (0.17)	22.79* (0.75)	15.11* (0.63)	-7.68* (0.57)
IIC	11.22* (0.48)	8.44* (0.27)	-2.78* (0.24)	19.67* (0.67)	14.59* (0.67)	-5.08* (0.29)
IID	11.99* (0.41)	8.93* (0.22)	-3.06* (0.23)	20.55* (0.76)	14.96* (0.59)	-5.59 (0.39)
IIE	11.87* (0.36)	8.84* (0.2)	-3.04* (0.21)	19.67 (0.8)	14.35* (0.7)	-5.32 (0.29)
IIIA	10.56* (0.29)	8.19* (0.27)	-2.37* (0.18)	18.34* (0.63)	14.08* (0.68)	-4.27* (0.3)
IIIB	11.33* (0.24)	8.79* (0.28)	-2.54* (0.14)	18.16* (0.52)	13.99* (0.68)	-4.17* (0.33)
IIIC	11.30* (0.41)	8.41* (0.22)	-2.88* (0.21)	20.38* (0.76)	14.88* (0.66)	-5.51 (0.36)
IIID	12.12* (0.42)	9.06* (0.26)	-3.05* (0.22)	20.64* (0.85)	14.95* (0.62)	-5.69 (0.38)
IIIE	12.90*	9.74*	-3.15*	20.49*	14.80*	-5.68

	(0.44)	(0.42)	(0.18)	(0.81)	(0.71)	(0.31)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. **p*-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

Vertical breast displacement for 75D braless condition vs. Bra condition X

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.87 (0.28)	11.18 (0.41)	-9.69 (0.29)	22.31 (0.71)	8.6 (0.43)	-13.71 (0.6)
IA	17.83* (0.28)	13.69* (0.26)	-4.14* (0.18)	17.45* (1.17)	13.39* (1.15)	-4.06* (0.24)
IB	15.27* (0.31)	11.35* (0.73)	-3.92* (0.55)	21.44* (0.4)	15.15* (0.37)	-6.29* (0.18)
IC	15.97* (0.23)	11.65* (0.14)	-4.32* (0.12)	21.05* (0.42)	14.97* (0.47)	-6.08* (0.18)
ID	19.01* (0.23)	13.25* (0.15)	-5.76* (0.2)	24.29* (0.4)	17.31* (0.4)	-6.98* (0.14)
IE	18.05* (0.31)	12.30* (0.16)	-5.75* (0.25)	23.04* (0.83)	16.05* (0.48)	-6.98* (0.8)
IIA	12.28* (0.26)	9.86* (0.32)	-2.42* (0.18)	18.05* (0.48)	13.92* (0.49)	-4.13* (0.12)
IIB	15.78* (0.25)	11.25* (0.14)	-4.53* (0.14)	20.23* (0.49)	14.02* (0.49)	-6.22* (0.19)
IIC	15.25* (0.19)	11.07* (0.15)	-4.19* (0.12)	21.01* (0.49)	15.14* (0.47)	-5.88* (0.13)
IID	18.34* (0.24)	12.97* (0.14)	-5.36* (0.18)	21.76* (0.48)	14.84* (0.99)	-6.92* (0.67)
IIE	18.40* (0.36)	12.40* (0.22)	-5.99* (0.29)	23.16* (0.42)	15.95* (0.42)	-7.21* (0.19)
IIIA	13.33* (0.15)	10.41* (0.18)	-2.92* (0.1)	18.64* (0.5)	14.29* (0.52)	-4.35* (0.14)
IIIB	13.27* (0.13)	10.53* (0.09)	-2.74* (0.11)	21.14* (0.44)	15.01* (0.46)	-6.13* (0.15)
IIIC	17.04* (0.28)	12.17* (0.14)	-4.87* (0.19)	23.19* (0.71)	15.97* (0.4)	-7.22* (0.7)
IIID	16.05 (0.33)	11.30* (0.18)	-4.75* (0.2)	23.17* (0.4)	15.62* (0.39)	-7.54* (0.15)
IIIE	18.95* (0.36)	12.78* (0.24)	-6.16* (0.24)	22.92* (0.34)	15.27* (0.3)	-7.65* (0.24)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. *p-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

Vertical breast displacement for 75B braless condition vs. Bra condition Y

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.31 (0.8)	11.83 (1.39)	-8.48 (0.87)	20.82 (0.42)	11.16 (0.47)	-9.66 (0.36)
IA	6.81* (0.19)	5.70* (0.21)	-1.12* (0.08)	19.03* (0.68)	16.74* (0.61)	-2.29* (0.4)
IB	6.39* (0.31)	5.04* (0.33)	-1.35* (0.1)	14.96* (0.92)	11.51* (0.54)	-3.45* (0.76)
IC	7.81* (0.31)	6.36* (0.29)	-1.45* (0.09)	16.37* (0.77)	12.67* (0.52)	-3.70* (0.44)
ID	8.63* (0.35)	6.99* (0.36)	-1.63* (0.11)	15.15* (0.84)	11.65* (0.69)	-3.50* (0.31)
IE	9.35* (0.37)	7.17* (0.36)	-2.18* (0.15)	16.87* (1.11)	13.12 (0.78)	-3.75* (0.55)
IIA	6.78* (0.31)	5.72* (0.28)	-1.06* (0.09)	12.03* (0.73)	9.15* (0.63)	-2.88* (0.18)
IIB	9.68* (0.43)	7.93* (0.33)	-1.75* (0.18)	15.42* (1.15)	11.74* (0.79)	-3.68* (0.48)
IIC	7.74* (0.25)	6.22* (0.29)	-1.52* (0.08)	15.04* (0.92)	11.73* (0.87)	-3.31* (0.45)
IID	8.71* (0.43)	6.71* (0.36)	-2.00* (0.11)	17.05* (0.99)	13.39 (0.66)	-3.65* (0.47)
IIE	10.65* (0.5)	8.07* (0.45)	-2.58* (0.14)	17.41* (1.01)	13.45 (0.72)	-3.96* (0.47)
IIIA	5.97* (0.38)	4.74* (0.33)	-1.23* (0.13)	15.17* (0.95)	11.88* (0.75)	-3.29* (0.48)
IIIB	8.96* (0.42)	7.15* (0.37)	-1.80* (0.15)	14.10* (1.04)	11.50* (0.77)	-2.60* (0.68)
IIIC	8.01* (0.35)	6.48* (0.49)	-1.52* (0.29)	15.35* (1.06)	11.94* (0.91)	-3.41* (0.28)
IIID	9.21* (0.63)	7.24* (0.47)	-1.97* (0.22)	16.86* (1.08)	13.32 (0.75)	-3.54* (0.4)
IIIE	10.25* (0.65)	7.89* (0.45)	-2.36* (0.41)	17.54* (1.06)	13.36 (0.82)	-4.18* (0.5)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. **p*-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

Vertical breast displacement for 75D braless condition vs. Bra condition Y

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.87 (0.28)	11.18 (0.41)	-9.69 (0.29)	22.31 (0.71)	8.6 (0.43)	-13.71 (0.6)
IA	11.79* (0.28)	8.83* (0.26)	-2.95* (0.18)	17.56* (1.17)	13.26* (1.15)	-4.29* (0.24)
IB	13.34* (0.31)	9.26* (0.73)	-4.08* (0.55)	17.89* (0.4)	13.26* (0.37)	-4.64* (0.18)
IC	13.95* (0.23)	10.19* (0.14)	-3.77* (0.12)	17.45* (0.42)	13.06* (0.47)	-4.39* (0.18)
ID	12.99* (0.23)	9.07* (0.15)	-3.93* (0.2)	18.67* (0.4)	13.04* (0.4)	-5.63* (0.14)
IE	13.22* (0.31)	9.32* (0.16)	-3.90* (0.25)	19.68* (0.83)	14.23* (0.48)	-5.46* (0.8)
IIA	11.99* (0.26)	7.43* (0.32)	-4.55* (0.18)	15.59* (0.48)	12.23* (0.49)	-3.36* (0.12)
IIB	11.92* (0.25)	8.84* (0.14)	-3.08* (0.14)	16.55* (0.49)	12.62* (0.49)	-3.94* (0.19)
IIC	12.52* (0.19)	9.24* (0.15)	-3.28* (0.12)	18.39* (0.49)	13.53* (0.47)	-4.86* (0.13)
IID	12.61* (0.24)	9.02* (0.14)	-3.59* (0.18)	18.31* (0.48)	12.88* (0.99)	-5.43* (0.67)
IIE	14.42* (0.36)	9.68* (0.22)	-4.73* (0.29)	19.58* (0.42)	13.75* (0.42)	-5.83* (0.19)
IIIA	11.24* (0.15)	8.17* (0.18)	-3.07* (0.1)	15.14* (0.5)	11.72* (0.52)	-3.41* (0.14)
IIIB	11.11* (0.13)	8.35* (0.09)	-2.76* (0.11)	16.55* (0.44)	12.62* (0.46)	-3.94* (0.15)
IIIC	11.52* (0.28)	8.41* (0.14)	-3.11* (0.19)	18.25* (0.71)	14.11* (0.4)	-4.14* (0.7)
IIID	14.01* (0.33)	10.24* (0.18)	-3.77* (0.2)	18.58* (0.4)	13.92* (0.39)	-4.66* (0.15)
IIIE	14.69* (0.36)	9.87* (0.24)	-4.82* (0.24)	20.09* (0.34)	13.94* (0.3)	-6.15* (0.24)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. *p-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

Vertical breast displacement for 75B braless condition vs. Bra condition Z

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.31 (0.8)	11.83 (1.39)	-8.48 (0.87)	20.82 (0.42)	11.16 (0.47)	-9.66 (0.36)
IA	13.97* (0.37)	10.80* (0.3)	-3.17* (0.21)	21.23* (2.7)	15.86* (2)	-5.37* (0.77)
IB	14.59* (0.28)	11.41 (0.23)	-3.18* (0.19)	21.95 (3.59)	16.04* (2.13)	-5.92* (1.51)
IC	17.66* (0.38)	12.45* (0.15)	-5.21* (0.32)	23.37* (2.86)	16.45* (0.96)	-6.92* (2)
ID	18.80* (0.32)	13.25* (0.26)	-5.55* (0.22)	24.81* (3.76)	16.84* (1.31)	-7.97* (2.51)
IE	19.89* (0.39)	13.16* (0.24)	-6.73* (0.21)	23.68* (3.05)	16.27* (0.99)	-7.41* (2.15)
IIA	14.85* (0.3)	11.06 (0.24)	-3.79* (0.22)	21.33* (3.4)	15.95* (2.37)	-5.38* (1.43)
IIB	18.89* (0.4)	13.34* (0.27)	-5.55* (0.25)	23.43* (4.17)	16.34* (2.01)	-7.09* (2.19)
IIC	16.22* (0.49)	12.15* (0.27)	-4.07* (0.28)	21.75* (2.51)	16.15* (1.18)	-5.60* (1.43)
IID	16.57* (0.26)	12.28* (0.13)	-4.29* (0.22)	23.96* (3.66)	16.92* (1.73)	-7.04* (1.99)
IIE	20.17* (0.39)	13.39* (0.14)	-6.77* (0.29)	24.44* (3.45)	16.49* (1.25)	-7.95* (2.29)
IIIA	14.90* (0.45)	11.32 (0.38)	-3.58* (0.23)	21.92 (3.72)	16.02* (2.1)	-5.90* (1.64)
IIIB	20.37* (0.41)	13.57* (0.15)	-6.80* (0.32)	24.25* (4.21)	16.46* (1.73)	-7.79* (2.49)
IIIC	16.91* (0.31)	11.77* (0.18)	-5.14* (0.3)	23.94* (3.06)	16.62* (1.25)	-7.32* (1.85)
IIID	20.84 (0.27)	13.85* (0.21)	-6.98* (0.2)	24.72* (3.88)	16.85* (1.55)	-7.87* (2.39)
IIIE	19.98* (0.32)	13.34* (0.18)	-6.64* (0.22)	24.46* (3.29)	16.49* (1.14)	-7.97* (2.19)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. *p-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

Vertical breast displacement for 75D braless condition vs. Bra condition Z

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	20.87 (0.28)	11.18 (0.41)	-9.69 (0.29)	22.31 (0.71)	8.6 (0.43)	-13.71 (0.6)
IA	17.38* (0.27)	12.50* (0.22)	-4.88* (0.26)	23.90* (0.39)	13.99* (0.28)	-9.91* (0.37)
IB	17.80* (0.56)	11.72* (1.09)	-6.08* (0.58)	21.56* (1.07)	12.31* (0.44)	-9.25* (1)
IC	18.94* (0.71)	12.53* (0.37)	-6.42* (0.97)	22.12 (0.49)	12.50* (0.26)	-9.63* (0.39)
ID	17.77* (0.22)	12.07* (0.21)	-5.70* (0.16)	22.95* (0.59)	12.76* (0.37)	-10.19* (0.45)
IE	19.24* (0.26)	12.76* (0.22)	-6.48* (0.23)	24.92* (0.52)	14.34* (0.33)	-10.58* (0.44)
IIA	15.76* (0.29)	11.93* (0.23)	-3.83* (0.18)	21.59* (0.6)	13.28* (1.07)	-8.31* (0.86)
IIB	18.49* (0.24)	12.47* (0.22)	-6.01* (0.12)	22.89 (0.89)	12.77* (0.19)	-10.12* (0.86)
IIC	18.52* (0.22)	12.46* (0.22)	-6.07* (0.17)	21.72* (0.48)	12.02* (0.23)	-9.70* (0.38)
IID	19.69* (0.29)	12.75* (0.26)	-6.94* (0.25)	24.29* (0.46)	13.52* (0.28)	-10.78* (0.4)
IIE	20.36* (0.28)	12.92* (0.25)	-7.44* (0.22)	23.43* (0.6)	13.00* (0.29)	-10.43* (0.45)
IIIA	18.94* (0.25)	12.96* (0.23)	-5.98* (0.21)	23.36* (0.4)	12.72* (0.39)	-10.64* (0.46)
IIIB	18.44* (0.24)	12.16* (0.21)	-6.29* (0.16)	22.85* (0.46)	12.37* (0.27)	-10.48* (0.42)
IIIC	18.56* (0.27)	12.33* (0.24)	-6.23* (0.19)	22.07 (0.56)	11.76* (0.45)	-10.31* (0.51)
IIID	18.32* (0.3)	11.89* (0.25)	-6.43* (0.2)	22.45 (0.45)	11.70* (0.27)	-10.75* (0.42)
IIIE	19.19* (0.28)	12.56* (0.31)	-6.63* (0.24)	24.96* (0.55)	13.52* (0.36)	-11.45* (0.48)

Notes: I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. *p-value < 0.05 as compared to braless condition. Highlighted text indicates best fit with shoulder strap and underband length (IIA). Number in parentheses refers to the standard deviation in determining the average peak vertical breast displacement.

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