Analysis of Dynamic Vertical Breast Displacement for the Design of Seamless Moulded Bras

Cheuk-wing Lee[a], Kit-lun Yick[a*], Sun-pui Ng[b] and Joanne Yip[a]

[a] *The Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China;* [b] *Hong Kong Community College, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*

*Correspondence: tcyick@polyu.edu.hk; Tel: +852 2766 6551

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Traditional breast displacement studies included human subjects and maintaining result consistency is restricted by biomechanical limitations. This study proposes an objective approach that investigates the effects of various bra features on breast support during movement by conducting a wear trial with the VICON motion capture system. The vertical breast displacement in five different bra conditions is assessed and compared. Results indicate that the effectiveness of bras depends on the cup material used and design. The foam cups which are low in density and fabricated from soft polyurethane induces less overall breast displacement during movement. Bras of full-cup style also offer better breast movement control with significant vertical breast displacement reduction as compared with the half-cup style. These findings enhance current breast displacement analysis and understanding of bra features associated with changes in the biomechanics of breasts, thereby providing objective methods for bra evaluation and a design basis for breast protection.

Keywords: vertical breast displacement, moulded bras, cup style, polyurethane foam

1. Introduction

The female breasts have limited anatomical support and are relatively free to move over the chest wall. Excessive motion of breasts during physical activities can lead to overstretching of breast tissue. Bras are primarily designed to protect the soft structure of the breasts and provide external support to hold breasts and prevent excessive movement and related discomfort (McGhee & Steele, 2011). Over the past decades, a wide range of bra styles and features, which provide different levels of support, softness and comfort, have been designed to meet the specific needs and expectations of customers. For example, specific sports bra styles with appropriate fabrication materials have been created to address different effect conditions and end uses such as running, yoga and other sporting activities. The positive effects of cross-back shoulder strap orientation and the addition of gel pads for breast support have been highlighted to minimise the pressure-induced discomfort of sports bras (Bowles & Steele, 2013). Conventional sports bra shoulder straps which are in a vertical orientation and large width (4.5 cm) can also preserve wear comfort during movement (Coltman, McGhee, & Steele, 2015). However, past research studies on the objective evaluation of breast support performance and/or comfort pressure only focused on the features of bra shoulder straps in the design of sports bras. With absence of reliable and scientific methods, studying bra support is mostly relying on the human wear trials and particular bra application. It is considered that incorrect choice of bra materials and properties may also result in loss of breast support and wear discomfort (Lu, Qiu, Wang, & Dai, 2016). Different combinations of cup materials and styles have been studied under the guideline of sensory test (Jung & Na, 2016). Up to now, there is very little work in the literature that provides accurate and objective techniques to measure the breast support performance of bra features and effects of material variations. For instant, as bra cups are designed to cover the breasts, the elasticity behavior of bra cup material is considered to be a key factor that influences the bra support performance particularly in reducing vertical breast displacement (McGhee & Steele, 2011). This study therefore proposes a new scientific approach to address the complex problems of measuring the vertical breast displacement to reduce the inconsistency during data collection of human wear trials. A soft breast manikin has been designed to simulate the dynamic breast movement. The influence of bra cup materials on the vertical breast displacement is systematically measured and compared that the most desirable features and fabrication materials for optimized bra support are identified, hence improving the future design of supportive bras.

2. Background

Bras are one of the most complicated engineered apparel products with complex construction and unique fitting requirements to enhance the body curve and provide adequate support and comfort. Conventional bra cups are produced by many cutting pieces to be sewn together to form a 3D bra cup to fit the breast anatomy of women. A well-fitting bra improves the shape of female's breasts and controls the displacement of the breasts during exercise.

2.1 Dynamic vertical breast displacement

Breast motion can cause breast pain for many women and often leads to embarrassment when participating in exercise. When designing a bra, breast elevation and compression for support and restricting the movement of the breasts are considered to reduce exercise-induced breast discomfort. Breast motion and movement with or without wearing a bra were evaluated and compared by using motion analysis systems to quantify the support performance of bras. Oqus infrared camera or VICON motion capture system are popular motion capture system for bra or breast motion evaluation (Lu et al., 2016; Scurr, White, & Hedger, 2011). Both types of equipment use the technology of capturing the 3D movement of the prepared markers which are positioned on the breast region. Nipples and suprasternal notch markers are critical in the biomechanical evaluation of bra performance and breast motion research (Haake & Scurr, 2011; White, Mills, Ball, & Scurr, 2015). Momentum and displacement of the breasts due to motion are influenced by the level of physical activity and breast mass (Burbage & Cameron, 2017; Mills, Risius, & Scurr, 2015). Analyses on breast motion and displacement were mainly limited to wear trials in which the subjects usually perform a set of different movements. These subjects were recruited following a list of criteria such as pre-menopausal participants and no history of breast surgery for the typical breast motion or bra examination studies (McGhee, Steele, Zealey, & Takacs, 2013). Criteria must be set to maintain the testing accuracy because hormone levels changes may lead to breast tissue variation. In addition to the subject recruitment time, many factors were not considered. Same jumping or running frequencies and speeds are not necessary for same breast size women to have equal breast motion. Limitations with subject recruitment exist due to individual variations, such as body weight, fat proportion, characteristics of the breast shape and breast tissue, health conditions and walking gait differences. These variations result in inconsistency during data collection and thus influence the testing repeatability. For bra evaluation, motion experiments conducted to measure breast displacement requiring several female subjects to wear different types of bras or go braless during physical activities bring about personal embarrassment and result in potential breast discomfort or injuries. Compared with subjective wear trial, a reliable and objective approach of breast displacement evaluation is necessary to reduce the human variations so as to identify the key design factors to facilitate the design process with optimal breast support and fit.

2.2 Design features of bra

The bra is considered as second skin. A typical bra design includes components of cup fabric, shoulder straps, underband, upperband, underwires and hook-and-eye fastener. The basic overall bra design is two cup fabrics that insert underwire wrap around the breast structure, connect with the elastic shoulder straps across the shoulder and bands over the back and finally join the two bands with a hook-and-eye fastener (Calasibetta, 1986). The bra cup is mainly made of stretch elastic fabric, polyurethane (PU) foam, spacer fabric or lace which provides the breast with coverage and bust profile. The elasticity behaviour of the fabric should allow upper torso motion and prevent excessive breast motion whilst enabling air and heat flow for preventing the emission of moisture from the body and leading to wear discomfort (Elkholy & Hafny, 2017). The pattern design of cup is a key element to improve the bra support function (Zhuo, Sheng, Wei, & Bin, 2011, 2011). Compared with a half-cup bra style, full-cup bras are believed to minimise the breast movement due to increased breast coverage. If the cup sizes are small, then the bra compresses the breasts and forces them to the armpits, resulting in the unaesthetic profile of thickened arms. If the cup sizes are large, then wrinkles form in the bra, and the breasts move within the bra (Jeong et al., 2012). Elastic materials are also used for the shoulder strap and band. Adequate elasticity of the strap and band allow the natural body expansion during breathing cycles (Page & Steele, 1999). When a rigid material is used, the wearer may experience discomfort, especially for the shoulders and body back, because the straps and bands would impose excessive restriction for the soft tissues. Appropriate adjustment for the straps and bands is also important because it prevents excess pressure to the body and maintains the bra in place during motion, thus providing the optimal breast support and comfort (Coltman et al., 2015; Zheng, Yu, & Fan, 2008). The influence of the shoulder strap width and orientation on controlling the breast displacement was evaluated (Zhou & Yu, 2013).

Underwire insert at the underneath of the cup helps uplift the breast structure and enhances the bra support. Underwire is caution positioned to prevent the exertion of excess pressure towards the lymph codes of the breast (Stamford, 1996). Metal or plastic are generally used materials for the underwire. Inappropriate fitting of the planar underwire easily occurs and may result in underwire digging problem, which increases the discomfort for the wearers. To date, only few scientific works provide accurate and objective techniques to evaluate the effect of various bra features and the types of materials used to control breast movement. With absence of accurate breast motion behaviour, poorly designed and ill-fitting bras have endured for a long time.

2.3 Bra cup materials

Compared with conventional cut-and-sewn bras made of elastic fabrics, seamless mould bra cups made of PU foam materials offer a wide range of design with various softness and shapes, which eliminate bulky seams and reduce labour costs in sewing and assembling. In the bra cup moulding process, a pair of 3D female and male mould heads made of aluminium was designed according to the customers' specification. The foam sheets were stretched and compressed by the heated mould at a temperature that higher than the foam softening temperature (Yu, Fan, Harlock & Ng, 2006). The specified 3D bra cup shape and volume may differ from the cavity between the male and female moulds because the flexible PU foam sheet shrinks after moulding and cooling. Owing to the large variations in foam properties, cup styles and sizes and geometric features of graduated padding, the mould head design and production processes of seamless bra cups are highly complex and consist of many engineering stages and specialised technologies.

Flexible PU foam is available in an extremely wide range of stiffness, hardness, densities and thermo–physical and mechanical properties and has many applications such as upholstery, bedding, automobiles, footwear, apparel and medical and healthcare appliances (Kim, Yoon, Park, Kim, & Park, 2013; Luo, Wu, Lu, Yang, & Shi, 2017; Sakurai, Hashikawa, Yokoo, Terashi, & Tahara, 2007). PU foam has the unique properties of being lightweight, insulates heat and gently absorbs energy (Gnanasundaram, Durairaj, Gopalakrishna, & Das, 2013). A minor change in the polymer composition of PU foam may considerably change the foam properties and behaviour (Shah, 1998). Rigid PU foams are effective for heat insulation, whereas flexible PU foams are more commonly used for apparel including bra cups to accommodate the shape of the breasts and enhance wearing comfort. Nevertheless, scientific and reliable methods to analyse the breast support performance of PU foam cups and effects of material properties have not been fully reported in the field. It is important to take a closer look at the current bra design features and bra cup materials for improving the support and comfort of bras.

In response to the limitations discussed above, this study aims to investigate the effects of bra cup styles and materials on vertical breast displacement during movement by using a soft breast manikin with dynamic features. The manikin allows multiple wear trials and repeatable evaluation of breast displacement in various bra conditions. The material properties and bra cup design of foam cups are hypothesised to be related to changes in vertical breast displacement during body movement compared with the braless condition. Compared with soft bra cup, rigid bra cup may offer better control of breast movement. The results of this study provide insights into the biomechanical evaluation of breast motion in the bra design process, thereby enhancing breast protection and comfort.

3. Materials and methods

3.1 Bra cup materials

Two types of flexible PU foams (denoted as Foams I and II) with a thickness of 10 mm and an open cell structure were used for the experiments. These materials are commercially available and applied in bras. A rigid fabric with a warp knitted structure was also examined to facilitate a comparison of the foam materials for the bra cups. A summary of the material specifications and test methods in Table 1 shows that Foam I is a high-density PU foam with high compressive stress and hardness, whereas Foam II is a low-density foam material with a high degree of softness.

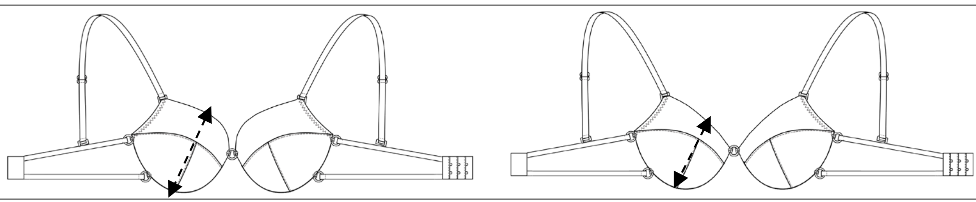
Table 1 Summary of specifications and properties of studied materials

	Material			
Physical property	PU Foam I	PU Foam II	Fabric	
Density (kg/m^3), *ISO845-1998*	45.07±0.41	30.71±0.30	/	
Thickness (mm)	10	10	0.27	
Tensile strength at 8% strain (kPa), *ISO7231-1984*	4.80±1.23	5.10±0.74	/	
Initial Young's modulus (N/cm), *ASTM 6614-07*	2.96	2.84	33.36 (wale)	33.06 (course)
Compression stress at 40% strain (kPa), *ISO3386/1-1996*	3.59±0.05	1.98±0.01	/	
Hardness (°ShD), *ASTM D2240*	43.98±0.68	23.02±1.42	/	
Foam type	Open-cell	Open-cell	Warp knitted	

3.2 Bra samples

Five bra samples with a 75D cup size were designed and fabricated. Table 2 provides the material fabrication and design information of the bra samples. The full-cup styles (Samples A and B) have a cup height measurement of 14.6 cm, thus offering large coverage for the upper breasts. The half-cup styles (Samples C, D and E) have a low cup height of 12.6 cm to ensure that they only cover half of the breasts and are extend horizontally to cover the nipples (Jung & Na, 2016). The dimensions of the shoulder straps and bra band were fixed in all bra conditions to minimise the slipping of the bra straps off the shoulders, prevent the bra band from digging into the backside and allow the samples to control motion and support the breasts.

Table 2 Bra samples



Sample	A	B	C	D	E
Cup material	Foam I	Foam II	Foam I	Foam II	Fabric
Cup style	Full (cup height of 14.6 cm)		Half (cup height of 12.6 cm)		

3.3 Evaluation of breast displacement

An eight-camera VICON motion capture system with retro-reflective markers that are 14 mm in diameter was used to record the breast motion and movements in various bra conditions (Figure 1). The retro-reflective markers are passive wireless markers used to avoid breast deformation under the different bra conditions. Figure 2 shows the retro-reflective markers on eight locations of the breast area, including the suprasternal notch, nipples, shoulders, ribs and the 7th cervical vertebra (C7) (Zhou, Yu, & Ng, 2012). The retro-reflective markers were attached on the bra and the manikin. Prior to the motion capture recording, the system was statically and dynamically calibrated. The 3D coordinates of the retro-reflective markers were recorded at a sample frequency of 100 Hz. The representative marker position in computing the breast displacement was assumed to be the nipple because it is the most deviating point of the breast structure.

Figure 1 VICON motion capture camera (left) and retro-reflective marker (right)

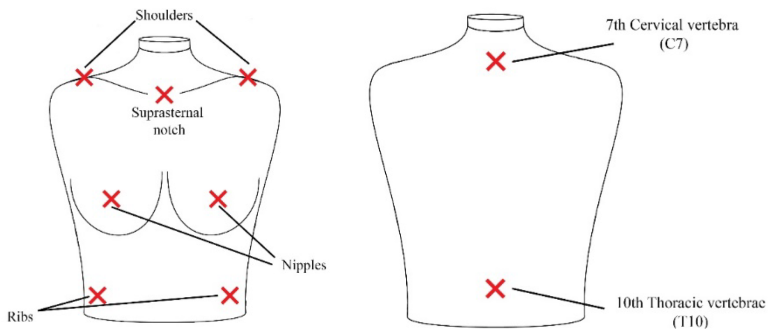


Figure 2 Front and back views of marker placement

A soft breast manikin with D cup breasts was used to model the vertical dynamic movement of the breasts (Figure 3). Two speeds including 2.30 km/h (slow walking) and 4.08 km/h (fast walking) were adopted to simulate locomotion in daily activities. A pneumatic system was designed with an auxiliary mechanical device to give the manikin dynamic movement. With change in movement speed during walking or running, a special waveform (similar to a sine function in mathematic) of different frequency and displacement amplitude of the breast motion was identified (Haake & Scurr, 2011). With references to Haake and Scurr (2011), the vertical breast displacement pattern under fast walking in around 4 km/h was obtained and a cam was then designed and developed based on the extracted waveform pattern (Figure 4). By dividing the breast moving pattern of one foot step into 360°, a circular shape cam with a groove was designed by using the SolidWorks software. Following the cam profile, the vertical movement of the manikin can be controlled. The manikin can move up and down in a continuous repeatable motion, which corresponds to heel strike in a gait cycle, and each cycle is equivalent to half in a gait cycle. The speed of the auxiliary mechanical device (rotation frequency) can be adjusted with a motor.

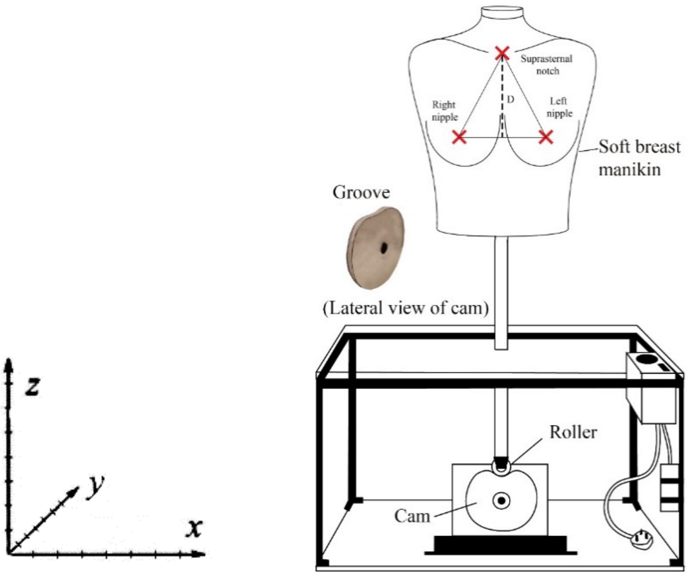


Figure 3 Pneumatic system with auxiliary mechanical device - dynamic movement of manikin

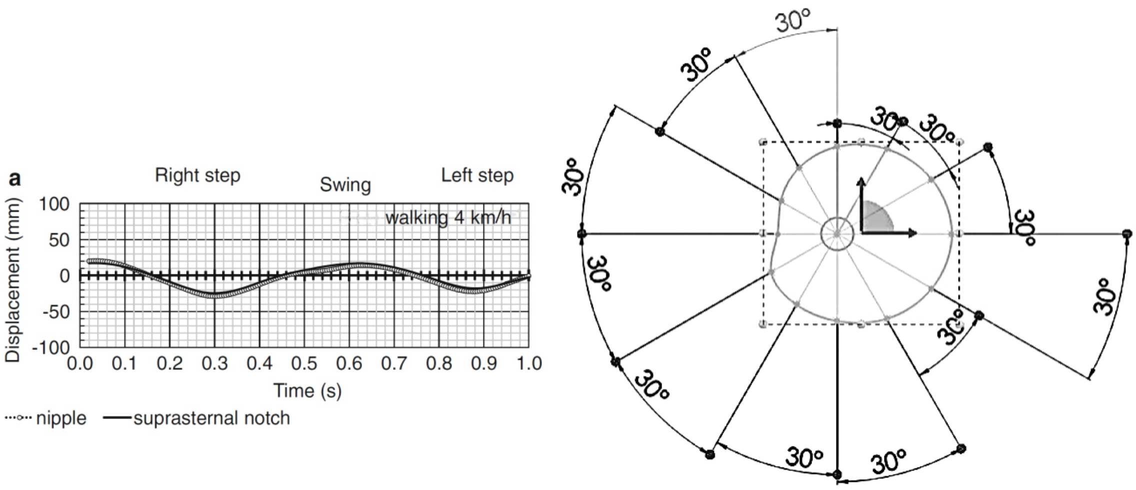


Figure 4 Displacement–time graph of breast for human subject walking under 4 km/h (Haake & Scurr, 2011) (left) and the derived design for the cam to simulate the vertical breast movement (right)

In this study, changes in the Z coordinates of the VICON motion capture system were recorded and studied in the vertical direction. Vertical breast displacement was then calculated by referring to the suprasternal notch and nipple markers. Displacement in the vertical direction was studied because this direction shows more significant changes during breast motion (Lu et al., 2016). Final displacement values were obtained by differences in the position between the suprasternal notch and the nipple which correspond to the mean position (Haake & Scurr, 2011). The overall vertical displacement of the body during normal walking was eliminated, and the net vertical displacement was subsequently obtained. The results were then averaged over 10 selected gait cycles for the most representative vertical breast displacement values (Bowles & Steele, 2013).

The vertical breast displacement was examined in the upward and downward directions. The formula below shows that the vertical breast displacement is the difference in the average distance between the suprasternal notch and nipple. When vertical breast displacement at time frame *i* (ΔD_i) is negative, the distance between the two reference points is reduced, and the breasts are moving upward. A positive value of ΔD_i indicates that the nipples are moving away from the suprasternal notch, and the breasts are moving downward. The average displacement caused by upward and downward movements is the total vertical breast displacement of the breasts.

$$\mathrm{\Delta D_i = D_i - D_0} \qquad (1)$$

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

3.4 Validation

A female subject with a cup size of 75D and no prior history of breast surgery was invited to participate in a wear trial to validate the breast motion data obtained from the soft breast manikin. The experiment was approved by the Human Subjects Ethics Sub-committee at the Hong Kong Polytechnic University. A brief overview of the study and testing procedures was provided to the subject, and her written consent was obtained prior to the start of the experiment.

The subject was asked to first walk at a rapid pace on a treadmill at 4.08 km/h in the different bra conditions. Before the recording started, she was given a 2-minute warm-up session to become familiar with the walking speed. The subject performed in all bra conditions, starting with the braless condition. Sample E was randomly selected in result validation. The dynamic movement of her breasts was then recorded with different bra strap and band tensions.

3.5 Data analysis

All data were reported as a mean value. SPSS software was used to test the homogeneity of variance and normality, and the results of a one-way ANOVA repeated test were used to evaluate the significant differences between the tested conditions. The coefficient of determination (r2) was calculated to determine the effectiveness of the soft breast manikin in simulating the vertical movement of the breasts and compare the results of the soft breast manikin with those of the human subject.

4. Results and discussions

4.1 Breast displacement in braless condition

The amplitude of the vertical breast displacement in the upward and downward directions and the total vertical breast displacement for each of the bra conditions were measured and compared with those for the braless condition by using a soft breast manikin. In the braless condition, the total breast displacement values were 20.95 and 22.31 mm at walking speeds of 2.30 and 4.08 km/h, respectively. A fast walking speed showed significantly larger vertical breast displacement compared with a slow walking speed ($p<0.05$).

Figure 5 shows the differences in the vertical breast displacement of the two walking speeds over time. Except for the level of amplitude, the breast movement variations for the two walking speeds included movement repeatability and oscillation after peak displacement (Lu et al., 2016). The vertical breast motion had a fast repeating frequency (0.5 s) for a walking speed of 4.08 km/h, whereas the repeating frequency for a walking speed of 2.30 km/h was slow (0.7 s). The oscillation level was also high at 4.08 km/h. When the pace of walking was increased, the breast acceleration also increased. According to Newton's second law (F=ma), the increase in the acceleration might increase the impact force on the body. A gravity effect exists for different breast volumes and breast weights (McGhee et al., 2013). A high impact force exerted onto the breasts means that high internal energy is transferred as kinetic energy and causes great displacement. Women with large breast size also have a heavy breast weight. Therefore, the support requirements of their bra should be high to protect the soft breast tissues and minimise the possibility of breast injuries.

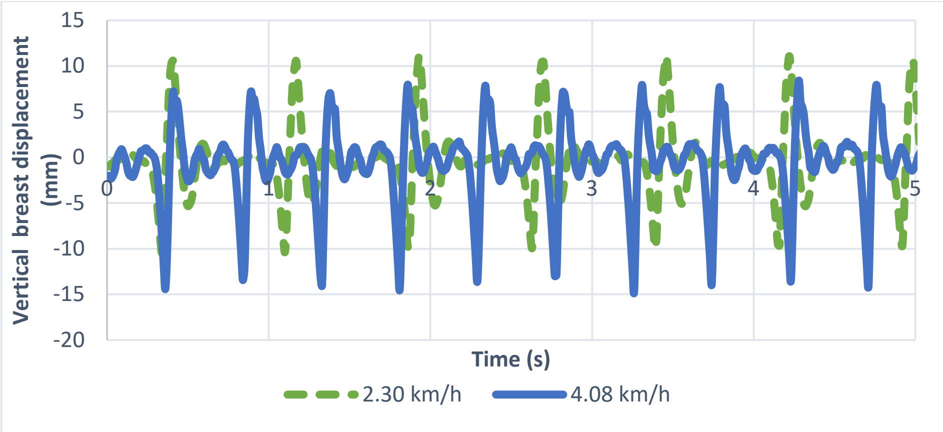


Figure 5 Vertical breast displacement of soft breast manikin: 2.30 km/h vs 4.08 km/h

The results show a great displacement in the upward direction at a walking speed of 4.08 km/h compared with that at 2.30 km/h. This finding is consistent with those of Mason, Page, and Fallon (1999) who conducted wear trials for breast displacement at different movement speeds. In the braless condition, the breasts are free to move in any direction. However, gravity causes the breasts to sag in the static position. When the body starts to move, the forces that are opposite of the attractive forces exceed the gravity force, and upward displacement is observed. With regard to the increase in the momentum of motion due to a faster movement speed, the opposite forces on the breasts are great, and the upward movement increases. The results show that downward displacement was reduced with the increase in walking speed. Scurr, White, and Hedger (2009) indicated that vertical breast displacement only accounts for an average of 56% of the overall breast displacement during treadmill walking and running, whereas the combined effect of gravity and breast mass has a greater influence on the displacement. The breasts may also move in the medial and lateral directions (Milligan & Scurr, 2016; Scurr et al., 2009). In human wear trials, the absolute breast displacement may also be affected by shoulder rotation.

4.2 Breast displacement with various foam materials and bra conditions

A summary of the vertical breast displacement results is presented in Table 3. The magnitude of the breast displacement in the five bra conditions was measured and compared with that of the braless condition by using the soft manikin. Most of the bra conditions showed a significant reduction ($p<0.05$) of the total vertical breast displacement compared with the braless condition. A similar result in which support from wearing a bra reduces breast vibration was reported by Lu et al. (2016). A reduction in vertical breast displacement could reduce the impact forces on the breast tissue during motion.

Compared with that in the braless condition, the reduction of upward breast displacement when wearing a bra may be explained by the elevation of the breasts by the bra, which reallocates the momentum of the motion to another direction and minimises the vertical displacement. Wearing a bra can effectively raise the nipples. When the breasts are elevated, the Cooper's ligaments and skin tissue that primarily support the breast structure may act as a breast spring and restrain breast motion more effectively (McGhee & Steele, 2010). Table 3 shows the downward displacement in all bra conditions was greater than that of the braless condition while table 4 presents the standard deviation of the results. Insufficient support to uplift the breasts led to greater downward displacement of the breasts such that they freely sagged during dynamic motion. The main difference between the different bra conditions was the capability of the condition to limit downward movement. The variations amongst the different types of materials or cup styles in reducing upward displacement of the breasts were relatively less apparent. Pain scores in previous researches indicate the overall comfort of the total breast motion (Mason, Page & Fallon, 1999; Zhou, Yu, Ng & Hale, 2009). Since the increased downward breast motion has a non-linearity in strain, it is postulated that this would be easier to exceed static strain during standing and would be one of the important parameters for the perceived comfort (Haake & Scurr, 2011). The bra features and materials that offer sufficient breast support to avoid displacement are crucial in preventing negative health effects, such as sagging breasts or pain in women with large breasts (McGhee & Steele, 2010; McGhee & Steele, 2011).

Table 3 Vertical breast displacement at 2.30 km/h and 4.08 km/h for 75D cup: different foam cup material and styles

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	10.73	3.42	-7.31	10.99	1.79	-9.20
Sample A	10.08*	4.02*	-6.06*	11.58	4.55*	-7.03*
Sample B	8.53*	2.93*	-5.60*	10.15*	3.29*	-6.87*
Sample C	10.70	4.64*	-6.06*	12.18*	5.15*	-7.03*
Sample D	9.46*	4.00*	-5.45*	10.83	3.77*	-7.06*
Sample E	8.83*	3.39	-5.44*	11.10	3.61*	-7.49*

*p-value < 0.05 as compared to the braless condition

Table 4 Standard deviation of the vertical breast displacement at 2.30 km/h and 4.08 km/h for 75D cup: different foam cup material and styles

Walking speed	2.30 km/h			4.08 km/h		
Condition	Total (mm)	Downward (mm)	Upward (mm)	Total (mm)	Downward (mm)	Upward (mm)
Braless	0.15	0.18	0.14	0.52	0.29	0.37
Sample A	0.40	0.30	0.30	0.28	0.33	0.22
Sample B	0.28	0.33	0.22	0.25	0.20	0.24
Sample C	0.36	0.18	0.41	0.31	0.29	0.31
Sample D	0.22	0.37	0.32	0.28	0.24	0.25

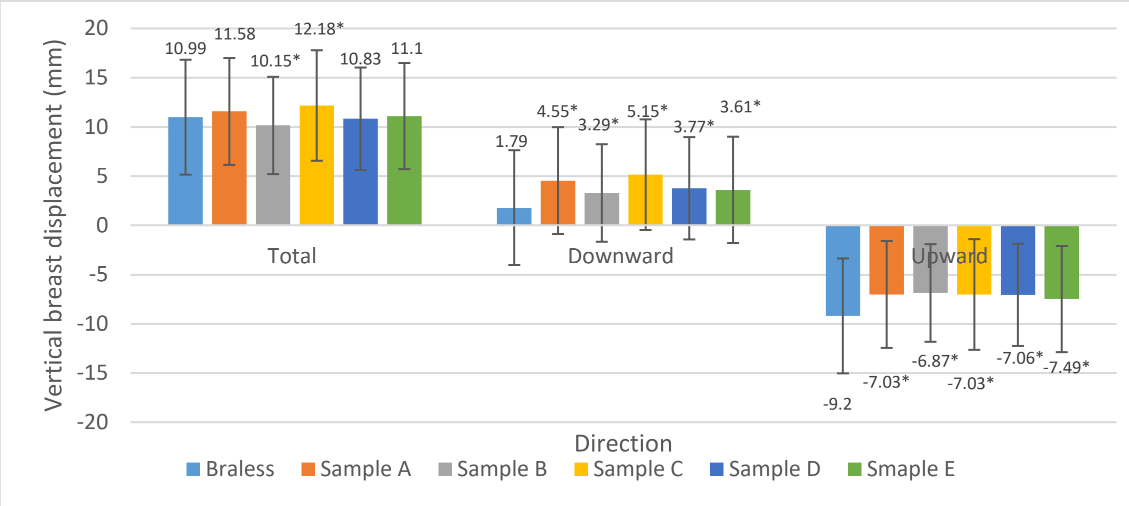
Sample E	0.55	0.54	0.77	0.36	0.27	0.35

With regard to material properties, Wu, Yick, Ng, and Yip (2012) indicated that the physical and thermal properties of foam materials have a major effect on bra design, especially in terms of the support. Samples B and D, which were fabricated with Foam II (a low-density PU), had a slightly better control over breast displacement than Samples A and C, which were fabricated with Foam I. Amongst the five bra conditions, Sample B showed the best performance in controlling the total vertical breast displacement. Compared with the braless condition, Sample B can reduce breast displacement by 20.56% and 7.58% at walking speeds of 2.30 and 4.08 km/h, respectively.

In this study, Foam II, which had a low compressive stress and high degree of softness, can provide better control over breast movement compared Foam I. This finding greatly deviated from the conventional understanding that rigid materials effectively control breast motion. This result could be explained by the good fit of Foam II, whereas Foam I was rigid and less deformable with a high Young's modulus and difficult to fit the 3D shape of the breasts. The use of soft foam material with lower compressive stress and good cup fit could induce increased control over breast displacement. Foam cup properties affect bra fit with substantial gapping and lead to bra and breast displacements during body movement. Although bras provide external support by elevating and compressing the breasts, they may induce excessive pressure onto the soft breast tissues and increase breast movement, particularly when they are made of rigid materials (Lu et al., 2016). The use of highly compressive materials and design features may cause the breasts to move away from the bra. This phenomenon would offset the stabilising effect of the bra based on compressing the breasts and result in overall less control over breast movement. In this study, Sample E which was fabricated with a rigid fabric material (high modulus) can effectively reduce breast displacement during walking at a slower pace of 2.30 km/h compared with the braless condition. Nevertheless, when the subject was walking at a faster pace of 4.08 km/h, Sample E failed to sufficiently support the breasts and absorb the impact force caused by body movement. The compressive stress, Young's modulus of bra materials and bra fit remarkably affect the support performance of the bra in reducing breast displacement during movement (McGhee & Steele, 2011).

With regard to bra style, Sample B (fabricated with Foam II with full-cup style) provided the largest reduction in the vertical movement of the breasts as shown in Figure 6. The bras with a full-cup design which have higher cup height and more breast coverage (Samples A and B) provided more control over total vertical breast displacement than those with a half-cup design (Samples C and D). Half-cup designs are generally preferred by women who have a medium breast size owing to less breast compression and better wear comfort. Full-cup designs offer large coverage of the breasts and increased breast support and are preferred by women with large breasts at a cup size of 75D or higher (McGhee & Steele, 2011). Lu et al. (2016) explained that the effect due to gravity inertia is large and increases in the breast displacement amplitude with high oscillation during motion. If large surfaces of the breasts are covered by the bra, then the impact loading during breast motion is distributed into different directions. The full-cup design allows an even distribution of the momentum of movement and provides increased breast support. When designing bra for women with large breasts, the full-cup design offers a good impact redistribution effect and improves bra support function.

Figure 6 Vertical breast displacement in various bra conditions and walking speed of



4.08 km/h

*p-value < 0.05 as compared to the braless condition

When the subject was walking at a speed of 4.08 km/h with a bra, the amplitude of the vertical breast displacement in the upward and downward directions, and the total vertical breast displacement increased more than those observed for a walking speed of 2.30 km/h. Walking speed can considerably facilitate breast motion and movement regardless of the bra conditions. The increased breast displacement could be caused by the increased momentum of motion and the associated impact forces on the breasts at faster walking speeds. A similar trend of the two walking speeds with the different cup styles and foam materials was obtained.

The results indicate that Foam I had higher density and hardness than Foam II. Fabric offers limited tensile strength than the PU foam. Moreover, the materials used to produce bra cups substantially affect the support performance of the bras as compared with the cup design. The results show that the physical properties of PU foams and design features provided important information on the characteristics of the foam. A similar trend for the bra support performance was observed at the two walking speeds in terms of amplitude and frequency differences. Foam specifications can influence the fabrication process of foam cups and the functional performance of the final product. Changes in the foam material show its effectiveness for controlling breast motion compared with the braless condition as indicated by the effect of the differences in the foam material and cup style towards bra support, particularly in reducing breast displacement. Therefore, foam properties should be evaluated when they are applied in bra design to improve the material selection efficiency and achieve good bra support function.

4.3 Validation of breast motion results

The breast displacement results obtained from the soft breast manikin in the braless condition and with use of Sample E were validated based on the measurements obtained from the motion experiment with a human subject in wear trials at faster walking speeds. Figure 7 shows the measured total vertical breast displacement obtained from the soft breast manikin and human subject in the braless condition and with the use of Sample E. Although the total vertical breast displacement from the soft breast manikin was consistently higher than that from the human subject, a strong linear relationship can be found ($r^2 = 0.76$; $p<0.05$). The use of a dynamic soft breast manikin provided comparable results with the human wear trials. In particular, the simulated breast motion allows a repeatable and continual evaluation for different bra features. Changes of bra features in combination with various fabrication materials and properties in relation to the control of breast motion can be objectively measured and analysed. This idea could be further applied to assess the breast support efficiency of the designed bra prototype prior to actual manufacturing.

The linear regression equation of the vertical breast displacement between the subject and manikin is shown below:

$$D_{human} = 0.5125D_{manikin} - 2.3467 \quad (2)$$

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

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

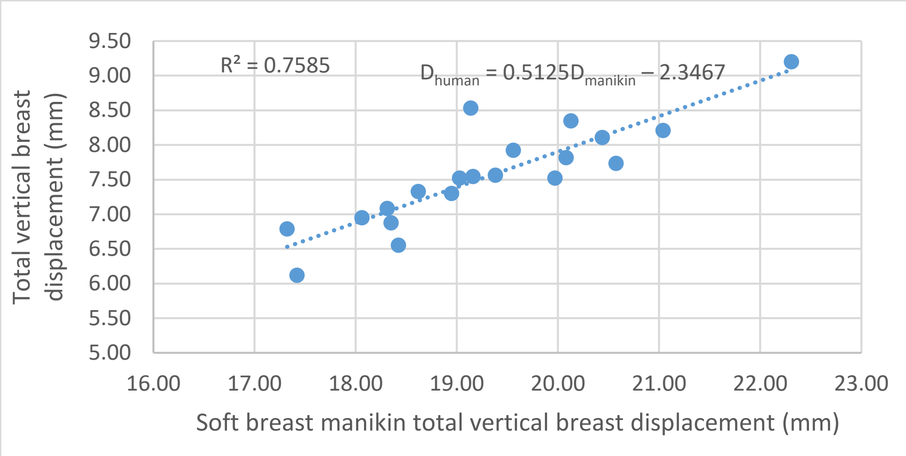


Figure 7 Scatter plot: vertical breast displacement − soft breast manikin vs. subject

This preliminary study on breast displacement has some limitations, including the 3D shape conformity and fit of the foam cup. The parameters of bra cup moulding including the mould head design, moulding temperature and dwell time and the corresponding changes in material properties have a major effect on the cup shape and fit and consequently on the breast displacement performance of the bra samples in this study. Apart from the analysis of the vertical motion of the breasts, the mediolateral and anteroposterior displacement effects can also be explored. Variation in speed or movement other than walking is another possibility for future work. Nonetheless, this study provides preliminary evidence that the type of foam material in bras remarkably affects their performance in controlling breast vertical displacement during dynamic motion. The findings serve as the basis for future studies to develop and design suitable bras to improve breast protection and bra comfort.

5. Conclusions

In this study, a soft breast manikin with dynamic features is used to evaluate bra features. A repeatable test approach that reduces human variations is adopted. The breast motion and amplitude of displacement in relation to various bra styles and cup materials are measured and compared with those under the braless condition. The results indicate that the bra samples with different cup material properties tend to produce different amounts of vertical displacement of the breasts during body movement as compared with the braless condition. The common belief that rigid foam materials could provide good control of breast displacement is opposed by bra fit and the compressive behaviour of foam material. Wearing a bra with low-density soft foam would provide better fit and displacement control effect compared with the traditional use of rigid foam and stiff fabric with a high Young's modulus. The effect of cup style and walking speed also substantially changes vertical breast displacement. Given that subject variables could be neglected in this study, these findings provide insights into breast displacement evaluation with repeatable and reliable information to facilitate further examination of the effects of material and design towards the supporting function of bras for improved breast protection and reduced tissue injuries and associated breast pain and discomfort.

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