World Academy of Science, Engineering and Technology
International Journal of Materials and Textile Engineering
Vol:13, No:2, 2019

Influence of Bra Band Tension and Underwire Angles on Breast Motion

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***Abstract*—**Daily activities and exercise may result in large displacements of the breasts, which lead to breast pain and discomfort. Therefore, a proper bra design and fit can help to control excessive breast motion to prevent the over-stretching of the connective tissues. Nevertheless, bra fit problems, such as excessively high tension of the shoulder straps and a tight underband could have substantially negative effects on the wear comfort and health of the wearer. The purpose of this study is to, therefore, examine the effects of bra band tension on breast displacement. Usually, human wear trials are carried out, but there are inconsistencies during testing. Therefore, a soft manikin torso is used to examine breast displacement at walking speeds of 2.30 km/h and 4.08 km/h. The breast displacement itself is determined by using a VICON motion capture system. The 3D geometric changes of the underwire bra band tension and the corresponding control of breast movement are also analyzed by using a 3D handheld scanner along with Rapidform software. The results indicate that an appropriate bra band tension can help to reduce breast displacement and provide a comfortable angle for the underwire. The findings can be used by designers and bra engineers as a reference source to advance bra design and development.

***Keywords*—**Bra band, bra features, breast displacement, underwire angle.

I. Introduction

WOMEN'S breasts have a soft structure and viscoelastic properties. They are mainly composed of ligaments, skin, subcutaneous tissues and milk ducts. They do not have specific muscles to support them and instead rely on the Cooper ligaments for anatomical support [1]. Excessive breast motion will therefore cause overstretching of the connective tissues within the breasts, thus leading to breast pain, discomfort and sagging. A higher breast mass means greater breast movement; hence, women with large breasts may require more breast support. Musculoskeletal disorders that cause pain in the back, neck, head and shoulders have been commonly reported by large-breasted women [2]. Irreversible damage of the thin connective tissues also occurs since there is insufficient elasticity of the ligaments to sustain breast motion [3]. Apart from breast size, the proportion of fat in the breasts, age, activity level, etc. may also affect breast motion. Therefore, specific bra styles with fabrication materials that target such issues have been designed to address the different impact conditions and end-uses such as running, yoga, or other sporting activities. Studies on breast motion and sports bra design have indicated that compression sports bras are effective for restricting the movement of the breasts by compressing and flattening them against the body, particularly for women with smaller breasts (cup sizes A and B) [1], [4], [5].

In term of bra design features, previous studies have mainly focused on the effect of the shoulder strap width and orientation on breast support. They recommend cross-back shoulder straps and additional padding of the shoulder straps to improve wear comfort which prevent the straps from slipping and reduce the pressure from the bra so that the straps are not digging into the skin [6]. However, cross-back straps have been proven less effective for controlling breast displacement due to the vertical strap orientation that is conventionally used [7]. It is hypothesized that a secure underband structure with a suitable amount of tension can provide better breast support and minimize bra displacement during movement in daily activities. On the other hand, steel and/or plastic underwires that are used to shape and support the lower periphery of the bra cups have long been adopted to enhance the support performance of bras. The underwire (typically planar and semi-circular) are encased with fabric strips, and sewn onto the bottom rim of the bra cups. Perfectly fitting underwires are challenging due to the complex 3D geometry of the breasts, which adversely affects the support performance and perceived comfort of bras. Past studies on bra design have indicated that the curvature and fit of the underwire to the circular arc underneath the breasts are important variables in designing underwires with optimal fit and support [8]-[10]. Desirable underwire shape and features that accommodate the curve under the breasts and thoracic cavity could have significant effects on the ability of a bra to reduce breast displacement during movement. Nevertheless, inherent ambiguity is found when defining the outline of the breasts, and hence the true shape and size of the breasts seem to be a particular problem in determining the ergonomics of bras [11]. The purpose of this study is therefore to evaluate the bra band tension and underwire fit, and their effects on breast support during movement in daily activities.

II. Methods

A. Test Conditions

To facilitate the adjustment of the bra band tension during collection of data on breast displacement, a bra design that can be easily modified is used in this study [12], see Fig. 1. By moving the position of the slider, the bra band tension can be

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adjusted to the desired testing condition. The bra band width used is 1.2 cm in the experiment. Based on the underbust measurements of the soft breast manikin, the tested length of the bra band ranged from 65 cm (best fit) to 81 cm (loose fit) with band size increments of 4 cm. The shoulder straps have the conventional vertical strap orientation. Since adjustment of the shoulder straps which are elastic material may also contribute to breast support, the shoulder straps were set to the best fitting condition of 40 cm in length based on the recommendations of a professional bra fitting expert. To ensure there was no deterioration of the bra band material, an electronic calibrator was used to measure the bra band tension before each testing condition was carried out. Table I summarizes the bra testing conditions, including the braless and five different bra conditions in which breast displacement and circumference of the underbust are examined.

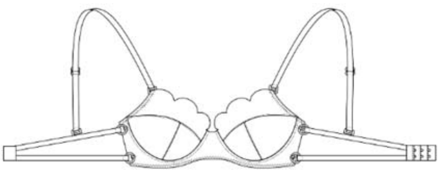


Fig. 1 Changeable bra

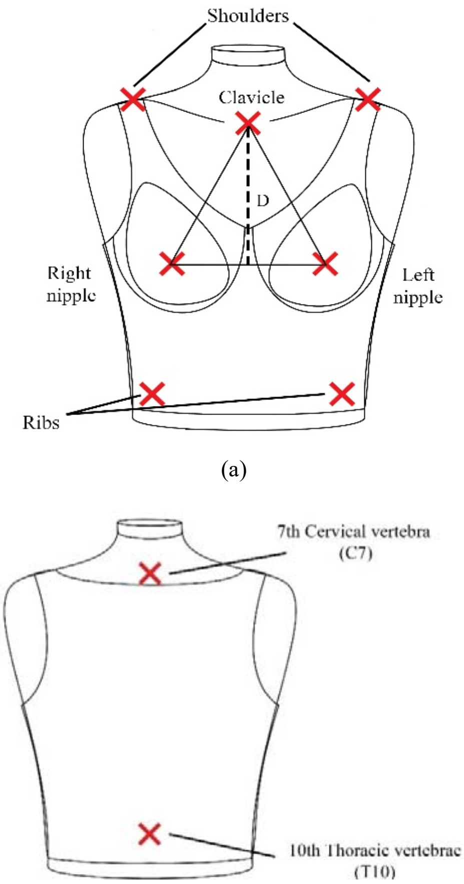
TABLE I
TESTED CONDITIONS

Tested bra conditions	Bra band circumference (cm)
A	65
B	69
C	73
D	77
E	81

B. Breast Displacement Analysis

For the breast displacement analysis, a VICON motion capture system with eight cameras was used to collect the data on breast displacement. A dynamic soft breast manikin with a cup size of 75B was used to test breast movement in the vertical direction by using a pneumatic system that simulates human movement. In this case, walking at speeds of 2.30 km/h and 4.08 km/h are simulated. Fig. 2 shows the retro-reflective markers placed onto C7 (the 7th cervical vertebra), clavicle, left and right nipples, shoulders and ribs [13], [14]. The markers placed on the nipples are assumed to measure the breast displacement most accurately because the nipples are the most protruding tip of the breasts. A sampling frequency of 100 Hz was used to capture the motion from the markers and give the coordinate expressions.

Breast displacement in the vertical direction is the main direction used to compare the support function of the different bra band tension combinations in this study. The Z coordinate is considered to be the vertical direction in the pre-setting of the VICON motion capture system. Vertical breast displacement was calculated by using the distance between the clavicle and nipples based on their mean position. In doing so, this eliminates the overall vertical movement that occurs naturally during walking and provides the net vertical displacement value of the breasts. The results were taken from over 10 different cycles of breast movement to obtain the most representative values. Upward and downward movements could be also further analyzed. The vertical breast displacement was determined by calculating the average distance between the clavicle and nipple; see (1). If the vertical displacement value in a particular time frame i (ΔDi) is positive, this means that there is a greater distance between the nipples and the clavicle, with downward movement of the breasts. A negative value of ΔDi means that the distance between these two points is reduced, and the breasts are moving upward. The total vertical displacement of the breasts was obtained by adding together the upward and downward movements. Besides, the displacement vs. time can be plotted by using Microsoft Excel 2016. Statistical Package for the Social Sciences (SPSS) was also used to analyze the homogeneity of variance and normality. To determine if there were any significant differences between the collected results, a one-way repeated measured ANOVA was conducted.



(a)

(b)

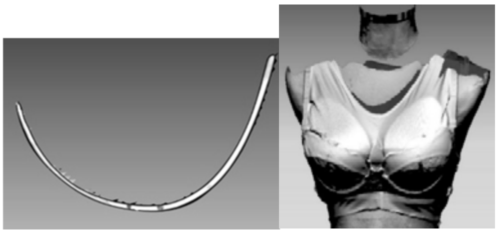
Fig. 2 (a) Front view, and (b) back view of marker positions

$$\Delta D_i = D_i - D_0 \quad (1)$$

ΔD_i - represents vertical breast displacement at time frame i, D_i - represents vertical distance between clavicle and nipple at time frame i, D_0 - represents vertical distance between clavicle and nipple in initial position

C. Measuring Angle of Underwire

Since the underwire is attached to the bottom rim of the bra cups and band, the bra band tension induced during wear results in a pulling force towards the thoracic cavity so that the 2D planar underwire is laterally deformed into a 3D shape. In this study, a regular steel underwire with a 2D planar shape is used and the corresponding changes in the lateral curvature with three different bra band tensions (Bra Conditions A, C and E) are measured. An Artec™ Eva 3D scanner was used to carry out the measurements. After the scanning process, the generated image files were analyzed by using Rapidform XOR 3D scanning software (Fig. 3). A 2D flat plane (without band tension) and a 3D inclined plane (with band tension) were then generated (Fig. 4). The reference planes for the underwire and curve under the breasts were obtained so that the start (the innermost point), mid-point and end-point (the outermost point) of the underwire are landmarked. By aligning the start and mid-point of the underwire with and without band tension, the coordinate differences in the end-point between the two planes can be quantified by measuring the angle (Fig. 5).



(a) (b)

Fig. 3 3D scanned image of (a) planar underwire, (b) soft breast manikin with donned bra

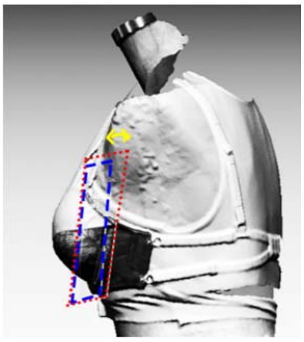


Fig. 4 Generating two planes

III. Results and Discussion

A. Breast Displacement under Braless Condition

Vertical breast displacement can be examined as movement in the upward and downward directions. The total vertical displacement of the breasts refers to the average values of the upward and downward movements. Fig. 6 shows the plotted vertical breast displacement vs. time for two walking speeds of 2.30 km/h and 4.08 km/h under a braless condition. A lower frequency amplitude of the total vertical displacement of the breasts can be observed for a walking speed of 2.30 km/h in comparison to a faster walking speed of 4.08 km/h and is significant (p-value less than 0.05). At a walking speed of 4.08 km/h, the repeated frequency is higher at 0.2 seconds faster than a walking speed of 2.30 km/h.

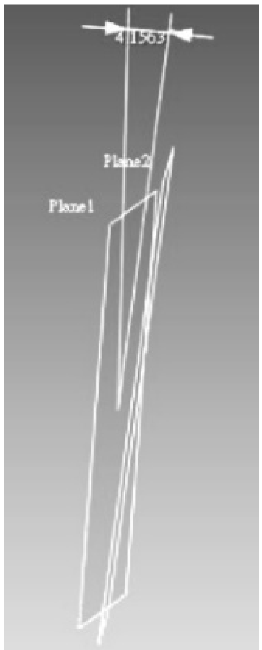


Fig. 5 Measured angle of underwire

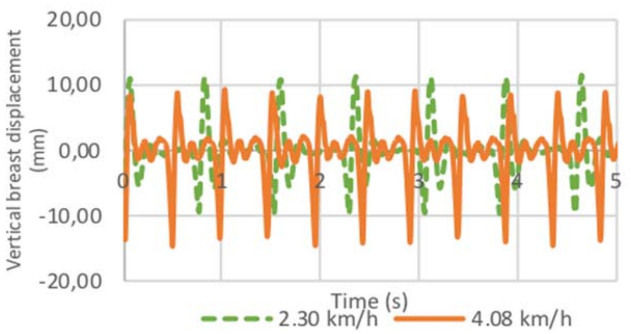


Fig. 6 Vertical breast displacement vs. time under braless condition at walking speeds of 2.30 km/h and 4.08 km/h

Since breast displacement was determined by calculating the difference in distance between the clavicle and nipple markers, a negative value means that there is a shorter distance apart between the two types of markers and the nipple is moving upward. A faster walking speed causes greater upward displacement of the breasts. In addition, higher amplitude values and oscillation rates were observed for the walking speed of 4.08 km/h after the total vertical displacement peak value was reached in each repeated cycle. Similar results have been found in evaluations of breast displacement under different walking and running conditions in a study by Mason et al. [4]. This makes sense because the momentum of movement is higher for the same breast volume when the walking speed is increased. Greater oscillation of the breasts could be resultant of greater deformation of the breast structure due to greater breast motion. A higher movement frequency is necessary in order to bring the breasts back to their original position after movement.

B. Breast Displacement under Different Bra Band Tensions

The total, downward and upward breast displacement values are presented in Table II. Compared to the braless condition, all of the other conditions in which a bra is donned show a significant reduction in the total vertical displacement of the breasts at the two walking speeds. After a bra is donned, the breasts are elevated against natural gravity forces and maintain a neutral position. The corresponding breast oscillations and movement can then be reduced from the uplifting effect of the bra. When a bra is donned, the total vertical displacement of the breasts is reduced from 20.31 mm to 9.50 mm ± 1.95 mm at a walking speed of 2.30 km/h and to 16.05 mm ± 1.78 mm at a walking speed of 4.08 km/h. The reduction in the percentage of the total vertical displacement of the breasts can range from 24% to 63%. This is consistent with the findings in a previous study by Haake and Scurr [15], who conclude that bras may help to control vertical breast displacement and therefore improve wear comfort.

TABLE II
VERTICAL BREAST DISPLACEMENT WITH BRA CONDITIONS AT WALKING SPEEDS OF 2.30 KM/H AND 4.08 KM/H

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	11.83	-8.48	23.36	11.79	-11.57
A	7.55*	6.04*	-1.51*	14.27*	11.52	-2.76*
B	8.96*	7.39*	-1.57*	15.06*	12.52*	-2.55*
C	9.28*	7.21*	-2.07*	16.69*	13.94*	-2.75*
D	10.48*	8.35*	-2.13*	16.58*	13.56*	-3.02*
E	11.24*	8.42*	-2.81*	17.64*	14.04*	-3.60*

[a] "*" refers to *p-value* < 0.05 as compared to the braless condition

The results show that the use of a bra helps to support the structure of the breasts. Adequate support minimizes potential breast pain, sagging or discomfort [16]. Particularly, it can be observed that the downward displacement value when a bra is worn is higher than that of the braless condition at 4.08 km/h. This could be related to the bra design which cannot sufficiently support the weight of the entire breast and cannot redistribute the force. Moreover, a normal cup size, that is, a B cup, is used in the wear trial in this study. When the cup size is larger, both the weight and volume of the breasts increase. The corresponding breast movement may also be greater at the same walking speed. These could infer that women with larger breasts need more and adequate support in order to avoid negative effects of a poorly fitting bra.

Fig. 7 presents the trends of the breast displacement amplitude of the bra bands with less tension at a walking speed of 4.08 km/h. Bra Condition A results in the lowest total vertical displacement at the two walking speeds. In fact, the total vertical displacement of the breasts is reduced by 63% and 39% in Bra Condition A at 2.30 km/h and 4.08 km/h, respectively. When the bra band tension is reduced from Bra Condition A to Bra Condition E, this results in less reduction in vertical breast displacement in both the upward and downward directions. When the tension in the bra band is reduced, the shoulder straps become the primary means of support to sustain the dynamic forces produced by walking and the weight of the breasts. Since the shoulder straps might not be able to absorb all of the impact forces and momentum from movement, the stabilizing effect of the bra is subsequently reduced.

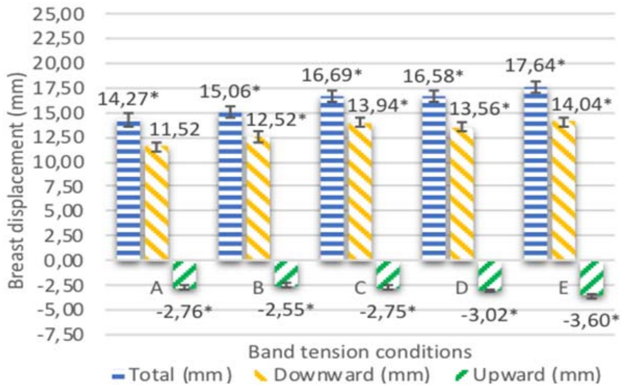


Fig. 7 Vertical breast displacement with different bra band tensions at 4.08 km/h. [a] "*" refers to *p-value* < 0.05 as compared to the braless condition

C. Measuring Angle of Underwire

The steel underwire in a bra is planar in shape and during wear, is slightly bent by the elastic bra band so that the bra can securely sit on the breasts [17]. The 3D shape and the ultimate fit of the underwire depend on its curvature and bending properties as well as the pulling force induced by the bra band tension during wear. Fig. 8 shows the measured angle of the underwire with different bra band tensions and curves under the breasts. As compared to Bra Condition A and Bra Condition C, the pulling force of a bra with less bra band tension or Bra Condition E cannot fully extend the underwire, thus resulting in a small lateral curvature of the underwire. Besides, the angle of the underwire in Bra Condition A approximates that of the curve under the breasts. This shows that Bra Condition A can provide a better fit for the breasts with a better support function.

The curvature of the underwire has been considered one of the most important features of bra designs as it directly influences the shape of the bra. The shape, width and curve of the underwire need to match the curve under the breasts for fit and comfort. In this study, the curvature of the underwire is correlated to controlling breast displacement during motion. As shown in Fig. 9 (b), the underwire in Bra Condition E is slightly opened to its 3D form as compared to the 2D planar underwire. The mismatch of the breast curvature with Bra Condition E results in the greatest amount of breast displacement at both walking speeds of 2.30 km/h and 4.08 km/h. The bra band tension and pulling force need to be increased to produce a 3D underwire shape that would better fit and support the breasts. To avoid a poorly fitting underwire, soft and/or a 3D design could be used when a low band tension is necessary. Shin [17] suggested a bra band circumference with an ease allowance of 10 cm to 15 cm for the underbust girth in order to provide the best fitting bra. This is therefore based on the properties of the underwire and the structural design of the bra band [18].

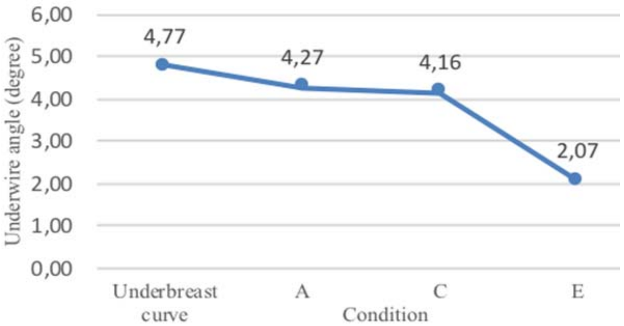
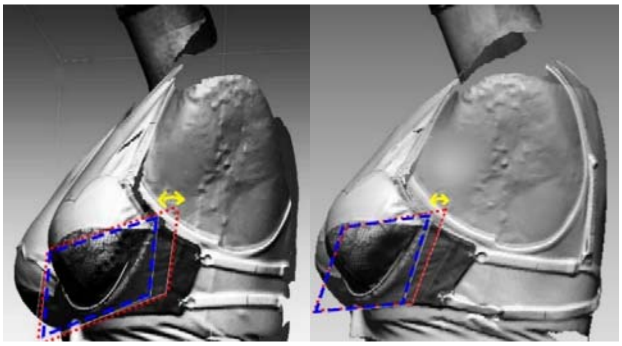


Fig. 8 Measured angle of underwire



(a) (b)

Fig. 9 Angle of underwire in (a) Bra Condition A and (b) Bra Condition E

The physical properties of the underwire are one of the factors that should be taken into consideration for improving the support function of bras. When the bending rigidity of the underwire is high, a higher corresponding bending force is necessary to bend the underwire into the desired angle and match the curve under the breasts [8]. However, over tightening the bra band results in pain or breathing difficulties [16]. Therefore, bra band tension needs to be carefully adjusted in order to balance comfort and support.

IV. Conclusion

The breasts have a soft structure which relies on the ligaments and skin for anatomical support. It is therefore important to provide external support to the breasts in order to minimize the over-stretching of the connective tissues and discomfort. The impacts of bra band tension and angle of underwire on breast movement have been systematically investigated in this study. To avoid the inconsistencies involved in human wear trials, a repeatable scientific method in which a soft breast manikin is used to examine breast displacement is used. Bra wear provides a significant reduction in the total vertical displacement of the breasts especially in terms of upward movement when compared to the braless condition. Appropriate adjustments of the tension of the bra band contribute to the support function of the bra, and increase breast stability during movement. The angle of the underwire is found to be greater with increased tension. Therefore, an appropriate amount of tension can bend the underwire into the best angle to accommodate the volume of the breasts. The improved fit would facilitate better bra support. The findings in this study provide insights for the industry so that practitioners can offer bra designs and fit that have a better support performance.

Acknowledgment

This research was supported by the Research Grant Council for this research project through project account PolyU 152375/16E and the Central Research Grant support through project account PolyU 152089/15E.

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