Xiaona Chen[1,2*]
Guangwu Sun[1]
Jianping Wang[2,3]
Yanmei Li[1]
Hong Xie[1]

Effects of Breast Support and Gait Speed on Three-Dimensional Breast Displacement for Women with Small Breasts

DOI: 10.5604/01.3001.0014.6088

[1] **Shanghai University of Engineering Science, School of Textiles and Fashion,**
Shanghai 201620, P.R. China,
Phone: +86 (0)21 67791297,
* e-mail: chenxn@sues.edu.cn

[2] **Key Laboratory of Clothing Design & Technology, Donghua University, Ministry of Education,**
Shanghai 200051, P.R. China

[3] **Donghua University, Fashion and Art Design Institute,**
Shanghai 200051, P.R. China

Abstract
This paper investigated three-dimensional breast displacement under different breast support conditions and gait speeds for women with small breasts. The breast coordinates of fifteen female participants with small breasts (sizes ranging from A to C) were recorded during treadmill walking and running tests under two different sports bra conditions and a no bra condition. The results showed that although vertical breast displacement was always the greatest in each condition, mediolateral breast displacement was significantly greater than anteroposterior breast displacement. Mediolateral breast displacement was not effectively reduced in the two sports bra conditions compared to the no bra condition. It is recommended that sports bra designed for women with small breasts should aim to limit mediolateral breast displacement instead of anteroposterior breast displacement, on the premise of controlling vertical breast displacement. The findings also suggest that the effectiveness of sports bras at reducing side-to-side breast movement requires further optimisation.

Key words: *women with small breasts, multiplanar breast displacement, breast support condition, gait speed, side-to-side breast movement.*

Introduction

Prior breast motion research has mainly been aimed at women with large breasts, such as C and C+ cup size [1-8]. Nevertheless, women with smaller breasts also require adequate breast support [9, 10]. One survey targeted at Chinese women found that the percentage (63%) of respondents suffering from breast pain or discomfort at times or frequently was comparable with the percentage (64%) reported by Australian women [11], although the most common reported breast size (75B, Chinese bra sizing standard) of Chinese women was smaller than that of Australian women (12B in the Australian bra sizing standard, equivalent to 75C in the Chinese bra sizing standard). Brown et al. [12] found that the average distance from the suprasternal notch to the nipple of women with smaller breasts was less than the average distance observed in women with larger breasts. Brown and Scurr [13] found that smaller breasted woman runners had a faster marathon time than larger breasted runners in long-distance running. Bowles et al. [14] concluded that bra size significantly affected some temporal measures of respiration at both rest and during maximal exercise ability. It seems to be common sense that a larger breast produces more breast movement during exercise than a smaller one. However, some questions, such as whether a larger breast produces more breast displacement than a smaller breast in all directions at each gait speed, cannot be answered without rigorous scientific data.

Although it is generally acknowledged that breast support requirements in the three directions are different, inconsistent conclusions have been reached in the last two decades. Most studies concluded that vertical breast displacement was larger than anteroposterior breast displacement and mediolateral breast displacement. However, a study found that vertical breast displacement was not significantly greater than anteroposterior breast displacement or mediolateral breast displacement during walking [6]. Mason et al. [15] suggested that vertical and mediolateral breast displacement should be limited by an adequate support bra. Similarly, a study found that mediolateral displacement (-1.1 cm to 4.2 cm) was greater than anteroposterior breast displacement (up to 2.2 cm) for women with D cup in the unsupported breast condition at 10 km/h [8]. Nevertheless, two studies reported that the mediolateral (4.0 ± 2.0 cm at 10.8 km/h and 4.8 ± 3.4 cm at 15 km/h) and anteroposterior breast displacement (4.0 ± 1.0 cm at 10.8 km/h and 5.1 ± 3.4 cm at 15 km/h) for women with D cup in the no bra condition were at a similar level [6, 7]. Furthermore, a different study reported a complicated result in the form of a figure, where anteroposterior breast displacement was greater than mediolateral breast displacement for women with a cup size ranging from A to C during a two-step star jump, and was less than mediolateral breast displacement for women with the cup size ranging from D cup to G cup [16]. Since no consistent conclusion has been drawn on breast displacement in the anteroposterior and mediolateral directions, further research should be conducted to confirm the direction in which breast displacement (anteroposterior versus mediolateral) is greater. Besides, most of the previous studies on three-dimensional breast displacement focused on women with large breasts, and only limited studies on women with small breasts.

Many studies have confirmed that vertical breast displacement decreases as the breast support increases. However, limited literature has been found on the effect of breast support on mediolateral and anteroposterior breast displacement. Besides this, inconsistent conclusions exist on the effectiveness of sports bras. Scurr et al. [8] reported that the amplitude of breast displacement can be reduced by breast support during walking

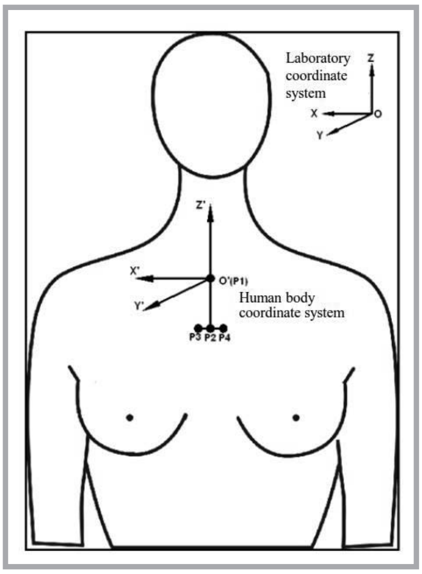

***Figure 1.** Definition of laboratory coordinate system and human body coordinate system.*

and running but did not indicate which direction of breast displacement was affected. White et al. [7] reported significant greater vertical, mediolateral and anteroposterior breast displacement for participants with D cup breasts during 10.8 km/h treadmill running in the no bra condition than in sports bra conditions, but no significant differences in vertical, mediolateral and anteroposterior breast displacement between an encapsulation sports bra and compression sports bra. Scurr et al. [8] found that vertical, mediolateral and anteroposterior breast displacement for women with D cup breasts during 10 km/h treadmill running were significantly reduced as the breast support increased from no bra to everyday bra to sports bra ($p < 0.02$). The existence of inconsistent results for mediolateral and anteroposterior breast displacement warrants further investigation. Furthermore, little literature was found on the effect of breast support on mediolateral and anteroposterior breast displacement for women with small breasts.

Gait speed has been reported to be related to breast displacement. For instance, test results showed that each 1 km/h increment in treadmill speed resulted in a significant increase in breast displacement from 5 km/h up to 10 km/h with no bra, up to 9 km/h in an everyday bra, and a less uniform pattern with both sports bras [6]. Another study reported that none of the bras tested consistently provided a significant reduction in resultant breast movement at all speeds (4 km/h, 6 km/h, 8 km/h, and 10 km/h) during treadmill tests [10]. However, attention was focused on resultant breast displacement instead of that in each direction at different gait speeds. The effect of gait speed on breast displacement in three dimensions should be more useful for bra design because this information can offer more detailed data for each direction. Furthermore, the increased breast displacement per km/h in each direction was not quantified, which should be useful when designing a speed-specific bra.

The aim of this study was to quantify multiplanar breast displacement for women with small breasts and confirm in which direction (anteroposterior versus mediolateral) breast displacement was greater. The study also investigated how the selection of the breast support condition and gait speed may affect multiplanar breast displacement. It was first hypothesised that vertical breast displacement would be significantly greater than mediolateral breast displacement and anteroposterior breast displacement, but no difference would exist between mediolateral and anteroposterior breast displacement. Second, it was hypothesised that vertical, mediolateral and anteroposterior breast displacement would be significantly reduced as breast support increased from the no bra condition to sports bra condition. Finally, it was hypothesised that vertical, mediolateral and anteroposterior breast displacement would significantly increase as the gait speed increases.

***Table 1.** Breast measurements of all participants.*

Participant number	Bra size	Breast measurement, cm		
		Upper breast circumference	Breast circumference	Under breast circumference
1	85B	92.0	96.9	84.1
2	80C	90.1	92.3	78.4
3	60A	71.8	72.3	62.1
4	75C	88.2	89.5	75.4
5	80C	88.3	92.3	78.2
6	70B	84.5	82.2	69.1
7	85C	93.8	97.8	82.7
8	75A	86.1	84.4	74.5
9	65A	76.3	74.8	66.0
10	70A	82.0	80.7	70.2
11	75A	80.5	82.7	75.2
12	65B	78.3	79.2	66.4
13	75B	85.7	85.9	72.8
14	75A	86.1	86.3	77.0
15	75B	85.1	88.7	76.6

Materials and methods

Participants

Fifteen female participants (mean ± SD: age 24.0 ± 2.9 years, height 162.1 ± 5.9 cm, body mass 58.3 ± 10.9 kg) were selected for this study. The participants had no history of pregnancy, breast cancer or surgery, because these factors can affect breast tissue and displacement [17]. The study was approved by the Institutional Ethics Committee. Written informed consent was obtained from each participant.

Participants' breast sizes were measured by a trained bra fitter. The breast sizes of the participants were determined by calculating the difference between the breast circumference and under breast circumference. The detailed breast measurements of all participants are shown in *Table 1*.

Laboratory coordinate system and human body coordinate system

To accurately collect and compute breast displacement in three dimensions, a laboratory coordinate system and human body coordinate system were developed.

Definition of laboratory coordinate system and human body coordinate system

The laboratory coordinate system was defined as follows:

- Origin O: the left posterior corner of the treadmill;
- +X axis: from the origin to the right posterior corner of the treadmill;
- +Y axis: from the origin to the left anterior corner of the treadmill;
- +Z axis: vertically upwards from the origin.

Before the human body coordinate system was defined, four points were chosen to decide the directions of the three axes of the human body coordinate system. The four points can be easily found in the human body, and their positions relative to the torso rarely differed during exercise. The four points were set as point P_1 (front neck point), P_2 (4 cm below the front neck point), P_3 (1 cm horizontally right of point P_2) and P_4 (1 cm horizontally left of point P_2), as shown in ***Figure 1***.

The human body coordinate system was defined as follows:
- Origin O’: P_1;
- +X’ axis: direction from P_4 to P_3;
- +Y’ axis: perpendicular to the plane X’O’Z’ and directed toward the anterior of the human body;
- +Z’ axis: direction from P_2 to P_1.

Transformation from laboratory coordinate system to human body coordinate system

The coordinates of an arbitrary point P were assumed to be (X, Y, Z) in the laboratory coordinate system and (X’, Y’, Z’) in the human body coordinate system. The translation parameters and rotation parameters from the laboratory coordinate system to the human body coordinate system were assumed to be (ΔX, ΔY, ΔZ) and (ωX, ωY, ωZ), as shown in ***Figure 2***. The transformation matrix from the laboratory coordinate system to the human body coordinate system can be expressed as

$$R(\omega X) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega X & \sin\omega X \\ 0 & -\sin\omega X & \cos\omega X \end{bmatrix} \quad (1)$$

$$R(\omega Y) = \begin{bmatrix} \cos\omega Y & 0 & -\sin\omega Y \\ 0 & 1 & 0 \\ \sin\omega Y & 0 & \cos\omega Y \end{bmatrix} \quad (2)$$

$$R(\omega Z) = \begin{bmatrix} \cos\omega Z & \sin\omega Z & 0 \\ -\sin\omega Z & \cos\omega Z & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

If it is defined that R (ω) = R (ωX) R (ωY) R (ωZ), then the transformation model from the laboratory coordinate system to the human body coordinate system is

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + R(\omega) \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (4)$$

After substituting ***Equations (1)***, ***(2)*** and ***(3)*** into R (ω) = R (ωX) R (ωY) R (ωZ) ***Equation (5)***.

Normally ωX, ωY and ωZ is the micro angle; therefore, it can be assumed that cos ωX = cos ωY = cos ωZ = 1 and sin ωX = ωX, sin ωY = ωY, sin ωZ = ωZ, and sin ωX sin ωY = sin ωX sin ωZ = sin ωY sin ωZ = 0.

Thus, ***Equation (5)*** can be simplified to

$$R(\omega) = \begin{bmatrix} 1 & \omega Z & -\omega Y \\ -\omega Z & 1 & \omega X \\ \omega Y & -\omega X & 1 \end{bmatrix} \quad (6)$$

After substituting ***Equation (6)*** into ***Equation (4)***, the transformation model can be written as ***Equation (7).***

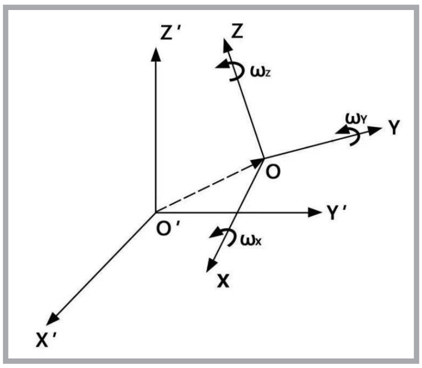

Figure 2. *Transformation from the laboratory coordinate system to the human body coordinate system.*

The coordinates of at least three common points in the laboratory coordinate system and human body coordinate system were needed to obtain the six transformation parameters (ΔX, ΔY, ΔZ, ωX, ωY and ωZ). The coordinates of four points (P_1, P_2, P_3 and P_4) used to establish the laboratory coordinate system and human body coordinate system were already known. The four points can be used as common points in the two coordinate systems.

After introducing the coordinates of the common points into ***Equation (7)***, six transformation parameters can be obtained. By substituting these six parameters into R (ω), R (ω) changed into a transformation matrix with only constants. The human body coordinates can be obtained if the laboratory coordinates are multiplied by R (ω).

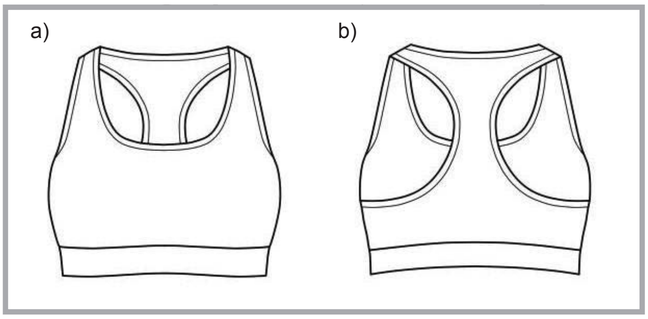

Figure 3. *Compression sports bra: a) front view, b) back view.*

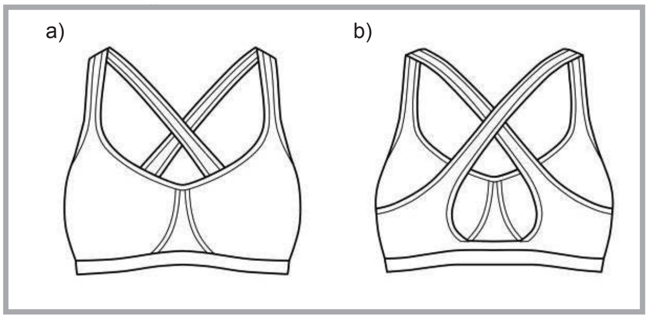

Figure 4. *Encapsulation sports bra: a) front view, b) back view.*

$$R(\omega) = \begin{bmatrix} \cos\omega Y\cos\omega Z & \cos\omega Y\sin\omega Z & -\sin\omega Y \\ -\cos\omega Y\sin\omega Z + \sin\omega X\sin\omega Y\cos\omega Z & \cos\omega X\cos\omega Z + \sin\omega X\sin\omega Y\sin\omega Z & \sin\omega X\cos\omega Y \\ \sin\omega X\sin\omega Z + \cos\omega X\sin\omega Y\cos\omega Z & -\sin\omega X\cos\omega Z + \cos\omega X\sin\omega Y\sin\omega Z & \cos\omega X\cos\omega Y \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + \begin{bmatrix} 0 & \omega Z & -\omega Y \\ -\omega Z & 0 & \omega X \\ \omega Y & -\omega X & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (7)$$

Equation (5) and (7).

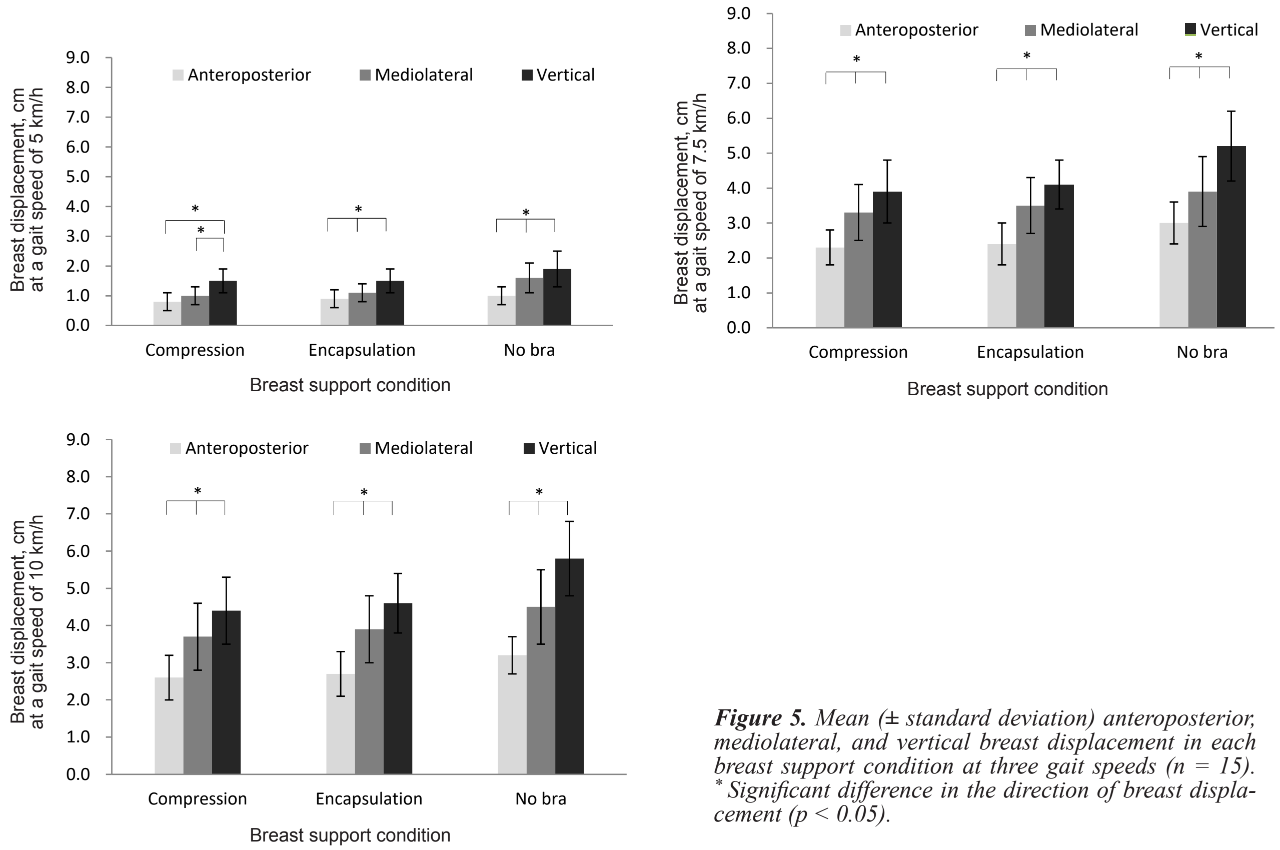

__Figure 5.__ Mean (± standard deviation) anteroposterior, mediolateral, and vertical breast displacement in each breast support condition at three gait speeds (n = 15). * *Significant difference in the direction of breast displacement (p < 0.05).*

Breast support conditions

A no bra condition and two different breast support conditions were chosen in this research: (i) no bra, (ii) a compression sports bra (***Figure 3***), and (iii) an encapsulation sports bra (***Figure 4***). The compression sports bra selected (Nike Pro, Nike, Shanghai, China; shell fabric was made from 88% regenerated polyester and 12% polyurethane, and the mesh cloth was made from 80% polyester and 20% polyurethane) was the most common compression sports bra in China. The encapsulation sports bra selected (Sloggi Sporty HP, Triumph, Shanghai, China; shell fabric was made from 90% cellulose fibre and 10% polyurethane, and the lining fabric of the cup was made from 90% polyester and 10% polyurethane) was readily commercially available in China.

Experimental protocol

Infrared light-emitting markers (2-mm diameter) were placed at points P_1, P_2, P_3, and P_4 and on the left and right nipples using double-sided surgical tape. The marker coordinates were collected when participants were exercising at speeds of 5 km/h, 7.5 km/h and 10 km/h under two different breast support conditions and a no bra condition. The three gait speeds selected in this study represented three modes of motion: walking (5 km/h), jogging (7.5 km/h) and running (10 km/h). Moreover, these three gait speeds were also selected because they were comparable to those used in previous breast motion research [3, 4, 8, 18]. A random number table was used to determine the breast support condition order. Before the test, bra fit was checked according to the standard referenced in previous research [17, 19].

Participants completed a standardised warm-up on the treadmill (SportsArt T650ME, Tainan City, Taiwan) at the three gait speeds before the formal test. In each bra condition, the treadmill speed was gradually increased from a static condition to a walking speed of 5 km/h, and the marker coordinates were recorded for 60 s after a 30 s familiarisation period at a speed of 5 km/h. Then the treadmill speed was decreased to a stop. There was a 5-min rest period between two bra condition running trials. Data were collected in the same procedure in a 5 km/h trial when the participants had exercised at the other two speeds. The three-dimensional displacement of the markers was tracked using two Optotrak 3020 position sensors (100 Hz; Northern Digital, Ontario, Canada).

Statistical analysis

A previous study noted that there was a significant difference between dominant and nondominant breast displacement; thus, the study concluded that displacement data on both breasts should be collected in breast motion research [3]. In this paper, displacement data of both the left and right breast were collected, and the average breast displacement was used as the breast kinematic data in the following analysis. Means and standard deviations were calculated for breast displacement in three dimensions. After the K-S test was applied to confirm the normality of the three-dimensional breast displacement data in each breast support condition at each speed, a paired-samples *t*-test was employed to analyse if there was a significant difference in breast displacement between any two directions. One-way analysis of variance (ANOVA) was performed to reveal the effects of the breast support condition and gait speed on three-dimensional breast displacement. The least significant difference (LSD)

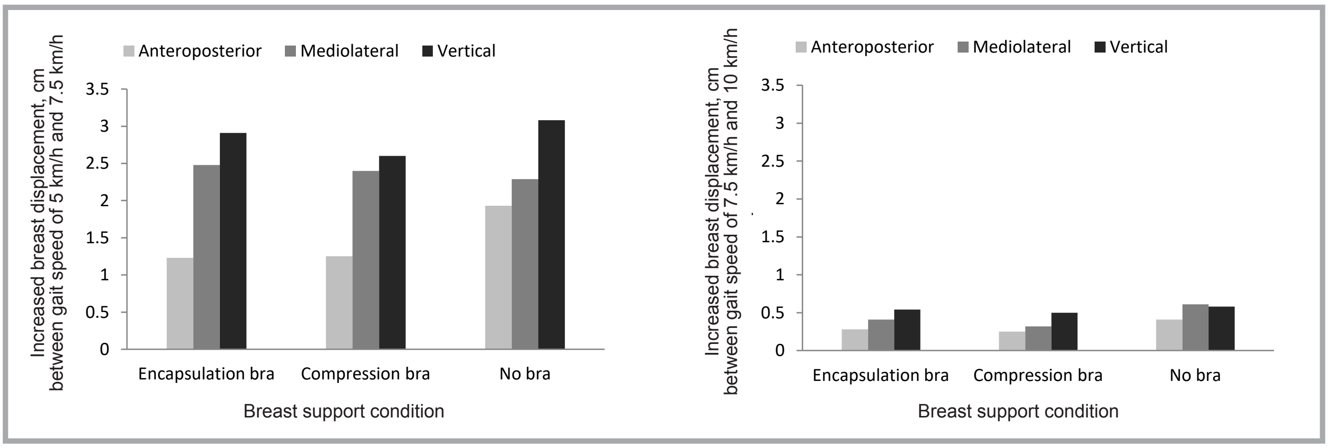

Figure 6. *Increases in breast displacement between gait speeds in each direction under the two sports bra conditions and no bra condition (n=15).*

test was employed to identify where any significant between-condition differences were. The differences in three-dimensional breast displacement between any two breast support conditions and any two gait speed conditions were detected by LSD test. All statistical procedures were conducted in the Statistical Package for the Social Sciences (IBM Inc., Armonk, NY, USA, version 17.0). All analysis results were deemed significant at an alpha level of $P \leq 0.05$.

Results

Difference in breast displacement between directions

Three-dimensional breast displacement is shown in ***Figure 5***. The result of the paired-sample t test revealed that mediolateral breast displacement was significantly ($p < 0.001$) greater than anteroposterior breast displacement in each breast support condition at each speed, while there was no significant difference between mediolateral and anteroposterior breast displacement in the compression sports bra condition at 5 km/h ($p = 0.162 > 0.05$). Vertical breast displacement was always significantly greater than both mediolateral and anteroposterior breast displacement in all breast support conditions at each speed ($p < 0.05$).

Effect of breast support condition on breast displacement

The result of the ANOVA test showed that the breast support conditions did not have a significant effect on mediolateral breast displacement ($p = 0.108 > 0.05$); however, the breast support conditions had significant effects on the anteroposterior ($p = 0.036 < 0.05$) and vertical breast displacement ($p = 0.022 < 0.05$). Post-hoc analysis (LSD test) revealed that anteroposterior and vertical breast displacement were significantly greater in the no bra condition than in the two sports bra conditions, whereas no significant difference was found between the two sports bra conditions ***(Table 2***).

Effect of gait speed on breast displacement

The result of the ANOVA test showed that gait speed had a significant effect on breast displacement in all directions (all $p < 0.001$). Post-hoc analysis (LSD test) confirmed that there were significant differences in breast displacement between any two gait speeds in each direction (***Table 3***), indicating breast displacement in three dimensions significantly increased as the gait speed increased.

In order to find in which direction the effect of the gait speed on breast displacement occurred most, the increase in breast displacement between gait speeds in each direction under the two sports bra conditions and the no bra condition was calculated (***Figure 6***).

Discussion

This paper quantified the three-dimensional breast displacement of fifteen women with small breasts (cup sizes ranging from A to C, Chinese bra sizing standard) in two different sports bra conditions and no bra condition at three gait speeds. Moreover, the study explored the effects of the breast support condition on breast displacement in the vertical, mediolateral and anteroposterior directions. The effect of the gait speed on three-dimensional breast displacement was also tested. It was found that mediolateral breast displacement was significantly greater than anteroposterior breast displacement in each breast support condition at each speed except in the compression sports bra condition at 5 km/h. Anteroposterior and vertical breast displacement significantly differed among the breast support conditions and gait speeds. Mediolateral breast displacement significantly increased along with the gait speed, whereas no significant difference was found between breast support conditions. The implications of these findings are discussed further on in this article.

Table 2. *P values illustrating significant (* p < 0.05) differences in anteroposterior and vertical breast displacement (cm) data between various breast support conditions.*

Breast support condition	Anteroposterior displacement	Vertical displacement
Encapsulation bra-no bra	0.040*	0.013*
Compression bra-no bra	0.022*	0.005*
Compression bra-encapsulation bra	0.817	0.714

Table 3. *P values illustrating significant (*p < 0.05) differences in mediolateral, anteroposterior and vertical breast displacement (cm) data between various gait speeds.*

Speed, km/h	Anteroposterior displacement	Mediolateral displacement	Vertical displacement
5-7.5	0.000*	0.000*	0.000*
5-10	0.000*	0.000*	0.000*
7.5-10	0.004*	0.003*	0.000*

Difference in breast displacement between directions

In this study the vertical, mediolateral and anteroposterior breast displacement for women with small breasts in the no bra condition at 10 km/h were 5.8 ± 1.0 cm, 4.5 ± 1.0 cm and 3.2 ± 0.5 cm, respectively. The vertical value in this study was less than 8.0 ± 3.0 cm, as reported by White et al. [7] for women with D-cup breasts at 10.8 km/h. However, the vertical value was similar to those (4.9 ± 1.1 cm) reported in a previous study for B and C cup participants at the same exercise level [20]. This is consistent with previous literature that proposed that vertical breast displacement increased with cup size [21]. In this study anteroposterior breast displacement in the no bra condition at 10 km/h was less than 4.0 ± 2.0 cm, as reported by White et al. [7] for D cup participants, which is also consistent with a previous study [21]; however, mediolateral breast displacement in the no bra condition was greater than 4.0 ± 1.0 cm, as reported by White et al. [7] for D cup participants, which is contrary to that reported by Wood et al. [21], who found mediolateral breast displacement significantly increased with breast cup size. The first hypothesis is partially rejected as mediolateral breast displacement was significantly greater than anteroposterior breast displacement, which is different from the results observed in previous research, wherein the mediolateral and anteroposterior breast displacement were at a similar level [6]. It was reported that the average vertical distance from the suprasternal notch to the nipple of women with small breasts was 16.5 cm, which was 3.1 cm less than the average distance observed in women with large breasts [12]. In this study the average vertical suprasternal notch-to-nipple distance of women was 16.0 ± 1.4 cm, which is similar to that reported for small breasts in a previous study. This may explain why mediolateral breast displacement was greater than anteroposterior breast displacement in women with small breasts. The change in the comparison of mediolateral and anteroposterior breast displacement in women with small breasts illustrates that different breast support requirements exist between women with large breasts and women with small breasts. A sports bra designed for women with small breasts should aim to reduce mediolateral breast displacement as opposed to anteroposterior breast displacement, though vertical breast displacement should be the first focus. This finding supports the idea that consideration should be given to reducing mediolateral breast displacement. The findings of the current study also support previous claims that an adequate support bra should limit motion both vertically and laterally relative to the body [15].

Effect of the breast support condition on three-dimensional breast displacement

Anteroposterior and vertical breast displacement significantly differed depending upon the breast support condition, which is consistent with previous research [6-8, 15]; however, no significant difference was found in mediolateral breast displacement among the breast support conditions, which was inconsistent with previous research [6-8]. Hypothesis two was partially accepted, as there was significantly less anteroposterior and vertical breast displacement in the two sports bra conditions than in the no bra condition, confirming previous conclusions on vertical and anteroposterior breast displacement [6-8]. Page and Steele [9] proposed that a compression sports bra was more effective for women with small breasts. Zhou et al. [22] also concluded that one of the features of the most effective bras was compression after they assessed seven commercial sports bras for participants with breast sizes B and C. However, no significant difference in anteroposterior and vertical breast displacement was found between the two sports bra conditions in this study. Despite supporting the findings of White et al. [7], this result was also contrary to that reported by Scurr et al. [6], who found significantly less anteroposterior and vertical breast displacement in the encapsulation sports bra condition than in the compression sports bra condition. Aside from the smaller average breast size (B cup) of the participants in this study compared to that of their corresponding participants (D cup) in a previous study [6], different materials and tiny differences in bra styles may explain the inconsistent results. This explanation suggests that experimental bras with a similar style but of different materials may reduce breast motion to different extents. This finding also warrants further research to explore how bra materials affect breast motion reduction and whether tiny changes in bra style can influence breast motion limitation. Further research should consider different bra styles with the same material or the same bra style with different materials to ensure one factor change in the experimental bras. As the effect of bras on breast displacement may be attributed to the pressure and frictional force they exert on the breast, future studies should also examine pressure and frictional force data of different bras when assessing their effects on breast displacement.

Previous research established that there was a significant effect of the breast support on mediolateral breast displacement, whereby mediolateral breast displacement was significantly reduced as the breast support increased from no bra to sports bra [6, 8]. Nevertheless, in the present study no significant difference was found in mediolateral breast displacement between breast support conditions, which means the two sports bra did not significantly reduce mediolateral breast displacement compared to the no bra condition. This result was similar to those reported by White et al. [7] that no significant difference was found in mediolateral breast displacement between an encapsulation bra and everyday bra, suggesting that the effectiveness of the two sports bras at reducing side-to-side breast movement requires optimisation. In the current study, the mediolateral breast displacement was 1.0-3.7 cm for compression bras, 1.1-3.9 cm for encapsulation bras, and 1.6-4.5 cm for no bra, indicating a large and overlapping range between any two breast support conditions, which may explain the insignificant difference in mediolateral breast displacement between the breast support conditions. Mediolateral breast displacement ranging from -1.1 to 4.2 cm for D cup participants running at 10 km/h was reported by Scurr et al. [8], which was comparable to that in this study (from 1.6 to 4.5 cm) despite the different breast size of participants (average B cup versus D cup).

Effect of gait speed on breast displacement

Gait speed had significant effects on vertical, mediolateral and anteroposterior breast displacement ($P < 0.01$); thus, hypothesis three was accepted. This finding was consistent with the results reported in a previous study [6]. Breast movement occurred because the position of breast tissue relative to the torso changed during exercise. Increased breast movement was induced by two causes. First, breast deformation increased to cater for the greater amplitude of torso movement. Second, the lag between torso movement and breast movement increased as the gait speed increased, which created more relative displacement between the torso and breast. However, the amplitude of breast deformation and torso movement cannot increase without limitation, which is why the breast displacement amplitude does not change when the running speed increases above 10 km/h [6]. This result indicates that sports bras intended for high-speed exercise should be designed to be more supportive.

The greatest increase in breast displacement among the gait speeds occurred in the vertical direction, followed by the mediolateral and anteroposterior directions, which implied that the effect of speed on breast displacement was greatest in the vertical direction and least in the anteroposterior direction. However, the increase in breast displacement in the mediolateral direction was similar to that in the vertical direction in the compression sports bra condition between gait speeds of 5 km/h and 7.5 km/h, as well as in the no bra condition between gait speeds of 7.5 km/h and 10 km/h.

The increase in breast displacement between gait speeds of 5 km/h and 7.5 km/h was obviously greater than that between gait speeds of 7.5 km/h and 10 km/h. A speed of 5 km/h represents walking, while those of 7.5 km/h and 10 km/h represent jogging and running, respectively. The exercise mode changed from walking to jogging when the speed was increased from 5 km/h to 7.5 km/h, but it did not change when the speed was increased from 7.5 km/h to 10 km/h. The exercise mode change may be the cause of the greater increase in breast displacement between gait speeds of 5 km/h and 7.5 km/h.

Strengths and limitations

It is acknowledged that a limitation of this study was the small sample size, and hence the results must be confirmed in larger sample groups. The current study was also limited by the lack of the everyday bra condition. Multiplanar breast displacement for women with small breasts was assessed only in the two sports bra conditions and no bra condition. Consequently, the results of this research are only applicable for the sports bra condition and no bra condition. However, individuals usually walk 4961 steps per day in daily life [23], which may produce considerable accumulated multiplanar breast displacement. Thus, multiplanar breast displacement for women with small breasts in the everyday bra condition also warrants further research. Finally, the present study was limited by the lack of pressure and frictional force data. As the effect of bras on breast displacement fundamentally works through the force they exert on the breast, the difference or similarity of pressure and frictional force data between the two sports bra conditions may help explain why breast support conditions significantly affected anteroposterior and vertical breast displacement, but did not significantly affect mediolateral breast displacement. Despite the aforementioned limitations, this research first systematically evaluated three-dimensional breast displacement for women with small breasts. In this study the greater breast displacement in the mediolateral direction than in the anteroposterior direction for women with small breasts confirmed the notion that the breast support requirements for women with small breasts are different from those for women with large breasts, especially in the mediolateral direction. Furthermore, the values of multiplanar breast displacement for women with small breasts assessed in this research are useful for sports bra design and optimisation for this population cohort.

Conclusions

Mediolateral breast displacement was significantly greater than anteroposterior breast displacement in women with small breasts; however, vertical breast displacement was always greatest. It is recommended that sports bra design for women with small breasts should aim to limit mediolateral breast displacement instead of anteroposterior breast displacement, on the premise of controlling vertical breast displacement. As the breast support condition did not significantly affect mediolateral breast displacement, the two sports bra conditions were not effective in reducing mediolateral breast displacement compared to the no bra condition. It is therefore recommended that sports bras designed for small breasts should be optimised to improve their function in controlling side-to-side breast movement. Although the mediolateral breast displacement observed in this study highlights that different breast support requirements, especially in the mediolateral direction, exist between large breasts and small breasts, future research with a larger sample size including both a small-breasted group and large-breasted group is warranted to ensure comparison of multiplanar breast displacement and breast support requirements between the two groups. Such research can exclude the effect of the difference in bra style and bra materials in different research.

Conflicts of interest

The authors declare that there is no conflict of interest.

Acknowledgements

This study was funded by the National Natural Science Foundation of China (Grant No.11802171), the Shanghai Fostering Program of Young Teachers in University (Grant No. ZZGCD15112), the open fund of the Key Laboratory of Clothing Design and Technology (KLCDT2020-01), and the National Key Research and Development Program of China (2018YFC2000905).

References

1. Mills C, Loveridge A, Milligan A, et al. Can Axes Conventions of the Trunk Reference Frame Influence Breast Displacement Calculation During Running? *Journal of Biomechanics* 2014; 47(2): 575-578.
2. Mills C, Ayres B, Scurr J. Breast Support Garments are Ineffective at Reducing Breast Motion During an Aqua Aerobics Jumping Exercise. *Journal of Human Kinetics* 2015; 46: 49-58.
3. Mills C, Risius D, Scurr J. Breast Motion Asymmetry During Running. *Journal of Sports Sciences* 2015; 33(7): 746-753.
4. Mills C, Loveridge A, Milligan A, et al. Is Torso Soft Tissue Motion Really an Artefact within Breast Biomechanics Research? *Journal of Biomechanics* 2014; 47(11): 2606-2610.
5. Risius D, Milligan A, Mills C, et al. Multiplanar Breast Kinematics During Different Exercise Modalities. *European Journal of Sport Science* 2015; 15(2): 111-117.
6. Scurr JC, White JL, Hedger W. Supported and Unsupported Breast Displacement in three Dimensions Across Treadmill Activity Levels. *Journal of Sports Sciences* 2011; 29(1): 55-61.
7. White JL, Scurr JC, Smith NA. The Effect of Breast Support on Kinetics During Overground Running Performance. *Ergonomics* 2009; 52(4): 492-498.
8. Scurr JC, White JL, Hedger W. The Effect of Breast Support on the Kinematics of the Breast During the Running Gait Cycle. *Journal of Sports Sciences* 2010; 28(10): 1103-1109.
9. Page KA, Steele JR. Breast Motion and Sports Brassiere Design. *Sports Medicine* 1999; 27(4): 205-211.
10. Nolte K, Burgoyne S, Nolte H, et al. The Effectiveness of a Range of Sports Bras in Reducing Breast Displacement During Treadmill Running and Two-Step Star Jumping. *Journal of Sports Medi-*

cine & Physical Fitness 2016; 56(11): 1311-1317.
11. Chen X, Wang J, Wang Y, Gho SA, Steele JR. Breast Pain and Sports Bra Usage Reported by Chinese Women: Why Sports Bra Education Programs are Needed in China. *FIBRES & TEXTILES in Eastern Europe* 2019; 27, 4(136): 17-22. DOI: 10.5604/01.3001.0013.1815.
12. Brown N, White J, Milligan A, et al. The Relationship between Breast Size and Anthropometric Characteristics. *American Journal of Human Biology* 2012; 24(2): 158-164.
13. Brown N, Scurr J. Do Women with Smaller Breasts Perform Better in Long-Distance Running? *European Journal of Sport Science* 2016; 16(8): 965-971.
14. Bowles KA, Steele JR, Chaunchaiyakul R. Do Current Sports Brassiere Designs Impede Respiratory Function? *Medicine & Science in Sports & Exercise* 2005; 37(9): 1633-1640.
15. Mason BR, Page KA, Fallon K. An Analysis of Movement and Discomfort of the Female Breast during Exercise and the Effects of Breast Support in three Cases. *Journal of Science & Medicine in Sport* 1999; 2(2): 134-144.
16. Bridgman C, Scurr J, White J, et al. Three-Dimensional Kinematics of the Breast During a Two-Step Star Jump. *Journal of Applied Biomechanics* 2010; 26(4): 465-472.
17. Mcghee DE, Steele JR. Breast Elevation and Compression Decrease Exercise-Induced Breast Discomfort. *Medicine & Science in Sports & Exercise* 2010; 42(7): 1333-1338.
18. White J, Scurr J, Hedger W. A Comparison of three-Dimensional Breast Displacement and Breast Comfort during Overground and Treadmill Running. *Journal of Applied Biomechanics* 2011; 27(1): 47-53.
19. Chen X, Gho SA, Wang J, et al. Effect of Sports Bra Type and Gait Speed on Breast Discomfort, Bra Discomfort and Perceived Breast Movement in Chinese Women. *Ergonomics* 2016; 59(1): 130-142.
20. Chen X, Wang J, Jiang D, et al. Breast Motion and Discomfort of Chinese Women in Three Breast Support Conditions. *World Academy of Science, Engineering & Technology* 2012;(72): 1709-1714.
21. Wood LE, White J, Milligan A, et al. Predictors of Three-Dimensional Breast Kinematics during Bare-Breasted Running. *Medicine & Science in Sports & Exercise* 2012; 44(7): 1351-1357.
22. Zhou J, Yu W, Ng SP. Identifying Effective Design Features of Commercial Sports Bras. *Textile Research Journal* 2012; 83(14): 1500-1513.
23. Althoff T, Sosic R, Hicks JL, et al. Large-Scale Physical Activity Data Reveal Worldwide Activity Inequality. *Nature* 2017; 547(7663): 336-339.

❑ ***Received 24.09.2019 Reviewed 02.07.2020***