A Comparison of Three-Dimensional Breast Displacement and Breast Comfort During Overground and Treadmill Running

Jennifer White, Joanna Scurr, and Wendy Hedger

Comparisons of breast support requirements during overground and treadmill running have yet to be explored. The purpose of this study was to investigate 3D breast displacement and breast comfort during overground and treadmill running. Six female D cup participants had retro-reflective markers placed on the nipples, anterior superior iliac spines and clavicles. Five ProReflex infrared cameras (100 Hz) measured 3D marker displacement in four breast support conditions. For overground running, participants completed 5 running trials (3.1 m/s ± 0.1 m/s) over a 10 m indoor runway; for treadmill running, speed was steadily increased to 3.1 m/s and 5 gait cycles were analyzed. Subjective feedback on breast discomfort was collected using a visual analog scale. Running modality had no significant effect on breast displacement ($p > .05$). Moderate correlations ($r = .45$ to .68, $p < .05$) were found between breast discomfort and displacement. Stride length (m) and frequency (Hz) did not differ ($p < .05$) between breast support conditions or running modalities. Findings suggest that breast motion studies that examine treadmill running are applicable to overground running.

**Keywords:** kinematics, bra, support

The importance of firm breast support has been documented, especially for larger-breasted women (Boschma et al., 1994; Gehlsen & Albohm 1980; Lorentzen & Lawson 1987; Mason et al., 1999; White et al., 2009), yet some females refrain from exercise due to the discomfort and/or embarrassment associated with excessive breast motion (Bowles et al., 2008; Page & Steele, 1999).

Most previous studies of breast motion during running have been conducted on treadmills (Campbell et al., 2007; Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Mason et al., 1999; McGhee et al., 2007; Scurr et al., 2009; Starr et al., 2005). Treadmills are used extensively in locomotion research, as they are a convenient way of testing in a controlled environment, the assumption being that treadmill locomotion is similar to overground locomotion. However, biomechanical and physiological studies that have compared treadmill and overground running are not consistent in their findings. It is unknown whether the biomechanics of the breast differs between overground and treadmill running. This may influence breast displacement and comfort, with implications for future research in this area utilizing an overground running protocol.

Some previous research has indicated differences between treadmill and overground running (Dingwell et al., 2001; Elliott & Blanksby, 1976; Frishberg, 1983; Nelson et al., 1972; Nigg et al., 1995; Wank et al., 1998; Wheat et al., 2004), while others have refuted these differences (Cunningham & Perry, 2007; Donoghue & Harrison, 2004; Riley et al., 2008; Riley et al., 2007; Schache et al., 2001, Van Ingen Schenau, 1980). A reduced step length and an increased stride frequency has been reported for treadmill running compared with overground running between 3.98 m/s and 6 m/s (Elliott & Blanksby, 1976; Schache et al., 2001; Wank et al., 1998), although a comparison of sprint kinematics (8.46 m/s to 8.54 m/s) between overground and treadmill running (Frishberg, 1983) and level running at 3.35 m/s (Nelson et al., 1972) revealed no significant differences in stride length or frequency.

Nigg et al. (1995) warned that adaptations to treadmill running differ between individuals, with kinematic changes dependent on shoe type, activity speed and the type of treadmill used. Treadmill runners have been found to have longer periods of support, a smaller vertical velocity of their center of mass and less variation in the vertical and horizontal velocities of their center of mass (Nelson et al., 1972). In contrast, the mechanics of treadmill gait has been reported as qualitatively and quantitatively similar to overground gait (Riley et al., 2007). Riley et al. (2008) concluded that treadmill-based analysis of running mechanics can be generalized to overground running provided the treadmill surface is sufficiently stiff and the belt speed is regulated.

Gait parameters may also be influenced by the level of breast support. Changes in whole-body kinematics (Boschma et al., 1994) and kinetics (Shivitz, 2001; White
et al., 2009) due to the level of breast support have been reported. Conversely, gait parameters have been shown to influence the biomechanics of the breast; stride frequency (Eden et al., 1992; Shivitz, 2001) and speed (Mason et al., 1999) are known to affect the magnitude of breast displacement. Eden et al. (1992) reported that downward and medial breast displacements were significantly greater when participants used a freely selected stride rate (mean 85 steps/min), as opposed to a quicker enforced stride rate of 96 steps/min.

The movement of the breast is influenced by the movement of the body’s center of mass; therefore changes in the biomechanics of the center of mass that may occur due to running modality (Nelson et al., 1972) may influence breast movement and comfort. The difference in the magnitude, frequency and comfort of breast displacement during overground and treadmill running is unknown, yet is important to understand, to ensure breast motion has not been underestimated in earlier treadmill studies. Therefore, the first aim of this investigation was to assess breast motion, stride length and stride frequency during overground and treadmill running at a similar speed in a no bra, everyday bra and two sports bra conditions. The second aim was to subjectively assess breast discomfort during each condition. Firstly, it was hypothesized that there would be no significant difference between the amount of resultant, vertical, mediolateral (m/l) or anteroposterior (a/p) breast displacement, stride length (m), stride frequency (Hz) or breast discomfort during overground and treadmill running in all breast support conditions. Secondly, it was hypothesized that breast discomfort would increase as the amount of breast support decreased, as found in previous research (Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Mason et al., 1999).

**Method**

**Participants**

The study was approved by the Institutional Ethics Committee. Six female participants (mean ± SD: age 24.8 ± 7.3 years, height 1.66 ± 0.04 m, body mass 65.68 ± 6.84 kg) gave written informed consent to take part in the study. Exclusion criteria ensured participants were aged between 18 and 40 years, were currently active (exercised aerobically at least once a week), were not pregnant, had not given birth or breast-fed in the last year, had no previous surgery to the breasts and were a D cup breast size. This breast size was chosen as Lorentzen and Lawson (1987) found that breast discomfort during exercise is more prevalent in women with a D cup size and above.

A trained bra fitter measured the participant’s breast size, following the recommendations of McGhee and Steele (2006). A measurement of 26–28, 28–30 and 30–32 inches equated to a 32, 34 and 36 inch chest size, respectively (mean of 34 ±1.8 inches). To establish cup size a 4 inch difference between chest and breast girth equated to a D cup size.

**Experimental Design**

Retro-reflective markers were placed on the clavicles (directly superior to the nipples), nipples (over the bra when applicable), anterior superior iliac spines (ASIS) and the right heel of the trainer. As with previous investigations in breast kinematics (Campbell et al., 2007; Gehlsen & Albohm, 1980; Himmelsbach et al., 1992; Lorentzen & Lawson, 1987; Starr et al., 2005), markers positioned on the bra were assumed to indicate underlying breast motion. Providing the bra is well-fitted, independent movement of the breast inside the bra should not occur. There were four breast support conditions; no bra, everyday bra and two types of sports bras. The everyday bra was the UK best selling bra from Marks & Spencer (2005) (seamfree plain underwired T-Shirt Bra, nonpadded; made from 88% Polyamide and 22% elastane lycra). The two sports bras were the UK leading branded sports bra manufacturers’ compression (Shock Absorber, B515 racing back design; made from 57% polyester, 36% elastane, 4% polyamide and 3% xstatic silver nylon) and encapsulation (Shock Absorber, B109; made from 89% polyester, 6% nylon polyamide, 5% elastane) sports bras. Photographs of the three bras used in the study can be seen in Figure 1.

To assess breast motion during overground running participants completed five successful running trials in the four randomized breast support conditions. Participants were allowed sufficient practice to ensure a consistent running speed through timing gates (Sprint timer CM LSMEM, Brower, UK). To enable comparisons with previous breast motion studies (Gehlsen & Albohm 1980; Lorentzen & Lawson 1987; Mason et al., 1999) participants ran at 3.1 m/s (± 0.1 m/s) along a 10 m runway within the laboratory. Five calibrated ProReflex infrared cameras (Qualisys, Sweden, 100 Hz) were positioned around the runway to capture visual data from one gait cycle.

![Photograph 1: Everyday bra](image1.png)

![Photograph 2: Encapsulation bra](image2.png)

![Photograph 3: Compression bra](image3.png)

Figure 1 — Photographs of the three bras used.
To assess breast motion during treadmill running, participants completed treadmill running trials in the four randomized breast support conditions. Marker coordinates were recorded by five calibrated ProReflex infrared cameras, positioned around a calibrated treadmill (H/P/Cosmos Mercury, Germany). For familiarization, each trial began at a comfortable walking speed (1.4 m/s), the speed was then steadily increased over a one minute period up to 3.1 m/s. Three-dimensional marker coordinates were then recorded during five treadmill gait cycles (analyzing just five gait cycles has been shown to be adequate for consistent breast displacement values [<1.3% CV]; Scurr et al., 2009).

An external trigger marked right foot heel strike at the start of the 3.1 m/s trial. The external trigger was connected to a Biometrics Datalink unit (100 Hz) and synchronized via a synchronization unit (Qualisys, Sweden) with the visual analysis system. To determine running gait cycles, the a/p coordinates of a marker positioned on the right heel were derived to calculate velocity. The instant that the a/p velocity vector of the heel marker changed from positive to negative and then negative to positive indicated heel strike and then toe-off for each running gait cycle (Zeni et al., 2008). Shoe type remained the same between conditions; adequate rest was provided between trials and conditions.

To establish the level of breast discomfort (related to breast movement), subjective feedback was collected from participants after each overground and treadmill running condition. Subjective data were collected using a numerical visual analog scale of 0 to 10 (Mason et al., 1999); with 0 being comfortable, 5 being uncomfortable, and 10 being painful.

Data Analysis

All markers were identified and three-dimensional data reconstructed in the Qualisys Track Manager Software (version 1.10.282, Qualisys, Sweden) using a grid calibration for internal camera parameters and a wand calibration for external camera parameters (bundle adjustment technique). Raw marker position-time data in mm (vertical, m/l and a/p) were exported into Excel (Microsoft Office 2007) and converted to cm. To establish relative displacement (peak-to-peak amplitude) of the right nipple and eliminate the six degrees-of-freedom movement of the body, a reference grid of left and right clavicles and ASIS markers converted the global to an orthogonal local coordinate system (LCS) using a transformation matrix. The left and right clavicle markers created an anatomical axis (Nguyen & Baker, 2004) to calculate trunk rotation (yaw) and lateral trunk flexion (roll). A virtual point at the mid-ASIS made up the anatomical plane and identified trunk flexion/extension (pitch). The virtual midclavicle marker was the origin of the LCS from which breast translation was calculated.

From these relative 3D breast coordinates, breast displacement was calculated and averaged for five discontinuous gait cycles during overground running and five continuous gait cycles during treadmill running. Stride frequency (1/stride duration [s]; Hz) and stride length (speed of trial [m/s] / stride frequency [Hz]; m) were also calculated.

Statistics

Post hoc power calculations (G*Power [v3.1.2]) indicated that for breast displacement measures a sample size of six provided a power of 1.00 (support) and 0.91 (surface); for gait parameters a power of 0.1 (for support and surface) was calculated; effect sizes (partial eta squared, η²) have been presented to give an indication of the meaningfulness of results (small effect, η² = .10; large effect, η² = .50). The data were normally distributed (Kolmogorov–Smirnov and Shapiro-Wilk, p > .05) and sphericity was assumed (Mauchly’s test of sphericity, p > .05). Multiple two-way repeated-measures ANOVA examined differences in breast displacement (cm), stride frequency (Hz) and stride length (m) between the four breast support conditions and the two running modalities.

As the interaction between dependent variables was not of interest, no multivariate ANOVAs were considered. Post hoc analysis used multiple paired-samples t tests with a Bonferroni adjustment (p < .008). As breast discomfort data were ordinal, Mann–Whitney U tests were conducted to assess differences in breast discomfort between support conditions and running modalities.

A Pearson correlation coefficient explored the relationship between breast displacement and stride frequency and length, with r > .7 indicating a strong correlation and r > .4, a moderate correlation (Fallowfield et al., 2005). A Spearman rank correlation coefficient assessed the relationship between breast discomfort and mean resultant, vertical, m/l and a/p breast displacement. The significance level for the main effects was set at .05. All statistical analyses were computed using PASW statistics software (v18).

Results

Bare-breasted treadmill running produced the greatest resultant breast displacement (12.9 ± 4 cm), while the least resultant breast displacement was measured in the compression sports bra (5.04 ± 1.8 cm) during overground running (Figure 2). The sports bras produced the least resultant, vertical, m/l and a/p breast displacement out of all breast support conditions, with a reduction in vertical breast displacement of 61.2% and 58.8% for overground and treadmill running respectively. Repeated-measures two-way ANOVAs showed that running modality had no significant effect on resultant (F(1,5) = 3.58, p = .117, η² = .417), vertical (F(1,5) = 3.51, p = .120, η² = .413), a/p (F(1,5) = 4.47, p = .088, η² = .474) or m/l (F(1,5) = 0.77, p = .422, η² = .133) breast displacement; additionally, no significant interaction effects were found (p > .05).

There was a significant difference in resultant (F(3,15) = 30.77, p = .000, η² = .887), vertical (F(3,15) = 35.83, p = .000, η² = .966), a/p (F(3,15) = 10.59, p = .001, η² = .846) and m/l (F(3,15) = 15.10, p = .000, η² = .863) breast
displacement between the breast support conditions. Post hoc analysis revealed no significant differences ($p > .008$) between the two sports bra conditions; however differences in resultant, vertical, a/p and m/l breast displacement were seen between other support conditions (Table 1).

Stride frequency (Figure 3) and length did not differ significantly ($p > .05$) across breast support conditions or running modality. In addition, no correlations were found between breast displacements and stride frequency or stride length ($p > .05$) across breast support conditions.

Mean breast discomfort ratings (Figure 4) identified the sports bras as the most comfortable breast support conditions during both overground and treadmill running. As expected, the bare-breasted condition was considered to be the most uncomfortable or painful condition. Breast discomfort did not significantly differ between running modalities ($U = 279.00; p = .81$), however significant differences existed in breast discomfort between all support conditions ($p < .05$), except for between the two sports bra conditions ($U = 46.00; p = .143$). Moderate significant ($p < .05$) correlations were found between breast displacement and discomfort (in the three supported conditions) for both running modalities (Table 2).

**Figure 2** — Mean (±) resultant, vertical, a/p and m/l breast displacement (cm) for all breast support conditions in both running modalities.

**Table 1** — $T$ values illustrating significant (*$p < .008$) differences in resultant, vertical, m/l, and a/p breast displacement (cm) data between various breast support conditions

<table>
<thead>
<tr>
<th>Within-Participant Effect</th>
<th>Mean Resultant Breast Displacement</th>
<th>Mean Vertical Breast Displacement</th>
<th>Mean m/l Breast Displacement</th>
<th>Mean a/p Breast Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encapsulation—Compression</td>
<td>1.67</td>
<td>1.02</td>
<td>2.32</td>
<td>1.15</td>
</tr>
<tr>
<td>Encapsulation—Everyday</td>
<td>$-5.29^*$</td>
<td>$-4.67^*$</td>
<td>$-2.64$</td>
<td>$-2.50$</td>
</tr>
<tr>
<td>Encapsulation—No bra</td>
<td>$-7.39^*$</td>
<td>$-12.14^*$</td>
<td>$-5.05^*$</td>
<td>$-3.45^*$</td>
</tr>
<tr>
<td>Compression—Everyday</td>
<td>$-6.61^*$</td>
<td>$-5.27^*$</td>
<td>$-5.69^*$</td>
<td>$-3.74^*$</td>
</tr>
<tr>
<td>Compression—No bra</td>
<td>$-8.81^*$</td>
<td>$-11.44^*$</td>
<td>$-6.25^*$</td>
<td>$-5.68^*$</td>
</tr>
<tr>
<td>Everyday—No bra</td>
<td>$-7.96^*$</td>
<td>$-4.65^*$</td>
<td>$-4.59^*$</td>
<td>$-3.33^*$</td>
</tr>
</tbody>
</table>
Table 2  Correlations (rs) between resultant, vertical, a/p and m/l breast displacement (cm) and breast discomfort scores

<table>
<thead>
<tr>
<th>Breast Discomfort</th>
<th>Overground running</th>
<th>Treadmill running</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resultant breast displacement</td>
<td>.453*</td>
<td>.675*</td>
</tr>
<tr>
<td>Vertical breast displacement</td>
<td>.490*</td>
<td>.680*</td>
</tr>
<tr>
<td>Mediolateral breast displacement</td>
<td>.475*</td>
<td>.625*</td>
</tr>
<tr>
<td>Anteroposterior breast displacement</td>
<td>.327</td>
<td>.658*</td>
</tr>
</tbody>
</table>

*Note. Significant correlations (p < .05) are marked with an asterisk (*).
Discussion

The magnitude of breast displacement in all support conditions for both running modalities compared well with previous studies (vertical breast displacement has ranged from 1.6 to 4.0 cm in a sports bra condition: Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Mason et al., 1999; White et al., 2009). As hypothesized, no significant differences were found in resultant, vertical, a/p or m/l breast displacements between overground and treadmill running in all breast support conditions. This suggests that data collected on breast displacement during treadmill running are comparable with overground running at the same speed.

The results of this study showed that breast displacement differed significantly between breast support conditions (Table 1). The two sports bras however demonstrated no difference in the amount of support they provided for both running modalities, confirming findings by White et al. (2009), yet contradicting Verscheure et al. (2000) who reported an encapsulation bra to be more effective than a compression bra at reducing breast displacement during drop jump landings. Differences will inevitably exist in the amount of support provided by different sports bra styles and manufacturers, therefore determining if one sports bra style is more effective than another is difficult. The benefit of wearing a sports bra during exercise was confirmed by this study as the greatest reduction in breast displacement (61.2%) was seen in a sports bra.

Despite significant differences in breast displacement across breast support conditions, similar stride frequencies and lengths were found. This suggests that changes in 3D breast displacement had no effect on these two gait parameters at this speed. The results also showed stride length and frequency did not differ significantly between running modalities at the speed chosen, supporting our first hypothesis and Nelson et al.’s (1972) and Frishberg’s (1983) research. However, this finding conflicts with research by Elliott and Blanksby (1976), Schache et al. (2001) and Wank et al. (1998) who reported a shorter stride length and increased stride frequency during treadmill running performed at a higher speed than the current study (3.98 m/s to 6 m/s). It is acknowledged that low statistical power for both gait parameters is a limitation to this study, although a futility analysis suggested a sample size of 75+ would be needed to detect the effects of running modality and breast support conditions on stride frequency and length.

Future research may look to manipulate running speed and stride frequency to investigate the effect of these gait parameters on 3D breast displacement. Furthermore, anecdotal evidence from participants suggested that upper body movements during running altered depending on the level of breast support, providing grounds for further research in to this area.

Moderate correlations (p < .05) were found between breast displacement and discomfort during treadmill and overground running, indicating that as breast support increased, breast discomfort decreased. This corresponds with previous research (Mason et al., 1999) and supports the second hypothesis of this study. Breast discomfort differed significantly between breast support conditions (Table 1); although the two sports bras achieved similar breast discomfort scores, the no bra condition was considered significantly more uncomfortable than all other bra conditions (Figure 4). This result emphasizes the importance of firm breast support for larger-breasted women when exercising (Boschma et al., 1994; Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Mason et al., 1999). Women should be encouraged to purchase bras specifically designed for exercising due to the significant reduction in breast displacement and increase in comfort experienced. An everyday bra does not provide as much support for the exercising D cup female when compared with a sports bra.

Breast discomfort was not perceived to differ between running modalities, therefore supporting the third hypothesis of this study. This was expected as similar levels of breast displacement were found in the two running modalities and a significant moderate correlation between breast displacement and discomfort was also identified (Table 2). Breast velocity was not assessed in this study, although it has been suggested that breast discomfort may correlate more closely with this variable (McGhee et al., 2007), prompting future research in this area.

Stronger correlations between breast displacement and discomfort were found during treadmill running compared with overground running; it is speculated that participants may have been able to focus more on comfort levels during the controlled activity of treadmill running. Interestingly, a stronger correlation between a/p breast displacement and discomfort was identified during treadmill running in comparison with overground running, highlighting the importance of 3D assessment of breast displacement. Further investigation into the complex relationship between the direction of breast movement and breast discomfort is warranted.

In conclusion, this study found that three-dimensional breast displacement and breast discomfort did not differ between treadmill and overground running; therefore previous breast motion studies that have examined treadmill running are applicable to females who run overground. Breast motion does not appear to have been underestimated during treadmill running and therefore future studies utilizing an overground running protocol will be comparable. Despite significant changes in breast displacement across breast support conditions, stride frequency and stride length were unaffected and remained similar in treadmill and overground conditions, suggesting that breast displacement does not influence these gait parameters. Breast discomfort increased as 3D breast displacement increased, reaffirming earlier findings in 2D studies. Future research should assess how upper body kinematics are affected by 3D breast displacement.
References


