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Breast Displacement in Three Dimensions During the Walking and Running Gait Cycles

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This study aimed to assess the trajectory of breast displacement in 3 dimensions during walking and running gait, as this may improve bra design and has yet to be reported. Fifteen D-cup participants had reflective markers attached to their nipples and trunk to monitor absolute and relative breast displacement during treadmill walking (5 kph) and running (10 kph). During the gait cycle, the breast followed a figure-of-eight pattern with four movement phases. Despite a time lag in resultant breast displacement compared with the trunk, similar values of breast displacement were identified across each of the four phases. Fifty-six percent of overall breast movement was vertical, suggesting that 3-D assessment and the elimination of trunk movement in 6 degrees of freedom are essential to accurately report breast displacement during the gait cycle.

Keywords: kinematics, bras, treadmill

Breast biomechanics is an underinvestigated area of health and sports performance, with a limited number of full empirical studies published (Campbell et al., 2007; Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Mason et al., 1999; McGhee et al., 2007; Starr et al., 2005). The multiplanar trajectory of the breast during gait has yet to be quantified and described in the literature. While the quantitative kinematics of the breast have been reported in the coronal plane, understanding the displacement of the breasts in three dimensions (3-D) may provide bra manufacturers with design criteria for improved breast support.

Previous research has shown a link between vertical breast displacement and breast pain, and this highlights the importance of reducing breast displacement. During physical activity, Mason et al. (1999) found that perceived breast pain followed the pattern of vertical breast displacement rather than maximum deceleration force, but the reason for this relationship requires further investigation. Further elucidation of the kinematics, kinetics, and temporal movement of the breast in relation to the body may facilitate our understanding of exercise-related breast pain.

The trajectory of breast displacement in the coronal plane was presented graphically by Gehlsen and Albohm (1980) during one running gait cycle for a B-cup participant. The trajectory demonstrated a figure-of-eight displacement path. However, this pattern represented the absolute displacement of the breast, which includes the displacement of the body, and no comprehensive description was provided. To eliminate the movement of the trunk from that of the breast, previous research has used a single trunk reference marker; the displacement of this reference marker has then been subtracted from the displacement of the breast. This gives an indication of the influence of the trunk on coronal plane breast movement. However, the trunk moves in more than one dimension during gait and the influence of mediolateral (m/l) and anteroposterior (a/p) trunk displacement on breast kinematics is unknown. In addition, the influence of trunk rotation (pitch, roll, and yaw) on breast displacement has yet to be presented. If the elimination of trunk movement in six degrees of freedom (6*df*) results in significant changes in breast displacement, this would be an important consideration for future breast biomechanics research.

The relative trajectory of the unsupported breast during physical activity and across multiple planes of movement has yet to be reported. While the majority of women may exercise wearing some form of breast support, a detailed understanding of the biomechanics of the unsupported breast defines the criteria for breast support against which commercial products can be assessed (Page and Steele, 1999).

Therefore, the aim of this investigation was to assess the absolute and relative displacement of the

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breast in three dimensions during treadmill walking and running gait cycles. It was hypothesized that there would be

1. Significant reductions in the magnitude of vertical, m/l, a/p, and resultant breast displacement when converted from absolute to relative breast displacement.
2. Significant differences in the temporal displacement of the breast compared with the clavicle trunk reference marker during treadmill walking and running.
3. Significant differences in relative resultant breast displacement during different phases of the gait cycle.
4. Significant differences in the percentage contribution of vertical, m/l, and a/p breast displacement during the gait cycle.

Methods

Following full institutional ethical approval, 15 female volunteers were selected to take part in this study. Due to the lack of published data on 3-D breast biomechanics, a priori power calculation was conducted using bare-breasted relative displacement data obtained during a walking and running pilot study with one D-cup participant (www.dssresearch.com/toolkit/spcalc/power_a1.asp). This pilot study indicated that a sample size of between 6 and 15 participants would provide a power of 0.88–1. Participants had an average age of 24 years (±4.8 years), body mass of 65.5 kg (±8.7 kg), height of 1.67 m (±0.05 m) and a mean sum-of-eight skinfolds of 146 mm (±36 mm) as measured by an accredited anthropometrist. Participants were selected if they were recreationally active (greater than 30 min of exercise, at least twice a week), had experienced no surgical procedures to the breasts, had not gone through pregnancy within the last year, and were a D-cup breast size. The D-cup breast size was selected for comparison with previous research (Campbell et al., 2007; Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Starr et al., 2005; Verscheure, 2000). All participants gave written informed consent to participate.

The participants' breast size was measured by a trained bra fitter. Following the recommendations of McGhee and Steele (2006), the participants stood braless with their arms relaxed by their side and all measurements were made with a metal anthropometric tape. Following expiration, chest girth was determined underneath the breasts, level with the inframammary fold and cup size was determined with a girth measurement taken over the fullest part of the breast. 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.

Participants completed a standardized warm-up on the treadmill at a self-selected speed (GX200, Powerjog, UK) wearing their own exercising bra. Following this, the bra was removed and passive retro-reflective markers (12 mm in diameter) were attached with hypoallergenic skin tape to the right nipple, the left and right clavicles (directly superior to the nipple, Eden et al., 1992; Gehlsen and Albohm, 1980), and the left and right anterior superior iliac spines (ASIS). Following a 2-min familiarization period, marker coordinates were recorded during five treadmill gait cycles at 5 kph (1.4 m·s^{-1}; a comfortable walking speed; Rose and Gamble, 2006) and 10 kph (2.8 m·s^{-1}; running; Campbell et al., 2007; Eden et al., 1992; Himmelsbach et al., 1992; Lorentzen & Lawson, 1987; Mason et al., 1999). Due to discomfort during bare-breasted activity, five gait cycles was the maximum that some participants could perform during running.

Three-dimensional displacement of the markers was tracked using five 100-Hz calibrated ProReflex Infrared cameras (Qualisys, Sweden) positioned around the treadmill. The laboratory coordinate system identified x as the line of progression (a/p), y as m/l, and z as vertical (Figure 1). An external trigger marking right heel strike at the start of each speed on the treadmill and foot switches (100 Hz, FS4, Biometrics,

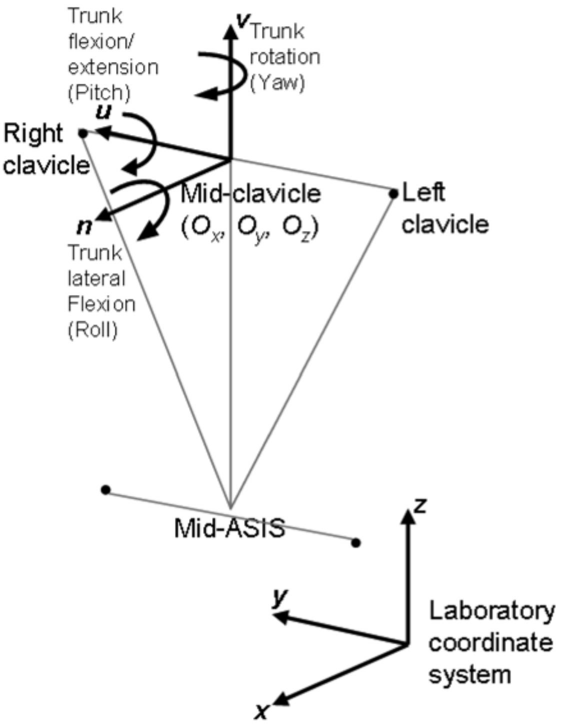

Figure 1 — Axis of the global and local coordinate systems. U defines an axis from the left to the right clavicle, v defines an axis from the mid-ASIS (virtual point) to the midclavicle (virtual point), and n defines an axis of the cross-product of u and v. Axes were established using a left-handed coordinate system.

UK) identifying each gait cycle were synchronized with the motion capture system via a 32-channel USB Interface Unit (Qualisys, Sweden).

Markers were identified (0.25-mm marker detection error) and 3-D data reconstructed in the Qualisys Track Manager Software (Qualisys, Sweden). The Cartesian *x*, *y,* and *z* coordinates for the five markers were exported into Microsoft Excel 2003 along with the external trigger and foot switch data. To establish relative breast movement independent to the 6*df* movement of the trunk, an orthogonal local coordinate system (LCS) converted absolute right breast coordinates to relative coordinates using a transformation matrix (Foley et al., 1995). The left and right clavicle markers created the anatomical reference axis *u* (Nguyen and Baker, 2004) to determine 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). Vector *n* was perpendicular to this anatomical reference plane, whereas *v* was perpendicular to *u* and *n*. The virtual midclavicle marker was the origin of the LCS from which breast translation was calculated (Figure 1).

Using the foot-switch data vertical, m/l, a/p, and resultant absolute and relative displacement of the breast were then calculated during five gait cycles (which equates to 10 breast cycles; McGhee & Steele, 2006) at 5 kph and 10 kph. Displacement was normalized to the position of the breast at right heel strike. All data were checked for normality using the Kolmogorov–Smirnov and Shapiro–Wilks tests. Parametric differences in the timing of the absolute and relative displacement inflection points of the breast and clavicle were compared using repeated-measures ANOVA followed by multiple paired *t* tests with a Bonferroni adjustment. Similar analysis was used to compare breast displacement across the phases of the gait cycle. Nonparametric differences between absolute and relative breast displacement were assessed using the Friedman test, followed by multiple Wilcoxon tests. Nonparametric differences in vertical, m/l, and a/p breast displacement were assessed using the Kruskal–Wallis test, followed by multiple Mann–Whitney *U* tests. Absolute typical error measurements (TEMs) in millimeters and the log-transformed percentage coefficients of variance (%CV) assessed the within-participant variance in breast displacement across five gait cycles during walking and running (Hopkins, 2000). An alpha level of 0.05 was adopted, except where a correctional factor was applied.

Results

Following the familiarization period at 5 kph, participants demonstrated consistent breast kinematics across five walking gait cycles with TEMs of 6 mm in resultant breast displacement (0.9%CV ± 0.6%CV). At this speed, mean trunk pitch was 5.2° (±1.6°), roll 6.5° (±2°), and yaw 9.7° (±3.3°). Despite the short duration spent running at 10 kph, within-participant TEMs of 9 mm (1.3%CV ± 0.8%CV) in resultant breast displacement was considered relatively low.

Phasic Activity of Breast Motion During an Average Gait Cycle (Figures 2–5)

Four phases of breast motion were identified during walking and running gait cycles. Phases 1 and 3 occurred as the body elevated from double to single support during walking and maximum knee flexion to midflight during running (A to B and C to D in Figures 2–5). Phases 2 and 4 occurred as the body changed direction and moved downward from single to double support during walking and midflight to maximum knee flexion during running (B to C and D to A).

Temporal Breast Displacement During an Average Gait Cycle (Figures 2–5)

Qualitatively, absolute breast displacement during an average walking (Figure 2) and running gait cycle (Figure 3) showed a double peak in vertical displacement. During walking (Figure 2), the medial and anterior displacement of the right breast peaked at left toe-off (phase 1). The breast then moved laterally (peaking at right toe-off) and posteriorly (peaking at left heel strike). During running, the absolute m/l and a/p displacement of the right breast showed a single medial and anterior peak occurring during midflight of the ipsilateral limb (Figure 3).

When breast displacement was calculated relative to the movement of the body (Figures 4 and 5), there was a significant reduction in vertical, m/l, a/p, and resultant displacement of the breast during walking and running ($p < .02$). The temporal pattern of vertical breast displacement still displayed a double-peaked trajectory (Figures 4 and 5). During walking, the initial anterior component of absolute breast displacement that occurred during left toe-off was still evident in relative breast displacement; this was followed by a small posterior movement of the breast (Figure 4). More m/l deviation occurred during right foot contact compared with left foot contact. For the running gait cycle, relative breast displacement displayed a trajectory similar to that of absolute displacement for the vertical and a/p component (Figure 5). However, the trajectory of m/l displacement changed, with the medial component evident during the flight phase of the contralateral limb significantly reduced.

Figures 2–5 display inflection points A to D, which occurred as the body changed direction (at the end of the acceleration and deceleration phases of each step). For the vertical component of displacement, there was a significant delay in the time taken for the breast to reach these inflection points and change direction compared with the body ($p < .008$). This time lag was evident in

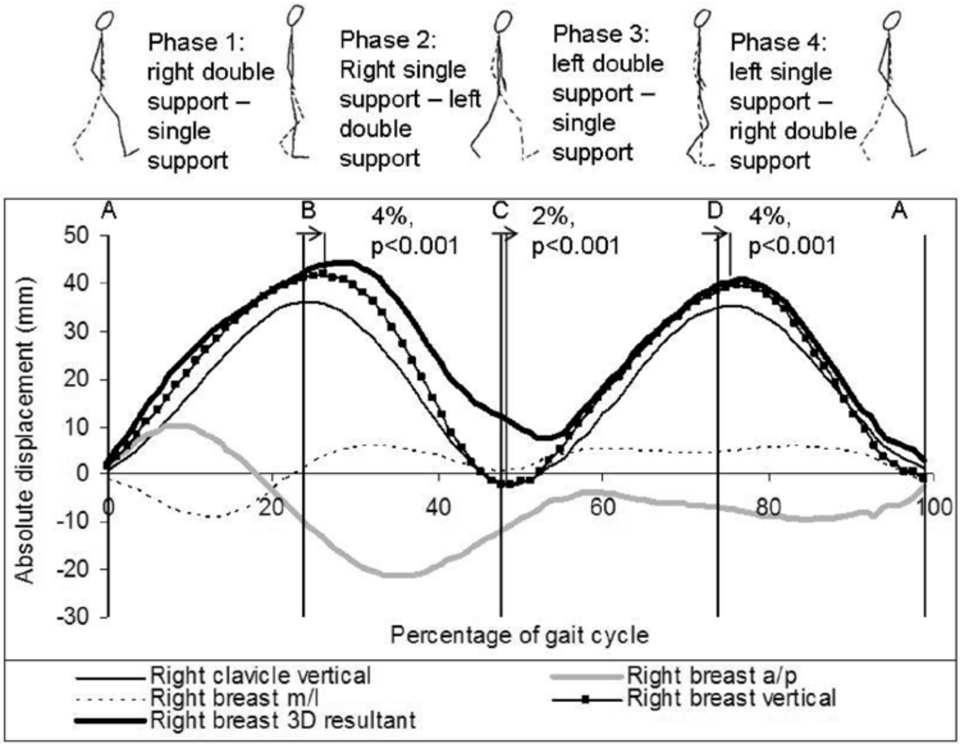

Figure 2 — Absolute right breast displacement (mm) normalized to the position of the breast during right heel strike and averaged during five treadmill walking gait cycles at 5 kph with no breast support ($n = 15$, D-cup participants). Lines A to D represent the inflection points of the vertical displacement of the right clavicle; arrows denote the significant increase in the percentage of the gait cycle to the inflection points of the vertical displacement of the right breast.

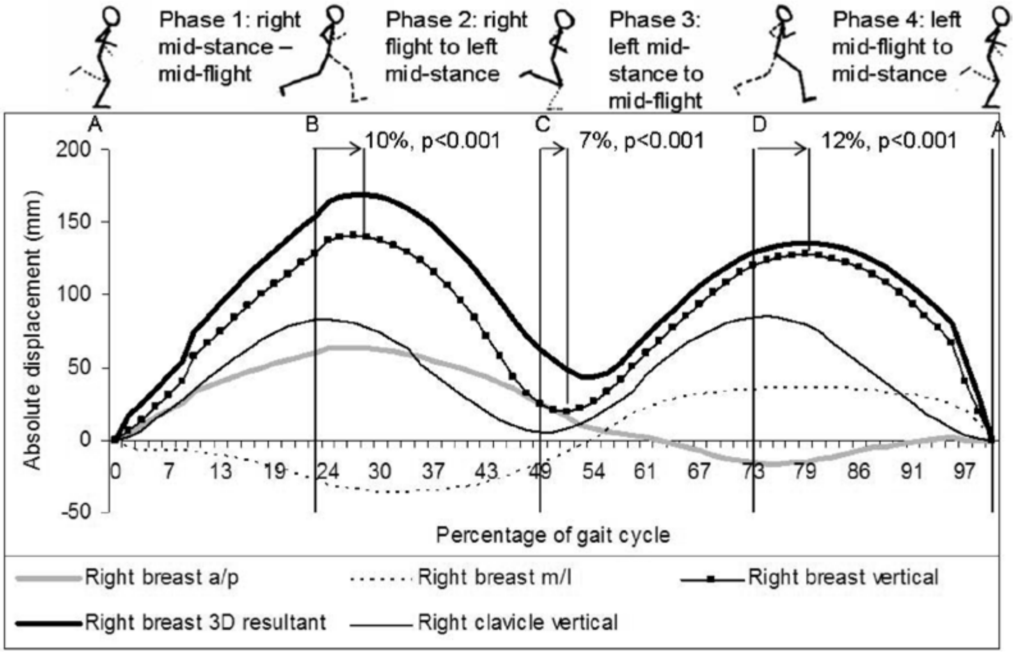

Figure 3 — Absolute right breast displacement (mm) normalized to the position of the breast during right heel strike and averaged during five treadmill walking gait cycles at 10 kph with no breast support ($n = 15$, D-cup participants). Lines A to D represent the inflection points of the vertical displacement of the right clavicle; arrows denote the significant increase in the percentage of the gait cycle to the inflection points of the vertical displacement of the right breast.

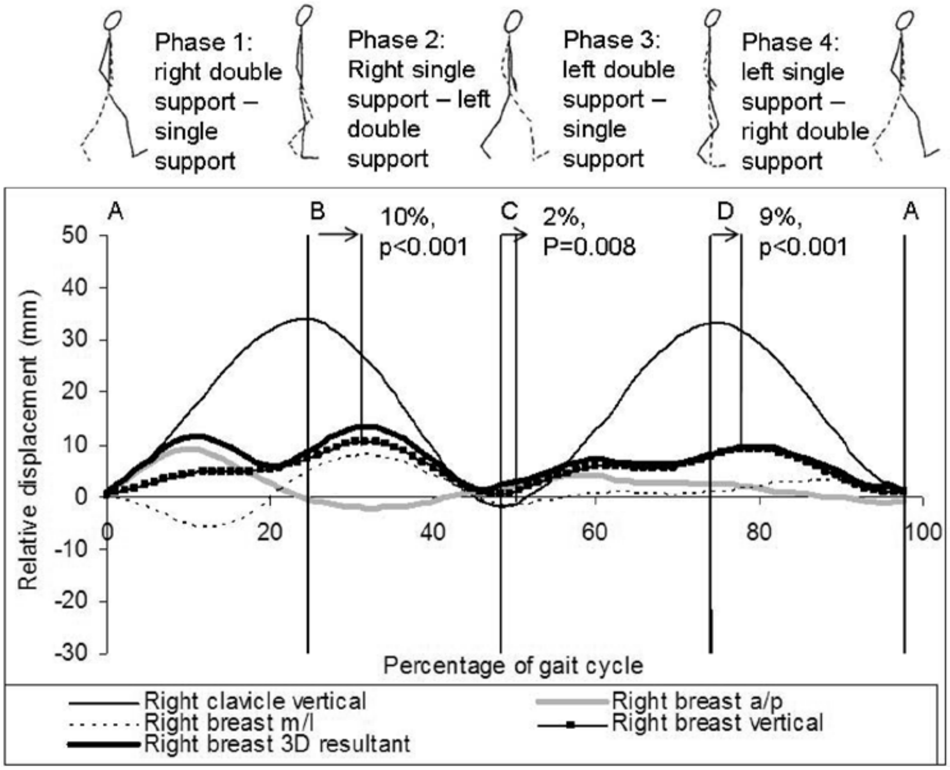

Figure 4 — Relative right breast displacement (mm) normalized to the position of the breast during right heel strike and averaged during five treadmill walking gait cycles at 5 kph with no breast support ($n = 15$, D-cup participants). Lines A to D represent the inflection points of the vertical displacement of the right clavicle; arrows denote the significant increase in the percentage of the gait cycle to the inflection points of the vertical displacement of the right breast.

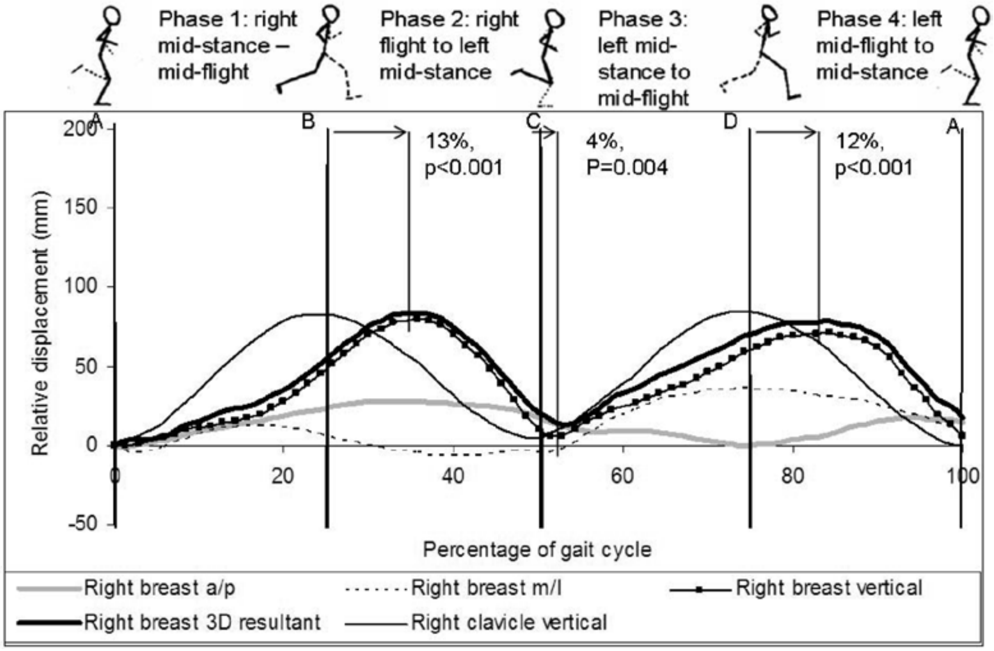

Figure 5 — Relative right breast displacement (mm) normalized to the position of the breast during right heel strike and averaged during five treadmill walking gait cycles at 10 kph with no breast support ($n = 15$, D-cup participants). Lines A to D represent the inflection points of the vertical displacement of the right clavicle; arrows denote the significant increase in the percentage of the gait cycle to the inflection points of the vertical displacement of the right breast.

absolute and relative breast displacement, with percentage time delays of up to 13% of the gait cycle. Statistical analysis revealed no significant difference in relative resultant breast displacement between each gait phase in walking, *F*(3) = 1.9, *p* = .15), and running, *F*(3) = 2.24, *p* = .1 (Figure 6).

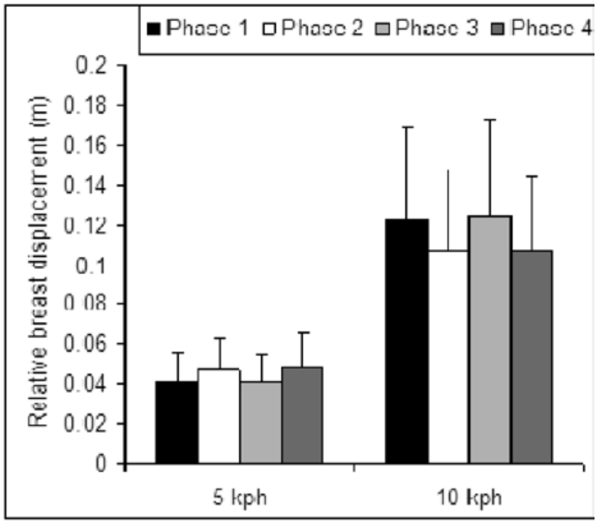

Figure 6 — Mean relative 3-D resultant breast displacement (mm) with no breast support, across the four phases of the gait cycle, for 15 D-cup participants during treadmill walking and running.

Trajectory of Breast Motion During an Average Running Gait Cycle

Both absolute and relative breast displacement displayed an approximate figure-of-eight trajectory in the coronal plane. Converting breast displacement from absolute to relative by eliminating the 6*df* trunk movement did not substantially alter the pattern of breast movement in the sagittal plane, but a significant reduction in medial breast displacement altered the trajectory in the coronal and transverse planes.

The three components of relative displacement (vertical, m/l, and a/p) made varying contributions to the total resultant displacement of the breast during each walking and running gait cycle. Figure 7 shows that significantly more vertical displacement occurred during walking and running (*p* < .001), but similar levels of m/l and a/p displacement were observed (*p* = .89).

Discussion

This article presents the trajectories of absolute and relative breast displacement in three dimensions during treadmill walking and running gait cycles. The results identified four phases of breast motion during each gait cycle. Both absolute and relative displacement of the breast demonstrated a double peak in vertical breast displacement and single peaks in m/l and a/p breast displacement, which is similar to the trajectory of the

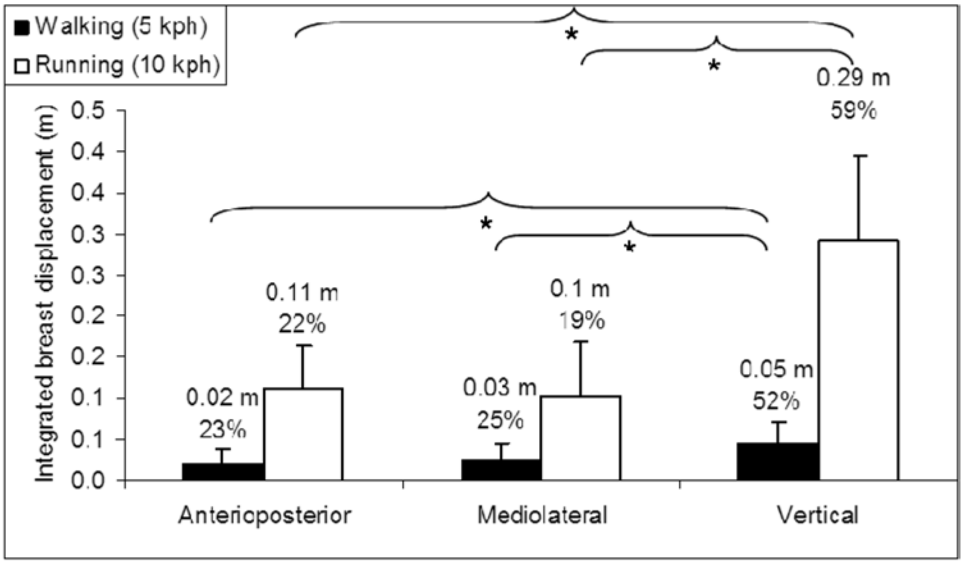

Figure 7 — Total displacement of the right breast (and percentage contribution) during each gait cycle (incorporating two breast cycles, one with the right step and one with the left step), averaged across five gait cycles for 15 D-cup participants. *Denotes significant differences, where *p* < .001.

whole-body center of mass during an average gait cycle (Kirtley, 2006). During walking and running when the movement of the trunk was eliminated from that of the breast, the magnitude of vertical, m/l, a/p, and resultant displacement was significantly reduced ($p < .02$), which accepts hypothesis 1.

In all phases of the gait cycle, a time lag was shown in the peak vertical displacement of the breast compared with the clavicle. This significant increase in time to maximum and minimum vertical breast displacement compared with the clavicle accepts hypothesis 2 ($p < .008$). It is suggested that this difference in phasic activity of the breast and clavicle is due to the elastic and inertial properties of the breast, leading to an increased acceleratory load on the supporting structures of the breast at these time points, which may influence exercise-related breast discomfort.

A figure-of-eight trajectory of absolute and relative breast displacement during bare-breasted running in the coronal plane was identified, similar to that presented by Gehlsen and Albohm (1980). Even though the trajectories of absolute and relative breast displacement were reasonably similar, it is interesting to note the significant reduction in the relative medial component of breast displacement, which was evident in absolute breast displacement and therefore must result from shoulder rotation. Despite differences in the trajectory of breast displacement throughout the gait cycle, the magnitude of resultant right breast displacement was similar across each phase, rejecting hypothesis 3 (Figure 6).

In comparison with relative m/l and a/p breast displacement, there was significantly greater relative vertical displacement during walking and running gait, which accepts hypothesis 4. Vertical displacement accounted for an average of 56% of overall breast displacement during treadmill walking and running. Despite the elimination of trunk movement in 6*df*, the m/l translation of the trunk, trunk rotation (yaw), and lateral trunk flexion (roll) led to considerable m/l breast displacement. The a/p translation of the trunk, trunk rotation (yaw), and trunk flexion/extension (pitch) led to considerable a/p breast displacement. The m/l and a/p variables combined accounted for 48% of breast displacement during walking and 41% during running and therefore should not be ignored when designing products to reduce breast motion at both high- and low-activity levels.

It is worth noting that no consensus exists in segment definition or technique for trunk kinematic analysis (Nguyen and Baker, 2004). Previous studies on 3-D trunk kinematics have predominantly focused on male participants, utilizing reference markers positioned on combinations of T1, T4, T6, T9, T10, C7, two paravertebral markers at T6 level, markers near the bottom of the rib cage, the supersternal notch, the xiphoid process, and the clavicles (Crosbie et al., 1997; Gutierrez and Saraste, 2002; Nguyen and Baker, 2004; Sartor et al., 1999; Van Emmerik et al., 2005). Although simplistic, the trunk reference marker set used in this study was not obscured by the bra (which may happen with the xiphoid process and T1 to T11) and demonstrated trunk kinematic values that compared favorably with those in previous literature (Krebs et al., 1992; Murray et al., 1964; Opila-Correia, 1990; Stokes et al., 1989; Thorstensson et al., 1984; Van Emmerik et al., 2005). However, further research is warranted on 3-D trunk kinematics in females. Finally, despite reasonable between-participant variance (Figures 6 and 7) and the limited familiarization period during bare-breasted running, five gait cycles produced consistent breast displacement (<1.3%CV). This result provides strength to the data collection procedure, but suggests that future research should investigate factors that discriminate between breast displacement values for participants of a similar breast size.

In conclusion, this study is the first to present trajectories of absolute and relative breast displacement in three dimensions during walking and running gait. Four phases of breast motion in a figure-of-eight pattern were identified during each gait cycle. The calculation of relative breast displacement from the absolute values resulted in significant reductions in vertical, m/l, a/p, and resultant breast displacement. This was particularly evident in substantial reductions in the medial displacement of the breast, suggesting that this variable was influenced by transverse plane shoulder rotation. The results of this study suggest that the elimination of 6*df* trunk movement is essential for reporting relative breast displacement, which may be overestimated without this form of analysis. Despite a significant time lag in the displacement of the breast compared with the body, similar magnitudes of relative breast displacement occurred during each phase of the gait cycle. Previous research has primarily reported breast displacement in the coronal plane; the current study has shown that the vertical component accounted for an average of 56% of breast motion during treadmill walking and running. These results highlight the need to consider m/l and a/p movement, in addition to vertical displacement, when designing bras for optimal support. Finally, this study on bare-breasted activity outlines the multiplanar breast support requirements during walking and running for D-cup women.

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