THE INFLUENCE OF BREAST SUPPORT ON TORSO, PELVIS AND ARM KINEMATICS DURING A FIVE KILOMETRE TREADMILL RUN

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ABSTRACT

Many women wear sports bras due to positive benefits associated with these garments (i.e. reduction in breast movement and breast pain), however the effects these garments have on upper body running kinematics has not been investigated. Ten female participants (32DD or 34D) completed two five kilometre treadmill runs (9 km.h^{-1}), once in a low and once in a high breast support. The range of motion (ROM) and peak torso, pelvis, and upper arm Cardan joint angles were calculated over five gait cycles during a five kilometre run. Peak torso yaw, peak rotation of the pelvis, peak pelvis obliquity, ROM in rotation of the pelvis, and ROM in upper arm extension were significant, but marginally reduced when participants ran in the high breast support. The running kinematics reported in the high breast support condition more closely align with economical running kinematics previously defined in the literature, therefore, running in a high breast support may be more beneficial to female runners, with a high breast support advocated for middle distance runners.

KEY WORDS: *Female, Running, Kinematics, Cardan angles.*

INTRODUCTION

Reducing the magnitude of breast kinematics relative to the torso is a unique issue for the female athlete. Without effective breast support, the breast tissue moves independently to the torso, with a significant time-lag evident between the torso and breast during running (Scurr, White, & Hedger, 2009). Research studies within breast biomechanics have investigated; the direction and magnitude of breast kinematics during running (Scurr, White, & Hedger, 2009; White, Scurr, & Smith, 2009), the number of females exercising in appropriate breast support (Bowles, Steele, & Munroe, 2008), the relationship between breast kinematics and exercise-related breast pain (Scurr, White, & Hedger, 2010; McGhee, Steele, & Power, 2007), the number of females who identify breast movement as a barrier to physical activity (Bowles, Steele, & Munro, 2008), and how the direction and magnitude of breast kinematics can inform breast support design (Starr et al., 2005; Scurr et al., 2010). However, few papers have considered the impact of breast support on human movement.

Without muscle or bone, the breast tissue may be described as a wobbling mass situated on a rigid torso segment. A female of a 34D bra size has an additional mass of approximately 920 g (460 g per breast) (Turner & Dujon, 2005) situated on the torso segment. Due to the location of the breast it is important to consider how the magnitude of independent movement of this additional mass may influence the kinematics of the torso and other upper body segments during exercise. Many have argued that the energetic cost of running is influenced by segment structure, for example, a segment with a greater distribution of mass from the axis of rotation, specifically at the distal end (Taylor, Shkolnik, Dmi’el, Baharav, & Borut, 1974; Myers & Steudel, 1985; Martin & Morgan, 1992) will have a greater moment of inertia, and will therefore require greater torque to rotate the segment about its axis. This argument is based on the notion that a substantial portion of metabolic demand during running is associated with accelerating and decelerating the limbs with each stride (Martin & Morgan, 1992). Dependent upon the amount of compression and elevation provided, a breast support may distribute the breast tissue differently over the torso, with the breast tissue assumed to be more proximal to the torso and more compressed to the chest wall in a sports bra. Without adequate breast support, the breast tissue may be located closer to the distal end of the torso and further away from the chest wall, with less restriction of independent movement (Scurr, White, & Hedger, 2010; McGhee, Steele, Zealey, & Takacs, 2012),which may therefore influence the kinematics of the torso during running.

Within gait literature the relationships between segments are emphasised (Novacheck, 1998), with efficient energy transfer between segments equating to economical running mechanics and a reduced metabolic cost (Williams & Cavanagh, 1987). In order to maintain a constant velocity during running, counter-rotation occurs between the pelvis and torso, which enables an individual to maintain a constant step length and frequency (Novacheck, 1998; Bruijn, Meijer, van Dieën, Kingma, & Lamoth, 2008). The role of the pelvis in energy conservation has been emphasised by Schache, Bennell, Blanch, and Wrigley (1999), suggesting that the degree of anteroposterior tilt at the pelvis should be minimised to conserve energy and maintain efficiency in running. Furthermore, Schache et al., (1999) proposed that the degree of pelvic obliquity (the deviation of the pelvis from the horizontal in the frontal plane) plays a role in shock absorption during the running gait cycle. With every foot strike a shock wave is transmitted throughout the body, reaching the upper body and head, which results in soft tissue vibrations (Hamill, Derrick, & Holt, 1995; Mercer, Vance, Hreljac, & Hamill, 2002). Without muscle to dampen these vibrations at the breast, it may be desirable for a female runner to attenuate the shock wave before it reaches the torso, reducing potential breast movement associated with ground contact. As a result of the different magnitudes of independent breast movement and exercise-related breast pain experienced across breast support conditions (Scurr et al., 2010; 2011; McGhee et al., 2012), the kinematics of the pelvis, that contribute to natural shock absorption, may differ between breast support conditions as a strategy to reduce the magnitude of independent breast movement.

Arm swing is a distinctive characteristic of walking and running, with the magnitude and frequency defined as compensatory and synchronous with the action of the legs (Hinrichs, 1990; Pontzer, Holloway, Raichlen, & Lieberman, 2009; Eke-Okoro, Gregoric, & Larsson, 1997). For example, during sprinting leg mechanics are forceful and explosive, the arms must move in large controlled flexion and extensions at the shoulder to support the increase in velocity (Hinrichs, 1990). As the pace is slowed, the arms move through shorter arcs and swing across the torso towards the midline of the body (Hinrichs, 1990). There are many benefits of arm swing reported in the literature; it has been shown that the arms serve to reduce fluctuations in mediolateral and anteroposterior displacement of the centre of mass during running, improving energy costs (Hinrichs, 1990; Pontzer et al., 2009; Bruijn, Meijer, Beek, & van Dieën, 2010). In addition, arm swing and shoulder rotation counteract the torque seen in the torso about the vertical axis that is imparted by the rotation of the pelvis to put the legs through their alternating patterns of stance and swing (Kuhtz-Busvhbeck & Jing, 2012; Hinrichs, 1990). The kinematics of the arm is an under investigated area, with little research published in comparison to the lower body limbs, particularly for female runners. Moreover, whilst the link between arm swing mechanics and torso rotation has been documented (Bruijn et al., 2010; Ohsato,1992; Hinrichs, 1990), the influence of breast support and breast movement on arm swing mechanics during running is unknown. When considering the female athlete, movement patterns that enable an individual to maintain a faster running velocity, such as greater torso rotation, and increased upper and lower body extremity velocities and ranges of motion (Hinrichs, 1990), could elicit greater magnitudes of breast movement, which has been shown to increase ratings of breast pain and could prevent an individual from running at faster velocities.

Individuals will self-optimise mechanically and metabolically for efficient locomotion (Williams, 1990; Hamill, Derrick, & Holt, 1995). However, the desire to reduce the magnitude of breast movement and exercise-related breast pain through alterations in running kinematics may supersede the self-optimisation required for optimal mechanical efficiency. In order to answer this question, it is important firstly to ascertain if female upper body running kinematics are affected by the level of breast support worn. The aim of this preliminary investigation was to quantify the kinematics of the torso, pelvis, and arms during a five kilometre treadmill run in a low and high breast support condition. It was hypothesised that the peak orientation and ROM of the torso, pelvis and upper arm would be significantly less in the low breast support condition when compared to the high breast support condition.

METHODS

Due to the lack of published data on the effect of breast support on running kinematics, an a priori power calculation was conducted using pilot data during treadmill running. The power calculation indicated that a sample size of between 8-10 participants would provide sufficient power. Following institutional ethical approval, ten female volunteers (experienced treadmill and outdoor runners currently training ≥ 30 min, ≥ five times per week) with a mean and standard deviation (SD) age of 23 years (2 years), body mass 62.1 kg (5.4 kg), and height 1.6 m (0.05 m), participated in this study. All participants provided written informed consent to participate. Participants had not had children and not experienced any surgical procedures to the breast. Participants' bra size was measured employing the best fit criteria recommended by White and Scurr (2012). Participants were required to fit either of the cross-graded bra sizes of

34D or 32DD, to fall within the same breast volume as the current proposed UK average of a 36C (Treleaven, 2007).

The study was a counterbalance repeated measures design, where participants performed two five kilometre treadmill runs on separate days, 24 to 72 hours apart; once in a low breast support (Marks and Spencer's Seamfree Plain Underwired T-Shirt Bra, non-padded, made from 88% polyamide and 12% elastane lycra) and once in a high breast support (Shock Absorber's B4490, made from 57% polyester, 34% polyamide, and 9% elastane). These two breast supports were selected based upon their use within previous breast biomechanics literature (Scurr, White, & Hedger, 2010). Participants selected a maintainable running speed, commonly employed during training, this ranged from 8.5 $km\cdot h^{-1}$ to 10.5 $km\cdot h^{-1}$, with an average of 9 $km\cdot h^{-1}$ (1 $km\cdot h^{-1}$). Once selected, this speed remained constant throughout both run trials. Participants wore the same footwear and lower body clothing for both trials. Fourteen retro-reflective hemi-spherical markers (diameter of 12 mm) were positioned with hyper-allergenic tape on the anatomical landmarks which defined the segment end points and additional tracking markers for each segment (Visual3D, C-motion Inc.), detailed in table 1. One additional marker was positioned directly over the right nipple on top of the bra, in the two breast support conditions (Scurr et al., 2010). Multiple tracking markers were positioned on the torso segment due to the potential obscuring of these markers in the two breast support conditions. In order to calculate the compression and elevation provided by each breast support a marker was positioned on the bras directly over the nipple (Scurr et al., 2010). Further to this, to track and identify the phases of the gait cycle, an additional marker was positioned on the left heel of each participant's trainer (Zeni, Richards, & Higginson, 2008). Participants were asked to rate their breast pain on a 0 to 10 numerical visual analogue scale (White et al., 2009), at two minutes of running and at the fifth kilometre interval in both breast supports.

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Three-dimensional coordinates of the markers were tracked by eight calibrated Oqus infrared cameras (Qualisys, Sweden) positioned around the treadmill, which sampled at 200 Hz. The global coordinate system (GCS) identified x as the line of progression on the treadmill (anteroposterior), y as mediolateral, and z as vertical. To calculate the amount of compression and elevation provided by each breast support, static captures were recorded with the participant standing in the anatomical position in each breast support condition. Following each static capture, the participants began the five kilometre treadmill run. Cameras recorded the final ten seconds of the first two minutes of running, and for ten seconds within the final 100 m of each kilometre interval thereafter (e.g. 1:50 minutes, 900 m, 1900 m, etc.).

Raw three-dimensional coordinate data were exported from Qualisys Track Manager (QTM) to a Fast Fourier Transform (FFT) program in MATLAB (MathWorks, UK). A cut-off frequency of 8 Hz was selected for the low pass second-order Butterworth filter, with the majority of the signal power reported below this frequency. Filtered three-dimensional global coordinates for all markers and trials were exported to Visual3D for further analysis (C-Motion, Inc.).

Segment Coordinate Systems (SCS) for the torso, pelvis, and upper arm segments were created within Visual3D. The orientation of the SCS axes followed the same right-hand rule orientation as the GCS, when the runner was in the anatomical position, z was defined as pointing along the distal to proximal segment axis (vertical), x was defined as the line of progression anteriorly (anteroposterior), and y extending to the left (mediolateral) (Schache et al., 2001), with the origin created at the superior end of the torso and upper arm segment, and at the midpoint between the right and left ASIS for the pelvis segment.

To eliminate the influence of torso orientation on the breast ROM, compression and elevation calculations, the global nipple coordinates were converted to relative nipple coordinates (relative to the torso origin) using a transformation matrix within Visual3D (Milligan, Mills, & Scurr, 2014; Mills, Loveridge, Milligan, Risius, & Scurr, 2014). Using the relative nipple coordinates, minima positional coordinates were subtracted from maxima coordinates of the right nipple, during each gait cycle (n = 5) (Scurr et al., 2009; 2010) to calculate breast range of motion (ROM) in three-dimensions. The average relative anterior and inferior distances from the torso origin provided the magnitude of compression and elevation provided by each breast support, respectively.

Cardan angles were calculated for each segment of interest, with the ISB recommended sequence employed, i.e. mediolateral axis rotation (flexion/extension), anteroposterior axis rotation (abduction/adduction), and vertical axis rotation (internal/external) (Figure 1) (Cappozzo, Della Croce, Leardini, & Chiari, 2005) The terminology and direction of peak axis rotation for each segment has been defined in Table 1.

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The Cardan angles for the torso segment were calculated relative to the GCS, whereas the pelvis and upper arm Cardan angles were calculated relative to the torso segment. The Cardan angles were time normalised to each gait cycle at 1% intervals, with Cardan angles calculated over five gait cycles. Peak orientation and range of motion (ROM) were calculated for each Cardan angle during each gait cycle. Peak orientation was calculated by identifying the maxima and minima value about each axes of rotation for each segment. Range of motion was calculated by taking the minima orientation angle away from the maxima orientation angle, about each axes of rotation for each segment over each gait cycle. Coefficient of variance (C*v*), reported as a relative percentage, quantified the within-participant variance in the range of motion in Cardan angles for each segment over five gait cycles at each interval of the five kilometre run.

All data were checked for normality using the Kolmogorov-Smirnov and Shapiro-Wilk tests, with normality assumed when $p > .05$. Two-way repeated measures ANOVAs were performed to examine the main and interaction effects of breast support conditions and run distance on the Cardan joint angle for each segment. *Post-hoc* pairwise comparisons, with Bonferroni adjustment, were performed to determine where any differences lay. Effect size (η^2) and observed power (1-β) are presented to indicate the strength of the results.

RESULTS

No differences were reported in the amount of compression provided by the low (4.5 cm) and high (4.7 cm) breast supports. However, the high breast support provided significantly more nipple elevation (14.8 cm from the torso origin) when compared to the low breast support (16.3 cm from the torso origin) ($t_{(9)} = 3.187$, $p = 0.11$).

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Significant reductions in the magnitude of independent multiplanar breast ROM ($p = .001$) and ratings of breast pain ($p = .001$) were reported in the high breast support compared to the low breast support at all intervals of the five kilometre run. Significant increases in anteroposterior, mediolateral, and superioinferior breast ROM were reported in the high breast support, 0.4 cm, 0.4 cm, and 0.5 cm, respectively, and 0.7 cm in the superioinferior ROM in the low breast support, from the first two minutes to the fifth kilometre interval ($F_{(5)} = 13.140$, $p = .001$, $\eta^2 = .593$, $1\text{-}\beta = 1.000$) (Table 2). Ratings of breast pain remained unchanged in the high breast support (pain rating of 0); however, significantly less breast pain was reported at the fifth kilometre (pain rating of 3) compared to the first two minutes (pain rating of 5) in the low breast support (*p* = .016).

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The degree of peak torso roll (Table 3) and ROM in torso roll (Table 4) did not differ between support conditions and remained unchanged over the five kilometre run within both breast support conditions. Within the low breast support condition, the degree of peak torso flexion significantly increased from the first two minutes of running to the third and fourth kilometre intervals, an average increase of 2° (Table 3). The ROM in torso pitch was significantly greater in the low breast support compared to the high breast support from the first two minutes to the second kilometre interval (Table 4). Peak clockwise torso yaw was significantly less from the first kilometre to the fifth kilometre interval when participants ran in the high breast support when compared to the low breast support, with an average difference of 3° (Table 3). The ROM in torso yaw when participants ran in the high breast support was significantly greater during the fourth and fifth kilometre interval when compared to the low breast support (Table 4).

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When participants ran in the high breast support, peak pelvic obliquity (right) was significantly less than in the low breast support during the first to the fourth kilometre interval (Table 5). No differences were reported in the ROM in pelvic obliquity between or within the two breast support conditions (Table 6). When participants ran in the low breast support the peak anti-clockwise rotation of the pelvis was on average 4° greater than in the high breast support condition (Table 5). In addition, the ROM in pelvic rotation in the low breast support was 3° greater on average during the first, second, and fourth kilometre intervals than in the high breast support (Table 6).

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Peak upper arm abduction, extension, and rotation did not differ within or between the low and high breast support conditions during the five kilometre run (Table 7). Similarly, the ROM in upper arm abduction and internal rotation did not differ within or between the low and high breast support conditions during the five kilometre run (Table 8). The ROM in upper arm extension did however significantly differ during the first two minutes to the second kilometre interval between the low and high breast support conditions, on average a 7° greater ROM in the low breast support (Table 8).

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DISCUSSION

This is the first study to investigate the influence of breast support on torso, pelvis, and upper arm kinematics during a five kilometre treadmill run. It was hypothesised that the peak orientation and ROM of torso, pelvis, and upper arm would be significantly less in the low breast support condition, with participants making compensatory adjustments to restrict the ROM of the segments in order to reduce increased independent breast movement. Interestingly, the opposite effect was reported, with marginally greater peak clockwise torso yaw, peak pelvic obliquity (right), peak pelvic anti-clockwise rotation, and marginally greater ROM in torso pitch, torso yaw, rotation of the pelvis, and upper arm extension reported in the low breast support condition when compared to the high breast support condition, rejecting hypothesis one.

The amount of elevation provided by the high breast support was significantly greater than the low breast support, positioning the breast mass at a more proximal location on the torso. It has been argued that the distribution of mass on a segment from the segment axis of rotation can influence the moment of inertia and the energetic cost of movement (Taylor, Shkolnik, Dmi'el, Baharav, & Borut, 1974; Myers & Steudel, 1985). Similarly, load carriage literature has identified that an additional mass positioned at a proximal location or closer to the segment centre of mass were more cost effective than a mass located at a more distal location with few alterations to running biomechanics (Soule, Pandolf, & Goldman, 1977; Martin & Nelson 1986; Knapik, Harman, & Reynolds, 1996). Though this literature employed substantial greater loads to that of the breast, these concepts could be applied to the results of the current study and females with greater breast mass. It is postulated that the high breast support may reduce the moment of inertia of the torso segment, requiring less torque during running, as demonstrated in the reduction in torso yaw within this support condition. Based upon these results and previously explored concepts of energetic costs, it could be proposed that a sports bra should position the breast tissue at the proximal end of the torso, and restrict the magnitude of independent movement, ensuring the breast and torso are moving in synchrony.

When participants ran in the low breast support, marginally greater rotation was reported in peak torso yaw compared to the high breast support; interestingly this difference was unilateral (clockwise direction only). Due to joint anatomy of the humerus and shoulder, arm swing occurs as a result of the rotation of torso (yaw), with the magnitude and frequency defined as compensatory and synchronous to the action of the legs to counterbalance rotation about the vertical axis (Hinrichs, 1990; Pontzer, Holloway, Raichlen, & Lieberman, 2009). This relationship can be seen within the results of the current study when participants wore the low breast support, with greater clockwise torso yaw was associated with an increase in upper arm extension and increased contralateral pelvic rotation. It is currently unclear why asymmetry was reported in peak torso yaw; one suggestion is that this may be as a result of the asymmetry recently identified in the magnitude of breast range of motion between the dominant and non-dominant breast (Mills, Risius, & Scurr, 2015). Future research investigating the effect of breast support on running kinematics could examine both breasts to further examine this proposed relationship.

Hausswirth, Bigard, and Guezennec (1997), and Saunders et al., (2004) associated greater peak torso flexion with a less economical running style, reporting greater cost of energy with greater peak torso flexion during running. When participants ran in the high breast support, the ROM in torso pitch was significant but marginally less (2°) than when participants ran in the low breast support. Furthermore, peak torso flexion remained unchanged across the five kilometre run in the high breast support; however, a marginal increase (2°) was reported from the start to the end of the run in the low breast support. Adaptation to torso kinematics, in the low breast support, may shift the centre of mass lower and place undesirable strain on the postural muscles to stabilise the upper body during running (James & Brubaker, 1972), and could be considered as a disadvantage to the performer.

It is important to consider the magnitude of the differences reported in torso pitch and torso yaw, and the influence these may have on the female runner. Previous literature has identified a between trial standard deviation of up to 3° (Krebs, 1992; Nguyen & Baker, 2004), which exceeds the current mean differences reported. The within-participant variance in torso pitch and yaw were considered low (15% and 8%, respectively) for upper body kinematics. It is proposed that the mean difference of 1° reported in thorax pitch and 3° reported in thorax yaw, between the low and high support, would not be considered as a detriment to female runners, with the variance in these data exceeding the difference. However, the magnitude of differences reported in torso pitch across all participants ranged from 1° to 6° during the five kilometre run, demonstrating the importance of also considering the effect on a case by case basis.

Pelvic obliquity, alongside greater knee flexion and ankle dorsi flexion plays an important role in shock absorption during the running gait cycle (Novacheck, 1998; Lafortune, Hennig, &

Lake, 1996; Hardin, Van Den Bogert, & Hamill, 2004). Alterations in a runner's mechanical shock absorbers may assist in the attenuation of soft tissue vibrations of the upper body associated with ground contact, which may be an advantageous strategy to a female runner who experiences large magnitudes of breast movement and high ratings of breast pain. Interestingly, though significant increases were reported in the superioinferior breast ROM from the first two minutes to the fourth and fifth kilometre intervals in the low breast support, perceived ratings of breast pain significantly reduced over this time period. These findings suggest participants perceived breast pain to be worse during the initial stage of a five kilometre run, and this pain reduced over time. It is postulated that this may be a habituation to running in a low breast support over a five kilometre run within this cohort.

The degree of peak pelvic obliquity was marginally greater (up to 2°) in the low breast support compared to the high breast support. It is postulated that this may have been a compensatory strategy to increase the mechanical shock absorption throughout the five kilometre run in the low breast support, due to the lack of artificial shock absorption provided compared to that of the high breast support. It would be of interest to examine a participant's lower body kinematics and foot striking patterns to determine if additional kinematic alterations are employed to attenuate soft tissue vibrations associated with impact forces during running.

To afford efficient energy transfer between the upper and lower body, the counter-rotation between the pelvis and torso is imperative to running. Saunders et al., (2004) suggested reduced rotation of the pelvis would enable the preservation of energy during running. Furthermore, it is also important to consider the influence this counter-rotation of the torso and pelvis on breast movement during running. Based upon the deformable characteristics of the breast tissue and the location on the torso, the magnitude of rotation may influence the magnitude of breast movement. The ROM and peak rotation of the pelvis and peak torso yaw were marginally less in the high breast support condition, which suggests that running in a high breast support may enable greater preservation of energy and further reduction in breast displacement during a five kilometre run, both beneficial to the female runner.

Of the Cardan angles investigated between the breast support conditions, the greatest magnitude of difference was reported in upper arm extension. When substantial alterations were forced upon arm swing mechanics, such as arm strapping, differences in energy expenditure (Umberger, 2008) and alterations in ground reaction forces (Collins, Adamczyk, & Kuo, 2009) have previously been reported. The combined effect of these alterations to running performance may however have a detrimental effect to the female runner. Due to joint anatomy of the humerus and shoulder, arm swing occurs as a result of the rotation of torso (yaw), with the magnitude and frequency defined as compensatory and synchronous to the action of the legs to counterbalance rotation about the vertical axis (Hinrichs, 1990; Pontzer, Holloway, Raichlen, & Lieberman, 2009). This mechanical relationship between torso yaw and upper arm extension is demonstrated within the current study, with less torso yaw and upper arm extension in the high breast support condition compared to when participants ran in the low breast support. Controlled upper arm movement is required to reduce vertical excursions of the centre of mass (CoM) (Umberger, 2008) and actively support postural control of the body, increasing the efficiency of gait (Elftman, 1939; Hinrichs, 1990). With the participants running the same speed in both breast supports, it is proposed that the reduced upper arm extension combined with the reduction in torso yaw in the high breast support maybe more beneficial to female runner.

Though statistical differences were reported in thorax, pelvis, and arm kinematics between a low and high breast support, it is important to consider the magnitude of the differences for the female runner, with many of these differences considered as marginal. The quantification and exploration of the within-participant variance in these data helped to distinguish between a statistical difference and a meaningful difference, with the magnitude of difference required to outweigh the differences reported, ensuring appropriate conclusions are drawn (Knudson, 2009). Moreover, it is important to consider the generalisability of the study findings. To ensure any differences reported were a result of the breast support worn, strict participant inclusion criteria were set resulting in a homogenous sample. Participants were required to fit within two bra sizes, as large deviations in breast mass could have masked any trends in the results. Furthermore, significant differences (Moore, Jones, & Dixon, 2012; Slawinski, & Billat, 2004) and reduced fluctuations in variability (Nakayama, Kudo, & Ohtsuki, 2010) have been reported in running kinematics when training status and age (Nigg, Baltich, Maurer, & Federolf, 2012) have been explored, therefore, these were important factors to control.

Whilst the direct influence of breast support on resulting breast ROM is prevalent within the current study, and has been published frequently within the literature (White, Scurr, & Smith, 2009; Scurr et al., 2010; Risius, Milligan, Mills, & Scurr, 2014), the indirect influence of changes in breast support on running kinematics were not as apparent within the investigated cohort. This is the most comprehensive investigation of the effect of breast support on upper body running kinematics and provides the first insights into this area of investigation. Based upon the magnitude of differences and the effect size and power statistics reported in this preliminary study, it is proposed that future research include more than ten participants to confirm further effects of breast support on upper body running kinematics.

CONCLUSION

This preliminary study has explored the influence of low and high breast supports on torso, pelvis, and upper arm kinematics, and the interaction between these segments during a five kilometre treadmill run. Key findings indicate significant but marginal differences to running kinematics between a low and high breast support conditions, suggesting that the level of breast support did not cause a meaningful difference in the torso, pelvis and arm kinematics over a five kilometre run in this group of young women. With only marginal differences reported, it is suggested that future research increase the sample size investigated to extend upon this preliminary investigation into the influence of breast support on upper body running kinematics.

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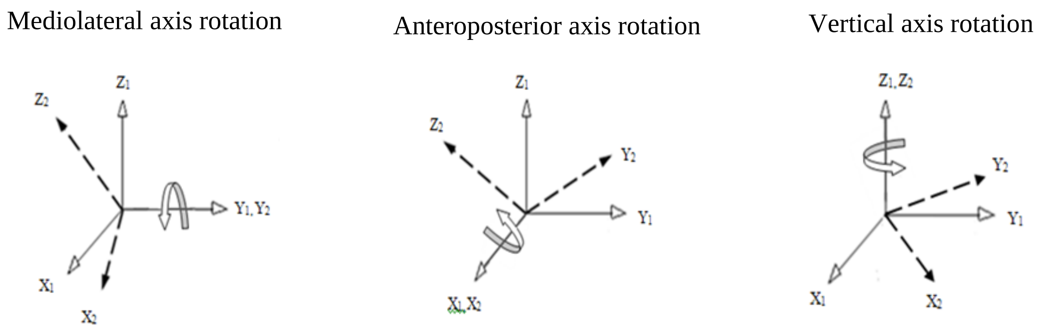
FIGURES



Mediolateral axis rotation

Anteroposterior axis rotation

Vertical axis rotation

Figure 1. Axes of rotation and the Cardan sequence employed

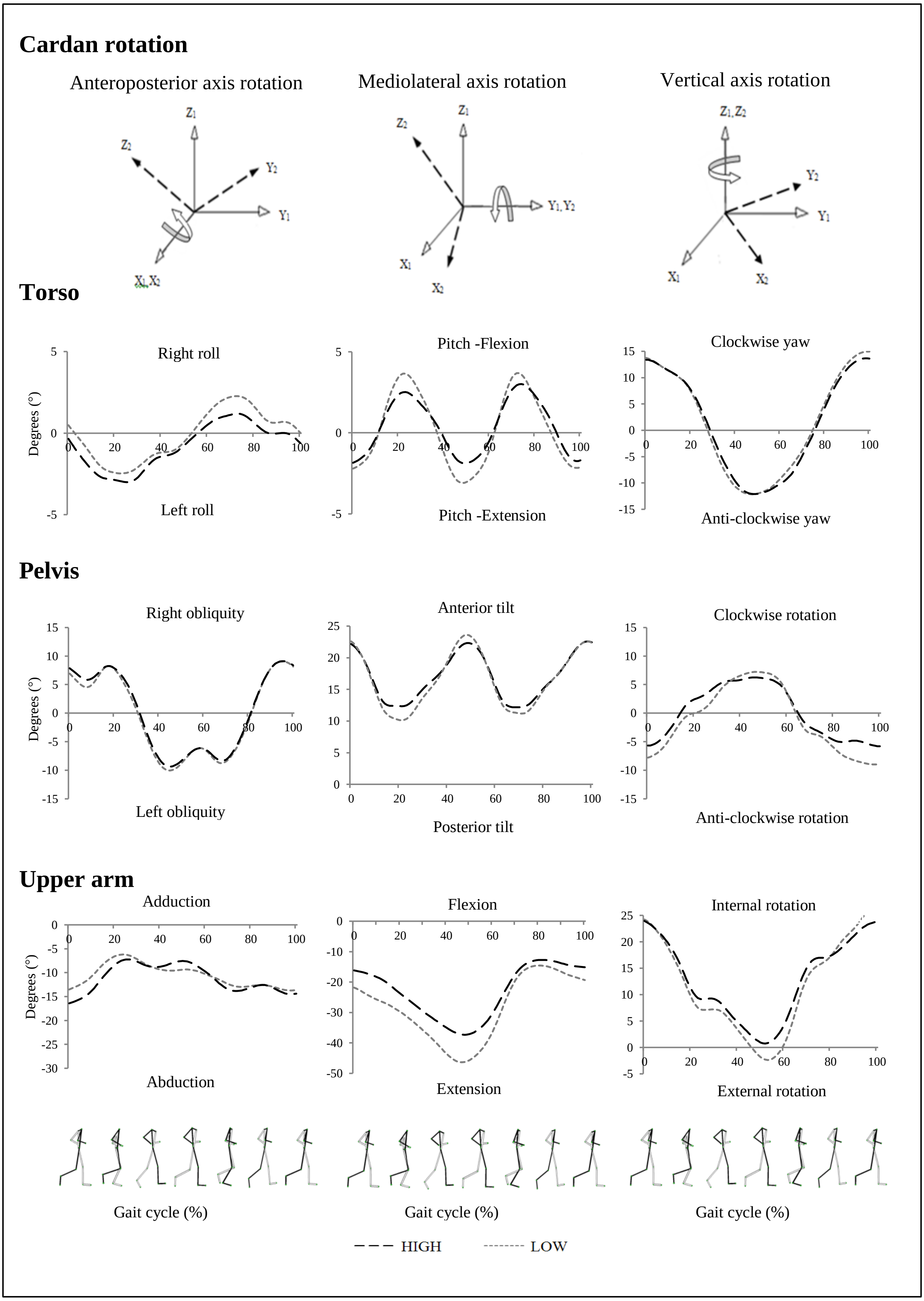


Figure 2. Mean orientation of the torso, pelvis, and upper arm segment, averaged over five gait cycles during the first two minutes of the five kilometre run in the low and high breast support conditions (n = 10).

TABLES

Table 1. Marker locations to define the torso, pelvis, and upper arm segments (Visual3D guidelines, C-motion), and employed terminology of axes rotation for each segment.

Segment	**Marker locations**	**Anteroposterior axis (x)**	**Mediolateral axis (y)**	**Vertical axis (z)**
Torso	**Segment end points:** Suprasternal notch, Right and left anterioinferior aspect of the 10th rib **Tracking markers:** T8, C7, XP	**ROM:** Torso roll **Peak directions:** right and left roll	**ROM:** Torso pitch **Peak directions:** flexion/ extension	**ROM:** Torso yaw **Peak directions:** clockwise/anti-clockwise
Pelvis	**Segment end points:** Left and right anterior superior iliac spines (ASIS), Left and right posterior superior iliac spines (PSIS).	**ROM:** Pelvic obliquity **Peak directions:** right and left obliquity	**ROM:** Pelvic tilt **Peak directions:** anterior/ posterior tilt	**ROM:** Pelvic rotation **Peak directions:** clockwise/anti-clockwise
Upper arm	**Segment end points:** Acromion process, Medial and lateral condyles of the humerus at the radial-humeral junction **Tracking markers:** outer shoulder (5 cm from acromion)	**ROM:** Upper arm abduction **Peak directions:** Abduction	**ROM:** Upper arm extension **Peak directions:** Extension	**ROM:** Upper arm rotation **Peak directions:** Internal/ external

N.B. Torso markers (Scurr et al. 2010, Milligan, Mills, & Scurr, 2014), Pelvis markers (Schache et al. 2001, Visual3D, C-motion Inc. marker set recommendations), Upper arm markers (Visual3D, C-motion Inc. marker set recommendations).

Table 2. Mean multiplanar relative breast ROM (cm) at each interval of the five kilometre treadmill run (n =10) and the delta change in ROM from the first two minutes to the fifth kilometre (Milligan, Mills, & Scurr, 2014; Milligan, Mills, Corbett, & Scurr, 2015).

Relative breast ROM (cm)	**LOW**						Δ change
	2 MINS	1KM	2KM	3KM	4KM	5 KM	
Anteroposterior	3.4*	3.6*	3.8*	3.8*	3.7*	3.7*	0.3 cm
Mediolateral	3.6*	3.9*	4.1*	4.0*	4.0*	3.9*	0.3 cm
Superioinferior	3.4*	3.8*	3.9*	4.0*	4.0*†	4.1*†	0.7 cm
Relative breast ROM (cm)	**HIGH**						Δ change
	2 MINS	1KM	2KM	3KM	4KM	5 KM	
Anteroposterior	2.4	2.7	2.8	2.8	2.7	2.8†	0.4 cm
Mediolateral	2.7	3.0	3.1	3.2	3.2†	3.1†	0.4 cm
Superioinferior	1.8	2.1	2.3	2.3	2.3†	2.3†	0.5 cm

*Denotes a significant difference between the low and high breast support conditions.

†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. Δ change is from the first two minutes of running to the fifth kilometre interval.

Table 3. Mean peak (°) torso roll, flexion, and yaw in the low and high breast support conditions, averaged over five gait cycles at each interval of the five kilometre run (n = 10).

Interval	Torso roll				Torso pitch				Torso yaw			
	Right roll		Left roll		Flexion		Extension		Clockwise		Anti-clockwise	
	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
2 min	3 ± 2	2 ± 2	-3 ± 2	-4 ± 2	4 ± 2	4 ± 3	-3 ± 3	-3 ± 3	16 ± 5	13 ± 4	-13 ± 3	-13 ± 3
1 km	3 ± 2	2 ± 2	-3 ± 2	-4 ± 2	5 ± 3	4 ± 2	-3 ± 2	-3 ± 2	16 ± 6*	13 ± 5*	-13 ± 3	-13 ± 4
2 km	3 ± 2	2 ± 2	-3 ± 2	-4 ± 2	6 ± 3	5 ± 3	-3 ± 3	-2 ± 3	17 ± 7*	13 ± 5*	-12 ± 4	-14 ± 4
3 km	3 ± 2	2 ± 2	-3 ± 2	-4 ± 2	6 ± 3†	5 ± 3	-2 ± 3	-3 ± 3	16 ± 6*	13 ± 5*	-12 ± 3	-13± 4
4 km	3 ± 2	2 ± 2	-3 ± 2	-3 ± 2	6 ± 3†	5 ± 3	-2 ± 3	-2 ± 3	16 ± 5*	12 ± 3*	-14 ± 4	-14 ± 5
5 km	3 ± 2	3 ± 2	-3 ± 1	-4 ± 2	6 ± 3	5 ± 3	-2 ± 3	-2 ± 3	15 ± 5*	14 ± 5*	-14 ± 3	-12 ± 4
MEAN	3 ± 0.3	2 ± 0.2	-3 ± 0.1	-4 ± 0.2	6 ± 0.5	5 ± 0.5	-3 ± 0.2	-3 ± 0.5	16 ± 0.6	13 ± 0.4	-13 ± 0.4	-13 ± 0.3

*Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. Breast support significantly influenced peak torso yaw during the five kilometre run ($F_{(1)} = 9.856$, $p = .012$, $\eta^2 = .523$, $1-\beta = .797$). Peak flexion of the torso significantly increased from the first two minutes to the third and fourth kilometre ($F_{(2.239)} = 7.157$, $p = .004$, $\eta^2 = .443$, $1-\beta = .912$) within the low breast support.

Table 4. Mean ROM (°) in torso roll, pitch, and yaw in the low and high breast support conditions, averaged over five gait cycles at each interval of the five kilometre run (n = 10).

Interval of run	Torso roll		Torso pitch		Torso yaw	
	LOW	HIGH	LOW	HIGH	LOW	HIGH
2 minutes	6 ± 2	5 ± 2	8 ± 2*	7 ± 2*	27 ± 3	27 ± 3
1 km	6 ± 2	6 ± 2	8 ± 2*	7 ± 2*	27 ± 5	26 ± 5
2 km	6 ± 2	6 ± 2	8 ± 2*	7 ± 2*	27 ± 5	27 ± 5
3 km	6 ± 2	6 ± 2	8 ± 2	8 ± 2	27 ± 5	27 ± 5
4 km	5 ± 1	6 ± 2	8 ± 2	7 ± 1	26 ± 4*	29 ± 6*
5 km	5 ± 1	5 ± 2	7 ± 2	7 ± 2	26 ± 5*	28 ± 5*
MEAN	6 ± 0.3	6 ± 0.2	8 ± 0.2	7 ± 0.3	27 ± 0.8	27 ± 1.0
CV%	16%	16%	15%	15%	8%	7%

*Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. Breast support significantly influenced the ROM in torso pitch during the five kilometre run ($F_{(1)} = 6.011$, $p = .037$, $\eta^2 = .400$, $1-\beta = .590$). The ROM of torso yaw during the five kilometre run ($F_{(1)} = 6.550$, $p = .031$, $\eta^2 = .421$, $1-\beta = .629$) was significantly affected by the level of breast support worn.

Table 5. Mean peak (°) pelvic obliquity, tilt, and rotation (°) in the low and high breast support conditions, averaged over five gait cycles at each interval of the five kilometre run (n = 10).

Interval	Pelvic Obliquity				Pelvic tilt				Pelvic rotation			
	Left		Right		Anterior		Posterior		Clockwise		Anti-clockwise	
	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
2 min	10 ± 3	10 ± 1	-11 ± 2	-10 ± 1	24 ± 6	25 ± 7	N/A	N/A	8 ± 5	8 ± 4	-10 ± 5*	-7 ± 4*
1 km	10 ± 3	10 ± 1	-11 ± 2*	-10 ± 1*	23 ± 6	25 ± 8	N/A	N/A	8 ± 4	8 ± 4	-10 ± 5*	-7 ± 4*
2 km	10 ± 3	10 ± 1	-11 ± 2*	-10 ± 1*	22 ± 6	24 ± 8	N/A	N/A	8 ± 4	8 ± 4	-12 ± 5*	-7 ± 4*
3 km	10 ± 3	10 ± 2	-11 ± 2*	-9 ± 2*	22 ± 7	24 ± 8	N/A	N/A	8 ± 4	8 ± 4	-10 ± 5*	-7 ± 3*
4 km	10 ± 3	10 ± 1	-11 ± 2*	-10 ± 1*	21 ± 7	21 ± 8	N/A	N/A	8 ± 5	8 ± 4	-11 ± 5*	-6 ± 3*
5 km	10 ± 4	10 ± 1	-11 ± 3	-9 ± 1	24 ± 9	23 ± 8	N/A	N/A	8 ± 4	8 ± 4	-10 ± 4	-8 ± 4
MEAN	10 ± 0.2	10 ± 0.1	-11 ± 0.3	-10 ± 0.3	22 ± 1	24 ± 1	N/A	N/A	8 ± 0.3	8 ± 0.6	-11 ± 0.7	-7 ± 0.5

*Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. Breast support significantly affected peak pelvic obliquity during the five kilometre run ($F_{(1.000)} = 10.247$, $p = .011$, $\eta^2 = .532$, $1-\beta = .812$). Peak pelvic rotation was significantly different between breast support conditions the five kilometre run ($F_{(1)} = 5.950$, $p = .037$, $\eta^2 = .398$, $1-\beta = .585$).

Table 6. Mean ROM (°) in pelvic obliquity, tilt, and rotation (°) in the low and high breast support conditions, averaged over five gait cycles at each interval of the five kilometre run (n = 10).

Interval of run	Pelvic obliquity		Pelvic tilt		Rotation	
	LOW	HIGH	LOW	HIGH	LOW	HIGH
2 minutes	19 ± 3	20 ± 3	13 ± 3	12 ± 3	19 ± 5	15 ± 3
1 km	21 ± 3	19 ± 3	14 ± 2	13 ± 3	18 ± 4*	15 ± 3*
2 km	21 ± 3	20 ± 3	14 ± 3	12 ± 2	20 ± 4*	16 ± 2*
3 km	21 ± 3	19 ± 3	14 ± 3	13 ± 2	18 ± 4	16 ± 3
4 km	19 ± 3	19 ± 4	14 ± 3	12 ± 2	18 ± 4*	16 ± 2*
5 km	19 ± 3	19 ± 3	13 ± 3	13 ± 2	17 ± 3	16 ± 3
MEAN	20 ± 0.8	19 ± 0.5	14 ± 0.4	13 ± 0.3	18 ± 0.7	16 ± 0.3
CV%	7%	7%	10%	11%	11%	12%

*Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. ROM in pelvis rotation was significantly affected by breast support condition during the five kilometre run ($F_{(1)}$ = 7.066, p = .026, η^2 = .440, 1-β = .659).

Table 7. Mean peak (°) upper arm abduction, extension, and rotation in the low and high breast support conditions, averaged over five gait cycles at each interval of the five kilometre run (n = 10).

Interval	Upper arm abduction				Upper arm extension				Upper arm rotation			
	Adduction		Abduction		Flexion		Extension		Internal		External	
	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
2 min	N/A	N/A	-17 ± 3	-17 ± 3	N/A	N/A	-43 ± 6	-41 ± 8	25 ± 9	26 ± 5	-4 ± 3	N/A
1 km	N/A	N/A	-18 ± 4	-18 ± 3	N/A	N/A	-45 ± 5	-42 ± 8	29 ± 10	26 ± 8	-6 ± 4	N/A
2 km	N/A	N/A	-18 ± 3	-18 ± 3	N/A	N/A	-44 ± 6	-41 ± 6	30 ± 13	32 ± 12	-6 ± 4	N/A
3 km	N/A	N/A	-18 ± 3	-19 ± 3	N/A	N/A	-42 ± 5	-42 ± 7	29 ± 14	29 ± 12	-5 ± 4	N/A
4 km	N/A	N/A	-18 ± 3	-18 ± 4	N/A	N/A	-42 ± 6	-42 ± 7	31 ± 16	34 ± 11	-2 ± 3	N/A
5 km	N/A	N/A	-18 ± 3	-18 ± 4	N/A	N/A	-40 ± 6	-42 ± 5	29 ± 12	27 ± 11	-2 ± 4	N/A
MEAN	N/A	N/A	-18 ± 1	-18 ± 1	N/A	N/A	-43 ± 2	-42 ± 1	29 ± 2	30 ± 3	4 ± 0.3	N/A

*Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

Table 8. Mean ROM (°) in upper arm abduction, extension, and rotation in the low and high breast support conditions, averaged over five gait cycles at each interval of the five kilometre run (n = 10).

Interval of run	Upper arm abduction		Upper arm extension		Upper arm rotation	
	LOW	HIGH	LOW	HIGH	LOW	HIGH
2 minutes	10 ± 3	11 ± 3	33 ± 6*	26 ± 4*	31 ± 10	26 ± 5
1 km	11 ± 4	11 ± 2	35 ± 7*	28 ± 5*	34 ± 9	28 ± 7
2 km	12 ± 4	10 ± 3	37 ± 8*	29 ± 8*	35 ± 8	31 ± 11
3 km	12 ± 4	11 ± 3	34 ± 11	31 ± 8	34 ± 10	30 ± 10
4 km	11 ± 3	11 ± 1	33 ± 9	35 ± 10	31 ± 11	31 ± 9
5 km	11 ± 3	11 ± 3	31 ± 7	30 ± 9	28 ± 8	30 ± 9
MEAN	11 ± 1	11 ± 0.4	34 ± 2	30 ± 3	32 ± 3	30 ± 2
CV%	13%	11%	10%	11%	16%	16%

*Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. The ROM in upper-arm extension during the five kilometre run distance ($F_{(1)} = 16.578$, $p = .003$, $\eta^2 = .648$, $1\text{-}\beta = .950$) was significantly affected by breast support conditions.