Title: Understanding key performance indicators for breast support: An analysis of breast support effects on biomechanical, physiological and subjective measures during running.

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**Abstract**

To assess the effectiveness of breast support previous studies monitored breast kinematics and kinetics, subjective feedback, muscle activity (EMG), ground reaction forces (GRFs), and physiological measures in isolation. Comparing these variables within one study will establish the key performance variables that distinguish between breast supports during activities such as running. This study investigates the effects of changes in breast support on biomechanical, physiological and subjective measures during running. Ten females (34D) ran for ten minutes in high and low breast supports, and for two minutes bare breasted (2.8 $m \cdot s^{-1}$). Breast and body kinematics, EMG, expired air, and heart rate were recorded. GRFs were recorded during 10m overground runs (2.8 $m \cdot s^{-1}$) and subjective feedback obtained after each condition. Of the 62 variables measured, 22 kinematic and subjective variables were influenced by changes in breast support. Willingness to exercise, time lag, and superioinferior breast velocity were most affected. GRFs, EMG and physiological variables were unaffected by breast support changes during running. Breast displacement reduction, although previously advocated, was not the most sensitive variable to breast support changes during running. Instead breast support products should be assessed using a battery of performance indicators, including the key kinematic and subjective variables identified here.

**Introduction**

Due to the weak intrinsic support in the breast, physical activity such as running causes independent breast movement. This breast movement can result in a number of negative consequences including breast pain (Gehlsen & Albohm, 1980), embarrassment (Burnett, White & Scurr, 2014), changes in ground reaction forces (White, Scurr & Smith, 2009), changes in breathing mechanics (White, Lunt & Scurr, 2011), and altered running technique (White, Mills & Scurr, 2012). Due to these negative consequences, previous research has recommended the use of external breast support. External breast support, such as sports bras, has been reported to reduce breast pain (Brown, White, Brasher & Scurr, 2013), reduce embarrassment (McGhee & Steele, 2010), and alter performance variables (Shivitz, 2002; White, Mills & Scurr, 2012) during running. Despite these recommendations, recent research has shown that only 32% of UK adult females always wore a sports bra during physical activity (Brown, Burnett & Scurr, 2015).

With the majority of UK women not engaging in sports bra use during physical activity, understanding factors that are influenced by changes in breast support will not only determine the impact of such choices, but will also establish the key performance variables affected by such garments. Whilst individual studies may have considered a variety of variables influenced by changes in breast support, these have generally been investigated in isolation. We have yet to understand the key performance variables that distinguish between levels of breast support during activities such as running and as yet, there is no industry standard to determine the performance of breast support garments Such an investigation would need to use breast support conditions that are known to differ. Previous literature has reported substantial differences in breast biomechanics and breast comfort during running in no bra, everyday bras and sports bras (Mills, Loveridge, Milligan, Risius & Scurr, 2014).

To determine the key performance variables that distinguish between changes in breast support, we then need to consider all potential variables that may be influenced within a single cohort. There are a number of potential dependent variables that may be influenced by changes in breast support that have been investigated previously. Typically, sports bra performance has been investigated through reductions in breast pain, breast displacement, velocity and acceleration (Mason, Page & Fallon, 1999; McGhee, Steele & Zealey, 2010; Scurr, White & Hedger, 2009; Scurr, White & Hedger 2010; Scurr, White & Hedger, 2011). Breast position within a bra (breast compression and elevation) has also been linked to breast discomfort during exercise (McGhee & Steele, 2010). Limiting force through the breast, calculated using estimated breast mass and acceleration data, has also been reported as an important aspect of sports bra design (McGhee, Steele, Zealey & Takacs, 2013).

Similarly, greater breast momentum has been previously related to increased breast pain (Gehlsen & Albohm, 1980). Bra-breast stiffness reflects the interaction between breast acceleration and displacement, and was shown to be influenced by the level of breast support (Shivitz, 2002). Finally, Scurr, White and Hedger (2009) reported a time lag in peak vertical trunk and nipple displacement, which reduced as breast support increased, suggesting that this may also be an important variable to investigate.

When investigating key breast support performance variables, additional to these breast kinematic measures, other variables may be affected by changes in breast support. Adaptations in running mechanics have been reported; changes in stride frequency and length (Eden, Valiant & Himmelsbach, 1992; Shivitz, 2002), running speed (Mason, Page & Fallon, 1999) and vertical trunk movement (Boschma, Smith & Lawson, 1996). Additionally, Shivitz (2002) and White, Scurr and Smith (2009) found changes in ground reaction forces (GRFs) with increasing breast support. With many variables influencing running performance, it is yet to be established whether these gait parameters are a key performance variable, influenced by changes in breast support.

If changes in breast support cause changes in running mechanics, muscle activity may also be affected. Scurr, Bridgman and Hedger (2010) and Milligan, Mills and Scurr (2014) investigated the influence of breast support on upper body muscle activity in using electromyography (EMG) during running.  Both studies found reduced pectoralis major activity as breast support increased, suggesting that EMG analysis may also be an important variable in breast support assessment.

The effect of breast support on physiological function during activities such as running has received little attention, despite the potential for appropriate breast support to increase running economy due to reduced upper body muscle activity and changes in mechanics. White, Lunt and Scurr (2011) found reduced breathing frequency in bare breasted running compared to running in bras, concluding that changes in breast support may affect cardiovascular and physiological function. Additionally, Bowles, Steele and Chaunchaiyakul (2005) investigated whether bra style influenced breathing function, but found no effect during running. The rate of oxygen consumption has frequently been used as a measure of running economy and it is acknowledged that changes which allow runners to use less oxygen are advantageous (Williams & Cavanagh, 1987) and warrant further investigation related to changes in breast support.

Finally, as well as the variables detailed above, literature suggests that appropriate breast support should increase willingness to exercise (Haake, Milligan & Scurr, 2012; McGhee & Steele, 2010; McGhee, Steele & Munro, 2010; Scurr, White & Hedger, 2011; Scurr, White, Milligan, Risius & Hedger, 2011; Shivitz, 2002; Verscheure, Arate & Hreljac, 2000; White, Scurr & Smith, 2009) and reduce embarrassment (McGhee & Steele, 2010; Scurr, White & Hedger, 2011; White, Lunt & Scurr, 2011; White, Scurr & Smith, 2009). These subjective variables should be incorporated into breast support assessment alongside numeric analogue scales which have been routinely used to assess breast comfort, perceived breast support and bra fit (Mason, Page & Fallon, 1999; McGhee & Steele, 2010).

These previous investigations on the influence of breast support during running fall into five areas; breast biomechanics, gait parameters and running mechanics, muscle activity, physiological measures and subjective measures. However, no studies have considered a holistic investigation of all these variables on the same cohort, such a study would determine the key performance variables that distinguish between breast support conditions during running. Therefore, this study aims to investigate the effect of changes in breast support on biomechanical, physiological and subjective variables during running. Based on previous research it is hypothesised that changes in breast support will result in significant changes in breast biomechanics, gait parameters and running mechanics, muscle activity, physiological measures and subjective measures.

## Methods

Following institutional ethical approval (SFEC App 2013-024), ten female volunteers with a mean (standard deviation) body mass of 65 kg (6 kg), height of 1.66 m (0.04 m) and age 27 years (6 years) were selected to participate in this study. Participants had not experienced any breast surgical procedures, were not undergoing any breast treatments, had not gone through pregnancy and were regular treadmill runners who exercised for >30 minutes, >twice a week.  All participants wore bras daily and during sporting activity.

Participants attended a preliminary laboratory session.  Following a full explanation of procedures participants provided written informed consent and were professionally bra fitted using best-fit criteria (White & Scurr, 2012). Females who were not a UK 34D breast size were excluded; this breast size was investigated as it has been reported that it is particularly important for larger-breasted women (D cup and above).

Each participant then attended a laboratory testing session, which began with a warm up. Participants performed activities in three random order breast support conditions; bare breasted, an everyday bra (low support: Marks & Spencer T-shirt bra, 92% cotton, 8% elastane lycra) and a sports bra (high support: Shock Absorber Run Bra, 81% polyamide, 10% polyester, 9% elastane).  These breast support conditions were chosen as they have been reported to be functionally different (Mills, Loveridge, Milligan, Risius & Scurr, 2014). Adequate rest periods (>10 minutes) were implemented between each condition to return participant's heart rate and breathing to resting levels.

The activities undertaken were 10 minutes of treadmill running at 2.8 $m\cdot s^{-1}$ in the two bra conditions (for the collection of physiological measures), this was reduced to 2 minutes of treadmill running at 2.8 $m\cdot s^{-1}$ in the bare breasted condition to minimise breast pain (Scurr, White & Hedger, 2010; Zhou, Yu & Ng, 2012), and five 10 m over ground runs also at 2.8

$m \cdot s^{-1}$. In an attempt to mitigate for changes in natural running gait due to the testing conditions, before each trial participants were given adequate time to familiarise themselves with the breast support condition, the exercise mode and the equipment. To determine breast biomechanics, gait parameters and running mechanics, during the treadmill running conditions, retroreflective markers (5 mm diameter) were attached to the following anatomical landmarks on both side of the body; acromiales, acromioclavicular joints, medial and lateral humeral epicondyles, radius and ulnar styloid processes, anterior superior iliac spines, posterior superior iliac spines, medial and lateral femoral epicondyles, calcaneous, medial and lateral malleolus, second and fifth metatarsals (Visual 3D, www.c-motion.com). Additional markers were positioned on the trunk and right nipple (directly or on the bra) using the Scurr, White and Hedger (2010) marker set to determine relative breast kinematics. Three-dimensional marker coordinates were tracked for up to four gait cycles at the end of each running trial (to enable comparison across all breast support conditions) using a calibrated motion capture system (Qualisys, Oqus, Sweden), sampling at 200 Hz.

During treadmill running surface EMG was recorded at 1000 Hz from upper body muscles associated with running mechanics (right pectoralis major, anterior and posterior deltoid, rectus abdominis, trapezius, latissimus dorsi, erector spinae, and external oblique; Datalink Biometrics, UK). Following skin preparation (shaving and cleansing) SENIAM recommendations were utilised and electrodes (Biometrics SX230 active (Ag/AgCl) bipolar pre-amplified disk electrodes) attached parallel to the muscle fibres and on the muscle bellies (De Luca, 1997). After two minutes of running, the start of the EMG and motion capture systems were synchronised using a wireless trigger and receiver (Neewer RT-16, China). From three to ten minutes of running physiological variables were measured. Heart rate was recorded every minute using a chest strap heart rate monitor (Polar T31, UK) positioned just below the participant's bra band. Expired air was measured using an online gas analysis system (Cosmed, Quark B2, Italy), which required participants to be fitted with a breathing mask (Hans Rudolph, V mask) covering the nose and mouth.

During over ground running GRFs were collected at 1000 Hz using a Kistler Force Plate (9281CA; Switzerland, 0.6 x 0.4 m) embedded in the laboratory floor. Participants performed five successful, non-targeted, 10 m runs over the force platform. Timing gates (Sprint Timer CM LSMEM, Brower) matched over ground and treadmill running speeds (2.8 $m \cdot s^{-1}$ ±5%).

Immediately following each condition, participants completed a numeric analogue scale (Mason, Page & Fallon, 1999) assessing breast pain, bra fit, perceived breast support, and embarrassment. Willingness to exercise was assessed on a validated exercise scale (Ajzen, 2014; Rhodes & Matheson, 2005), and rating of perceived exertion using the Borg scale (Borg, 1982) was included as a new comparative measure between breast support conditions.

During treadmill and over ground running, up to four gait cycles in each breast support condition were analysed. Gait cycles were determined using the left heel marker (Zeni, Richards & Higginson, 2008). All markers were identified in Qualisys Track Manager (QTM, Sweden Version 2.9). The trunk and nipple markers were filtered with a second order low pass Butterworth filter (13 Hz cut-off; Mills, Loveridge, Milligan, Risius & Scurr, 2014) and used to calculate relative right nipple coordinates (Scurr, White & Hedger, 2010). Using the relative nipple coordinates from each gait cycle, 14 breast kinematic variables were calculated as detailed in Table 1. Breast force and breast momentum were excluded from this analysis because theoretically the mass of the breast within a cohort of similar breast size should be constant. Full body marker coordinates were exported to Visual 3D to calculate the 19 gait parameters and running mechanics defined in Table 1. Joint angles were calculated using Cardan angles. Ground reaction force variables (x 10) were normalised to participant's body weight (bw) (Bioware, Version 5.1.3.0, USA) (Table 1). The eight EMG variables detailed in Table 1 were processed and analysed in DataLink

Management and Analysis software (Version 8.6). Oxygen consumption was measured breath by breath, running economy and minute ventilation were averaged every minute from the third to the tenth minute of running. All objective results are presented as means (standard deviations) across gait cycles in each breast support condition. Subjective variables were recorded at the end of each breast support condition (after all activities had been undertaken).

Data were statistically analysed using PASW (Version 18). All objective data were normally distributed (Kolmogorov-Smirnov and Shapiro-Wilk, P>0.05), with the exception of vertical trunk oscillation. Statistical analysis using repeated measures ANOVAs, followed by multiple Paired Samples T-Tests were conducted to determine significant differences across breast support conditions and then between conditions. Vertical trunk oscillation and the subjective data were compared across breast support conditions using Friedman Tests, followed by multiple Wilcoxon Tests. Where multiple paired tests were performed Bonferroni correction factors were used to determine significant differences where $P \leq 0.02$. Effect sizes were calculated (parametric: $\eta^2$, non-parametric: $r$) to rank the variables which were affected by breast support (strong effect size >0.5, moderate 0.5 to 0.3, and a weak effect <0.3 (Field, 2009, p. 389)). All statistical comparisons demonstrated strong power >0.9 (Cohen, 1988) in all variables except peak pelvis rotation where power was 0.68.

## Results

Sixty two variables were investigated across the five categories (Table 1). Across all variables, 22 were significantly affected by changes in breast support. Willingness to exercise was the most affected by changes in breast support, followed by high time lag, superioinferior velocity and superioinferior acceleration (Table 2). Fourteen variables were sensitive to changes in the bra (from low to high breast support). Within the breast kinematic analysis, bare breasted running demonstrated significantly greater nipple kinematics in all directions compared to the bra conditions (Figure 1a-c). Interestingly, the breast support condition had a significant effect on time lag during the flight phase of the gait cycle (high time lag) (Figure 2a), but not during the contact phase (low time lag). High time lag was reduced by 56% in the low support and 70% in the high support compared to bare breasted running. Unsurprisingly, both bra conditions had a significant effect on breast elevation and compression when compared to bare breasted running (Figure 2b and c). As breast support increased vertical trunk oscillation increased by up to 2 cm from bare breasted running to running in high breast support (Figure 2d). Running mechanics identified significantly less pelvis (Figure 3a and 3b) and trunk rotation (Figure 3c and 3d) during bare breasted running, compared to either bra.

The GRFs, EMG and physiological variables investigated were not significantly influenced by changes in breast support during running. Participants rated the high breast support condition as providing significantly greater breast comfort, bra comfort, and breast support, compared to the low support condition, and (where applicable) the bare breasted condition (Figure 4a,b,d). The high breast support condition was also rated as less embarrassing than both the other conditions (Figure 4c), and participants were more willing to exercise in the high breast support condition compared to the other conditions (Figure 4e). However, no differences were identified in rating of perceived exertion between the breast support conditions.

**Discussion**

The current study is the first to investigate the effect of changes in breast support on a comprehensive range of biomechanical, physiological and subjective variables within a single cohort during running. The aim was to identify the key performance variables that distinguish between changes in breast support. Of the 62 variables analysed, 22 were influenced by changes in breast support, and despite a small sample size, all 22 demonstrated a strong effect (>0.5) and power (>0.68). Fourteen variables demonstrated sensitivity to changes in the bra from low support (an everyday bra) to high support (a sports bra). It is acknowledged that there may be other variables that have not been included in this study (e.g. thermal properties, body composition) as they have received little attention in the literature or have as yet not been investigated. However, this is the most comprehensive study undertaken in the area to date.

The majority of previous research in this area has used reductions in breast displacement, velocity, acceleration and pain to assess the performance of bras and this study supports this, demonstrating reductions in breast displacement, velocity, acceleration and pain with increases in breast support. However, it is interesting to note is that changes in breast support also had a strong (sometimes stronger) effect on other variables. In this cohort of 34D participants, the variables most sensitive to changes in breast support were firstly, willingness to exercise, followed by high time lag, superioinferior breast velocity and superioinferior breast acceleration. These results highlight the importance of a comprehensive approach to performance assessment of breast support.

The results of this study showed that willingness to exercise was effected to the greatest extent by changes in breast support during running. This subjective variable incorporates participant’s preferences, for example, a woman may find a sports bra comfortable and supportive, but may find it too revealing. This result concurs with Risius, Thelwell, Wagstaff and Scurr (2012) who concluded that whilst the majority of previous empirical research on bras has focused on support, it appears the important functions of a bra are more diverse, incorporating subjective measures as well as objective. The importance of incorporating subjective measures is further evidence by the significantly higher ratings of breast comfort, bra comfort and breast support observed in the high breast support condition, compared to the low breast support condition, with all variables demonstrating strong effect sizes. As these subjective data are quickly and easily obtained, and demonstrate significant differences between breast support conditions, their inclusion within a battery of assessment measures when assessing the performance of breast support is recommended.

The time lag between the trunk (sternal notch) and the breast reaching inflection points in the gait cycle has only been investigated in one previous study (Scurr, White & Hedger, 2009) where time lag reduced as breast support increased. Despite the limited research in this area, the results of the current study show that of the 62 variables investigated, high time lag was the second most sensitive variable to changes in breast support during running, suggesting that time lag is an important breast support performance variable. Scurr, White and Hedger (2009) speculated that time lag was related to the inertia property of the breast, this suggests that appropriate breast support needs to reduce breast inertia during running. Reductions in time lag suggest greater synchrony between the temporal displacement of the trunk and breast. Interestingly, changes in breast support had a significant effect on time lag during the flight phase of the gait cycle (high time lag), but not during the contact phase (low time lag). This may be due to differences in the elastic properties of the breast tissues that restrict inferior breast movement (stiffer due to gravitational effects over time), compared to the tissues that restrict superior movement (which may be more elastic).

The next variable most affected by changes in breast support was superioinferior breast velocity. Superioinferior breast velocity has been highlighted as an important variable in previous breast biomechanics research. Scurr, White and Hedger (2010) identified that reductions in superioinferior (referred to as vertical) velocity were most closely correlated to improvements in breast comfort during running at a similar speed to the current study, when compared to other breast kinematic variables (displacement, velocity and acceleration in three directions). Scurr, White and Hedger (2010) concluding that breast support should primarily be defined in terms of superioinferior breast velocity reductions.

A number of other breast kinematic  and running mechanics variables demonstrated significant effects across conditions. Breast acceleration (mediolateral and anterioposterior), breast compression, pelvis, and trunk kinematics demonstrated a significant effect across all conditions, but not between bra conditions. Despite previous literature reporting differences in vertical and medial GRFs following changes in breast support (Shivitz, 2002; White, Scurr & Smith, 2009), the kinetic data from this study showed no differences.  Muscle activity also showed no differences between breast support conditions, despite previous literature indicating a decrease in pectoralis major activity with increasing breast support (Scurr, Bridgman & Hedger, 2010).  This suggests that muscle activity assessment in these muscles do not contribute to  determining differences between breast support conditions. Finally, physiological variables were not influenced by changes in breast support during 10 minutes of running. This supports Bowles, Steele and Chaunchaiyakul (2005), but contradicts White, Lunt and Scurr (2011) who concluded that changes in breast support influenced cardiovascular and physiological function during running.  Although, it is acknowledged that in both of these previous studies participants exercised for less than five minutes, while previous research suggests that physiological variables may take six minutes to stabilise (Hardin, Van Den Bogert & Hamill, 2004). These results suggest that GRFs, muscle activity and physiological measures are not key performance variables in distinguishing changes in breast support for this cohort.

## Conclusions

In conclusion, this is the most comprehensive study undertaken to determine the key performance variables affected by changes in breast support during running.  Of the 62 variables investigated 22 kinematic and subjective variables were sensitive to changes in breast support and 14 to changes in bras during running.  The variables that were most sensitive to the level of breast support were willingness to exercise, high time lag and superioinferior breast velocity and acceleration.  Future research should consider a more comprehensive approach to the assessment of appropriate breast support during running incorporating the key kinematic and subjective variables identified in this study, rather than relying solely on the commonly reported breast displacement reduction.


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Table 1. The influence of breast support on each variable during running at 2.8 m·s$^{-1}$ (n=10). Statistical comparison across all breast support conditions ($P$<0.05).

| Variable | Units | Description | *P* value |
|---|---|---|---|
| BREAST KINEMATICS | | | |
| **Anterioposterior displacement** | m | Max - min relative nipple displacement (Scurr, White & Hedger, 2011) | 0.000 |
| **Mediolateral displacement** | m | Max - min relative nipple displacement (Scurr, White & Hedger, 2011) | 0.000 |
| **Superioinferior displacement** | m | Max - min relative nipple displacement (Scurr, White & Hedger, 2011) | 0.000 |
| **Anterioposterior velocity** | m·s$^{-1}$ | Derived, instantaneous peak | 0.000 |
| **Mediolateral velocity** | m·s$^{-1}$ | Derived, instantaneous peak | 0.000 |
| **Superioinferior velocity** | m·s$^{-1}$ | Derived, instantaneous peak | 0.000 |
| **Anterioposterior accel** | m·s$^{-2}$ | Derived, instantaneous peak | 0.003 |
| **Mediolateral accel** | m·s$^{-2}$ | Derived, instantaneous peak | 0.000 |
| **Superioinferior accel** | m·s$^{-2}$ | Derived, instantaneous peak | 0.000 |
| **High breast-body time lag** | % | Time between sternal notch and nipple reaching max superioinferior displacement as a % of gait cycle (Scurr, White & Hedger, 2010) | 0.000 |
| Low breast-body time lag | % | Time between sternal notch and nipple reaching max superioinferior displacement as a % of gait cycle (Scurr, White & Hedger, 2010) | NS |
| **Breast elevation** | m | Peak inferior sternal notch to nipple distance (McGhee & Steele, 2010) | 0.000 |
| **Breast compression** | m | Peak anterior sternal notch to nipple distance (McGhee & Steele, 2014) | 0.000 |
| Bra-breast stiffness | m·s$^{-2}$/cm | Peak superioinferior nipple acceleration / peak superioinferior nipple displacement (McGhee, Steele, Zealey & Takacs, 2013) | NS |
| GAIT PARAMETERS AND RUNNING MECHANICS | | | |
| Stride length | m | Right toe off to Right heel strike | NS |
| Stride frequency | Hz | Gait cycles per second | NS |
| **Trunk oscillation** | m | Peak vertical displacement of sternal notch | 0.032 |
| Peak ankle flexion | ° |  Internal segment angle | NS |
| Ankle range of motion | ° | | NS |
| Peak knee flexion | ° |  Internal segment angle | NS |
| Knee range of motion | ° | | NS |
| Peak hip flexion | ° |  Internal segment angle | NS |
| Hip range of motion | ° | | NS |

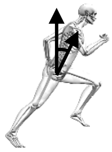
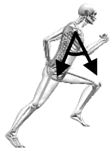
| | | | |
|---|---|---|---|
| **Peak pelvis rotation** | ° | Axial rotation of pelvis segment relative to trunk segment | 0.026 |
| **Pelvis range of motion** | ° | Axial rotation of pelvis segment relative to trunk segment | 0.002 |
| Peak trunk flexion | ° |  Trunk segment rotation about global nmediolateral axis | NS |
| Trunk flexion range of motion | ° | | NS |
| **Peak trunk rotation** | ° | Trunk segment axial rotation about the global vertical axis | 0.003 |
| **Trunk rotation range** | ° | Trunk segment axial rotation about the global vertical axis | 0.002 |
| Peak shoulder flexion | ° |  Internal segment angle | NS |
| Shoulder range of motion | ° | | NS |
| Peak elbow flexion | ° |  Internal segment angle | NS |
| Elbow range of motion | ° | | NS |
| GRF VARIABLES | | | |
| Loading rate | bw·s$^{-1}$ | Average peak vertical impact force/time to peak | NS |
| Mediolateral impulse | bw·s$^{-1}$ | Mediolateral force (bw) * time | NS |
| Anterioposterior impulse | bw·s$^{-1}$ | Anterioposterior force (bw) * time | NS |
| Vertical impulse | bw·s$^{-1}$ | Vertical force (bw) * time | NS |
| Active peak | bw | Second vertical force peak | NS |
| Impact peak | bw | First vertical force peak | NS |
| Peak medial force | bw | Peak medial force | NS |
| Peak lateral force | bw | Peak lateral force | NS |
| Peak propulsive force | bw | Peak posterior force | NS |
| Peak breaking force | bw | Peak anterior force | NS |
| MUSCLE ACTIVITY | | | |
| Pectoralis major | % | Full wave rectified and integrated to calculated total muscle activity during each running gait cycle, this was then normalised to the greatest activity in no bra running. | NS |
| Anterior deltoid | % | | NS |
| Posterior deltoid | % | | NS |
| Rectus abdominus | % | | NS |
| Upper trapezius | % | | NS |
| Latissimus dorsi | % | | NS |
| Erector spinae | % | | NS |
| External oblique | % | | NS |
| PHYSIOLOGICAL VARIABLES | | | |
| Breathing frequency | Breathes·min$^{-1}$ | Number of breaths per minute | NS |
| Minute ventilation | l·min$^{-1}$ | Total quantity of air breathed in/out in 1 minute | NS |
| Oxygen consumption | ml·min·kg$^{-1}$ | Collected breath by breath | NS |
| Running economy | ml·kg·km$^{-1}$ | $O_2$ consumption relative to body mass per km | NS |
| Heart rate | beats·min$^{-1}$ | Number of beats per minute | NS |
| SUBJECTIVE VARIABLES | | | |
| **Breast comfort** | | 0=comfortable, 10=painful. | 0.000 |
| **Bra comfort** | | 0=comfortable, 10=very uncomfortable. | 0.015 |
| **Embarrassment** | | 0=No Embarrassment, 10=High embarrassment | 0.000 |
| **Breast support** | | 0=Very supportive, 10=Very unsupportive | 0.003 |
| **Willingness to exercise** | | 0=Very unwilling, 7=Very willing | 0.000 |
| Rating of Perceived Exertion | | 6=No exertion, 20=Maximal exertion | NS |

Table 2: Variables that were significantly different (*P* values) across breast support conditions during running at 2.8 $m \cdot s^{-1}$ (n=10).

| Rank | Significant Variables | Across all breast support conditions | Between bra conditions |
|---|---|---|---|
| | | Effect size | *P* |
| 1 | Willingness to exercise | 0.982 | 0.003 |
| 2 | High breast-body time lag | 0.921 | 0.001 |
| 3 | Superioinferior velocity | 0.900 | 0.002 |
| 4 | Superioinferior acceleration | 0.880 | 0.001 |
| 5 | Embarrassment | 0.876 | 0.008 |
| 6 | Mediolateral velocity | 0.859 | 0.012 |
| 7 | Superioinferior displacement | 0.851 | 0.001 |
| 8 | Breast comfort | 0.850 | 0.007 |
| 9 | Mediolateral acceleration | 0.848 | NS |
| 10 | Breast compression | 0.842 | NS |
| 11 | Breast elevation | 0.808 | 0.001 |
| 12 | Perceived breast support | 0.806 | 0.003 |
| 13 | Anterioposterior displacement | 0.779 | 0.015 |
| 14 | Mediolateral displacement | 0.766 | 0.014 |
| 15 | Anterioposterior velocity | 0.743 | 0.014 |
| 16 | Vertical trunk oscillation | >0.733 | NS |
| 17 | Anterioposterior acceleration | 0.720 | NS |
| 18 | Trunk rotation range of motion | 0.592 | NS |
| 19 | Pelvis range of motion | 0.581 | NS |
| 20 | Peak trunk rotation | 0.574 | NS |
| 21 | Bra comfort | 0.515 | 0.003 |
| 22 | Peak pelvis rotation | 0.508 | NS |

Figure 1. Mean (standard deviation) nipple displacement (a), velocity (b) and acceleration (c) in each direction during treadmill running at 2.8 m·s$^{-1}$ in three breast support conditions (n=10).  Brackets and * show where significant differences at $P$≤0.05 occurred between each breast support condition.

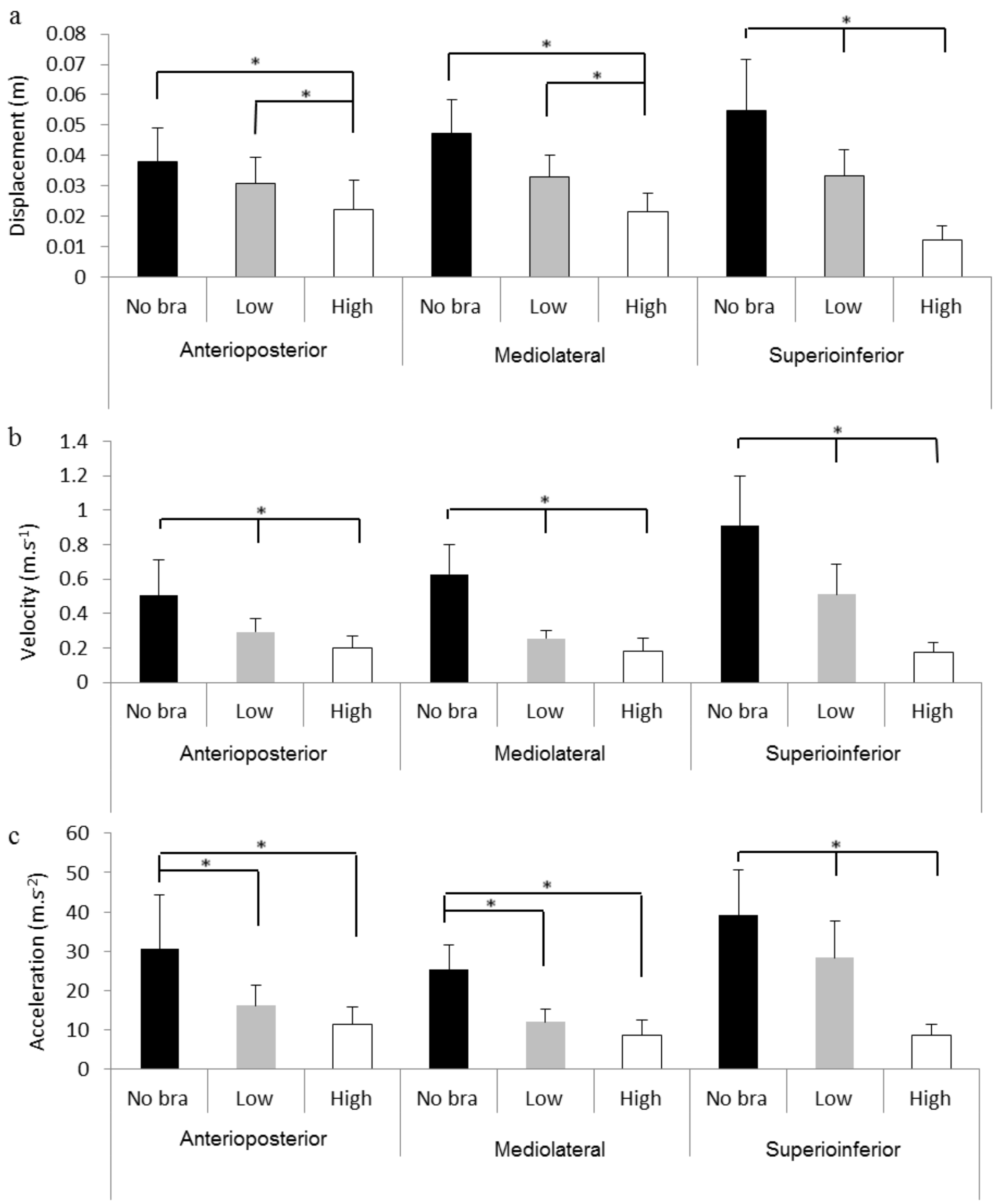


Figure 2. Mean (standard deviation) nipple variables (a-c) and vertical trunk oscillation (d) during treadmill running at 2.8 m·s$^{-1}$in three breast support conditions (n=10). Brackets and * show where significant differences at $P \leq 0.05$ occurred between breast support condition.

NB: Breast kinematic variables identified in Table 1 that showed no significant difference between breast support conditions are not presented.

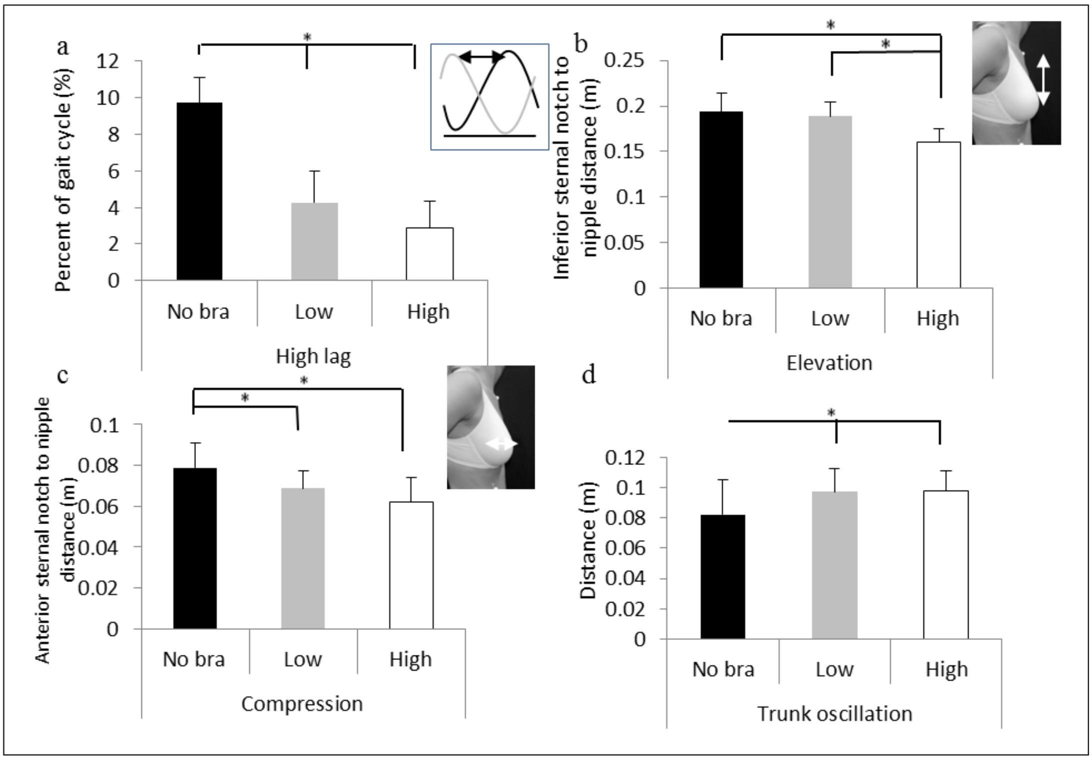


Figure 3. Mean (standard deviation) running mechanics during treadmill running at 2.8 m·s$^{-1}$ in three breast support conditions (n=10). Brackets and * show where significant differences at *P*≤0.05 occurred between breast support condition.

NB: Running mechanics variables identified in Table 1 that showed no significant difference between breast support conditions are not presented.

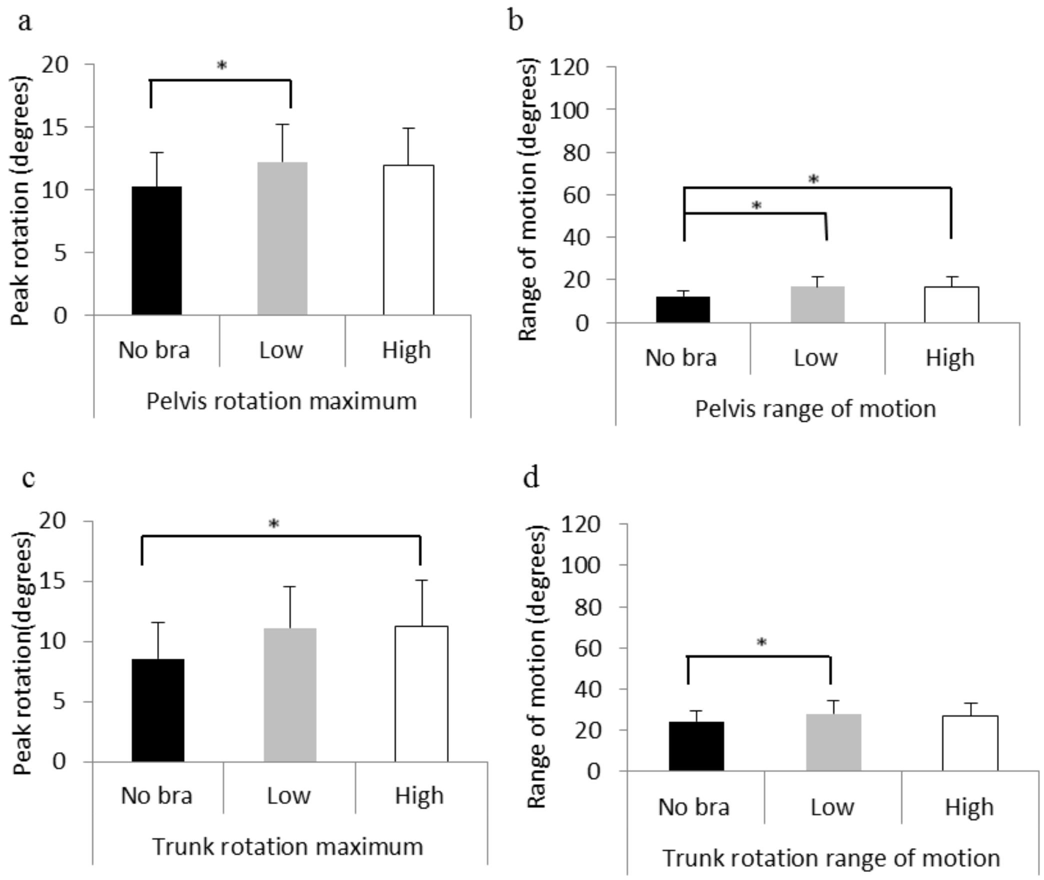


Figure 4. Mean (standard deviation) subjective ratings during treadmill and over ground running at 2.8 $m \cdot s^{-1}$ in three breast support conditions (n=10). Brackets and * show where significant differences at $P \leq 0.05$ occurred between breast support condition.

NB: Subjective rating variables identified in Table 1 that showed no significant difference between breast support conditions are not presented.