

Multiplanar Breast Kinematics During Different Exercise Modalities

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Abstract

Multiplanar breast movement reduction is crucial to increasing physical activity participation amongst women. To date, research has focused on breast movement during running, but until breast movement is understood during different exercise modalities, the breast support requirements for specific activities are unknown. To understand breast support requirements during different exercise modalities, this study aimed to determine multiplanar breast kinematics during; running, jumping and agility tasks. Sixteen 32D participants had markers attached to their right nipple and torso. Relative multiplanar breast displacement was calculated during bare breasted treadmill running (10 kph), maximum counter movement jumping, and an agility t-test. Exercise modality influenced the magnitude and direction of breast displacement, velocity and acceleration ($p < .05$). Jumping produced greater vertical breast displacement (.09 m) but less mediolateral breast displacement (.05 m) than running or the agility task, but agility tasks produced the highest multiplanar breast velocities and acceleration. Breast movement during jumping was predominantly in the vertical direction, whereas the agility task produced a greater percentage of mediolateral breast acceleration than running or jumping. Exercise modality impacted upon the magnitude and distribution of bare breasted multiplanar breast kinematics in this homogenous 32D cohort. Therefore, to reduce breast movement in women of a 32D bra size, manufacturers may wish to design sport specific products, with greater vertical support for exercise modalities incorporating jumping and greater mediolateral support for agility tasks.

Keywords: *biomechanics, exercise, performance, health*

Introduction

Participating in physical activity is key to maintaining a healthy lifestyle. However, excessive breast movement during exercise is commonly cited as a deterrent to exercise participation among women (Mason, Page, & Fallon, 1999; McGhee, Steele, & Munro, 2010; McGhee, Steele, Zealey, & Takacs, 2013; Verscheure, Arata, Hreljac, 1999). The sports bra is designed to restrict the movement of the breasts, subsequently increasing a woman's willingness to participate in exercise (Page & Steele, 1999; Scurr, White & Hedger, 2009; Starr et al., 2005). The majority of breast biomechanics literature has used treadmill running as the exercise stimulus (McGhee et al., 2013; Scurr et al., 2009; Scurr, White, & Hedger, 2011; Starr et al., 2005). However, until the movement of the breasts is understood during different exercise modalities, the breast support requirements for other activities are unknown. Literature suggests that appropriate breast support for all activities may not be achieved by a single bra design (McGhee et al., 2013); indicating an exercise specific sports bra may be required. As limited research has investigated breast movement during a variety of exercise modalities, the support requirements for any exercise specific bra have yet to be reported (Scurr et al., 2011).

Breast biomechanics literature has reported resultant breast displacement relative to the torso of over .15 m during running (Scurr et al., 2011), with 26-50% of this displacement occurring in the vertical direction, 25-35% in the anteroposterior direction and 25-38% in the mediolateral direction, dependent on the methodology employed (Scurr et al., 2011; Milligan et al., in press). Therefore, it is advised that kinematic analysis include three-dimensional breast displacement, particularly when activities involving greater axial rotation are incorporated. The literature also highlights differences in breast displacement due to breast mass (McGhee et al., 2013); this raises the question as to whether each bra size should be assessed individually to allow size specific bra design recommendations. Despite these

considerations, breast biomechanics literature typically does not refer to the influence of different exercise modalities, but implements treadmill walking or running to investigate breast movement. Breast support requirements may differ depending on the direction in which the majority of breast displacement occurs during different exercise modalities (Scurr et al., 2011). An assessment of breast displacement during frequent sporting movements, such as jumping, abrupt changes in direction and side stepping, may indicate sport specific breast support requirements.

To the author's knowledge, just four published studies have been found that assess the displacement of the breast during dynamic activities other than running (Bridgeman et al., 2010; Verscheure et al., 1999; White, Scurr & Hedger, 2009, 2010). The first (a conference abstract) reported the ability of different sports bras to attenuate forces during drop jumps; however, this study did not compare breast displacement during any other exercise modality (Verscheure et al., 1999). In 2010, Bridgeman et al investigated three-dimensional breast displacement during star jumping. The study found that the percentage distribution of multiplanar breast displacement during bare breasted star jumps was 19%, 23% and 58%, in the anteroposterior (a/p), mediolateral (m/l), and vertical direction, respectively. These results appear to differ somewhat from those reported during bare breasted running, which identify 26-50% of breast displacement occurring in the vertical direction (Scurr et al., 2011; Milligan et al., in press). In addition, a conference abstract reported breast displacement during maximum vertical jumping and found more than double the magnitude of relative vertical breast displacement (.12 m) compared to a/p (.04 m) and m/l (.05 m) (White et al., 2009). Finally, a conference abstract investigated breast displacement during jumping and agility tasks, common activities within many field and court sports (White, Scurr & Hedger, 2010). White's study showed differences in breast displacement between large and small breasted women, and between directions of breast displacement, yet did not compare

differences in displacement across exercise modalities. Due to this potential difference in percentage distribution of multiplanar breast displacement during jumping and running, further research is required to identify the influence of exercise modality on breast movement, to determine whether sports bra manufacturers need to vary the levels of multiplanar breast support in sports bras for different exercise modalities.

A direct comparison of breast displacement during different exercise modalities is lacking within the published literature, yet is essential when attempting to understand whether the support requirements of bras differ during a range of sporting activities. An understanding of the specific breast support requirements during different activities would identify the need for sport specific bras, which may better reduce multiplanar breast displacement, and therefore increase the willingness of women to participate in a range of exercise modalities. In order to understand the breast support requirements during frequent components of sporting actions (White et al., 2009; 2010), the aim of the current study was to determine multiplanar breast displacement during; running, jumping and an agility task, in order to inform breast support design during these different activities. It was hypothesised that:

1. There would be significant differences in the magnitude of a/p, m/l, and vertical breast displacement, velocity and acceleration during running, jumping and an agility task.
2. There would be significant differences in the percentage distribution of displacement, velocity and acceleration in each direction between running, jumping and an agility task.

Methods

Participants

Following institutional ethical approval, 16 female participants (mean \pm SD: age 22 ± 2 years, height $1.67 \pm .03$ m, body mass 64.0 ± 2.6 kg) gave written informed consent to take part in the study. Participants were selected if they were recreationally active (exercised aerobically for 30 minutes at least twice a week), aged between 18 and 40 years, were not pregnant, had no history of breast surgery, had not given birth or breast-fed in the last year, and were a 32D cup size. The 32D cup size was selected for comparison with previous research (Lorentzen & Lawson, 1987; White et al., 2009). Participant's bra breast size was measured by a trained bra fitter following UK best fit recommendations (White & Scurr, 2012).

Experimental Design

Participants completed a self-directed five minute treadmill warm up (H/P/Cosmos Mercury, Germany). A demonstration and familiarisation period ensured that participants were comfortable with the exercise modalities and were performing them correctly. Following the familiarisation and warm up period, retroreflective passive markers (.005 m radius) were positioned on the suprasternal notch, left and right anterior inferior aspect of the 10th ribs, and on the right nipple (Scurr et al., 2010). A nipple marker has previous been shown to be a reliable and valid measure of gross breast displacement (Mason et al., 1999; Scurr et al., 2011) and the right nipple was used to assess gross breast movement, as previous literature has shown no difference between left and right breast kinematics (Scurr et al., 2011). Three dimensional movement of the markers were tracked using optoelectronic cameras sampling at 200 Hz (Oqus, Qualisys, Sweden), positioned in an arc around the activity area, with tracking parameters of .25 mm and a technical error in the motion capture system of less than 1 mm. Cameras were calibrated using a coordinate frame and a handheld wand containing markers of predefined distances (QTM [Qualisys Track Manager]; version 1.10.828, Qualisys, Sweden).

A static trial was captured for POSE estimation, after which participants performed three exercise modalities in a random order whilst bare breasted. To replicate common sporting and exercise movements, the three exercise modalities implemented were; treadmill running, maximum counter movement jumping and an agility t-test. The treadmill activity required participants to run at $2.8 \text{ m}\cdot\text{s}^{-1}$ for a two minute familiarisation period (Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Scurr et al., 2010), after which marker coordinates were recorded for five gait cycles (Scurr et al., 2010; 2011). Participants were not given any specific instructions for running style, except to run naturally. Participants also completed five maximum effort two-footed vertical counter-movement jumps, which included the use of arm swing (White et al., 2010). Participants were also instructed to perform the agility t-test with maximal effort, the t-test required participants to run along the shape of a T (White et al., 2010). Thus, the t-test began with the participant running forwards toward the midpoint, side stepping both left and right, then running backwards to their initial position. The participant performed the t-test maximally five times, in order to standardise their movement as much as possible (White et al., 2010). Marker coordinates were recorded throughout. An additional heel marker was added during treadmill activity to track gait cycles (Starr et al., 2005; Scurr et al., 2010), and a manual event marker was used to identify the beginning of each t-test or jump. Participants wore the same shoes throughout and were offered regular rest periods between trials and conditions.

Data Analysis

Markers were identified and reconstructed in QTM, raw position-time data were exported into Visual 3D (Milligan et al., in press). Visual 3D filtered the data using a second order low pass Butterworth filter (13 Hz) (Winter, 1990). A POSE estimation was used with the vertical axis as the primary axis (Mills et al., 2014) in order to transform the global coordinate system into a local orthogonal coordinate system (Figure 1). This accounted for

the position and orientation of the torso in six degrees of freedom, thus establishing right nipple coordinates relative to the torso (Scurr et al., 2011) with the suprasternal notch identified as the origin (Scurr et al., 2010). Jumps were analysed in their entirety, whilst agility t-tests were analysed only during the side stepping phase, to ensure the t-test represented a cutting movement observed in many sports (White et al., 2010). The activities were performed 5 times each to reduced movement pattern variability, resulting in within-participant standard deviations of 24 mm for jump height (coefficient of variation of 7%) , and 0.05 m.s⁻¹ for side stepping speed during the agility task (coefficient of variation of 5%), both deemed acceptable levels of variance within the current study based on Hopkin's (2000) recommendations. Gait cycles during running were determined using the change in foot marker velocity along the x (a/p in the GCS) axis (Scurr et al., 2010), the instant at which the velocity vector of this marker changed from positive to negative indicated heel strike for each gait cycle (Zeni, Richards, & Higginson, 2008).

Breast displacement relative to the torso was subsequently calculated as the maximum minus the minimum position of the nipple within each gait cycle of the running (x5) and agility task (x5), and during each jump (x5) (Scurr et al., 2011). Instantaneous peak breast velocity and peak breast accelerations were calculated within Visual 3D, as a first and second derivative of filtered data. The data of five running gait cycles/jumps/agility tasks were averaged and a/p, m/l, and vertical displacement was reported in metres (m), velocity reported in m.s⁻¹, and acceleration reported in m.s⁻² (Scurr et al., 2009).

Insert Figure 1 here

Statistics

All data were checked for normality using the Kolmogorov-Smirnov and Shapiro-Wilks tests. All data were normally distributed ($p > .05$) and sphericity was assumed (Mauchly's test of sphericity, $p > .05$). Repeated measures ANOVAs were conducted to assess

differences in the magnitude of multiplanar breast displacement, velocity, acceleration and percentage distribution of breast displacement, velocity and acceleration between the exercise modalities. A Bonferroni correction factor was used for post hoc comparisons. Power and effect size (partial eta squared, η^2) are reported to provide an indication of the meaningfulness of results. A strong effect size was defined as $\eta^2 > 0.5$, moderate as between 0.5 and 0.3, and a weak effect size defined as < 0.3 , and acceptable power as $>.80$ (Field, 2009). Inter-participant variance was investigated and reported as a coefficient of variance (%) calculated according to Hopkins (2000), using the equation $\%CV = \left(\frac{sd}{mean} \right) * 100$.

Results

The results show that exercise modality had a strong influence on the magnitude of breast displacement ($F_{(2)}=62.889$, $p=.000$, $\eta^2=.807$, $1-\beta=1.000$), and peak breast velocity ($F_{(2)}=33.227$, $p=.000$, $\eta^2=.689$, $1-\beta=1.000$), but a moderate influence on peak breast acceleration ($F_{(2)}=8.283$, $p=.001$, $\eta^2=.356$, $1-\beta=.943$) (Figure 2). Jumping produced less m/l breast displacement on average (.047 m), but greater vertical breast displacement (.087 m) than either running (.057 m and .055 m, respectively) or the agility task (.062 m and .061 m, respectively). Differences in peak breast velocity were seen only between the agility task and jumping (Figure 2), in which the agility task produced higher a/p, m/l and breast velocities ($p<.05$). The agility task produced the greatest m/l breast acceleration ($39.8 \text{ m}\cdot\text{s}^{-2}$), followed by jumping, ($31.7 \text{ m}\cdot\text{s}^{-2}$) and running ($21.1 \text{ m}\cdot\text{s}^{-2}$). Average inter-participant variance of breast displacement was 26%, 24% and 29% during running, jumping and the agility task respectively.

Insert Figure 2 here

The percentage of multiplanar breast displacement, velocity, and acceleration distribution was also strongly influenced by exercise modality (Displacement, $F_{(4)}=27.649$, $p=.000$, $\eta^2=.754$, $1-\beta=1.000$) (Velocity, $F_{(2)}=42.325$, $p=.000$, $\eta^2=.738$, $1-\beta=1.000$)

(Acceleration, $F_{(2)}=10.497$, $p=.002$, $\eta^2=.412$, $1-\beta=.938$) (Table 1). Breast displacement during jumping was primarily seen in the vertical direction (48%), a smaller distribution of a/p (25%) and m/l (26%) breast displacement was seen in comparison to either running or the agility task ($p<.05$) (Table 1). Similarly, peak velocity was primarily in the vertical direction for jumping (47%), higher than either agility (39%) or running (42%). Interestingly, the distribution of peak vertical breast acceleration was highest during running, followed by jumping, then the agility task ($p<.05$). Peak breast acceleration during the agility task was primarily seen in the m/l direction (36%), accounting for a greater percentage of total breast acceleration than in either running (23%) or jumping (29%).

Insert Table 1 here

Discussion

This article is the first to present a direct within participant comparison of relative multiplanar breast displacement, velocity, and acceleration, during different exercise modalities. The results show significant differences in the magnitude of breast displacement, velocity, and acceleration in a homogenous 32D bra size cohort, during running, jumping and the agility task, hypothesis one is therefore accepted. White et al. (2009) provide the only published data during maximum vertical jumping, with average a/p, m/l, and vertical displacements reported for women of a D cup size (.04 m, .05 m, and .12 m, respectively). The current results showed comparable values for a/p and m/l breast displacement (.04 m and .05 m, respectively), although less vertical displacement (.09 m) which may be due to the methodological differences in axes convention and POSE estimated (Mills et al., 2014). White et al. (2010) presented bare breasted mediolateral breast displacement during the agility test of $.069 \pm .022$ m, similar to the current study which found an average of $.062 \pm .018$ m. However, White et al. (2010) did not present velocity or acceleration data, and the current study isolated the side-to-side stepping movement of the agility t-test. However,

velocity and acceleration are consistent with the limited available literature on bare breasted running breast kinematics (Scurr et al., 2010). White et al's (2009) abstract showed that exercise modalities incorporating jumping require a high level of vertical breast support. The current study develops this knowledge by suggesting that exercise modalities incorporating jumping actually require significantly greater vertical breast support than exercise modalities without jumping, thus sport specific sports bras may be necessary for women with 32D size breasts.

Hypothesis two was also accepted as significant differences in the percentage distribution of breast displacement, velocity, and acceleration, in each direction during the three exercise modalities were found. The results show that breast displacement during running or agility tasks is evenly distributed between a/p, m/l and vertical breast movement, however, breast displacement during jumping was predominantly in the vertical direction (48%). This contradicts some previous literature which commonly reports that the greatest distribution of movement occurs in the vertical direction during running (Scurr et al., 2010; 2011), and that just 25% of the movement occurs in the m/l direction (Scurr et al., 2011). This discrepancy may be due to methodological variations, such as the influence of utilising a POSE segment estimation method for the rigid torso segment, rather than a frame by frame matrix transformation (Scurr et al., 2010, 2011), or the primary axes as the vertical, rather than mediolateral axes (Mills et al., 2014). Indeed, more recent publications using identical data analysis methods to the current study show similar distribution of breast displacement results during treadmill running (Milligan et al., in press). Additionally, implementing a within-participant study design helps to ensure that the results are comparable within a single cohort, but not necessarily across different studies which have recruited a different cohort and inherently open to inter-participant variation (Milligan et al., in press). Regardless, the conclusions of this study concur with previous research which highlights the importance of

investigating multiplanar breast displacement rather than breast movement in the vertical direction alone (Scurr et al., 2009; 2010; 2011).

The percentage distribution of breast movement in each direction alters between displacement, velocity and acceleration. For example, the percentage distribution of vertical movement increases from 34% in breast displacement to 42% in breast acceleration during running (table 1). This is due to the frequency of breast movement in each direction. Vertical breast displacement peaks twice during the gait cycle, whereas mediolateral and anteroposterior breast movement peak just once. Therefore, although the magnitude of displacement covered in each direction may be similar, the velocity and acceleration of the breast in each direction has been shown to differ (Scurr et al., 2009; Zhou et al., 2012). Percentage distributions of velocity and acceleration data have not previously been reported, the current study therefore progresses knowledge by presenting such information (table 1) which can be used for the specification of sports bra designs.

As the percentage distribution of breast movement differed as a result of exercise modality, it is suggested that the assessment of multiplanar breast kinematics is equally important during exercise modalities other than running. The results indicate that women of a 32D bra size undertaking sports which incorporate jumping require greater breast support in the vertical direction than sports which do not, followed by running, then agility tasks, which requires a greater level of support in the m/l direction. These results suggest that specific design recommendations are required for sports bras in order to optimise their function for physically active women of a 32D bra size who participate in a range of different exercise modalities. Sports bras need to possess diverse mechanical properties if they are to be used during multiple exercise modalities. Specifically, they need to encompass both elasticity to enable upper body movement and enough stiffness to prevent breast displacement in the required direction (Page & Steele, 2009). To enable natural breathing the sports bra needs to

have a sufficient amount of elastic material along the horizontal plane (Bowles, Steele, & Chaunchaiyakul, 2005); yet more elasticated material may subsequently reduce the breast support provided. Conversely, the elastic material through the vertical plane must be kept to a minimum to prevent vertical displacement of the breasts, especially so during jumping (Page & Steele, 1999). However, it should be noted that the conclusions of this study result from a homogenous cohort, and may not be generalised to women of a smaller or larger bra size or different ages, as breast movement patterns are influenced by these factors (Wood et al., 2012).

Exercise modality has a significant impact upon the magnitude and distribution of multiplanar breast displacement, velocity, and acceleration of 32D bra size women, indicating different breast support requirements for different sports. Despite this finding, it remains unknown whether a single sports bra is capable of optimally minimising multiplanar breast kinematics during multiple exercise modalities. The findings suggest that sports bras for women of a 32D bra size used during jumping activities require greater vertical breast support, whereas sports bras for running require a more equal distribution of breast support in all directions, and sports bras for agility movements and cutting manoeuvres require greater m/l breast support. By appropriately designing either exercise specific sports bras or an appropriate multi-purpose sports bra, breast movement and a barrier to physical activity may be reduced (Mason et al., 1999; McGhee et al., 2010; 2013; Verscheure et al., 1999).

Literature has indicated that breast pain correlates with breast movement in the vertical, mediolateral and anterioposterior direction (White et al., 2011; Scurr et al., 2010), as these differ with exercise activity, the levels of breast pain may vary dependent on exercise modality. The lack of breast pain assessment is a limitation within the current study, and associated breast pain during different exercise modalities should be the focus of future research, to assess the subjective influence of sports bra use during these exercise modalities.

The inclusion of breast pain assessment during different exercise modalities in future breast biomechanics studies would further enhance our understanding in this area. Research on sports bra functionality should ensure that the exercise modality is carefully selected, as the data and subsequently support recommendations may differ based upon the activity undertaken by participants.

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Table 1. Percentage distribution of multiplanar breast displacement, velocity and acceleration (mean and *SD*) during different exercise modalities in a bare breasted condition. n=16.

Exercise modality	Distribution of breast displacement (%)			Distribution of breast velocity (%)			Distribution of breast acceleration (%)		
	a/p	m/l	v	a/p	m/l	v	a/p	m/l	v
Running	31 ± 4	36 ± 3	34 ± 5	28 ± 6	29 ± 4	42 ± 7	34 ± 8	23 ± 4	42 ± 8
Jumping	25 ± 3	26 ± 4	48 ± 6	27 ± 4	27 ± 6	47 ± 9	33 ± 6	29 ± 5	38 ± 8
Agility	28 ± 4	36 ± 4	36 ± 5	28 ± 4	33 ± 4	39 ± 6	34 ± 4	36 ± 5	32 ± 4

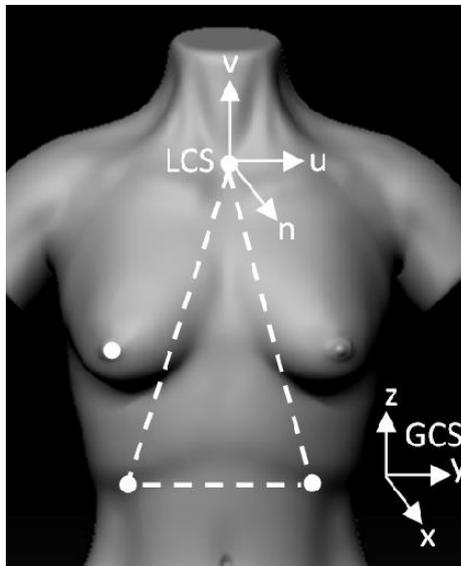


Figure 1. Marker positions, torso segment axes, and coordinate systems. LCS = Local Coordinate System, with v as the longitudinal axes, u as the transverse axes, and n as the line of progression. GCS = Global Coordinate System, with z as the longitudinal axes, y as the transverse axis, and x as the line of progression.

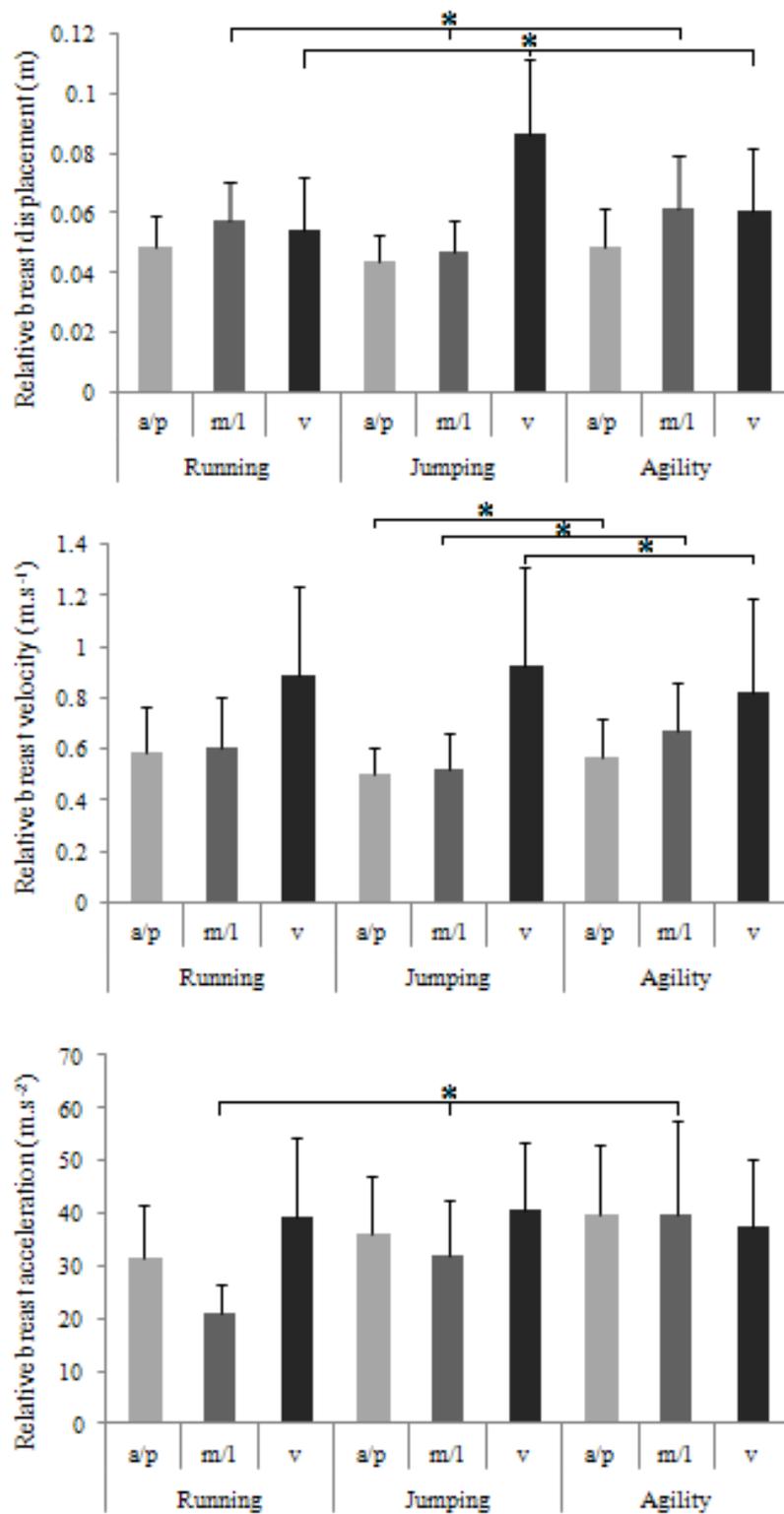


Figure 2. Mean multiplanar breast displacement, velocity and acceleration during different exercise modalities in a bare breasted condition. *Note:* * indicate a significant difference between exercise modalities, and error bars show standard deviations of the data.