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IS TORSO SOFT TISSUE MOTION REALLY AN ARTEFACT WITHIN BREAST BIOMECHANICS RESEARCH?

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Abstract

For rigid body POSE estimation, any relative movement of the tracking markers on a segment is often referred to as an artefact; however this may be an important part of the signal within breast biomechanics. This study aimed to quantify differences in breast range of motion when calculated relative to the torso segment using either direct or segment optimised POSE estimation algorithms. Markers on the torso and right nipple were tracked using infrared cameras (200 Hz) during five running gait cycles in three breast support conditions (no bra, everyday bra and sports bra). Multiplanar breast range of motion was calculated relative to the torso segment using two POSE estimation algorithms. Firstly, the torso segment was defined using direct POSE estimation (direct). Secondly, while standing stationary in the anatomical position; the positional data of the torso markers were used to construct the torso using segment optimised POSE estimation (optimised). The torso segment length defined using direct POSE estimation changed significantly by 3.4 cm compared to that of the segment optimisation POSE estimation in the no bra condition. Subsequently, superioinferior breast range of motion was significantly greater ($p<0.017$) when calculated using direct POSE estimation, within each of the three breast support conditions. Segment optimisation POSE estimation is recommended to minimise any differences in breast motion associated with intra segment deformation between physical activity types. However, either algorithm is recommended when evaluating different breast support garments, as a correctly fitted bra does not cause the torso markers to move relative to each other.

Keywords: trunk; displacement; running; POSE, kinematics

Introduction

Rigid body mechanics commonly uses segment optimisation position and orientation (POSE) estimation (Cappozzo et al., 1995; Lu & O'Connor, 1999) to minimise any segment deformation, whereby the body is assumed to be rigid and any change is a residual error associated with soft tissue artefact (Selbie, 2011; Cappello et al., 1997). Standard practice and most software in biomechanics attempts to represent the markers on the skin, used to define a segment, as rigid, with no relative marker movement. Within breast biomechanics research, the analysis of breast motion presents an unusual problem since the motion of the breast is calculated relative to the deformable non-breast soft tissue of the torso. Current methodologies in breast biomechanics research utilises both direct and segment optimised POSE estimation algorithms to determine the POSE of the torso. Scurr et al., (2010; 2011) used a direct POSE estimation algorithm to calculate relative breast motion where the position and orientation of the torso was recalculated every frame and no assumptions about torso segment rigidity were made. The second approach by Milligan et al., (2013) defined the non-breast soft tissue torso segment using a segment optimisation POSE estimation algorithm where any relative marker movement was assumed to be an artefact. To date it is unclear if there are any differences in the subsequent calculation of breast motion between these two methods and which of these approaches may be the most appropriate for breast biomechanics research.

The quantification of breast motion presents a unique challenge regarding the marker set used to represent the torso segment. The International Society of Biomechanics (ISB) recommend markers be placed on the Incisura Jugularis (IJ), Processus Xiphoideus (PX), 7th cervical spinous process (C7) and the 8th thoracic spinous process (T8) (Wu et al., 2005). However, this marker set has not been widely adopted in breast biomechanics research as both the XP and T8 sites are commonly obscured by the breast support garment worn by the participants. The alternative marker set used in breast biomechanics consists of three markers placed on the sternal notch, and left and right anterior aspects of the 10th rib (Scurr et al., 2010). Zhou et al., (2011) reviewed the use of marker sets in breast biomechanics and concluded that the marker set by Scurr et al. (2010) was the most appropriate as all three markers belong to the same segment and can be regarded as a stable reference frame. Furthermore, it was also noted that the distal marker locations of the Scurr et al. (2010) marker set (10th ribs) are placed around an anatomical location that is likely to have a substantial amount of subcutaneous fat, which may result in localised torso segment deformation. Assuming segment rigidity for a potentially non-rigid torso segment may influence subsequent calculations of breast kinematics, therefore the use of this marker set was of particular relevance to this research study.

The applied research in breast biomechanics is centred on two main themes; understanding the behaviour of the breast in a variety of physical activities and / or the development and understanding of breast support devices and how they may reduce breast motion. It may be possible that the markers on the soft tissue of the torso (especially the rib markers of Scurr et al., 2010) move with respect to one another, and the origin, when compared to the torso template used for segment optimisation. Any relative torso marker movement may subsequently alter the magnitude of breast range of motion when compared to a more stable torso defined by segment optimisation POSE estimation (Milligan et al., 2011). The magnitude of torso soft tissue artefact has also been shown to depend upon the type of physical activity performed by the participants (Heneghan and Balanos, 2010), with the arm elevation associated with jumping significantly increasing the soft tissue artefact at the torso.

The design of breast support garments themselves (such as the tightness of the underband or strap design) may alter the motion of the non-breast tissue of the torso segment by changing the position of the soft tissue markers at the ribs, which are located close to the underband of the support garment. This may make it difficult to compare breast motion data between garments using the direct POSE estimation algorithm. Furthermore, the direct POSE estimation algorithm may yield differences in the directional distribution of breast range of motion since any motion of the rib markers in particular, caused by physical activity, may alter the POSE of the torso segment. A torso segment, defined by a segment optimised POSE estimation algorithm, will provide a stable basis to assess breast motion, reducing any relative movement of the markers on the torso associated with skin artefact or support garment impingement between breast support conditions. However, in breast biomechanics there could be an argument for not always considering breast motion relative to a segment optimisation POSE estimation, as commonly used in other areas of biomechanics (Leardini et al., 2005), as the breasts are moving relative to the deformable, non-breast soft tissue of the torso. It is important to quantify the magnitude of any differences in relative breast motion during physical activity in varying breast support garments when using different POSE estimation algorithms in order to understand the appropriateness of any rigid body assumptions.

This study aimed to quantify differences in POSE estimation algorithms and subsequent relative breast range of motion, within three breast support conditions. The first hypothesis stated that there were no significant differences in torso segment lengths between POSE estimation algorithms, within each breast support condition. The second hypothesis stated no significant differences in torso segment length, using direct POSE estimation, between breast support conditions. The third hypothesis stated that there were no significant differences in multiplanar breast range of motion between POSE estimation algorithms, within each breast support condition.

Methods

Following institutional ethical approval and written informed consent, ten female participants (mean ± *SD*: age 22 ± 2 years, height 1.65 ± .04 m, body mass 61.0 ± 2.4 kg) were selected to participate in this study if they were recreationally active, aged between 18 and 39 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 (assessed using the bra fitting criteria set out by White and Scurr, 2012). Due to the lack of published multi-planar breast kinematic data a post-hoc power calculation was conducted (G*Power 3.1 software; Faul et al., 2007) after 10 participants had been tested; this indicated that a sample size of 10 would provide a power of 1, therefore no further participants were recruited.

Participants completed a self-directed treadmill warm up (Powerjog, H/P/Cosmos Mercury, Germany). Following the warm up period, retro-reflective passive markers (.006 m radius) were positioned on the sternal notch, left and right anterior inferior aspect of the 10th ribs, and on the right nipple (Scurr et al., 2011) (Figure 1). A nipple marker has previously been shown to be a reliable and valid measure of gross breast displacement (Mason et al., 1999). An additional heel marker was added to track gait cycles (Scurr et al., 2010). Three dimensional movement of the markers were tracked using twelve optoelectronic cameras sampling at 200 Hz (Oqus, Qualisys, Sweden), positioned in an arc around the treadmill. Cameras were calibrated using a coordinate frame positioned on the treadmill and a handheld wand containing markers of predefined distances (QTM [Qualisys Track Manager]; version 1.10.828, Qualisys, Sweden).

The participants stood statically in the anatomical position for 10 seconds, for use in the template for the segment optimisation POSE estimation algorithm, and then ran at 2.8 m.s^{-1} for a two minute familiarisation period, after which marker coordinates were recorded for five gait cycles (Scurr et al., 2010; 2011) in each breast support condition (no bra, everyday bra and sports bra). The everyday bra was a Marks and Spencer Seamfree Plain Under wired T-Shirt Bra, made from 88% polyamide and 12% elastane Lycra and the sports bra was the UK best-selling branded encapsulation sports bra (Shock Absorber Run bra, made from 81% polyamide, 10% polyester, 9% elastane).

Markers were identified and reconstructed in QTM, and a fast Fourier transformation was performed on the reconstructed data in MatLab (version R2010a). The power spectrum revealed that approximately 85% of the signal power was below 16 Hz and a subsequent residual analysis, based on Winter (2009), determined a cut-off frequency of 13 Hz. The data were subsequently filtered using a second order, zero phase shift, low pass Butterworth filter with a cut off of 13 Hz. Firstly, using the direct POSE estimation algorithm (Lu & O'Connor, 1999; Scurr et al., 2010), the position of the breast relative to the torso segment was calculated (direct). Secondly, the reconstructed marker positional data from both the static template and dynamic trials were imported into Visual 3D (C-Motion Inc, Germantown, USA) and a torso segment, using the segment optimisation POSE estimation algorithm (Cappello et al., 1997; Lu & O'Connor, 1999), was created using the markers placed on the torso (optimised). The right and left ribs were used to calculate a virtual mid-rib point. The normalised vector extending from the mid-rib point to the sternal notch defined the longitudinal axis (superioinferior axis). The sternal notch marker was then used to construct two vectors within the torso reference plane (vector 1 extending from the sternal notch to the left rib, and vector 2 extending from the right rib to the sternal notch). The normalised cross product between vectors 1 and 2 defined the second axis (anterioposterior). A right handed local co-ordinate system for the torso defined the mediolateral axis (Mills et al., 2014). Both torso construction methods used the same axes conventions and torso markers. The origin of the torso segment using direct POSE estimation was the sternal notch marker and the origin of the torso segment using the segment optimised POSE estimation was the proximal end of the segment.

Torso segment rigidity, for the direct POSE estimation algorithm, was assessed using the maximum change in vector length of the torso segment. The vector was defined using the sternal notch marker (origin) and virtual mid-rib marker (midpoint between left and right rib markers). Torso length was calculated by subtracting the minimum vector length from the maximum vector length of the torso segment (torso segment length). The optimised torso segment was confined to retain a constant segment length. Any deviation of the torso markers from their static template position was quantified using a segment residual. The segment residual was calculated using a least squares fit of the markers in the static trial compared to those in the dynamic trial (C-Motion Inc, Germantown, USA) for each frame and averaged over the sample. Breast range of motion was calculated by subtracting the minima positional coordinates from the maxima during each gait cycle (Scurr et al., 2010). Within both local reference frames the x axis represented anterioposterior breast motion; the y axis represented mediolateral breast motion and the z axis superioinferior breast motion (Figure 1). Five gait cycles were identified using the anterioposterior velocity of the heel marker (Zeni et al., 2008). For each participant, the change in torso segment length and breast range of motion was assessed in five gait cycles, and the mean was calculated for each breast support condition.

{Insert Figure 1 here}

Torso segment length and multiplanar breast range of motion were statistically analysed using PASW software (Version 18). All data were checked for normality (Shapiro-Wilk test) and the appropriate parametric (repeated measures ANOVA) or non-parametric (Friedman) statistical test was implemented. Effect sizes (parametric: Cohen's *d,* partial eta squared η^2; non-parametric: r) are reported for significant results ($P<0.017$) and a large effect size was defined as *d* or r > 0.8, moderate as between 0.8 and 0.5, and a small effect size defined as < 0.5 (Field, 2009).

Results

There were significant differences in torso segment length between the POSE estimation algorithms within each of the breast support conditions (no bra: z=-2.805, P=0.005, r = 0.89; everyday bra: z=-2.803, P=0.005, r = 0.89; sports bra: z=-2.807, P=0.005, r = 0.89). The greatest change in torso segment length, using the direct POSE estimation, was 3.4 cm in the no bra condition, followed by 3.0 cm in the everyday bra and 2.8 cm in the sports bra (Figure 2). There were no significant differences in torso segment length (F=1.979, P=0.200, $\eta^2=0.331$) using direct POSE estimation between the support conditions. The torso segment length using segment optimisation POSE estimation was fixed at 28.1 cm with segment residuals of 1.4 cm in the no bra, 1.3 cm in the everyday bra and 1.6 cm in the sports bra condition. There were no significant differences (F=0.265, P=0.345, $\eta^2=0.213$) in the optimised torso segment residuals between breast support conditions.

{Insert Figure 2 here}

There were significant differences in superioinferior breast range of motion between the POSE estimation algorithms within the no bra condition (t=-4.602, P=0.001, *d* = 2.0), everyday bra (t=-4.528, P=0.001, *d* = 1.7) and sports bra condition (t=-3.230, P=0.010, *d* = 0.5), with the greatest difference of 1.1 cm in the no bra condition (Figure 3). It is also interesting to note that within the no bra and everyday bra conditions the greatest breast range of motion occurred in the superioinferior direction when calculated using direct POSE estimation, however, this changed to the mediolateral direction when calculated using segment optimisation POSE estimation (Figure 3).

{Insert Figure 3 here}

Discussion

Breast motion has previously been calculated using either direct or segment optimisation POSE estimation. This study aimed to quantify any differences in torso segment length and subsequent relative breast range of motion between POSE estimation algorithms, within three breast support conditions. Key findings have shown that the torso segment, using direct POSE estimation, changes significantly in length compared to the torso segment using optimised POSE estimation, subsequently affecting the magnitude of relative superioinferior breast range of motion within each breast support condition.

This study has shown that the markers placed on the torso do move relative to each other, therefore significantly changing the length of the torso segment between POSE estimation algorithms, rejecting hypothesis one. The greatest change in torso segment length was 3.4 cm, representing approximately 50 % of the magnitude of superioinferior breast range of motion. This torso segment deformation, using direct POSE estimation, may be attributed to soft tissue artefact, as it is likely that there are substantial amounts of subcutaneous fat, close to the participants centre of mass, near the distal marker locations of the Scurr et al. (2010) marker set (10th ribs). As the foot impacts the ground during running the ground reaction force induces a soft tissue vibration wave that propagates superiorly from the foot towards the head. This soft tissue motion has been shown to be as great as 3 cm in the thigh (Pain & Challis, 2006) and as the soft tissue wave continues superiorly up through the torso, it causes a change in relative marker locations, deforming the length of the torso segment. Furthermore, the sinusoidal motion of the torso during running itself, which acts as a driving force for the breasts (Haake & Scurr, 2010; 2011), could also induce soft tissue motion of the non-breast tissue close to the rib markers. When investigating breast motion between different types of physical activities (for example, running and jumping), varying ground reaction forces may induce different magnitudes of non-breast soft tissue artefact, deforming the torso segment. Therefore it would be advisable to use a segment optimised POSE estimation algorithm to minimise any differences in breast motion due to intra segment deformation of the torso segment between physical activity types. Future work should also aim to quantify the segment residual in order to determine the effects of relative marker movement associated with different activity types.

It is interesting to note that the torso segment length, using direct POSE estimation, did not differ between breast support conditions, accepting the second hypothesis. The results suggest that the design of the bras used in this study do not significantly impinge, deform or change the relative positions of the markers on the torso segment during running between support conditions. Intra segment, non-breast, soft tissue movement of the torso, should not be considered an artefact if a study aims to evaluate different breast support garments, as a correctly fitted bra is situated on the skin and does not cause the markers located on the soft tissue of the torso segment to move relative to each other. It is recommended that either the direct or segment optimised POSE estimation algorithms can be used when investigating breast motion between different breast support garments.

The results of this study have demonstrated that during running the torso segment, using segment optimised POSE estimation, consistently produced lower magnitudes of breast range of motion compared to results using direct POSE estimation (Figure 3). Therefore, the changes in torso segment length, significantly affected the magnitude of relative multiplanar breast range of motion within each breast support condition, rejecting hypothesis three. Key findings have shown that the greatest difference in superioinferior breast range of motion (1.1 cm) between the POSE estimation algorithms occurred in the no bra condition. The reduced superioinferior breast range of motion, using segment optimisation POSE estimation, may have been due to the least squares fit used to determine the optimal POSE. The two rib markers weights the movement of the torso towards the inferior end of the segment, and since the length of the torso segment is fixed, the segment origin can move relative to the origin (sternal notch marker) of the torso segment defined using direct POSE estimation. The origin of the torso segment, using segment optimisation POSE estimation, moves superiorly during upward breast (and rib marker) movement and inferiorly during downward breast (and rib marker) movement compared to the sternal notch marker (used as the origin in the direct POSE estimation); therefore breast range of motion is reduced. Future research that aims to present breast kinematics relative to a torso segment using segment optimisation POSE estimation may need to investigate the use of a different marker set (for example, a modified International Society of Biomechanics thorax marker set, Wu et al., 2005) that reduces possible soft tissue artefact associated with the rib markers in this study, whilst not being obscured by the breast support garments worn by the participants.

Finally, the direction in which the greatest range of motion occurs differs depending upon the POSE estimation algorithm used for the torso segment. This has an important implication for breast biomechanics research since the superioinferior direction is often reported as the one in which the most breast motion occurs (Bridgman et al., 2010; Scurr et al., 2011), leading to recommendations that sports bras should predominantly reduce superioinferior breast range of motion (Scurr et al., 2011). The findings of this study show that when calculating breast range of motion during running using a direct POSE estimation algorithm, the superioinferior component is the greatest, however if breast range of motion is calculated using a segment optimisation POSE estimation algorithm, then the mediolateral component is the greatest in both the no bra and everyday bra conditions. This example illustrates the importance of considering the POSE estimation algorithm used to define the torso segment before calculating relative breast range of motion when recommending improvements to breast support garments.

In conclusion, the findings of this study have demonstrated that the magnitude of breast range of motion can differ up to 1.1 cm depending upon the POSE estimation algorithm used for the torso segment. A torso segment that utilises segment optimisation POSE estimation is recommended to minimise any differences in breast motion due to intra segment deformation of the torso segment between physical activity types. However, either the direct or segment optimised POSE estimation algorithms can be used when investigating breast motion between different breast support garments, as a correctly fitted bra is situated on the skin and does not cause the markers located on the soft tissue of the torso segment to move relative to each other. This study has also identified the need to develop a new torso marker set for use with segment optimisation POSE estimation that minimises the segment residuals associated with this study, whilst the markers are not obscured by the breast support garments.

Conflict of interest statement

The authors have declared no conflicts of interest associated with this research.

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Figure Captions:

Figure 1. Skin marker locations (sternal notch, left and right 10th rib, virtual mid rib, right nipple) used to represent the torso segment, including local axes orientation (x = anterioposterior, y = mediolateral, z = superioinferior).

Figure 2. Torso segment length during treadmill running in three breast support conditions (n = 10).

Figure 3. Multiplanar breast range of motion during treadmill running calculated relative to the torso segment (n = 10).

Figure 1

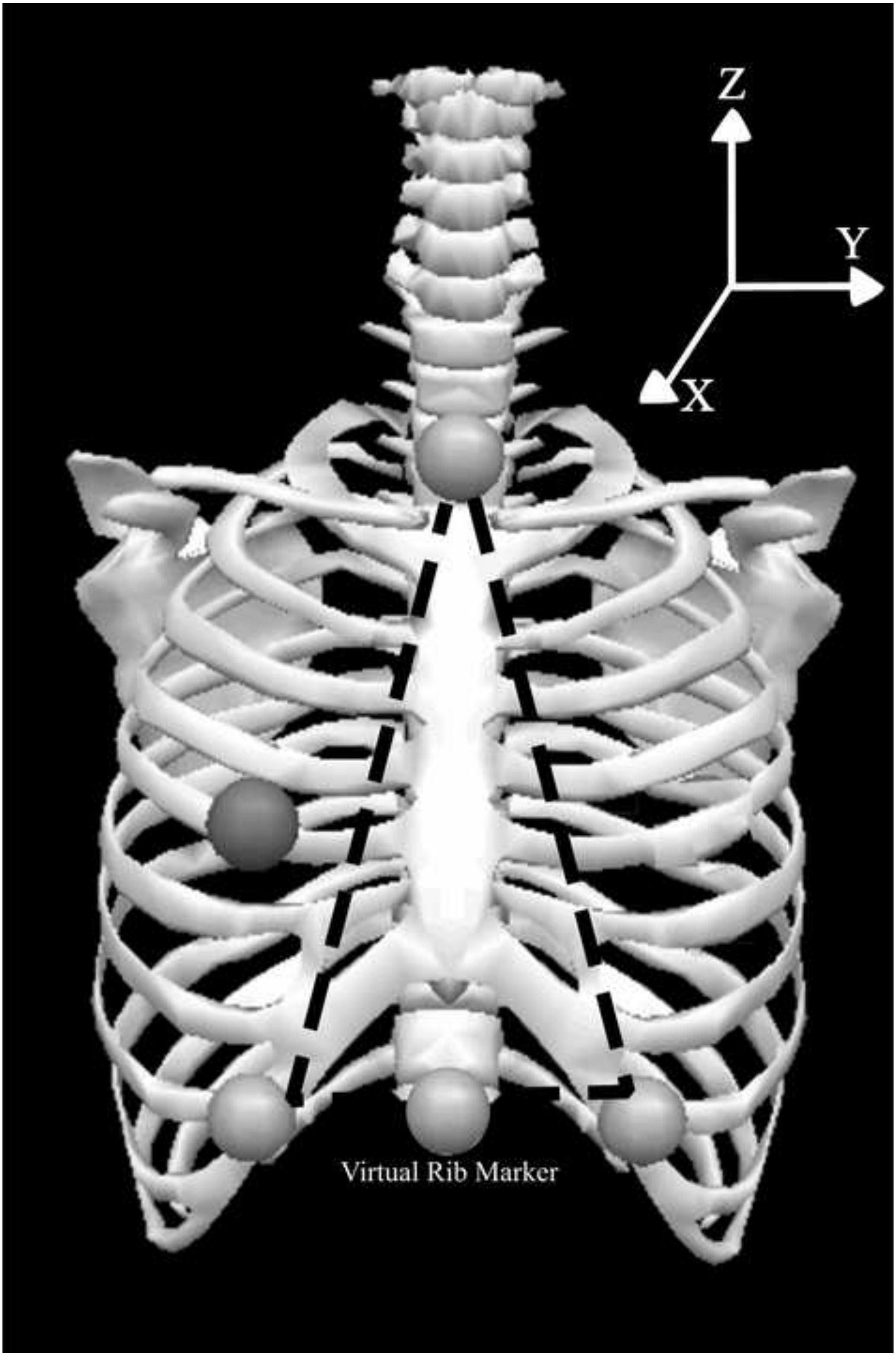


Figure 2

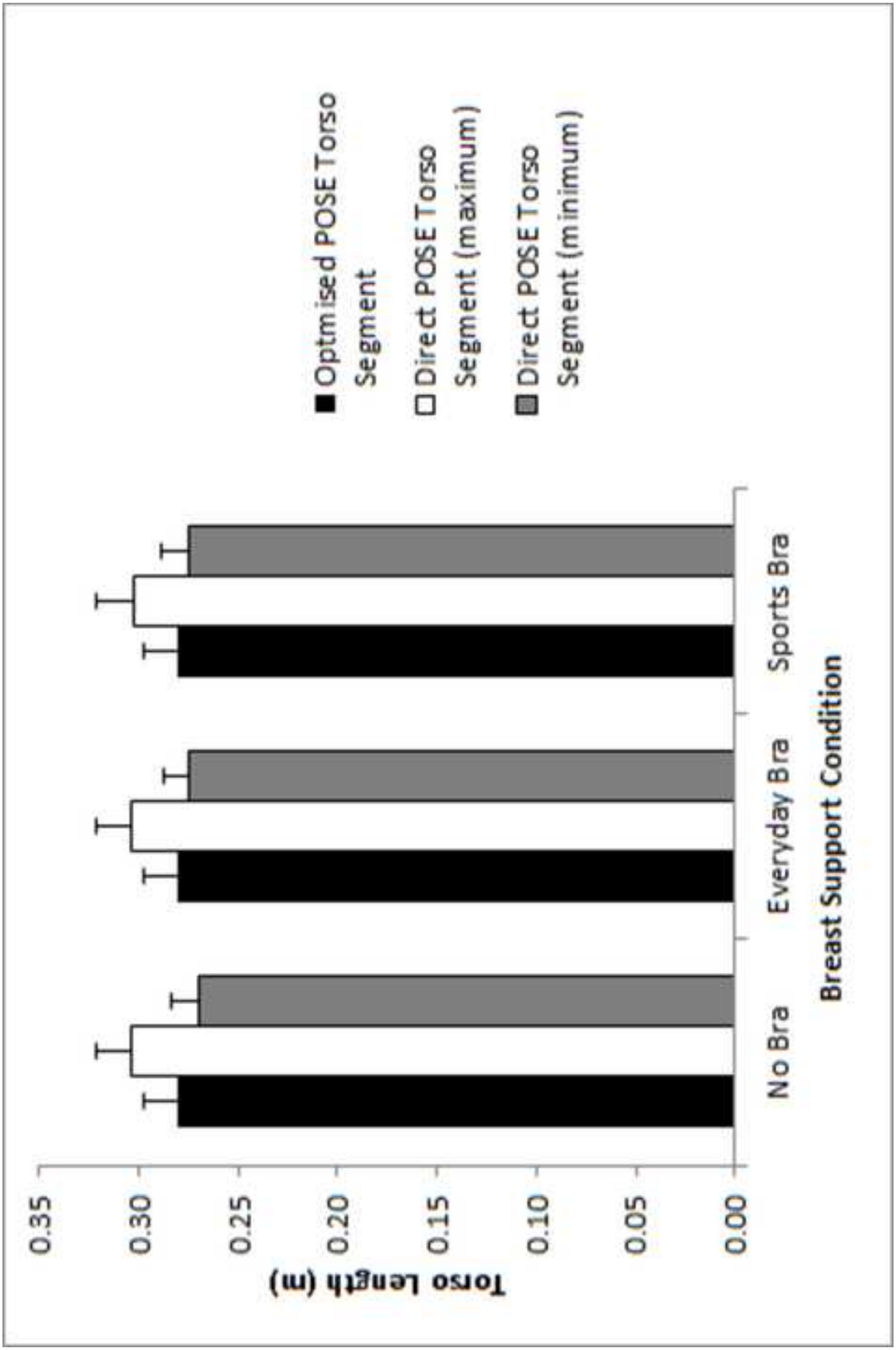
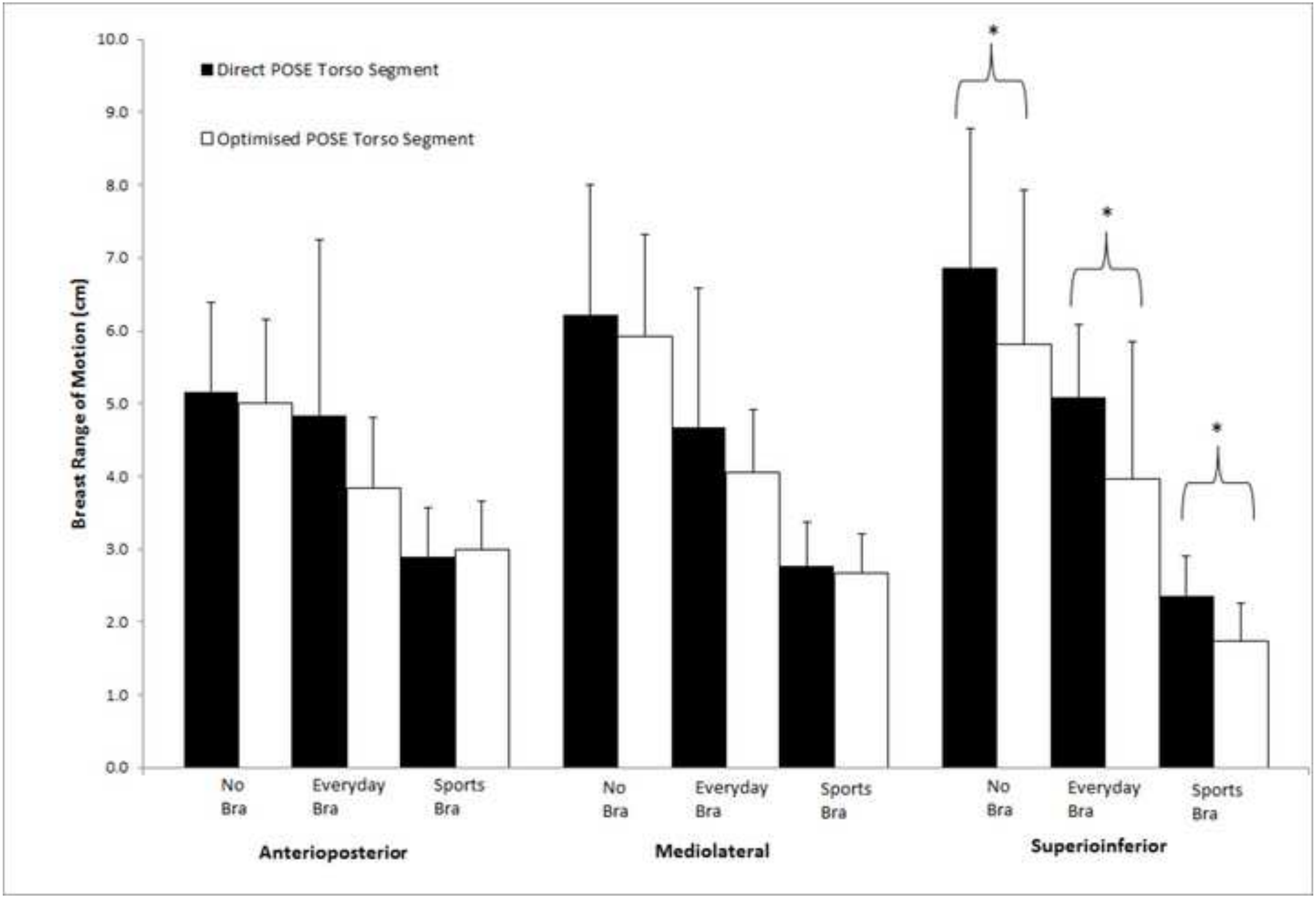

Torso Length (m)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
No Bra
Everyday Bra
Sports Bra
Breast Support Condition
■ Optmised POSE Torso Segment
□ Direct POSE Torso Segment (maximum)
▨ Direct POSE Torso Segment (minimum)

Figure 3


Breast Range of Motion (cm)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
■ Direct POSE Torso Segment
☐ Optimised POSE Torso Segment
*
*
*
No Bra
Everyday Bra
Sports Bra
Anterioposterior
No Bra
Everyday Bra
Sports Bra
Mediolateral
No Bra
Everyday Bra
Sports Bra
Superioinferior