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Trunk marker sets and the subsequent calculation of trunk and breast kinematics during treadmill running

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Abstract

Female participants present a unique challenge as the design of the bra used to support the breasts occludes the correct positioning of many recommended trunk marker sets. This study aimed to compare the effect of two existing and one new trunk marker set on the calculation of trunk and breast kinematics. Twelve females had markers placed on their trunk and right nipple; these markers were tracked using infrared cameras during five running gait cycles and used to define three trunk calculation methods. Trunk 1: suprasternal notch, right and left ribs; Trunk 2: supersternal notch, processus xiphoideus, 7th cervical and 8th thoracic spinous process; Trunk 3: Trunk 2 plus a marker 33% from the suprasternal notch to the processus xiphoideus, and another 50% between the 7th cervical and 8th thoracic spinous process. Trunk segment capture success, segment origin instability, segmental residual, trunk kinematics and breast range of motion (relative to the trunk segment), were calculated for each trunk segment. Segment capture success varied from 88% (Trunk 1) to 100% (Trunk 2 and 3). Segment origin instability ranged from 0.2 cm (Trunk 2 and 3) to 1.5 cm (Trunk 1). Maximum trunk extension differed by 7° and breast range of motion varied by 41% (anterioposterior), 54% (mediolateral), and 21% (superioinferior) between trunk calculation methods. The selection of marker set used to construct the trunk segment is critical before recommending improvements to bra design to improve breast support. The Trunk 3 marker set is recommended for subsequent breast research.

Keywords

displacement, breast motion, exercise, breast support

Introduction

Human motion is often analysed using markers to represent joint positon and segment length and camera systems that track skin based markers.[1] When creating a segment reference frame it is recommended that the marker locations used should be based on easily identified body landmarks.[2] The use of female participants presents a unique challenge as the design of the bra worn to support the breasts during locomotion compromises the positioning of the International Society of Biomechanics (ISB) recommended thorax marker set and alternative marker locations used on males to create the trunk segment.[3-5] Although bare-breasted protocols are often used as a base line to understand breast motion in a range of activities,[6] breast biomechanics research often uses participants wearing bras to inform bra design.[7] Recently two different trunk markers sets have been used on the female population, to quantify breast motion relative to the trunk with and without breast support garments being worn. Scurr et al.[7] utilised markers placed on the suprasternal notch (STN) and left and right anterioinferior aspects of the 10th ribs to define the trunk segment. Zhou, Yu, and Ng[8] used four markers based on the ISB recommendations:[9] STN; Processus Xiphoideus (PX); 7th cervical spinous process (C7) and the 8th thoracic spinous process (T8).

The marker set used by Scurr et al.[7] has been recommended for use within breast motion research as all three markers belong to the same trunk segment and their locations are typically unobstructed by breast support garments.[10] However, the distal rib markers are located in a region with high levels of subcutaneous fat that has been suggested to reduce the stability of the trunk segment calculation.[11] In addition, the use of only three markers on the trunk may compromise the segment capture success as obstruction of a single marker prevents the construction of the trunk segment with six degrees of freedom.

The marker set used by Zhou et al.[8] utilises the recommended ISB marker placements. Inclusion of markers on the posterior of the trunk means that the orientation of the trunk segment, created with this marker set, does not match that of Scurr et al.[7], making it difficult to compare results between studies. Similarly, the ISB marker set can be problematic within breast research as the PX and T8 markers can be obscured by the breast support garment worn by the female participants,[11,12] which can also lead to insufficient visible markers for segment reconstruction. Whilst it could be argued that markers positioned on the bra itself, could address this limitation, bras that do not lie flat to the skin between the breasts, [7,12] may inhibit accurate placement or tracking of a marker placed on the PX due to gaping between the bra fabric and the skin.

The need for the development and evaluation of trunk markers set for female participants has been highlighted in a number of studies. [10,11,13,14] Any improvements on the existing trunk marker sets would need to ensure segment capture success (minimisation of marker drop out), without compromising stability during bare-breasted trials, whilst also considering the location and design of bra straps and other bra design features such as the height of the neckline,[12] that may potentially obstruct marker placement during data collection with females wearing a bra. Marker locations should also be restricted to the trunk segment, rather than adjacent segments such as the pelvis or clavicles as relative motion of these bony structures would distort the trunk segment.[10] This study aimed to compare two existing and a modified trunk marker set used to calculate trunk and breast motion during treadmill running. The first hypothesis stated that there will be significant differences in marker capture success, trunk segment instability and segment residual between the three trunk segment calculation methods. The second hypothesis stated that there will be a significant difference in trunk kinematics between the three trunk segment calculation methods. The third hypothesis stated that there will be a significant difference in breast kinematics between the three trunk segment calculation methods.

Methods

Participant information

Following institutional ethical approval and written informed consent, twelve female participants [age: 23.8, SD=3.5 years, height: 1.68, SD=0.06 m, mass: 61.0, SD=5.8 kg, bra size: 32 to 34 underband with a B to D cup size (3 x 32B, 1 x 32D, 5 x 34B, 3 x 34C), determined by the researchers, using the bra fitting criteria set out by White and Scurr],[17] were selected to participate in this study.

Marker placement and trunk segment construction

Eight trunk markers were used to define the three trunk calculation methods (Figure 1). All trunk calculation methods were constructed in Visual 3D (C-Motion Inc, USA) using the software segment definitions and optimisation algorithm with the segment origin defined as the proximal end.[11] Two trunk calculation methods were based upon existing marker sets.[7,8]

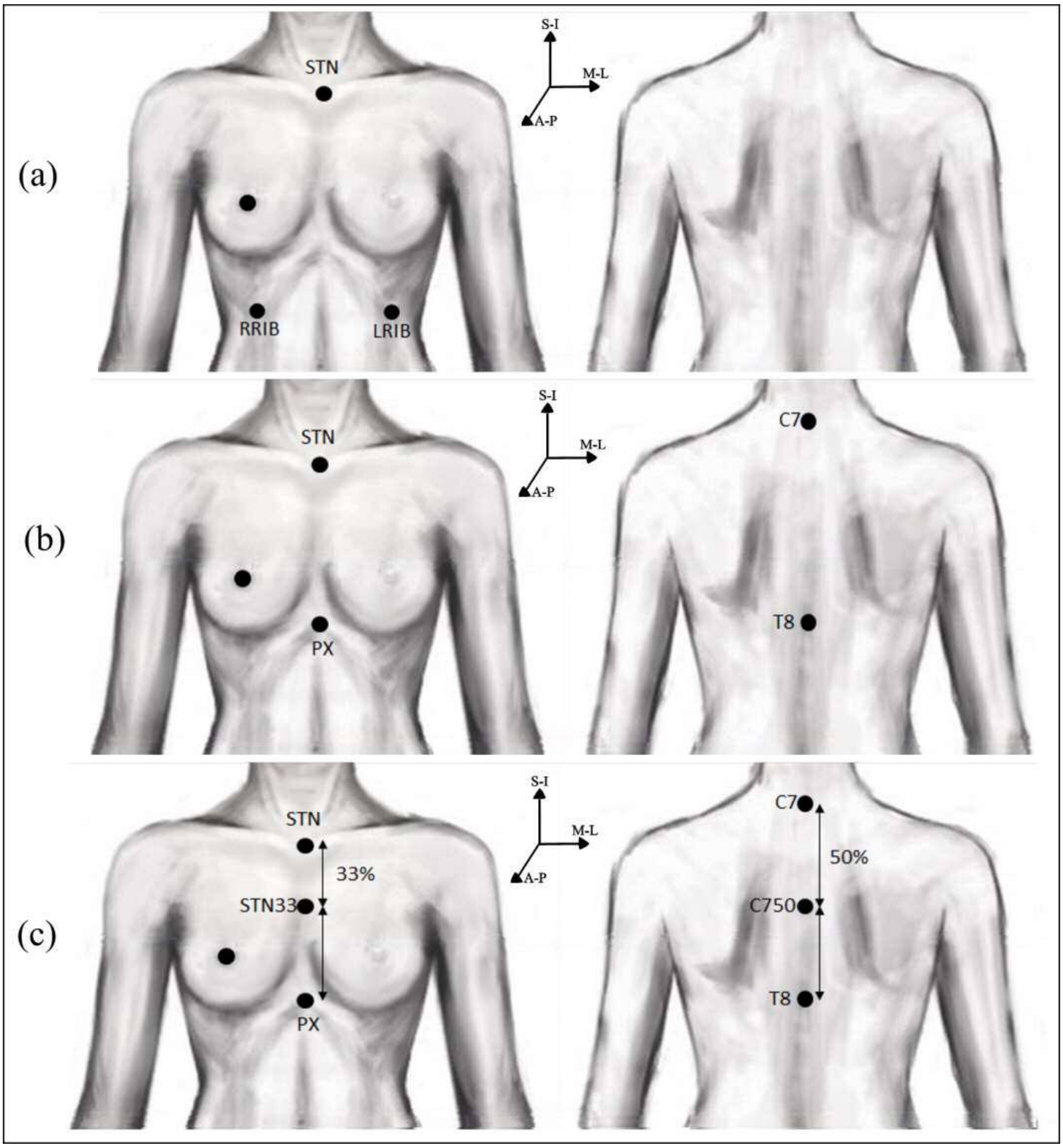

Figure 1. Illustration of marker locations on the female upper body. (a) Trunk 1: STN, left (LRIB) and right (RRIB) anterio-inferior aspect of the 10th ribs;[7] (b) Trunk 2: STN, PX, C7, T8;[9] (c) Trunk 3: trunk 2 plus an additional marker (STN33) positioned 33% of the distance from the STN to the PX, and a second marker (C750) placed 50% between the C7 and T8 markers.

Trunk 1 was defined using the STN as the proximal end of the segment with the right and left ribs as the lateral and medial distal end points (Figure 1a). The superioinferior (S-I) axis of Trunk 1 was defined by the vector extending from the distal (mid-rib point) to proximal end of the trunk segment. The anterioposterior (A-P) axis was determined by the vector that is perpendicular to both the plane (defined by the three segment markers) and the S-I axis. The mediolateral (M-L) axis was determined using the right hand rule (Figure 2).

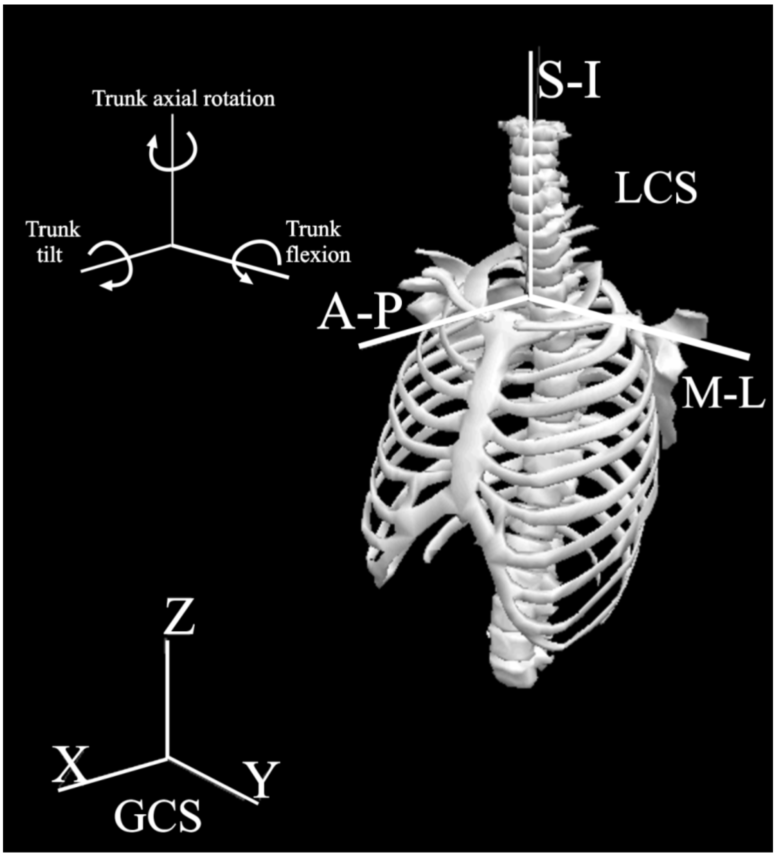

Figure 2. Axis of the global coordinate system (GCS) and local coordinate system (LCS), with associated trunk rotation angles defined (Trunk 1).

Trunk 2 was defined using the mid-point between the STN and C7 marker as the proximal end of the segment and the mid-point between the PX and T8 markers as the distal segment end (Figure 1b). The superioinferior axis of Trunk 2 was defined as the vector extending from the distal to proximal end of the trunk segment and the anterioposterior axis was determined by the vector that is perpendicular to both the plane (defined by the four segment markers) and the S-I axis. The mediolateral axis was determined using the right hand rule.

The third trunk segment was developed via pilot work, which involved participants wearing a sample of six different bras (Figure 3) in a random order, selected from published papers,[7,8,15] to determine possible marker locations, unobstructed by the majority of bra designs. Although the ISB marker set represents the latest recommendations for the positioning of trunk markers,[9] two of these recommended marker locations (PX, T8) were often obscured (Figure 3). The third marker set utilised the ISB recommendations (Figure 1b), plus an additional two tracking markers (Figure 1c), one on the anterior of the trunk (above the neckline of the sample bras) and one on the posterior (above the under bands and unobstructed by most strap designs) (Figure 3). Pilot testing found these locations were the simplest to place whilst also ensuring that the additional marker placements ensured the mean radius of the marker positions were greater than 10 times the assessed standard deviation of the errors.[16] Potential marker locations on the clavicles, scapula, lumbar spine or pelvis were excluded due to relative motion between these locations and the thoracic spine (over which the breasts are positioned) having been discussed.[10] At this stage it was noted that all Trunk 1 markers and at least three markers in Trunk 3 were visible in all six bra conditions, allowing subsequent trunk segment construction. However, insufficient Trunk 2 markers were visible in three of the six bras, therefore preventing trunk 2 segment construction.

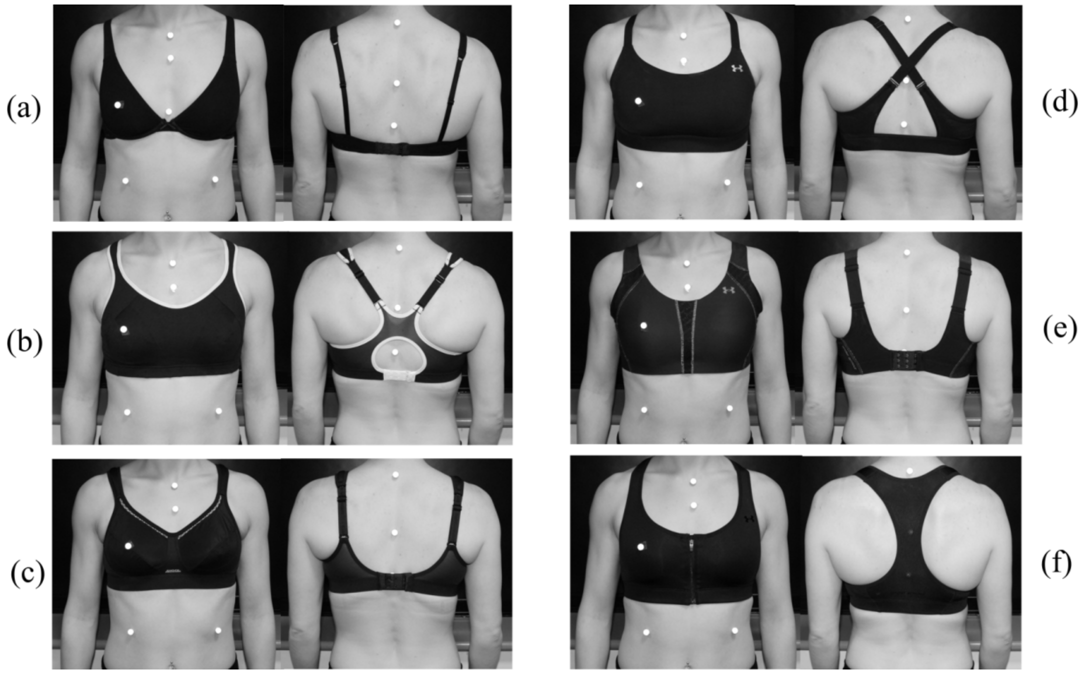

Figure 3. Example bra designs and the marker locations used to define the three trunk calculation methods. (a) Marks and Spencer T shirt bra;[7] (b) Shock Absorber Active Multi Sports Support S4490;[7] (c) Shock Absorber Active Classic Support SN102;[8] (d) Under Armour – Armour Bra; (e) Under Armour – Armour Bra Protegee; (f) Under Armour – Eclipse Bra. Bras (d) to (f) based upon different strap designs described in Bowles and Steele.[15]

Trunk 3 was defined as per the Trunk 2 segment, but with the addition of two tracking markers (STN33 and C750) (Figure 1c), creating redundancy for segment tracking during bra conditions, eliminating the need for XP and T8 if obscured by a bra (Figure 3). The S-I axis was used as the primary axis for all three of the trunk calculation methods.[13] For the purpose of assessing origin instability, two virtual landmarks (Trunk 2 virtual origin, Trunk 3 virtual origin) were created for Trunk 2 and Trunk 3 segments to represent the static origin of each trunk segment as defined in their construction.

Experimental protocol

Participants completed a self-directed treadmill warm up (H/P/Cosmos Mercury, Germany) and then removed their bra. Retro-reflective passive markers (.006 m radius) were positioned on the participant's trunk for the 3 models and on the right nipple (Figure 1). The anterioposterior coordinates of an additional heel marker was used to derive its velocity and the change from positive to negative indicated heel strike, defining each gait cycle.[7] Three dimensional motion of the markers was tracked using 15 calibrated optoelectronic cameras (200 Hz, Oqus, Qualisys, Sweden), positioned around the treadmill. For the segment estimation algorithm, participants stood statically in the anatomical position for 2 seconds bare-breasted.[11] To determine whether the trunk marker set affects trunk and breast kinematics when sufficient markers to construct the trunk segment are visible, participants then ran bare-breasted at 2.8 $m.s^{-1}$ on the treadmill.[18] Marker coordinates were recorded for five gait cycles.[19]

Data Analysis

Markers were identified and reconstructed in QTM (Qualisys Track Manager; v2.9, Qualisys, Sweden) and subsequently filtered, in Visual 3D (C-Motion Inc, USA), using a second order, recursive, low pass Butterworth filter with a cut off of 13Hz.[11] No data interpolation was used as marker obstruction was one of the parameters investigated within this study. The marker positional data from both the bare-breasted static and dynamic trials were used to construct the three trunks in Visual 3D.

Segment capture success (%) was defined (in QTM) as the percentage of time (over the 5 gait cycles) where three or more markers (from each trunk marker set) were visible and could be used to construct the trunk segment (Figure 4). Origin instability (m) was defined as the maximum resultant displacement between the marker / landmark used to define the segment origin in the static trial (STN or mid-point between STN and C7) and the position and orientation of the segments (POSE) calculated segment origin (proximal end of the segment) during the dynamic trial. Maximum segment residual (m) was defined in Visual 3D using a least squares fit of the marker locations in the static trial to the marker locations at each frame of the dynamic trial. Maximum trunk rotation was defined as the difference between the alignment of the axes of the local coordinate system of each trunk segment and axes of the global coordinate system. Trunk tilt, flexion and axial rotation represented rotation in the frontal, sagittal and transverse planes respectively (Figure 3). Multiplanar breast range of motion (ROM) was calculated by subtracting the minima from the maxima positional coordinates of the nipple marker along each axis, relative to each trunk segment during each gait cycle.[7] For each participant, parameters were assessed using each trunk segment for the same separate five gait cycles, averaged over the five gait cycles and the participant group mean and standard deviation were calculated.

Statistical Analysis

All data were checked for normality using Shapiro-Wilk tests ($P > 0.05$). Multiple one way repeated measures Analysis of Variance (ANOVAs) were used to determine differences in trunk segment capture success, trunk segment instability, trunk segment residual, trunk and breast kinematics (dependent parameters) associated with the three trunk calculation methods (independent parameters). ANOVAs were followed by post-hoc analysis in the form of multiple paired samples T-tests with a Bonferroni adjustment ($P < 0.017$). Effect sizes (partial eta squared η^2 for overall effect ($P < 0.05$) associated with the ANOVAs and Cohen's d for the post-hoc analysis) are reported, to provide an indication of the magnitude of the statistical result. A large effect size was defined as $\eta^2 > 0.5$ or $d > 0.8$, moderate between $\eta^2 <$

0.5 and > 0.3, or d < 0.8 and > 0.5, and a small effect size defined as $\eta^2 < 0.3$ and > 0.1, or d < 0.5 and > 0.2.[20]

Results

Mean trunk segment capture success using Trunk 1 was 88% (SD = 10.2%) with only one participant's markers being captured at 100%, during the bare-breasted running trial. This significantly improved with the remaining trunk calculation methods, where all participant's markers were captured at 100% ($F_{(2, 12)} = 16.541$, $P = 0.002$, $\eta^2=0.601$). It was interesting to note that despite a high capture success using Trunk 1, the missing data occurred at the times when the breast was near its maximum and minimum position (Figure 4).

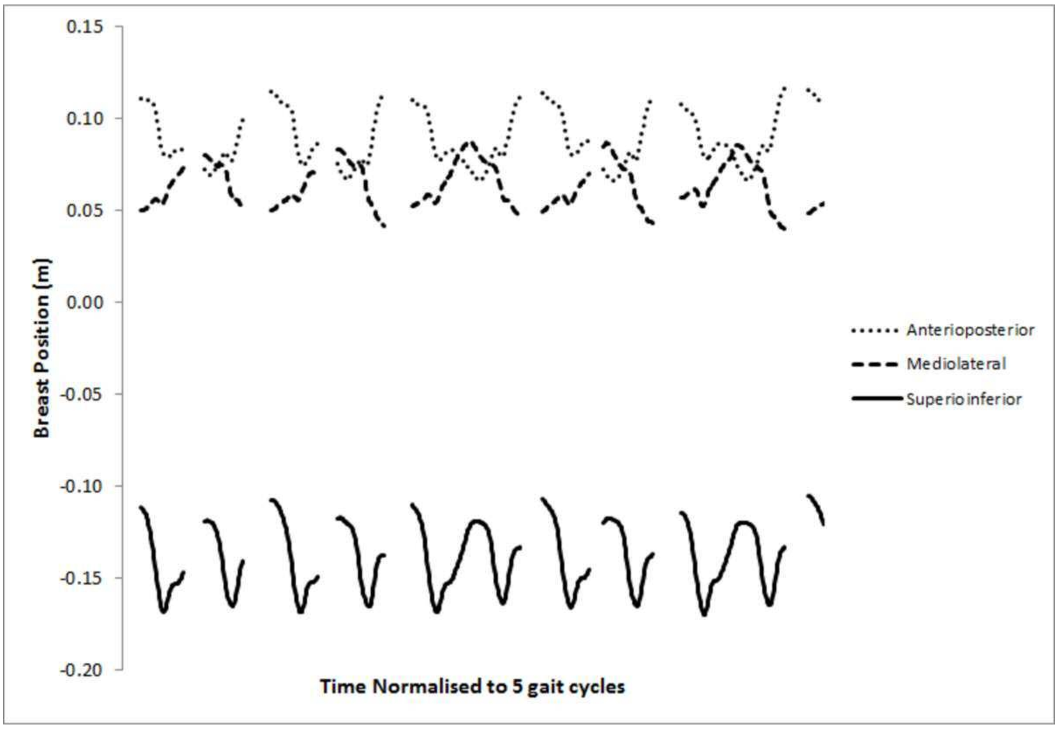

Figure 4. An example of a time history of the right breast over 5 gait cycles relative to the segment origin of Trunk 1 (n=1).

The greatest origin instability (0.015, SD = 0.008 m) was associated with Trunk 1, which was significantly less stable than Trunk 2 (0.002, SD = 0.001 m; t = 5.092, P<0.001, d = 2.16) and Trunk 3 (0.002, SD = 0.001 m; t = 5.341, P<0.001, d = 2.18). This suggests that the trunk segment origin displaces further away from its defined position when using Trunk 1. The marker set with the greatest segment residual was Trunk 1 (0.005, SD = 0.002 m), followed by both Trunk 2 and Trunk 3 marker sets (0.004, SD = 0.001 m), although these were not significantly different ($F_{(2, 12)}$ = 2.432, P = 0.111, η^2=0.533).

Significant differences were found in maximum trunk tilt ($F_{(2,12)}$ = 8.291, P = 0.002, η^2=0.438) and anti-clockwise and clockwise axial rotation ($F_{(2,12)}$ = 142.077, P<0.001, η^2=0.938; $F_{(2,12)}$ = 72.765, P<0.001, η^2=0.893), these differences were up to 7° between trunk calculation methods (Figure 5). Trunk maximum flexion and extension angles also varied significantly ($F_{(2,12)}$ = 39.972, P<0.001, η^2=0.784; $F_{(2,12)}$ = 40.329, P<0.001, η^2=0.786) by 7° depending upon the trunk segment. Trunk 1 maximum extension was greater than and maximum flexion less than, Trunk 2 and Trunk 3, whilst there were no significant differences between Trunk 2 and Trunk 3 (Figure 5).

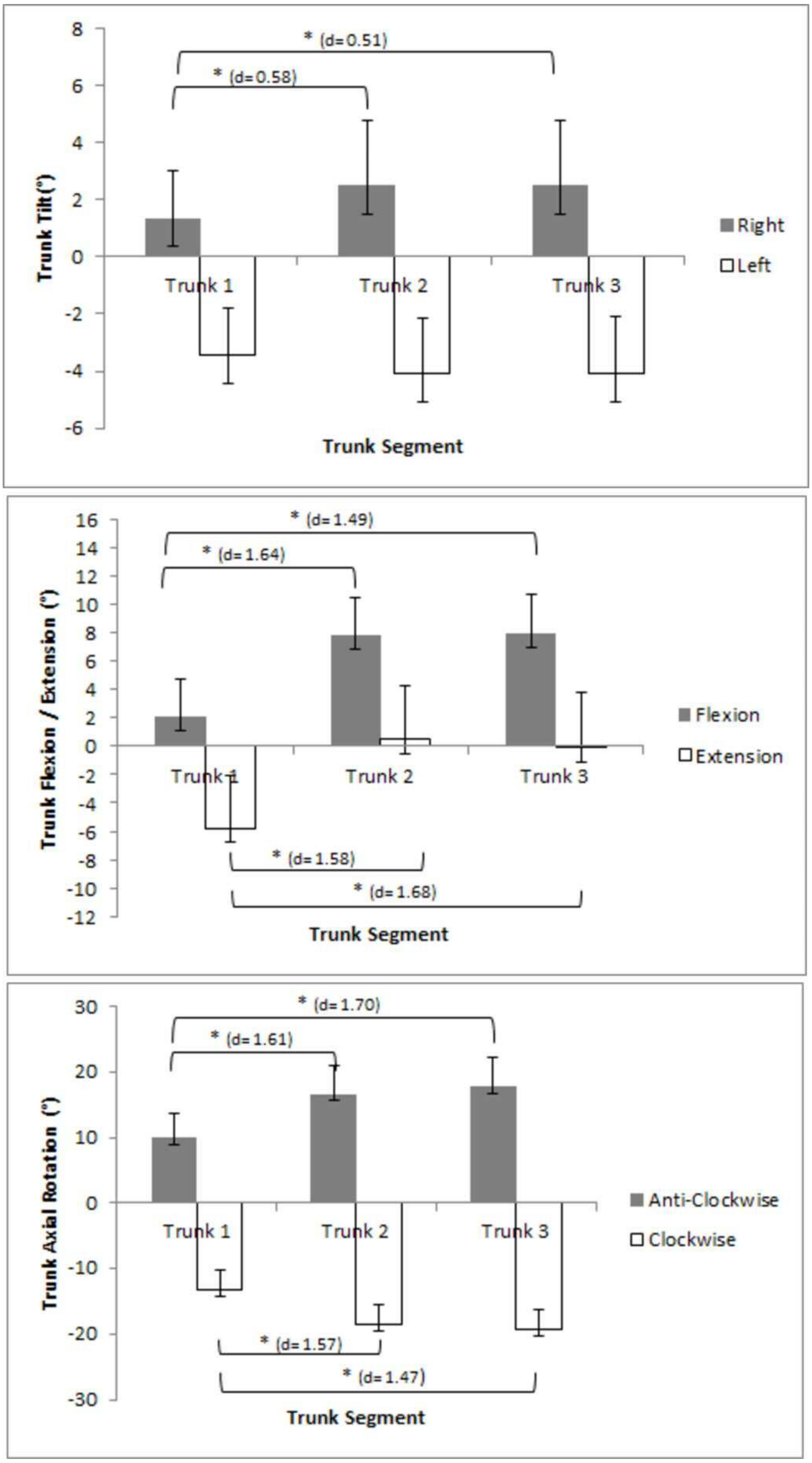

Figure 5. Maximum (SD) trunk tilt, trunk flexion / extension, trunk axial rotation for three trunk segment constructions during bare-breasted treadmill running (n=12). Zero represents alignment of the local and global coordinate systems. (* = p<0.001; d = effect size).

Breast ROM was significantly different in the anterioposterior ($F_{(2, 12)}$ = 153.762, P<0.001, η^2=0.933) and mediolateral ($F_{(2, 12)}$ = 110.870, P<0.001, η^2=0.910) directions when using Trunk 1 ($Trunk1_{A-P}$ = 0.039 m; $Trunk1_{M-L}$ = 0.035 m), compared to Trunk 2 and Trunk 3 ($Trunk2_{A-P}$ = 0.026 m, $Trunk3_{A-P}$ = 0.023 m; $Trunk2_{M-L}$ = 0.018 m, $Trunk3_{M-L}$ = 0.016 m). Finally, a significant difference was also found between trunk calculation methods ($F_{(2, 12)}$ = 27.584, P<0.001, η^2=0.715) in the superioinferior direction with greater ROM when using Trunk 2 and 3 ($Trunk2_{S-I}$ = 0.052 m; $Trunk3_{S-I}$ = 0.050 m) compared Trunk 1 ($Trunk1_{S-I}$ = 0.043 m). It was also found that Trunk 2 had significantly greater anterioposterior and superioinferior breast ROM when compared to Trunk 3 (Figure 6).

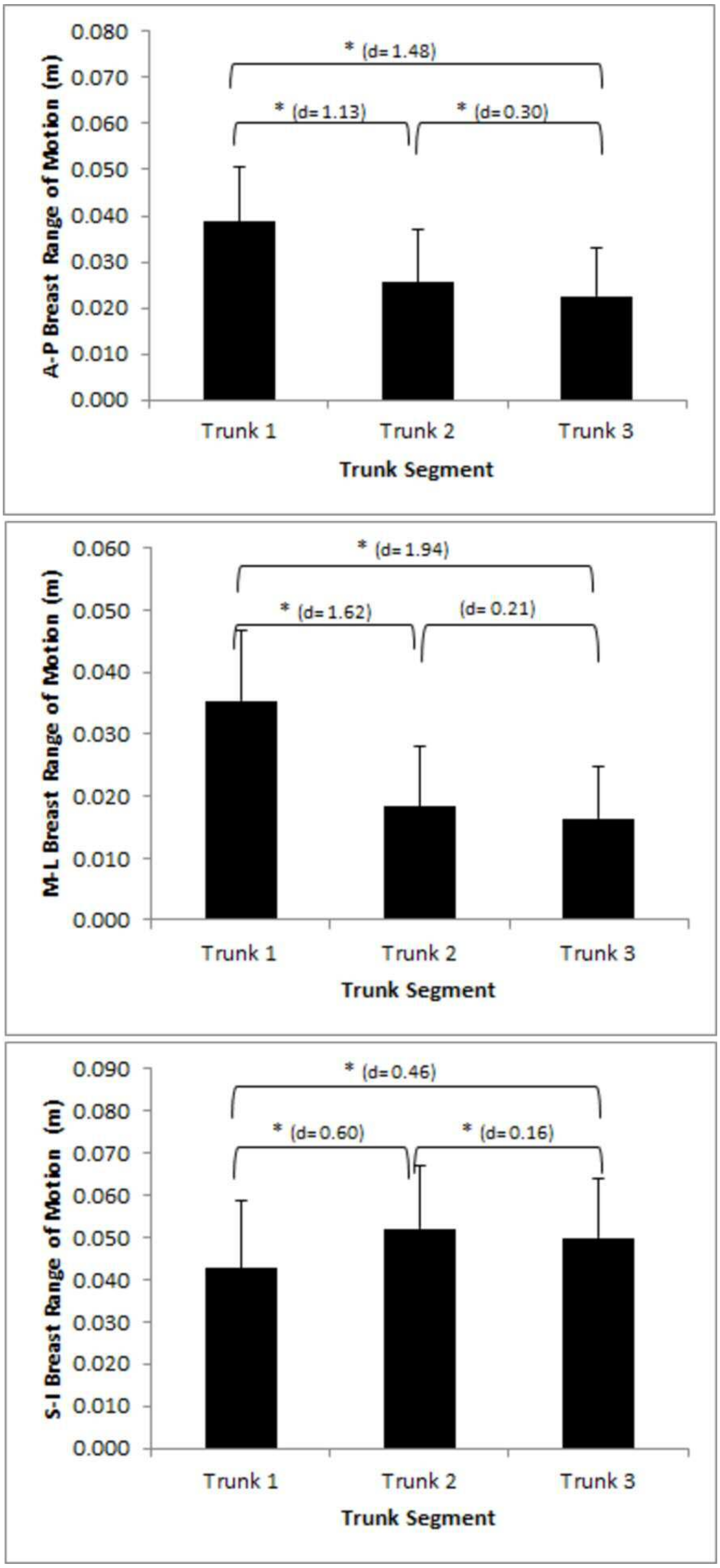

Figure 6. Breast range of motion calculated during bare-breasted treadmill running using three trunk calculation methods (n=12). (* = p<0.001; d = effect size).

The relative percentage distribution of breast ROM also differed depending upon the trunk segment used. Trunk 1 suggests an equal multiplanar distribution of breast ROM. In contrast the remaining trunk calculation methods suggest that the majority of breast motion occurred in the superioinferior direction (Figure 6).

Discussion

This study aimed to compare two existing and a modified trunk marker set used to calculate trunk and breast motion during treadmill running. Key findings showed that the markers used to construct the Trunk 1 segment was the only one to yield less than 100% capture success and also caused the greatest segment origin instability. Furthermore, the multiplanar distribution of relative breast ROM was up to 20% different when using Trunk 1 compared to Trunk 2 and Trunk 3 during bare-breasted running.

Marker capture success was significantly different between trunk calculation methods (partially accepting the first hypothesis) and is critical for subsequent construction of the trunk segment. Trunk 1 achieved 88 % segment capture, qualitative inspection of the optoelectronic data revealed that the arm swing used by the participants during running tended to alternately obscure the rib markers. Marker occlusion at time points where the breast was near its maximum or minimum displacement relative to the trunk may have reduced the magnitude of breast ROM measured using Trunk 1 which raises concerns over the suitability of this trunk marker set for the use with female participants during running, using the retro-reflective markers and cameras within this study.

It was shown from the pilot study that bras tend to obscure the PX and T8 markers (Figure 3), leaving insufficient markers to reconstruct the Trunk 2 segment. However, the additional tracking markers in the Trunk 3 marker set, particularly STN33, meant that this segment could still achieve 100% segment capture success due to the additional redundancy in the trunk segment. The Trunk 3 marker set was deemed more suitable for breast motion research based upon the potential for segment capture success during bra trials.

Segment origin instability results suggest significant differences in the three trunk segment calculation methods (partially accepting the second hypothesis) and that the proximal end of the Trunk 1 displaced the furthest (0.015 m) from the defined origin (STN) when compared to the other marker sets used in this study. It was found that the majority of this origin instability occurred in the superioinferior direction which may have been due to motion of the subcutaneous fat in this direction at the distal marker locations used for this trunk segment.[11] It was proposed that the reduction in superioinferior breast ROM relative to Trunk 1 was caused by in phase motion of the rib markers and nipple, which may have resulted in the segment origin displacing with the nipple over the gait, decreasing the breast ROM. This concept was supported by the observation that the sum of the origin displacement (0.015 m) and breast superioinferior ROM (0.043 m) measured using Trunk 1 was similar to the breast ROM measured using Trunk 2 and Trunk 3 (~0.051 m), which both had more stable segment origins (Figure 6). Reduced levels of soft tissue beneath the markers used in Trunk 2 and Trunk 3 may have led to improved segment origin stability and better overall segment stability assessed using the segment residual, however no significant differences were found between trunk segment calculation methods, partially rejecting the first hypothesis. Considering that the segment residual is a resultant value, for which one component will always be zero for a reference plane containing three markers (Trunk 1), it may be expected that segments created from four or more markers would produce higher residual values even if the individual locations of markers are more stable. It was concluded that the marker set used to construct Trunk 2 or Trunk 3 is more suitable for female participants when considering segment instability.

The effect of marker locations on the trunk segment construction is also an important consideration when assessing trunk rotation with female participants. Results showed significant differences in trunk kinematics between the trunk segment calculation methods (accepting the second hypothesis). The greatest difference (7°) occurred between Trunk 1 and Trunk 2 and 3 with Trunk 1 consistently producing lower ROMs in all directions. It is also interesting to note that Trunk 1 maximum extension was greater than and maximum flexion less than, Trunk 2 and Trunk 3. This may have implications as markers positioned only on the anterior aspect of the trunk (Trunk 1) tend to cause a backward tilt of the trunk segment relative to the global vertical axis. Postural or motor control assessment associated with neck or lower back pain must aim for neutral spine alignment as excessive sagittal flexion has been associated with higher risk groups. [21,22] Any misalignment of the trunk segment vertical axis to the global coordinate system may impact upon this postural assessment.

Additionally, differences in trunk segment rotation significantly altered the directional magnitudes of breast ROM, accepting the third hypothesis. Conclusions from breast motion studies often focus on implications for bra design to minimise breast motion and subsequent pain ,[18,23] however these recommendations may differ depending upon the marker set used to define the trunk segment. For example, based upon Trunk 1, bra design recommendations may include an equal focus on breast ROM reduction in all three directions; however, based upon Trunk 2 or Trunk 3, design recommendations may be revised to focus on breast ROM reduction in the superioinferior direction.

This study demonstrated that differences in trunk and breast kinematics are present, for the participants in this study, depending upon the trunk marker sets used. Trunk 2 or 3 could be used to construct the trunk segment during bare-breasted conditions, however, trunk 3 is recommended when participants are wearing a bra due to its marker redundancy from the additional tracking markers, eliminating the reliance on XP and T8 which may be covered by the bra.

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Conflict of interest statement

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

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