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Is torso soft tissue motion really an artefact within breast biomechanics research?

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2

3 IS TORSO SOFT TISSUE MOTION REALLY AN ARTEFACT WITHIN BREAST

4 BIOMECHANICS RESEARCH?

5

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7

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26 **Abstract**

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

46

47 **Keywords:** trunk; displacement; running; POSE, kinematics

48

49 **Introduction**

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

68

69 The quantification of breast motion presents a unique challenge regarding the marker set used
70 to represent the torso segment. The International Society of Biomechanics (ISB) recommend
71 markers be placed on the Incisura Jugularis (IJ), Processus Xiphoideus (PX), 7th cervical
72 spinous process (C7) and the 8th thoracic spinous process (T8) (Wu et al., 2005). However,
73 this marker set has not been widely adopted in breast biomechanics research as both the XP

74 and T8 sites are commonly obscured by the breast support garment worn by the participants.
75 The alternative marker set used in breast biomechanics consists of three markers placed on
76 the sternal notch, and left and right anterior aspects of the 10th rib (Scurr et al., 2010). Zhou et
77 al., (2011) reviewed the use of marker sets in breast biomechanics and concluded that the
78 marker set by Scurr et al. (2010) was the most appropriate as all three markers belong to the
79 same segment and can be regarded as a stable reference frame. Furthermore, it was also noted
80 that the distal marker locations of the Scurr et al. (2010) marker set (10th ribs) are placed
81 around an anatomical location that is likely to have a substantial amount of subcutaneous fat,
82 which may result in localised torso segment deformation. Assuming segment rigidity for a
83 potentially non-rigid torso segment may influence subsequent calculations of breast
84 kinematics, therefore the use of this marker set was of particular relevance to this research
85 study.

86
87 The applied research in breast biomechanics is centred on two main themes; understanding
88 the behaviour of the breast in a variety of physical activities and / or the development and
89 understanding of breast support devices and how they may reduce breast motion. It may be
90 possible that the markers on the soft tissue of the torso (especially the rib markers of Scurr et
91 al., 2010) move with respect to one another, and the origin, when compared to the torso
92 template used for segment optimisation. Any relative torso marker movement may
93 subsequently alter the magnitude of breast range of motion when compared to a more stable
94 torso defined by segment optimisation POSE estimation (Milligan et al., 2011). The
95 magnitude of torso soft tissue artefact has also been shown to depend upon the type of
96 physical activity performed by the participants (Heneghan and Balanos, 2010), with the arm
97 elevation associated with jumping significantly increasing the soft tissue artefact at the torso.

98

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

117
118 This study aimed to quantify differences in POSE estimation algorithms and subsequent
119 relative breast range of motion, within three breast support conditions. The first hypothesis
120 stated that there were no significant differences in torso segment lengths between POSE
121 estimation algorithms, within each breast support condition. The second hypothesis stated no
122 significant differences in torso segment length, using direct POSE estimation, between breast
123 support conditions. The third hypothesis stated that there were no significant differences in

124 multiplanar breast range of motion between POSE estimation algorithms, within each breast
125 support condition.

126

127 **Methods**

128 Following institutional ethical approval and written informed consent, ten female participants
129 (mean \pm *SD*: age 22 ± 2 years, height $1.65 \pm .04$ m, body mass 61.0 ± 2.4 kg) were selected to
130 participate in this study if they were recreationally active, aged between 18 and 39 years,
131 were not pregnant, had no history of breast surgery, had not given birth or breast-fed in the
132 last year, and were a 32D cup size (assessed using the bra fitting criteria set out by White and
133 Scurr, 2012). Due to the lack of published multi-planar breast kinematic data a post-hoc
134 power calculation was conducted (G*Power 3.1 software; Faul et al., 2007) after 10
135 participants had been tested; this indicated that a sample size of 10 would provide a power of
136 1, therefore no further participants were recruited.

137

138 Participants completed a self-directed treadmill warm up (Powerjog, H/P/Cosmos Mercury,
139 Germany). Following the warm up period, retro-reflective passive markers (.006 m radius)
140 were positioned on the sternal notch, left and right anterior inferior aspect of the 10th ribs, and
141 on the right nipple (Scurr et al., 2011) (Figure 1). A nipple marker has previously been shown
142 to be a reliable and valid measure of gross breast displacement (Mason et al., 1999). An
143 additional heel marker was added to track gait cycles (Scurr et al., 2010). Three dimensional
144 movement of the markers were tracked using twelve optoelectronic cameras sampling at 200
145 Hz (Oqus, Qualisys, Sweden), positioned in an arc around the treadmill. Cameras were
146 calibrated using a coordinate frame positioned on the treadmill and a handheld wand
147 containing markers of predefined distances (QTM [Qualisys Track Manager]; version
148 1.10.828, Qualisys, Sweden).

149

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

158

159 Markers were identified and reconstructed in QTM, and a fast Fourier transformation was
160 performed on the reconstructed data in MatLab (version R2010a). The power spectrum
161 revealed that approximately 85% of the signal power was below 16 Hz and a subsequent
162 residual analysis, based on Winter (2009), determined a cut-off frequency of 13 Hz. The data
163 were subsequently filtered using a second order, zero phase shift, low pass Butterworth filter
164 with a cut off of 13 Hz. Firstly, using the direct POSE estimation algorithm (Lu & O'Connor,
165 1999; Scurr et al., 2010), the position of the breast relative to the torso segment was
166 calculated (direct). Secondly, the reconstructed marker positional data from both the static
167 template and dynamic trials were imported into Visual 3D (C-Motion Inc, Germantown,
168 USA) and a torso segment, using the segment optimisation POSE estimation algorithm
169 (Cappello et al., 1997; Lu & O'Connor, 1999), was created using the markers placed on the
170 torso (optimised). The right and left ribs were used to calculate a virtual mid-rib point. The
171 normalised vector extending from the mid-rib point to the sternal notch defined the
172 longitudinal axis (superioinferior axis). The sternal notch marker was then used to construct
173 two vectors within the torso reference plane (vector 1 extending from the sternal notch to the
174 left rib, and vector 2 extending from the right rib to the sternal notch). The normalised cross

175 product between vectors 1 and 2 defined the second axis (anterioposterior). A right handed
176 local co-ordinate system for the torso defined the mediolateral axis (Mills et al., 2014). Both
177 torso construction methods used the same axes conventions and torso markers. The origin of
178 the torso segment using direct POSE estimation was the sternal notch marker and the origin
179 of the torso segment using the segment optimised POSE estimation was the proximal end of
180 the segment.

181

182 Torso segment rigidity, for the direct POSE estimation algorithm, was assessed using the
183 maximum change in vector length of the torso segment. The vector was defined using the
184 sternal notch marker (origin) and virtual mid-rib marker (midpoint between left and right rib
185 markers). Torso length was calculated by subtracting the minimum vector length from the
186 maximum vector length of the torso segment (torso segment length). The optimised torso
187 segment was confined to retain a constant segment length. Any deviation of the torso markers
188 from their static template position was quantified using a segment residual. The segment
189 residual was calculated using a least squares fit of the markers in the static trial compared to
190 those in the dynamic trial (C-Motion Inc, Germantown, USA) for each frame and averaged
191 over the sample. Breast range of motion was calculated by subtracting the minima positional
192 coordinates from the maxima during each gait cycle (Scurr et al., 2010). Within both local
193 reference frames the x axis represented anteroposterior breast motion; the y axis represented
194 mediolateral breast motion and the z axis superioinferior breast motion (Figure 1). Five gait
195 cycles were identified using the anteroposterior velocity of the heel marker (Zeni et al.,
196 2008). For each participant, the change in torso segment length and breast range of motion
197 was assessed in five gait cycles, and the mean was calculated for each breast support
198 condition.

199

200 {Insert Figure 1 here}

201

202 Torso segment length and multiplanar breast range of motion were statistically analysed
203 using PASW software (Version 18). All data were checked for normality (Shapiro-Wilk test)
204 and the appropriate parametric (repeated measures ANOVA) or non-parametric (Friedman)
205 statistical test was implemented. Effect sizes (parametric: Cohen's d , partial eta squared η^2 ;
206 non-parametric: r) are reported for significant results ($P < 0.017$) and a large effect size was
207 defined as d or $r > 0.8$, moderate as between 0.8 and 0.5, and a small effect size defined as $<$
208 0.5 (Field, 2009).

209

210 **Results**

211 There were significant differences in torso segment length between the POSE estimation
212 algorithms within each of the breast support conditions (no bra: $z = -2.805$, $P = 0.005$, $r = 0.89$;
213 everyday bra: $z = -2.803$, $P = 0.005$, $r = 0.89$; sports bra: $z = -2.807$, $P = 0.005$, $r = 0.89$). The
214 greatest change in torso segment length, using the direct POSE estimation, was 3.4 cm in the
215 no bra condition, followed by 3.0 cm in the everyday bra and 2.8 cm in the sports bra (Figure
216 2). There were no significant differences in torso segment length ($F = 1.979$, $P = 0.200$,
217 $\eta^2 = 0.331$) using direct POSE estimation between the support conditions. The torso segment
218 length using segment optimisation POSE estimation was fixed at 28.1 cm with segment
219 residuals of 1.4 cm in the no bra, 1.3 cm in the everyday bra and 1.6 cm in the sports bra
220 condition. There were no significant differences ($F = 0.265$, $P = 0.345$, $\eta^2 = 0.213$) in the
221 optimised torso segment residuals between breast support conditions.

222

223 {Insert Figure 2 here}

224

225 There were significant differences in superioinferior breast range of motion between the
226 POSE estimation algorithms within the no bra condition ($t=-4.602$, $P=0.001$, $d=2.0$),
227 everyday bra ($t=-4.528$, $P=0.001$, $d=1.7$) and sports bra condition ($t=-3.230$, $P=0.010$, $d=$
228 0.5), with the greatest difference of 1.1 cm in the no bra condition (Figure 3). It is also
229 interesting to note that within the no bra and everyday bra conditions the greatest breast range
230 of motion occurred in the superioinferior direction when calculated using direct POSE
231 estimation, however, this changed to the mediolateral direction when calculated using
232 segment optimisation POSE estimation (Figure 3).

233

234 {Insert Figure 3 here}

235

236 **Discussion**

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

244

245 This study has shown that the markers placed on the torso do move relative to each other,
246 therefore significantly changing the length of the torso segment between POSE estimation
247 algorithms, rejecting hypothesis one. The greatest change in torso segment length was 3.4
248 cm, representing approximately 50 % of the magnitude of superioinferior breast range of
249 motion. This torso segment deformation, using direct POSE estimation, may be attributed to
250 soft tissue artefact, as it is likely that there are substantial amounts of subcutaneous fat, close

251 to the participants centre of mass, near the distal marker locations of the Scurr et al. (2010)
252 marker set (10th ribs). As the foot impacts the ground during running the ground reaction
253 force induces a soft tissue vibration wave that propagates superiorly from the foot towards the
254 head. This soft tissue motion has been shown to be as great as 3 cm in the thigh (Pain &
255 Challis, 2006) and as the soft tissue wave continues superiorly up through the torso, it causes
256 a change in relative marker locations, deforming the length of the torso segment.

257 Furthermore, the sinusoidal motion of the torso during running itself, which acts as a driving
258 force for the breasts (Haake & Scurr, 2010; 2011), could also induce soft tissue motion of the
259 non-breast tissue close to the rib markers. When investigating breast motion between
260 different types of physical activities (for example, running and jumping), varying ground
261 reaction forces may induce different magnitudes of non-breast soft tissue artefact, deforming
262 the torso segment. Therefore it would be advisable to use a segment optimised POSE
263 estimation algorithm to minimise any differences in breast motion due to intra segment
264 deformation of the torso segment between physical activity types. Future work should also
265 aim to quantify the segment residual in order to determine the effects of relative marker
266 movement associated with different activity types.

267

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

276 direct or segment optimised POSE estimation algorithms can be used when investigating
277 breast motion between different breast support garments.

278

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

300

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

314

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

326

327 **Conflict of interest statement**

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

329

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Accepted manuscript

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411

412 **Figure Captions:**

413

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415

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

419

420 Figure 2. Torso segment length during treadmill running in three breast support conditions (n
421 = 10).

422

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

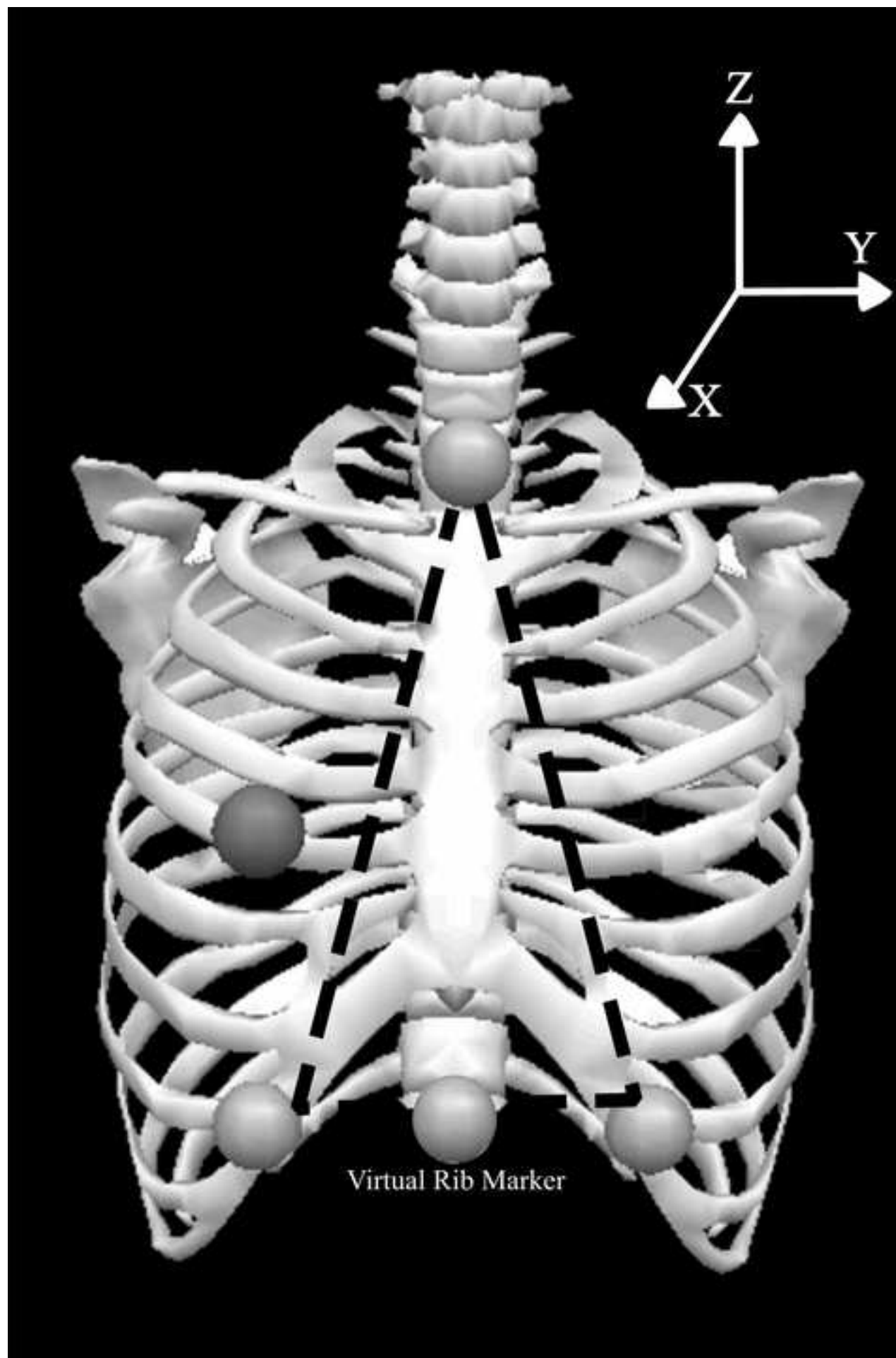
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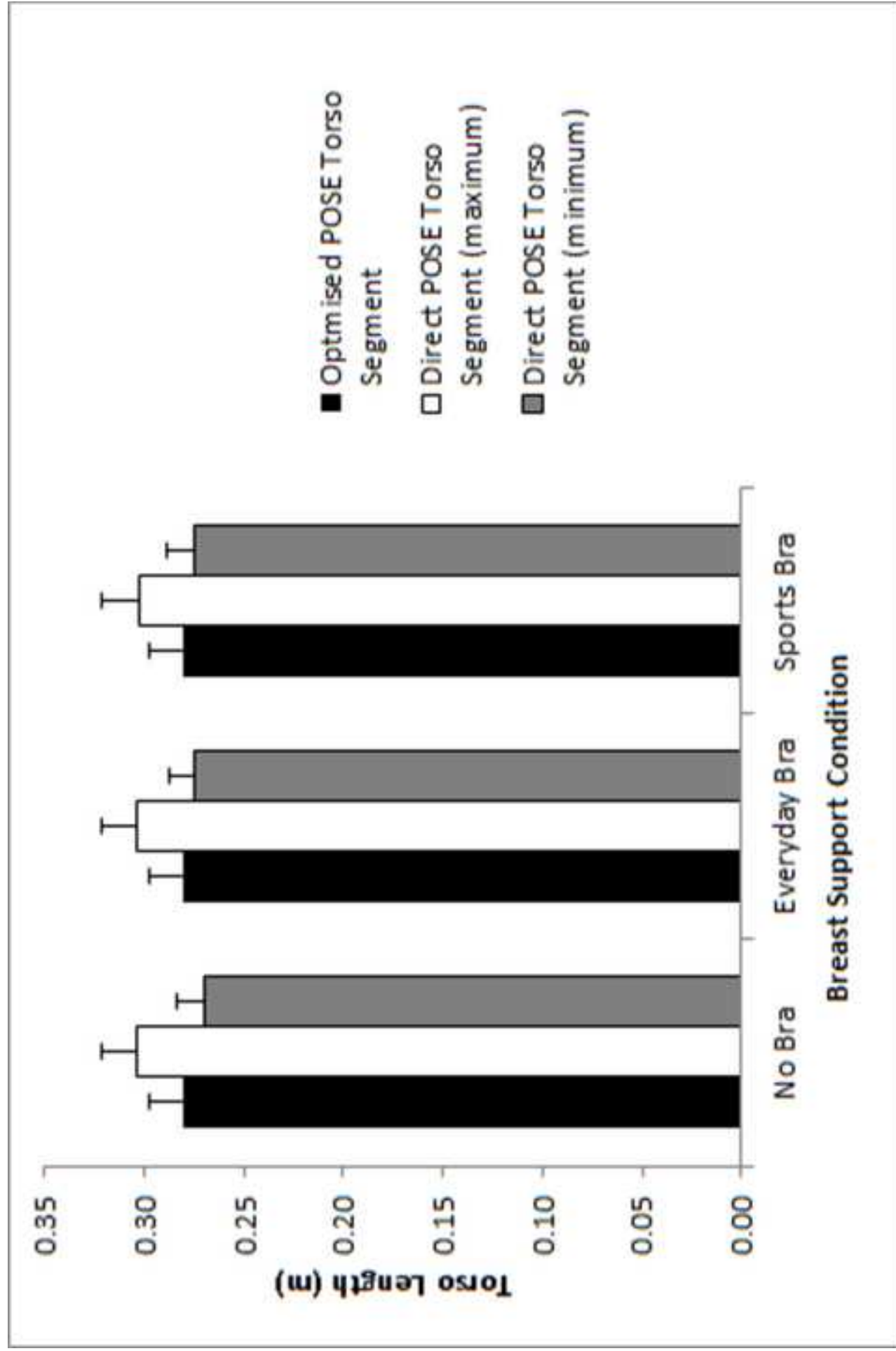


Figure 2

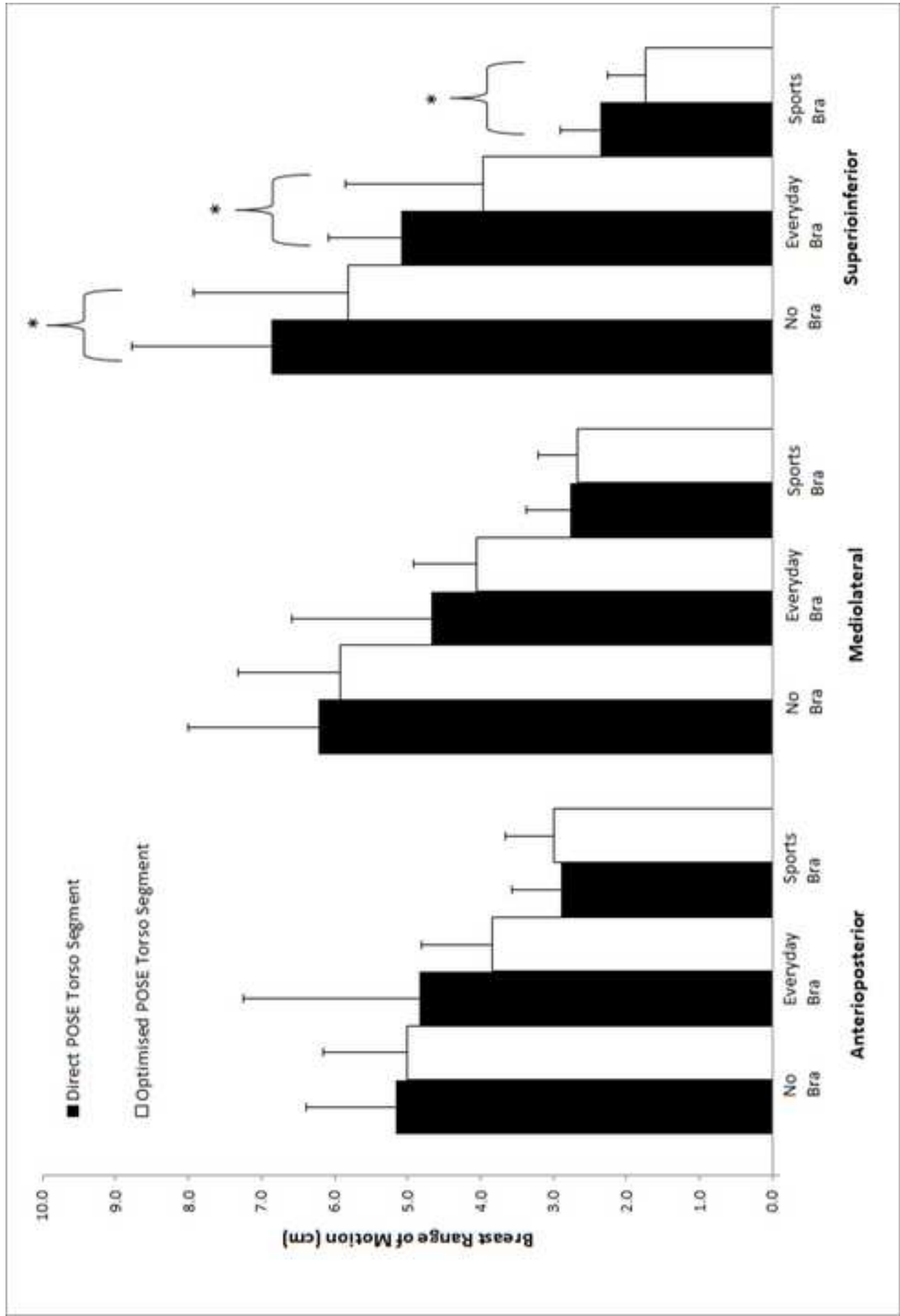


Figure 3