

1 **ORIGINAL ARTICLE** (ID RJSP-2013-0907_R2)

2 BREAST MOTION ASYMMETRY DURING RUNNING

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27 **Abstract**

28 Breast asymmetry is common in females, therefore, despite a similar driving force;
29 dynamic activity may result in asymmetrical breast motion. This preliminary study
30 investigated how breast categorisation (left/right or dominant/non-dominant) may
31 affect breast support recommendations and relationships to breast pain. Ten females
32 ran on a treadmill at 10 kph in three breast supports (no bra, everyday bra, sports
33 bra). Five reflective markers on the thorax and nipples were tracked using infrared
34 cameras (200 Hz) during five running gait cycles in each breast support. Multiplanar
35 displacements of both breasts were calculated relative to the thorax. Although the
36 maximum individual participant difference was 2.4 cm (mediolaterally) between the
37 left and right breast, no left/right differences were found in any direction or support
38 condition. Notably, correlations between breast pain and anteroposterior breast
39 displacement decreased from a strong relationship with the left breast ($r=0.614$) to a
40 moderate relationship with the right breast ($r=0.456$). Following participant
41 categorisation according to the greatest magnitude of superioinferior breast
42 displacement (dominant breast), results showed significant differences in
43 displacement for all directions across different breast supports. When using breast
44 kinematic data to examine relationships to breast pain or to recommend breast
45 support requirements, data on both breasts should be collected.

46

47 **Keywords:** displacement; bra; exercise; kinematics

48

49

50 **1. Introduction**

51 Females vary considerably in terms of the size, contour and density of their breasts at
52 maturity (Hoffmann, 2001). Breast asymmetry has been reported in 62% (Losken,
53 Fishman, Denson, Moyer & Carlson, 2005) and 82% (Gabriel et al. 2011) of the
54 population, with the left breast often being larger than the right (Losken et al. 2005;
55 Page & Steele, 1999). It has been reported that the mass of a non-lactating breast
56 ranges from 150 to 225 g (Macea & Fregnani, 2006) and differences in breast sizes
57 are usually attributed to variations in adipose tissue which may be representative of
58 different breast masses (Page & Steele, 1999). The mass of the breast has also been
59 shown to be related to the suprasternal notch to nipple distance, with increases in
60 breast mass being associated with inferior migration of the nipple during static
61 conditions (Brown et al., 2012). During dynamic movements the motion of the soft
62 tissue of the breast is governed by the driving force of the trunk (Haake & Scurr,
63 2010), the viscoelastic properties of the breast tissue (Gefen & Dilmoney, 2007), and
64 any external breast support garment being worn (Singha, 2012; Zhou, Yu & Ng,
65 2012a). During physical activities such as running breast mass asymmetry may result
66 in different kinematics for each breast based on the same driving force of the trunk.
67 A single breast (left; Zhou, Yu & Ng, 2012b), (right; Bridgman, Scurr, White,
68 Hedger & Galbraith, 2010; Scurr, White & Hedger, 2010; White, Scurr & Smith,
69 2009) is commonly used to make recommendations on improvements to breast
70 support design (Zhou et al., 2012a) and to investigate the effect of breast support
71 levels on breast kinematics and exercise induced breast pain (Bridgeman et al.,
72 2010; Scurr et al., 2010; White et al., 2009).

73

74 Multiplanar breast kinematics research during running has identified that the
75 greatest magnitude of breast displacement occurs superioinferiorly (Scurr, White &
76 Hedger, 2009; Scurr et al., 2011) and that sports bra design should aim to
77 predominantly reduce breast displacement in this direction (Scurr et al., 2011).
78 However, these recommendations are based on the analysis of breast kinematics
79 from only one breast. A further consideration is that the symmetrical design and
80 manufacture of a bra (Hardaker & Fozzard, 1997) means that any breast asymmetry
81 may reduce the effectiveness of the support of the bra for the smaller breast, since
82 bra fit recommendations suggest the bra should be fitted to the larger breast
83 (Fingleaves, 2007).

84

85 An increase in superioinferior breast displacement has also been positively correlated
86 with increases in exercise induced breast pain (Bridgeman et al., 2010; Scurr et al.
87 2010) and consequently breast biomechanics research has made recommendations to
88 wear a high level of breast support (sports bra) when exercising to reduce breast pain
89 (Bridgman et al., 2010; Scurr et al., 2010; White et al., 2009). Due to potential
90 differences in bilateral breast mass due to asymmetry, the strength of correlations
91 between breast kinematics and breast pain and subsequent recommendations for bra
92 design may depend upon the researcher's decision to analyse the left or right breast.
93 One previous study investigated the difference in resultant breast displacement
94 between the left and right breast during treadmill running and found no significant
95 differences (Scurr, White and Hedger, 2011). However, as differences in breast size
96 and mass may occur in either breast, it may be possible that the greatest breast
97 motion occurs in the left breast for some individuals and in the right for others,
98 resulting in no difference in displacement between the breasts as reported by Scurr et

99 al. (2011). If this is the case, different bra designs and support recommendations may
100 be required to further reduce levels of breast displacement and pain for asymmetrical
101 breasts.

102

103 In other areas of biomechanics the majority of research involving the execution of a
104 skill with a single limb has focussed on the dominant or preferred kicking (Anderson
105 & Dorge, 2011) or throwing limb (Forestier & Nougier, 1998). Limb movement
106 asymmetry has been investigated in various sporting activities, such as football
107 kicking (Barfield, Kirkendall & Yu, 2002; Dorge, Bullanderson, Sorensen, Simonsen,
108 2002) and cricket throwing (Sachlikidis & Salter, 2007). Limb asymmetry research
109 often categorises the participant's dominant or preferred limb, rather than the left and
110 right (Anderson & Dorge, 2011). It may be possible to re-categorise the breast in a
111 similar way using the magnitude of breast displacement, hence demonstrating a
112 possible difference in displacement and consequently the support requirements
113 between breasts. Therefore, it may be more appropriate to analyse the motion of both
114 breasts and report the side exhibiting the most superoinferior displacement
115 (categorised as the dominant breast) as the selection for subsequent correlations to
116 breast pain.

117

118 Segment mass can affect movement performance (Werner, Suri, Guido, Meister &
119 Jones, 2008), thus if breast asymmetry exists, the breast with a greater mass, moving
120 due to the same driving force, will have different kinematics. Investigating
121 differences in multiplanar breast displacement between the left and right, dominant
122 and non-dominant breast may help to inform experimental design, have implications
123 for breast support requirements and provide a further understanding of the

124 relationship between breast displacement and exercise induced breast pain. The aim
125 of this study was to quantify bilateral breast displacement in three breast support
126 conditions during treadmill running and subsequently investigate how the selection
127 of one breast over the other may affect breast support requirements and the
128 relationship to exercise induced breast pain. It was firstly hypothesised that there will
129 be no significant difference between multiplanar left and right breast displacements.
130 Secondly, there will be a significant difference in multiplanar dominant and non-
131 dominant breast displacements, with greater breast displacements being associated
132 with the dominant breast. Thirdly, the relationship between breast displacement and
133 exercise induced breast pain will differ depending upon breast categorisation.

134

135

136 **2. Methods**

137 Following institutional ethical approval, ten female participants (mean \pm *SD*: age 22
138 \pm 2 years, height 1.65 \pm .04 m, body mass 61.0 \pm 2.4 kg) gave written informed
139 consent to take part in the study. Participants were selected if they were
140 recreationally active, aged between 18 and 39 years, were not pregnant, had no
141 history of breast surgery, had not given birth or breast-fed in the last year, and were a
142 32D cup size. The 32D cup size was selected for comparison with previous research
143 and due to exercise related breast pain being more prevalent in women of a D cup
144 size or above (Lorentzen & Lawson, 1987; White et al., 2009). Participant's bra
145 breast size was measured by a trained bra fitter following best fit recommendations
146 (White & Scurr, 2012).

147

148 Participants completed a self-directed treadmill warm up (H/P/Cosmos Mercury,
149 Germany). Following the warm up, retroreflective passive markers (.005 m radius)
150 were positioned on the suprasternal notch, left and right anterior inferior aspect of
151 the 10th ribs, and on the left and right nipples (Scurr et al., 2011). A nipple marker
152 has previously been shown to give a reliable and valid measure of gross breast
153 displacement (Mason, Page & Fallon, 1999). An additional heel marker was added to
154 track gait cycles (Scurr et al., 2010). Three dimensional movement of the markers
155 were tracked using eleven optoelectronic cameras sampling at 200 Hz (Oqus,
156 Qualisys, Sweden), positioned in an arc around the treadmill. Cameras were
157 calibrated using a coordinate frame positioned on the treadmill and a handheld wand
158 containing markers of predefined distances (QTM [Qualisys Track Manager];
159 version 1.10.828, Qualisys, Sweden).

160

161 Participants ran at 10 kph for a two minute familiarisation period, after which marker
162 coordinates were recorded for five gait cycles (Scurr, White & Hedger, 2010; 2011)
163 in three breast support conditions (no bra, everyday bra and sports bra). The
164 everyday bra was a Marks and Spencer Seamfree Plain non-padded Under wired T-
165 Shirt Bra (made from 78% polyamide and 22% elastane lycra), and the sports bra
166 was the UK leading branded sports bra manufacturers best-selling encapsulation
167 sports bra (Shock Absorber Run bra, made from 81% polyamide, 10% polyester,
168 9% elastane). After each trial, participants rated their overall exercise induced breast
169 pain using a numerical scale for breast pain, this scale defines 0 as “no pain”, and 10
170 “painful” (Mason, Page & Fallon, 1999).

171

172 Markers were identified and reconstructed in QTM, and a fast Fourier transformation
173 was performed on the reconstructed data in MatLab (version R2010a). The power
174 spectrum revealed that approximately 85% of the signal power was below 16 Hz and
175 a subsequent residual analysis, based on Winter (2009), determined a cut-off
176 frequency of 13 Hz. The data were subsequently filtered using a second order low
177 pass Butterworth filter with a cut off of 13 Hz and exported into a transformation
178 matrix (Foley et al., 1995). This matrix transformed the global coordinate system
179 into a local orthogonal coordinate system using a direct frame by frame method
180 (Scurr et al., 2010), identifying the suprasternal notch as the origin and establishing
181 the right and left nipple coordinates relative to the trunk (Scurr et al., 2010). The
182 right and left ribs were used to calculate a virtual mid-rib point. The normalised
183 vector extending from the mid-rib point to the suprasternal notch defined the
184 longitudinal axis (superioinferior axis). The suprasternal notch marker was then used
185 to construct two vectors within the trunk reference plane (vector 1 extending from
186 the suprasternal notch to the left rib, and vector 2 extending from the right rib to the
187 suprasternal notch). The normalised cross product between vectors 1 and 2 defined
188 the second axis (anterioposterior). A right handed local co-ordinate system for the
189 trunk defined the mediolateral axis (Mills et al., 2014).

190

191 Gait cycles were determined using the change in foot marker velocity along the
192 anterioposterior axis, and the instant at which the velocity vector of this marker
193 changed from positive to negative indicated heel strike for each gait cycle (Zeni,
194 Richards & Higginson, 2008). Left and right breast displacement relative to the trunk
195 was subsequently calculated as the maximum minus the minimum position of each
196 nipple within one gait cycle. The data of five running gait cycles were averaged and

197 superioinferior, mediolateral and anterioposterior displacement was reported in
198 metres (m) (Scurr et al. 2010). Dominant and non-dominant breast categorisation
199 was implemented by examining the magnitude of superioinferior breast displacement
200 (the direction in which the greatest breast displacement occurred; Scurr et al. 2010)
201 of each breast, within each participant, and assigning the breast with the greatest
202 superioinferior displacement as the dominant breast and the least as the non-
203 dominant breast.

204

205 All data were checked for normality using the Shapiro-Wilks tests, paired samples T-
206 tests or Wilcoxon Signed rank tests were used to assess any differences between left
207 and right breast displacement (or dominant and non-dominant) within each breast
208 support condition. All data were parametric ($p > 0.05$) and were assessed using T-
209 tests, except superioinferior breast displacement in the everyday bra condition which
210 was assessed using the Wilcoxon Signed rank test. Effect sizes using Cohen's d (or r
211 for non-parametric) are reported for significant results to provide an indication of the
212 magnitude of the observed effect. A large effect size was defined as $d > 0.8$,
213 moderate as between 0.8 and 0.5, and a small effect size defined as < 0.5 (Field,
214 2013). Spearman's rho correlations assessed relationships between breast
215 displacement and exercise induced breast pain. Correlation coefficients (r) of 0.1 to
216 0.29 defined a small relationship, 0.3 to 0.49 a moderate relationship and 0.5 to 1 a
217 strong relationship (Field, 2013).

218

219

220 **3. Results**

221 Seventy percent of participants had greater superioinferior displacement of the left
222 breast during no bra running (Figure 1), 90 % in the everyday bra (Figure 2), 60 % in
223 the sports bra (Figure 3). The greatest individual participant difference was 1.6 cm
224 (superioinferiorly) between the left and right breast displacements in the no bra
225 condition (Figure 1), however, no significant differences ($p>0.05$) were found
226 between the left and right breasts in any direction or breast support condition
227 (Figures 2 and 3).

228

229 **** Insert figure 1 here ****

230 **** Insert figure 2 here ****

231 **** Insert figure 3 here ****

232

233 Interestingly, the direction in which the greatest left breast displacement occurred
234 was mediolaterally in both the no bra (0.064 m) and sports bra condition (0.030 m),
235 and anterioposteriorly in the everyday day (0.042 m). However, this was different for
236 the right breast, with the greatest displacement occurring in the mediolateral
237 direction in the no bra (0.059 m) and everyday bra (0.041 m) condition and in the
238 anterioposterior direction in the sports bra condition (0.031 m).

239

240 Following breast displacement categorisation into dominant and non-dominant
241 breast, significantly greater breast displacement in dominant breast was found in the
242 anterioposterior direction ($t=2.390$, $p=0.041$; $d = 0.52$), mediolateral direction
243 ($t=2.479$, $p=0.035$; $d = 0.35$) and the superioinferior direction ($t=6.445$, $p=0.000$; $d =$
244 0.31) compared to the non-dominant breast in no bra running. Significantly greater

245 dominant breast displacements were also found in the anteroposterior direction
246 ($t=3.397$, $p=0.008$; $d = 0.47$) and superoinferior direction ($Z=2.823$, $p=0.005$; $r =$
247 0.89) in the everyday bra condition and in the superoinferior direction ($t=3.597$,
248 $p=0.006$; $d = 0.33$) in the sports bra condition (Figure 4).

249

250 ****Insert figure 4 here ****

251

252 During running exercise induced breast pain was rated as 6.0 out of 10 in the no bra
253 condition, 4.4 in the everyday bra and 0.5 in the sports bra. The correlation
254 coefficient between breast pain and displacement differed for the left and right
255 breast. For example, breast pain showed a strong relationship ($r=0.614$) to
256 anteroposterior displacement of the left breast, but only a moderate relationship to
257 the right breast ($r=0.456$). Interestingly, the strength of the relationship did not differ
258 between the dominant and non-dominant breast (Table 1).

259

260 ****Insert Table 1 here ****

261

262

263 **4. Discussion**

264 The effect of any possible breast asymmetry on breast kinematics for the same trunk
265 driving force was unknown; therefore this preliminary study aimed to quantify the
266 displacement of both breasts during running and subsequently investigate how the
267 breast categorisation (left or right and dominant or non-dominant) may affect breast
268 support requirements and the relationship to exercise induced breast pain. Key
269 findings have shown that there are no significant differences in breast displacement

270 between the left and right breast within any of the three breast support conditions,
271 accepting hypothesis one. However, maximum individual differences were up to 1.6
272 cm in the superioinferior direction, with 70 % of the female participants having
273 greater superioinferior displacement of the left breast in the no bra condition, 90 %
274 in the everyday bra and 60 % in the sports bra compared to the right breast. This
275 suggests that individual differences within the sample group may have off set each
276 other when comparing the sample group mean.

277

278 Categorising breast displacement by the dominant (greatest displacement) and non-
279 dominant (least displacement) breast, based upon individual maximum
280 superioinferior breast displacement (the direction in which greatest breast motion
281 occurs; Scurr et al., 2009; 2011), revealed significant differences between dominant
282 and non-dominant breast displacements in all directions in the no bra condition.
283 Significant differences were also found in the anterioposterior direction and
284 superioinferior direction in the everyday bra and in the superioinferior direction in
285 the sports bra condition, accepting hypothesis two. This suggests breast movement
286 asymmetry does occur which may be linked with the reported differences in breast
287 size and density (Losken et al. 2005; Page & Steele, 1999), and hence mass, since
288 breast mass and individual breast size and density are difficult to measure directly
289 (Page & Steele, 1999). Other studies have also shown that mass can affect movement
290 performance (Werner et al., 2008) in which a leg or arm with a greater mass moving
291 due to the same driving force has a difference in kinematics. The reported
292 differences in kinematics between the breasts suggest different breast support
293 requirements exist for each breast. These results have significant implications for

294 bra design recommendations, advice on minimising exercise induced breast pain as
295 well as breast biomechanics research protocols.

296

297 Asymmetrical breast kinematics will have implications on bra design
298 recommendations since the direction in which the greatest breast displacement
299 occurred differed depending upon left or right breast selection. If this preliminary
300 study had collected breast displacement data from the left breast only, the conclusion
301 would have been to minimise anteroposterior breast displacement in everyday bras,
302 alternatively if this study had only collected data from the right breast it would have
303 concluded that mediolateral breast displacement reduction was necessary. Therefore,
304 this study highlights that future breast biomechanics research should collect data
305 from both breasts before making bra design recommendations. Furthermore, the
306 results raise the issue as to whether bra manufacturers could develop asymmetrical
307 cups or customisable bra cups to minimise the displacement of each breast
308 individually. This also raises a further challenge regarding how consumers determine
309 significant breast asymmetry that may require asymmetrical cup design and how
310 manufacturers can practically produce bras with asymmetrical cups that can cater for
311 all combinations and magnitudes of breast asymmetry. This approach may need to
312 begin with a case study of participants prior to possible breast asymmetry corrective
313 surgical intervention (Neto et al. 2007).

314

315 A further key finding of this study showed that the correlation coefficient between
316 exercise induced breast pain and breast displacement decreased from a strong
317 relationship in anteroposterior displacement for the left breast ($r=0.614$) to a
318 moderate relationship for the right breast ($r=0.456$), partially accepting hypothesis

319 three for this measure. Furthermore, if the left breast were selected for this study,
320 correlation coefficients suggest breast pain has the strongest relationship with
321 anteroposterior displacement, then superioinferior and finally mediolateral breast
322 displacement. However, if the right breast were selected instead, breast pain would
323 demonstrate the strongest relationship with mediolateral, followed by
324 superioinferior, then anteroposterior breast displacement. These findings have
325 implications on the recommendations made to bra manufacturers regarding design
326 features (Zhou et al. 2012a) aimed at reducing breast pain via a reduction in
327 multiplanar breast displacements. The categorising of the breasts to dominant and
328 non-dominant showed that breast pain had the strongest relationship with
329 superioinferior breast displacement, followed by mediolateral displacement and
330 finally anteroposterior displacement. These consistent findings using the dominant
331 and non-dominant breast reinforce this categorisation approach. In future breast
332 biomechanics research it is recommended that data on both breasts are collected
333 before making recommendations regarding reducing breast pain as data collected on
334 one breast may not be representative of the other due to movement asymmetry. One
335 note of caution relates to the marker set used in this study, it is likely that the distal
336 ribs markers are close to substantial amounts of subcutaneous fat. Future research
337 that aims to investigate breast kinematics and breast pain may need to investigate the
338 use of a different marker set (for example, a modified International Society of
339 Biomechanics thorax marker set, Wu et al., 2005) that reduces possible soft tissue
340 artefact associated with the rib markers in this study, whilst not being obscured by
341 the breast support garments worn by the participants.
342

343 It is interesting to note that during this study the direction in which the greatest
344 breast displacement occurred changed depending upon breast support level and the
345 left or right breast. This is in contrast to the majority of published research that has
346 reported that the greatest breast displacement occurs in the superioinferior direction
347 (Bridgeman et al., 2010; Scurr et al., 2010; White et al., 2009). White et al. (2009)
348 found 50% of breast displacement occurred in the superioinferior direction, 25% in
349 the both the mediolateral and anterioposterior directions within a no bra condition.
350 As support level increased this changed to 44% in the superioinferior direction, 28%
351 in the both the mediolateral and anterioposterior directions within a sports bra
352 condition. Despite the increase in breast support the greatest breast displacement
353 remained in the superioinferior direction for the right breast. The present study found
354 that the greatest breast displacement occurred in a different direction depending upon
355 breast support level and the breast used for analysis (left or right). For example, the
356 greatest left breast displacement occurred in the mediolateral direction for the sports
357 bra condition, but this changed to the anterioposterior direction for the right breast.
358 This conflict in findings also has implications on bra design recommendations such
359 as the direction in which bra design should minimise breast displacement, which
360 could depend upon the selection of either the right or left breast, and reinforces the
361 need for a robust methodology for the categorisation and calculation of breast
362 biomechanical data. Furthermore, this study has demonstrated that regardless of
363 breast asymmetry and without the need to measure it directly, it is still possible to
364 identify an effect and a categorisation method to deal with it.

365

366 **5. Conclusion**

367 The results of this preliminary study suggest that when using breast kinematic data to
368 understand breast support requirements, provide recommendations on bra design and
369 to examine relationships with breast pain it is advised that data are collected from
370 both breasts. The researchers can subsequently check for any movement asymmetry
371 by categorising the breasts as dominant or non-dominant then decide whether to
372 present data on both breasts or just the dominant one if movement asymmetry is
373 present. Furthermore, the selection of either the left or right breast may be
374 misleading in terms of recommendations regarding bra design.

375

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514

515 **Table 1.** The correlation between self reported breast pain and breast displacement

516 during running for each participant (n=10) across all breast support conditions.

	Spearman's correlation coefficient (r)	P-value
Anteroposterior		
Left breast displacement	0.614	0.000
Right breast displacement	0.456	0.011
Dominant breast displacement	0.500	0.005
Non-dominant breast displacement	0.562	0.001
Mediolateral		
Left breast displacement	0.503	0.005
Right breast displacement	0.661	0.000
Dominant breast displacement	0.576	0.001
Non-dominant breast displacement	0.563	0.001
Superioinferior		
Left breast displacement	0.600	0.000
Right breast displacement	0.596	0.001
Dominant breast displacement	0.605	0.000
Non-dominant breast displacement	0.598	0.000

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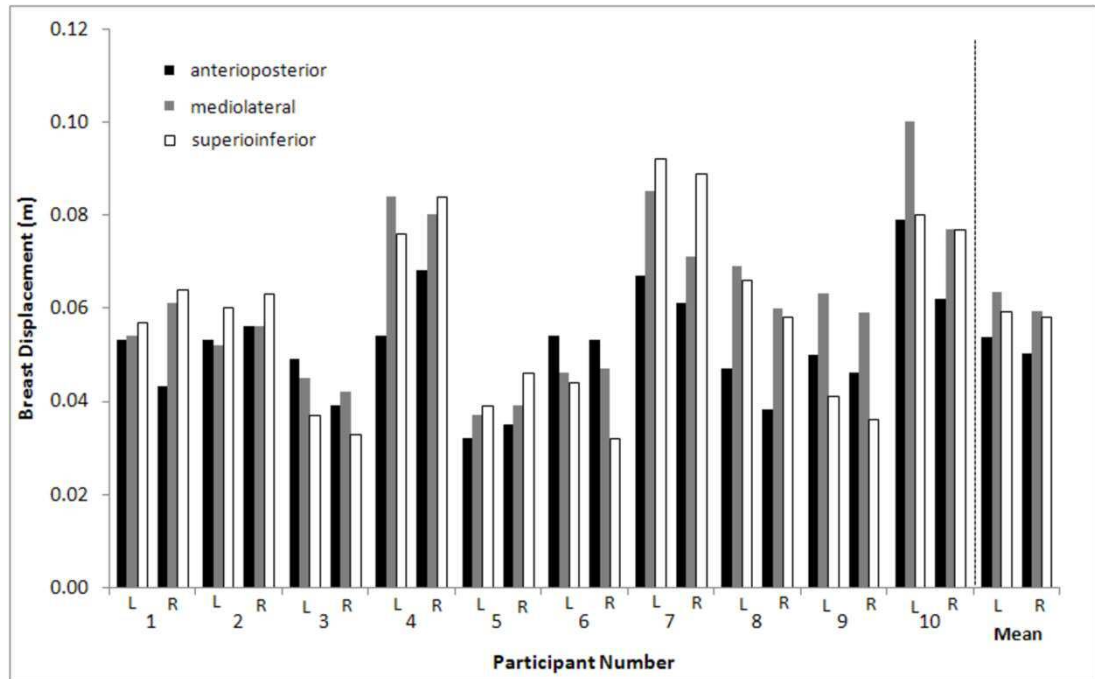
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520 **List of Figures**

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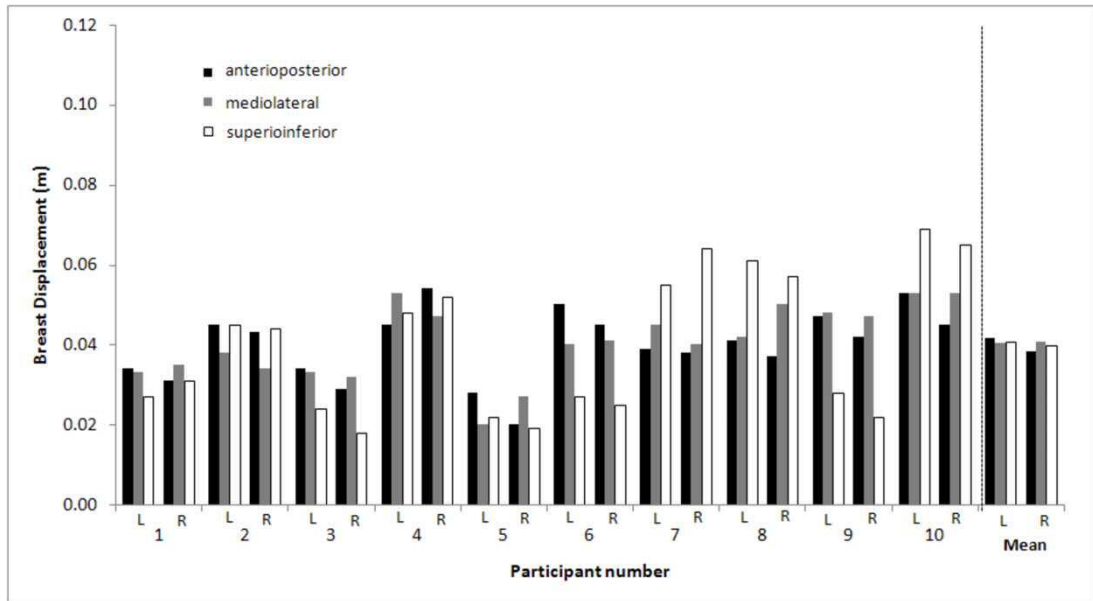
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523

524 Figure 1. Multiplanar breast displacement in the no bra condition during treadmill
525 running at 10 kph (L = left breast, R = right breast).

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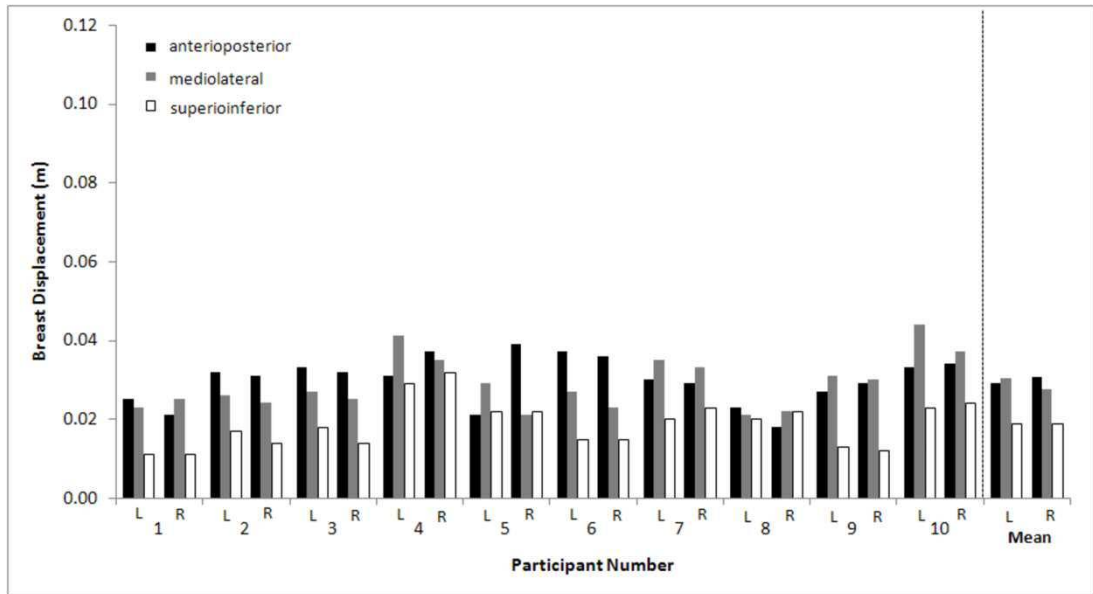
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528 Figure 2. Multiplanar breast displacement in the everyday bra condition during
 529 treadmill running at 10 kph (L = left breast, R = right breast).

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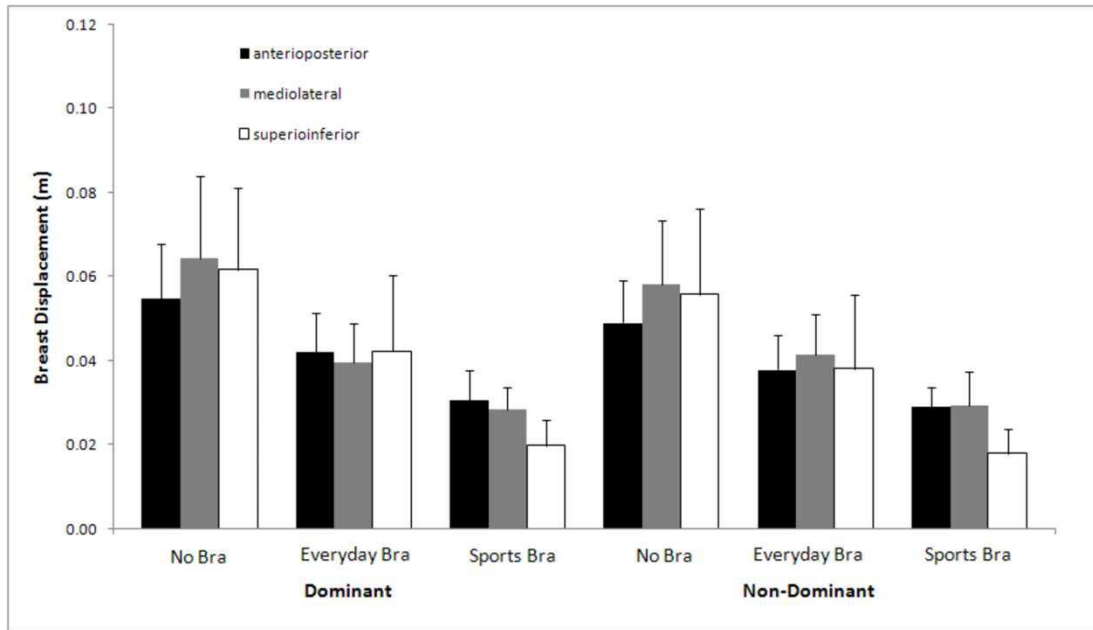
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534 Figure 3. Multiplanar breast displacement in the sports bra condition during
 535 treadmill running at 10 kph (L = left breast, R = right breast).

536



537

538 Figure 4. Mean (standard deviation) multiplanar breast displacement of the dominant
 539 and non-dominant breast during treadmill running at 10 kph in three breast support
 540 conditions (n = 10).

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