

1 **There are two sides to every story: implications of asymmetry on breast**
2 **support requirements for sports bra manufacturers**

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9 **There are two sides to every story: implications of asymmetry on breast**
10 **support requirements for sports bra manufacturers**

11 This study aimed to investigate: 1) the prevalence and magnitude of breast
12 movement asymmetry, 2) the interaction between static and dynamic breast
13 asymmetry and 3) the influence of sports bras on breast asymmetry during running.
14 Position data were collected from 167 females whilst treadmill running and then a
15 sub-group of twelve participants in different bra conditions. Breast movement
16 asymmetry existed in 89% of participants, with resultant static breast position
17 asymmetry larger in participants displaying dynamic asymmetry. Asymmetry was
18 most commonly caused (60 to 75%) by greater movement of the left breast. No
19 significant relationships were found between asymmetry and bra size or breast
20 pain. Sports bras reduced asymmetry prevalence from 75% to 33% of participants
21 in the antero-posterior direction but only from 75% to 67% of participants in the
22 infero-superior direction. The magnitude of range-of-motion asymmetry reduced
23 from 67 mm with no bra to between 6 and 64 mm in-bra in the infero-superior
24 direction, with the best performing bra incorporating encapsulating cups and
25 adjustable straps and underband. It is recommended that sports bras allow
26 underband and strap adjustment to facilitate individual breast support and that
27 asymmetry is considered when designing and fitting bras, which could utilise
28 resultant asymmetry measured statically.

29 Keywords: Breast Health, Garment Design, Running Gait, Kinematics

30

31 **Introduction**

32 Breast asymmetry relating to mass and shape of the breast has been reported to
33 exist in 94% (Losken, Fishman, Denson, Moyer, & Carlson, 2005), 88% (Rohrich,
34 Hartley, & Brown, 2006) and 18 to 55% (Brown, Ringrose, Hyland, Cole, & Brotherston,
35 1999) of the female population, depending on the measure. Furthermore, asymmetry of
36 breast size and shape has previously been reported to show a positive relationship with
37 overall breast size (Manning, Scutt, Whitehouse, & Leinster, 1997; Møller, Soler, &
38 Thornhill, 1995). Losken et al. (2005) also indicated that it was more common for the left

39 breast to be larger (62%) than the right (32%), with 6% showing no asymmetry in breast
40 size. This physical asymmetry has clear implications on breast support requirements,
41 which may differ for left and right sides due to potential asymmetry in the mass and
42 consequently force applied by each breast. Asymmetry within the human body has also
43 been widely reported relating to other physiological characteristics, such as limb length,
44 and performance measures in gait (Baylis & Rzonca, 1988; Kaufman, Miller, &
45 Sutherland, 1996; Perttunen, Anttila, Södergård, Merikanto, & Komi, 2004). Previous
46 work investigating biomechanical asymmetry in gait has identified it to be individualistic
47 in nature (Exell, Irwin, Gittoes, & Kerwin, 2012; Exell, Irwin, Gittoes, & Kerwin, 2017).
48 Based on these previous studies, it is unclear whether biomechanical asymmetry in breast
49 movement during gait would be due to greater movement of the left breast, due to the
50 typically larger breast size, or be individual as reported in other gait asymmetry measures.
51 In this manuscript, asymmetry is defined as any divergence from symmetry, which is
52 identical values for left and right sides of the body (Brown et al., 1999; Exell et al., 2012;
53 Losken et al., 2005).

54 The importance of correctly fitting and appropriate breast support garments
55 during exercise is an important topic that has received attention in the literature (Brown,
56 White, Brasher, & Scurr, 2014; Mason, Page, & Fallon, 1999; White, Mills, Ball, & Scurr,
57 2015; White & Scurr, 2012). However, if asymmetry is present within individuals' breast
58 movement during running, the support requirements may differ for each breast. From a
59 breast support perspective, information relating asymmetry in breast movement with
60 other predictive factors such as breast size or asymmetry when standing could be
61 beneficial in identifying when asymmetrical support may be required. Breast pain has
62 also been identified as an important consideration for exercising women (Brown et al.,
63 2014; Mason et al., 1999; White et al., 2015), which can reduce participation in physical

64 activity. To the authors' knowledge, breast pain has not been investigated in relation to
65 breast asymmetry, but asymmetry in the mass and subsequent force applied by the breasts
66 may lead to greater pain being experienced in one breast than the other, which could
67 influence individuals' reporting of pain. Previous studies have reported the varying
68 effects of different bras on breast movement (Lorentzen & Lawson, 1987; Mason et al.,
69 1999; Scurr, White, & Hedger, 2010), although it is unclear how differing bras influence
70 breast movement asymmetry. To the authors' knowledge, the only bras that are
71 commercially available to overcome breast asymmetry are everyday bras focussed on
72 aesthetics and producing a symmetrical overall breast shape, rather than customising
73 support for left and right breasts during exercise. As highlighted above, breast support to
74 reduce breast movement is important in relation to breast pain. Therefore, asymmetry of
75 breast movement identified during activities such as running would indicate the need for
76 more customised breast support for each side during such activities.

77 Asymmetry of breast movement during running has previously been reported to
78 exist in a preliminary study of ten 32D sized participants (Mills, Risius, & Scurr, 2015).
79 However, no previous studies investigating breast asymmetry have considered the
80 relationship between asymmetry when measured statically and during dynamic activities,
81 such as running. Furthermore, the relationship between breast movement asymmetry
82 during running and other factors such as breast size or pain have not been investigated.
83 Given the individual nature of biomechanical asymmetry reported in running gait (Exell
84 et al., 2017; Exell, Irwin et al., 2012), it is quite possible that individual asymmetry
85 profiles may exist relating to dynamic breast movement. Asymmetry of breast movement
86 during dynamic activities may have implications on breast support requirements, with
87 asymmetry in different movement directions indicating that bras may benefit from greater
88 adjustability to cater for this asymmetrical breast movement. Previous research

89 investigating breast movement in different directions and breast pain during activities
90 such as running has identified the vertical direction as having the strongest link with
91 breast pain (Mills et al., 2015; Scurr et al., 2010).

92 The aims of this study were to investigate: 1) the prevalence and magnitude of
93 kinematic breast asymmetry, 2) the interactions between static and dynamic breast
94 asymmetry and between breast asymmetry, breast pain and bra size and 3) the influence
95 of different sports bras on dynamic asymmetry during running. It was hypothesised that
96 significant breast movement asymmetry would exist during dynamic activities (H₁), that
97 it would be positively related with static breast asymmetry (H₂), bra size (H₃) and breast
98 pain (H₄) and that wearing a sports bra would reduce breast movement asymmetry (H₅).
99 The purpose of the study was to further current understanding of breast asymmetry and
100 to inform bra manufacturers, athletes and researchers about the incidence of breast
101 movement asymmetry during running. These findings may have implications on both
102 sports bra design requirements and future breast research data collection protocols.

103

104 **Methods**

105 Prior to data collection, ethical approval was gained from the University Research Ethics
106 Committee. All participants provided informed consent prior to their data being collected.
107 To address the research questions of the study, two separate protocols were utilised,
108 which are described separately and termed Collection A and Collection B. Collection A
109 involved a descriptive analysis of asymmetry prevalence and comparison with other
110 factors. Collection B incorporated an intervention of varying sports bras to assess the
111 influence on breast movement asymmetry.

112

113 ***Collection A***

114 *Participants and protocol*

115 To quantify the prevalence of dynamic breast movement asymmetry and relationships
116 with static asymmetry, bra size and breast pain, data were collected from 167 female
117 participants (25 ± 5 years, 63.3 ± 7.4 kg, 1.66 ± 0.06 m, bra size 32A - 34G), who
118 volunteered through the department's Research Group in Breast Health. Cross-graded bra
119 size was assessed by a trained bra fitter against published best fit criteria (McGhee &
120 Steele, 2010; White & Scurr, 2012) during each testing session, where a change of one
121 cross-grade size relates to an increase of one cup or underband size.

122 Breast and torso position data were collected using an automated motion capture
123 system (Oqus, Qualisys®, Sweden) operating at a minimum of 100 Hz. Following
124 calibration of the system, reflective markers were positioned on participants' suprasternal
125 notch, left and right anterior inferior aspects of the 10th ribs and on the left and right
126 nipples to track breast motion (Scurr, White, & Hedger, 2011). A heel marker was also
127 used to detect touchdown events during running (Scurr et al., 2010). Participants were
128 asked to stand so that their feet were aligned with the lab coordinate system whilst a static
129 trial was collected. Following an individually selected warm up, participants then ran on
130 a treadmill (H/P/Cosmos Mercury, Germany) aligned with the lab coordinate system at a
131 treadmill speed of 2.78 m/s whilst bare-breasted. This running speed (10 km/hr) was
132 selected as it has been frequently used in previous breast biomechanics research and is
133 common for recreational distance running (www.parkrun.org.uk), which leads to a large
134 number of repeated impacts over the duration of a run. Participants were asked to run for
135 a time of 2 minutes, following which, data were collected for five complete strides (i.e.
136 ten steps). Immediately after the running data were collected, participants rated the
137 highest amount of exercise induced breast pain throughout the running trial on a
138 numerical rating scale ranging from 0 (no pain) to 10 (extreme pain) (Mason et al., 1999).

139

140 *Data processing and analysis*

141 Data were reconstructed using Qualisys Track Manager software (Versions 1.10 - 2.13,
142 Qualisys, Sweden). Marker position data were filtered using a second-order low-pass
143 Butterworth filter with a cut- off of 13 Hz. Nipple position was calculated relative to the
144 local coordinate system of the trunk, defined by the suprasternal notch and rib markers
145 (Mills et al., 2015).

146 Using the antero-posterior velocity of the participants' heel markers, instants of
147 touchdown were identified as the epoch when velocity changed from being positive to
148 negative (Zeni Jr, Richards, & Higginson, 2008). Five complete strides were identified
149 for each participant.

150 Data were further analysed in Matlab (R2018b, The Mathworks ®, USA). Range
151 of motion (ROM) of each nipple marker was quantified using (1) in antero-posterior (AP),
152 medio-lateral (ML) and infero-superior (IS) directions as well as the resultant (RT)
153 direction.

154

$$155 \quad ROM = S_{Max} - S_{Min} \quad (1)$$

156

157 where S_{Max} and S_{Min} are the maximum and minimum displacement values of each nipple
158 within a gait cycle relative to the sternal notch in the local coordinate system, respectively.

159 *Asymmetry analysis*

160 Asymmetry was quantified for both static and dynamic trials using the modified
161 symmetry angle (Exell, Gittoes, Irwin, & Kerwin, 2012; Zifchock, Davis, Higginson, &
162 Royer, 2008) presented in (2). This measure provides a normalised quantification of

163 asymmetry where 0% indicates identical values for left and right sides and 100% indicates
164 values of equal magnitude and opposite polarity.

165

$$166 \quad \theta_{SYM} = \frac{|45 - (\tan^{-1} X_L/X_R)|}{90} \cdot 100\% \quad (2)$$

167

168 where θ_{SYM} is the asymmetry magnitude and X_L and X_R are the left and right values,
169 respectively for the variable of interest. Asymmetry magnitude was quantified using (2),
170 except where:

$$171 \quad 45 - (\tan^{-1} X_L/X_R) > 90$$

172 when (3) was substituted to correct for values >100%.

$$173 \quad \theta_{SYM} = \frac{|45 - (\tan^{-1} X_L/X_R)| - 135}{90} \cdot 100\% \quad (3)$$

174

175 Static asymmetry magnitude was calculated based on the mean displacement of each
176 nipple from the sternal notch marker during the static trial. For dynamic trials, the
177 significance of asymmetry in breast ROM was defined based on the method of Exell,
178 Gittoes et al. (2012) using significance testing between left and right values. Following
179 tests for normality (Shapiro-Wilks), paired samples t-tests or Wilcoxon tests were used
180 to test for significant asymmetry for normally and non-normally distributed data,
181 respectively (sig = 0.05).

182

183 *Statistical analysis*

184 Once asymmetry had been quantified, further statistical analyses were performed to
185 assess the relationship between breast movement asymmetry and other variables of
186 interest. Statistical tests were selected based on Kolmogorov-Smirnov normality testing.
187 The number of participants demonstrating significant asymmetry for nipple displacement

188 in each direction was calculated as the percentage of all 167 participants. Participants
189 displaying significant asymmetry were further analysed to investigate the direction of
190 asymmetry. For participants displaying significant asymmetry, the relationship between
191 breast size and asymmetry was investigated via the Spearman correlation coefficient. The
192 relationship between static and dynamic asymmetry was investigated by comparing the
193 correlation (Pearson) between static and dynamic asymmetry magnitude for participants
194 displaying significant dynamic asymmetry. Static asymmetry magnitude was also
195 compared in each direction between participants that displayed significant dynamic
196 asymmetry and those that did not, using independent t-tests (sig = 0.05). This approach
197 was taken to consider the influence of variability across trials during dynamic movement
198 by comparing those individuals that showed significant asymmetry between sides across
199 all five strides. Effect sizes were quantified for the comparison of dynamic asymmetry
200 magnitude by dividing difference in mean values by the average standard deviation
201 (Cohen, 2013). Effect Sizes were interpreted as: trivial (< 0.2), small (0.2–0.6), moderate
202 (0.6 –1.2) and large (>1.2) (Saunders, Pyne, Telford & Hawley, 2004).

203

204 ***Collection B***

205 *Participants and protocol*

206 To address the question of whether providing breast support reduced breast movement
207 asymmetry, a sub group of twelve participants that were a 34D bra size were randomly
208 selected for further analysis (25 ± 5 years, 64.8 ± 6.2 kg, 1.68 ± 0.05 m). This bra size
209 was selected for the intervention to allow comparison with previous research (Mills et al.,
210 2015) and due to the increased prevalence of reported breast pain for cup sizes of D and
211 larger (Lorentzen & Lawson, 1987; White, Scurr, & Smith, 2009). For the additional
212 testing stage, position data were collected at 240 Hz using an electromagnetic motion

213 tracking system (Micro Sensor 1.8TM, Polhemus, Colchester, Vermont, USA) allowing
214 sensor motion to be tracked underneath the material of the bra. Six sensors were placed
215 on participants at the following anatomical landmarks: suprasternal notch, xiphoid
216 process, seventh cervical (C7) and eighth thoracic (T8) vertebrae and on left and right
217 nipples. Each participant then ran on a treadmill (H/P/Cosmos Mercury, Germany) that
218 was aligned with the sensor system's coordinate system at a speed of 2.78 m/s during four
219 different breast support conditions, representing the range of sports bras commercially
220 available. During each bra condition, participants were asked to run for a time of 2
221 minutes, following which, data were collected for ten complete strides (i.e. twenty steps).

222 The conditions tested were:

- 223 1) Bare breasted.
- 224 2) Bra 1 - a high support nylon sports bra with an adjustable underband, adjustable
225 straps in a cross-back strap configuration and encapsulating cup support.
- 226 3) Bra 2 - a medium supporting polyester sports bra without adjustable straps or
227 underband, a racer back strap configuration and compression style support.
- 228 4) Bra 3 - a high supporting polyester sports bra with an adjustable underband, non-
229 adjustable straps in a racer back configuration and encapsulating cup support.

230

231 *Data processing and analysis*

232 Position data of each sensor were calculated relative to the electromagnetic system's base
233 station and were used to define the position of each nipple relative to the local coordinate
234 system of the trunk, as in Collection A. Position data were filtered using a second-order
235 low-pass Butterworth filter with a cut-off of 13 Hz. The trunk segment was defined based
236 on ISB recommendations (Wu et al., 2005) between the mid-point of the suprasternal
237 notch and C7 markers and the mid-point of the xiphoid process and PX and T8 markers.

238 The IS axis was defined along the vector connecting the ends of the segment, the AP axis
239 was determined by the vector that is perpendicular to both the plane defined by the four
240 segment markers and the IS axis. The ML axis was then determined using the right-hand
241 rule. Nipple position was calculated relative to the local coordinate system of the trunk.
242 Due to the smaller field of view of the sensor system used to allow position to be tracked
243 underneath the bra, it was not possible to position a marker on the heel. Therefore, running
244 strides were identified using the peak maximum IS position of the marker located on the
245 suprasternal notch.

246

247 *Asymmetry analysis*

248 Asymmetry significance was quantified as in Collection A using the method of Exell,
249 Gittoes et al. (2012). The number of participants displaying significant asymmetry was
250 calculated during each bra condition. Of the participants displaying significant symmetry,
251 the largest range of motion asymmetry was recorded for each condition.

252

253 **Results**

254 *Collection A*

255 Dynamic asymmetry prevalence for nipple range of motion within all participants is
256 presented in Table 1. In total, 149 participants (89%) demonstrated significant dynamic
257 breast asymmetry in at least one direction. More than half of the participants displayed
258 significant asymmetry in breast range of motion for all directions tested with most
259 occurrences of asymmetry (106) occurring in the IS direction. Mean asymmetry
260 magnitude was 16%, 13%, 10% and 11% for AP, ML, IS and RT directions, respectively.
261 The largest differences in mean range of motion of the left and right nipples for individual

262 participants were 58 mm, 70 mm, 33 mm and 29 mm for the AP, ML, IS and RT
263 directions, respectively. Table 1 also includes results for the direction of asymmetry,
264 which showed that a larger range of motion most often occurred in the left breast for
265 participants that displayed significant asymmetry. Differences in bra size between
266 asymmetrical and non-asymmetrical participants were small with the largest difference
267 being 0.24 cross grade magnitudes for the ML direction, where a value of 1 indicates an
268 increase of one cup or underband size.

269 Static nipple position asymmetry magnitudes are presented in Table 2. Mean
270 (\pm SD) asymmetry values are presented for participants that displayed significant
271 asymmetry during the dynamic trials and those that did not, allowing variability between
272 strides to be considered by comparing participants that did and did not display significant
273 asymmetry across all five strides. Static asymmetry was only significantly different
274 between dynamic asymmetry groups in the resultant direction, with a small effect size
275 (Table 2).

276 Relationships between dynamic asymmetry magnitude, breast size and breast pain
277 are presented in Table 3 for participants that displayed significant range of motion
278 asymmetry in each direction during running. No significant correlations were found, with
279 the largest ρ correlation magnitude being 0.18, indicating a weak relationship between
280 asymmetry magnitude and bra size.

281

282 ***Collection B***

283 Table 4 includes the number of participants of the sub-group that displayed significant
284 range of motion asymmetry during each bra condition. Asymmetry was prevalent in all

285 directions; however, the direction with the most participants displaying asymmetry varied
286 across support. The largest asymmetry prevalence was reported during the no bra
287 condition, followed by the Bra 2, which reduced the number of asymmetrical participants
288 by one in the ML and IS directions. The bra that reduced the number of participants
289 displaying significant asymmetry the most was Bra 1, which eliminated significant
290 asymmetry for all but two in the AP direction and seven in the IS direction.

291 The mean and largest magnitudes of range of motion asymmetry for each
292 condition and direction are shown in Table 5. For all directions, the largest asymmetry
293 was present in the no bra condition, with RT values of up to 80 mm. Largest resultant
294 range of motion asymmetry was reduced to 5 mm for Bra 1 and 21 mm for Bra 2;
295 however, Bra 3 still demonstrated a maximum asymmetry of 71 mm.

296

297 **Discussion and Implications**

298 The aims of this study were to investigate 1) the prevalence and magnitude of kinematic
299 breast asymmetry, 2) the interactions between static and dynamic breast asymmetry and
300 between breast asymmetry, breast pain and bra size and 3) the influence of sports bras on
301 dynamic asymmetry during running. Results demonstrate that asymmetry of breast
302 movement was present in one or more direction in almost 90% of the 167 women tested
303 during running, therefore accepting H_1 . The most prevalent direction of breast movement
304 asymmetry was the IS direction, with over half (63%) of the participants demonstrating
305 this, which is the direction most strongly linked with breast pain in previous studies (Mills
306 et al., 2015; Scurr et al., 2010). These results support the finding of asymmetry in breast
307 movement reported by Mills et al. (2015); however, asymmetry prevalence was lower in
308 the large group of participants examined in the current study than the group initially

309 investigated in the preceding study. Other than the larger sample size in the current study,
310 which may provide a more representative sample of the population, another possible
311 reason for the smaller number of participants being classed as displaying asymmetrical
312 movement in this study is the inclusion of a range of participants with different breast
313 sizes. Breast sizes in the current study ranged from 32A to 34G, compared to the single
314 size of 32D included in the previous study of Mills et al. (2015).

315 The asymmetry of breast movement reported in 89% of participants indicates that
316 the support requirements may differ between the left and right breast for the majority of
317 the female population. From a practical perspective, this difference in support
318 requirements is important when considering bra fitting (Brown et al., 2014; Mason et al,
319 1999; White et al., 2015; White & Scurr, 2012) and design. Therefore, during fitting,
320 support should be refined for each side to minimise breast movement during dynamic
321 activity. The side demonstrating greater movement was most often the left side,
322 supporting previous research that has indicated that the left breast is larger (Losken et al.,
323 2005). However, not all participants showing asymmetry demonstrated greater movement
324 on the left side. Therefore, it is recommended that asymmetry be considered on an
325 individual basis, in agreement with previous findings relating to static breast asymmetry
326 (Brown et al., 1999).

327 Static breast asymmetry did not significantly differ between asymmetrical and
328 non-asymmetrical participants during the dynamic activity when considering component
329 positions. However, in the RT direction, a significant difference (with small effect size)
330 in static asymmetry was reported between dynamically asymmetrical and non-
331 asymmetrical participants. Therefore, H₂ was partially accepted as a positive link was
332 evident between RT static breast asymmetry and dynamic asymmetry. When
333 investigating breast movement asymmetry magnitude and breast size, no meaningful

334 relationship was found between the two; therefore, H₃ was rejected. In addition, there was
335 no significant difference in the magnitude of breast size for participants displaying
336 asymmetry and those that did not, suggesting that a participant's overall breast size does
337 not lead to greater asymmetry prevalence. These findings conflict with previous research
338 that has investigated breast size and asymmetry of static breast shape (Manning et al.,
339 1997; Møller et al., 1995), which reported greater asymmetry in larger breasts. It is
340 suggested that this difference in findings is due to the previous studies investigating static
341 asymmetry and the current study investigating asymmetry during dynamic activity, when
342 breast movement is maximised. The important differences in findings during dynamic
343 activity compared with static measures indicates that, whilst both static and dynamic
344 breast asymmetry has been reported to exist, it may not be possible to predict dynamic
345 breast asymmetry by overall breast size or static asymmetry of nipple position measured
346 in each component direction. However, in the current study, a significant difference (with
347 small effect) was evident for static position asymmetry in the RT direction between
348 participants that did and did not display dynamic breast asymmetry when running. Based
349 on these results, it is recommended that, if it is not possible to include dynamic activity
350 when fitting or assessing sports bras, the difference in RT magnitude of the separation
351 from nipple to sternal notch may be a suitable measure to indicate dynamic breast
352 asymmetry; however this should be interpreted with caution based on the small effect.

353 Breast pain did not show any meaningful relationship with asymmetry, therefore,
354 rejecting H₄. The lack of relationship between the two variables suggests that asymmetry
355 doesn't influence overall reported breast pain. A limitation with the reporting of breast
356 pain used in this study was that overall breast pain was assessed, rather than pain being
357 reported specific to left and right breasts. Future work could further understanding in this

358 area by assessing which breast causes the greatest amount of pain to investigate whether
359 this is linked to asymmetrical movement.

360 Regarding the influence of bras on dynamic asymmetry, the number of
361 participants displaying significant asymmetry reduced in all bra conditions by varying
362 amounts. The largest reduction in the number of asymmetrical participants was
363 consistently achieved by Bra 1 (encapsulation), where the number of asymmetrical
364 participants reduced from nine to four for the AP direction and from eight to six in the
365 RT direction. In the IS direction, which has been most strongly linked with breast pain,
366 the number of participants showing significant asymmetry only reduced from nine to
367 eight when wearing Bra 1 or Bra 3 (both encapsulation) compared to the no bra condition;
368 however, the magnitude of asymmetry was greatly reduced when wearing Bra 1. The
369 worst performing bra in terms of reducing breast movement asymmetry was Bra 2
370 (compression), that only reduced asymmetry prevalence in the ML direction by one
371 participant and increased asymmetry in the RT direction. Bra 3 reduced asymmetry
372 prevalence compared with Bra 2; however, the magnitude of asymmetry was larger in
373 Bra 3. When considering magnitude of asymmetry in range of motion, Bra 1, again
374 performed the best. The general trend was for asymmetry prevalence and magnitude to
375 reduce in bra conditions; therefore, H₅ was accepted. The improved performance of Bra
376 1 compared with Bras 2 and 3 in reducing asymmetry suggests that the inclusion of
377 adjustable straps and an adjustable underband is an important factor allowing breast
378 support to be customised for each breast resulting in reduced asymmetry of breast
379 movement. Furthermore, the encapsulation styles of Bra 1 and Bra 3 appeared to be more
380 effective at reducing asymmetry prevalence than the compression style of Bra 2.
381 Biomechanical asymmetry has been reported to be individual to participants during
382 running gait (Exell et al., 2017; Exell, Irwin et al., 2010); therefore, it is likely that

383 individual asymmetry profiles exist relating to dynamic breast movement. The individual
384 responses of participants to different bras demonstrated in Collection B, along with the
385 fact that asymmetry was still present in all support conditions highlights the need for
386 further work to allow for customised breast support for each breast. This development
387 may be achieved by adding greater adjustability to each strap by way of different elastic
388 properties or by adding adjustability to the individual cups of sports bras.

389 From a data collection perspective, the high number of participants demonstrating
390 asymmetry of breast movement in at least one direction highlights the importance of
391 collecting bilateral data when investigating breast movement. Collection of unilateral data
392 is not recommended as it could change the conclusions being drawn from research studies
393 (Exell, Gittoes et al., 2012). Furthermore, it is not recommended that data are averaged
394 from left and right sides as asymmetry that is present may be functional or compensatory
395 and averaging across sides may lead to 'mythical average' data that does not truly
396 represent either side of the body.

397 Further research in this area should consider the influence of dynamic breast
398 asymmetry on asymmetry of other variables such as step characteristics during gait (Exell
399 et al., 2017) and other upper-body kinematics (White et al., 2015) to establish whether
400 relationships exist between asymmetry of breast movement and other performance
401 variables. In addition, it would be useful to quantify asymmetry differences related to
402 aging, to establish whether changes in the mechanical properties of the supporting skin
403 structure during aging increases asymmetry prevalence (Luebberding, Krueger &
404 Kerscher, 2014). When considering the practical applications and differing breast support
405 requirements between sides, it is suggested that manufacturers consider how bras can be
406 developed to allow more customisable support between sides, such as by adding size or

407 tension control to each cup independently and customising the elastic properties of each
408 strap.

409

410 **Conclusion**

411 The prevalence of breast movement asymmetry was high with 149 of the 167 women
412 tested showing significant asymmetry. The asymmetry reported was most often due to
413 greater movement of the left than right breast. Breast movement asymmetry was not
414 related to overall breast size, indicating that it may be present in participants of all breast
415 sizes. Use of a sports bra reduced the occurrence and magnitude of asymmetry, depending
416 on the bra, but did not eliminate it. In poorer performing sports bras, the larger movement
417 experienced by one breast may lead to pain in that breast when wearing a bra for exercise.
418 The most effective sports bra for reducing asymmetry allowed for adjustment of both the
419 shoulder straps and underband.

420

421 **Acknowledgements**

422 We would like to acknowledge Anna Marczyk and Dave Black for their assistance with
423 data collection.

424

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497 **Table 1.** Number of participants that displayed significant asymmetry, whether
 498 left or right ROM was larger for asymmetrical participants and mean cross grade
 499 size for significantly asymmetrical and non-asymmetrical participants during
 500 dynamic trials. Directions relate to the thorax coordinate system: AP = antero-
 501 posterior, ML = medio-lateral, IS = infero-superior, RT = resultant.

502

	Direction			
	AP	ML	IS	RT
Number of participants showing significant asymmetry (% or total)	84 (50%)	83 (50%)	106 (63%)	86 (51%)
Number of participants with L>R ROM, of those showing significant asymmetry (% or asymmetrical participants)	63 (75%)	51 (61%)	64 (60%)	56 (65%)
Mean cross grade size (significant asymmetry)	5.49	5.64	5.55	5.46
Mean cross grade size (non-significant asymmetry)	5.55	5.40	5.47	5.58

503

504 **Table 2.** Comparisons of static asymmetry magnitude for participants that displayed
 505 significant asymmetry during running trials and those that did not. Directions relate to the
 506 thorax coordinate system: AP = antero-posterior, ML = medio-lateral, IS = infero-
 507 superior, RT = resultant. ES = effect size.

508

	Direction							
	AP		ML		IS		RT	
	A	NA	A	NA	A	NA	A	NA
Mean	6.52	5.66	3.48	2.98	1.34	1.45	1.32	0.89
(±SD)	(6.00)	(4.15)	(2.88)	(2.48)	(1.27)	(0.96)	(1.05)	(0.66)
sig	0.40		0.35		0.64		0.04*	
ES	0.17 ^T		0.19 ^T		0.10 ^T		0.50 ^S	

509 * = significant difference between static asymmetry magnitude for asymmetrical
 510 (A) and non-asymmetrical (NA) groups during dynamic running. ^T = trivial, ^S = small
 511 effect sizes.

512 **Table 3.** Spearman (ρ) correlations between asymmetry magnitude and bra size / pain
 513 score for participants displaying significant asymmetry in each direction during dynamic
 514 trials (values in brackets are associated p-values). Directions relate to the thorax
 515 coordinate system: AP = antero-posterior, ML = medio-lateral, IS = infero-superior, RT
 516 = resultant.

517

	Direction			
	AP	ML	IS	RT
Size	0.06	-0.12	0.06	-0.01
p	(0.62)	(0.27)	(0.57)	(0.89)
Pain	0.03	0.02	0.12	0.18
p	(0.81)	(0.86)	(0.27)	(0.14)

518

519 **Table 4.** Number of participants from sub-group of twelve, displaying significant
 520 asymmetry in each direction during different bra conditions (values in brackets are
 521 associated percentages). Directions relate to the thorax coordinate system: AP = antero-
 522 posterior, ML = medio-lateral, IS = infero-superior, RT = resultant.

523

	Direction			
	AP	ML	IS	RT
No Bra	9 (75%)	10 (83%)	9 (75%)	9 (75%)
Bra 1	4 (33%)	7 (58%)	8 (67%)	7 (58%)
Bra 2	9 (75%)	8 (67%)	9 (75%)	11 (92%)
Bra 3	6 (50%)	10 (83%)	8 (67%)	7 (58%)

524

525 **Table 5.** Magnitude of largest range of motion asymmetry (mm) across all sub-group
 526 participants in each direction during all bra conditions. Directions relate to the thorax
 527 coordinate system: AP = antero-posterior, ML = medio-lateral, IS = infero-superior, RT
 528 = resultant.

529

		Direction			
		AP	ML	IS	RT
No Bra	Mean	8	11	14	19
	(sd)	6	11	20	24
	Max	22	38	67	80
Bra 1	Mean	3	1	3	3
	(sd)	2	0	2	1
	Max	6	1	6	5
Bra 2	Mean	4	3	7	6
	(sd)	2	1	6	6
	Max	9	5	22	21
Bra 3	Mean	6	4	10	12
	(sd)	6	8	22	26
	Max	18	25	64	71

530