

1 **Main title: The effect of match fatigue in elite badminton players using**  
2 **plantar pressure measurements and the implications to injury**  
3 **mechanisms**

4

5 **Running title: The effect of match fatigue in elite badminton players**

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7 Raúl Valldecabres<sup>1,2</sup> (orcid.org/0000-0002-7478-7526)

8 Jim Richards<sup>3</sup> (orcid.org/0000-0002-4004-3115)

9 Ana-María de Benito<sup>2</sup> (orcid.org/0000-0002-8836-4073)

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12 <sup>1</sup> Doctorate School, Valencia Catholic University San Vicente Mártir. Valencia, Spain.

13 <sup>2</sup> Physical Activity and Sports Science Faculty, Valencia Catholic University San Vicente  
14 Mártir. Valencia, Spain.

15 <sup>3</sup> Allied Health Research Unit, University of Central Lancashire, Preston, United  
16 Kingdom.

17

18 Corresponding author:

19 Raúl Valldecabres

20 raul.valldecabres@ucv.es

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22 **Main title: The effect of match fatigue in elite badminton players using**  
23 **plantar pressure measurements and the implications to injury**  
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27

28 Word count: 7557

29 **Abstract**

30 The purpose of this study was to investigate the differences in plantar pressure under the  
31 lead and trail foot between two lunge tasks to the net in the dominant (LD) and non-  
32 dominant (LND) directions, and to explore how fatigue affects the plantar pressure  
33 patterns whilst performing movements before and after a competitive match. Peak and  
34 mean pressure were measured with the Biofoot-IBV in-shoe system from five repetitions  
35 of each task, with sensors positioned under the calcaneus, midfoot and phalanges on the  
36 lead and trail foot. Data were collected pre and immediately post playing an official 1st  
37 national league competition match. The study was conducted with a sample of thirteen 1st  
38 league badminton players. A 2x2 repeated ANOVA found significant differences  
39 between the two tasks and between pre and post match (fatigued state). Players also had  
40 different foot pressure distributions for the LD and LND tasks, which indicated a  
41 difference in loading strategy. In a fatigued state the plantar pressure shifted to the medial  
42 aspect of the midfoot in the trail limb, indicating a reduction in control and a higher  
43 injury risk during non-dominant lunge tasks.

44

45 Abstract word count: 172

46

47 Keywords: biomechanics; kinetics; insole-system; competition

48

49

## 50 **Introduction**

51

52 Badminton is reported to be the fastest racket sport when considering ball velocity (Jaitner  
53 & Gawin, 2007). Its popularity has grown since its inclusion at the '92 Olympic Games  
54 in Spain and the use of a new scoring system in 2006 (Chen, Wu, & Chen, 2011), with  
55 up to 200 million players worldwide (Kwan, Cheng, Tang, & Rasmussen, 2010). The  
56 sport is characterised by short duration high intensity actions placing a high demand on  
57 the anaerobic system (Cabello & González-Badillo, 2003). The sport requires good  
58 footwork including; rapid turning, pivoting, jumps, lunges and running; in order for  
59 players to reach and hit the shuttlecock and to return to a defensive position in the centre  
60 of the court (Gibbs, 1988) which has not been analysed previously. There is a lack of  
61 quantification the court movements on the literature in a real competition context.

62

63 It has previously been reported that up to 70% of injuries are to the lower limbs, with the  
64 remaining 30% being due to loss of balance, slips and falls, landing or collisions with  
65 other players (Hensley & Paup, 1979; Krøner et al., 1990; Reeves, Hume, Gianotti,  
66 Wilson, & Ikeda, 2015). However, as in other racquet and field sports, badminton cannot  
67 be appropriately simulated in the laboratory setting (Faude et al., 2007). The majority of  
68 match based studies on badminton performance have focussed on notational performance  
69 analysis (Abián, Castanedo, Feng, Sampedro, & Abián-Vicén, 2014; Barreira,  
70 Chiminazzo, & Fernandes, 2016), game characteristics (Phomsoupha & Laffaye, 2014),  
71 or physiological and ground reaction force data (Chen et al., 2011; Ramos, Del Castillo,  
72 Polo, Ramón, & Bosch, 2016).

73

74 Players footwork during lunge movements has been previously reported (Kuntze,  
75 Mansfield, & Sellers, 2010), however the nature of on court movements had not been  
76 considered until recently (Valdecabres, de Benito, Casal, & Pablos, 2017). Valdecabres  
77 et al. (2017) divided the court into 12 parts, and described 3 different on court footwork  
78 movements which were commonly used to hit the shuttle, these were; diagonal, transverse  
79 and longitudinal, of which more than 50% were diagonal court movements.

80

81 Several studies have investigated injuries during badminton (Hensley & Paup, 1979;  
82 Jørgensen & Winge, 1990), with a higher risk of injury during competitions when  
83 compared to training sessions (Jørgensen & Winge, 1990). Of these injuries, 43% have

84 been reported as patellar tendinopathy (Shariff, George, & Ramlan, 2009), which is  
85 considered a common injury in sports with jumps, cutting manoeuvres and explosive  
86 running tasks (Tibesku & Pässler, 2005). The clinical injury risk incidence has also been  
87 analysed and found that 26% of players had previous symptoms before getting injured  
88 (Fahlström, Björnstig, & Lorentzon, 1998) being overuse sprains and strains the most  
89 musculoskeletal common injury (Goh, Mokhtar, & Mohaman, 2013; Hensley & Paup,  
90 1979; Shariff, George, & Ramlan, 2009). Lower limb dominance is an important  
91 consideration during sports tasks, and has been identified as a factor associated with  
92 potential Anterior Cruciate Ligament injury risk (Negrete, Schick, & Cooper, 2007).  
93 However, lower limb dominance seems to be more related to specific movement tasks  
94 which require different side to side movements (Peters, 1988), such as one side being  
95 used for more postural stabilization (Velotta, Weyer, Ramirez, & Winstead, 2011). This  
96 was highlighted by Sinsurin, Vachalathiti, Srisangboriboon & Richards (2018) who found  
97 better coordination during multi-direction jump landings on the non-dominant limb. The  
98 literature also suggests differences in the injury incidence between the dominant and non-  
99 dominant limbs for many sports, which has been attributed to side to side differences in  
100 loading as a result of differences in movement strategies between the sides (Vauhnik et  
101 al., 2008). For example, Kimura et al. (2010) reported that the knee on the lead limb side  
102 was the most commonly injured in badminton players, in particular during cutting and  
103 side-step movements to the racket-hand side. In addition, Krajnc et al. (2010) showed that  
104 the non-dominant leg, defined as the one that is not used to kick a ball, suffered more  
105 knee injuries than the dominant leg in soccer players, with players requiring more  
106 operations with greater pain or discomfort after surgery on the non-dominant limb. Side  
107 to side differences have also been identified in badminton (Kimura et al., 2010), with a  
108 higher number of injuries seen on the non-dominant leg.

109

110 The incidence of lower limb injuries has also been shown to be linked to fatigue, which  
111 has been associated with a decrease in neuromuscular control, impaired kinesthesia and  
112 proprioception of joints, and a diminishing maximum voluntary strength (Dickin & Doan,  
113 2008; Rozzi, Yuktanandana, & Pincivero, 2000; Saragiotto, Di Pierro, & Lopes, 2014;  
114 Whyte, Burke, White, & Moran, 2015). Links between fatigue and exercise have been  
115 investigated previously, however the exact definition of fatigue varies between studies  
116 (López-Calbet & Dorado-García, 2006). Fatigue may be considered as multidimensional  
117 or multifactorial (Hunter & Smith, 2007; Millet et al., 2011), which may be characterised

118 by the decrease of the capacity or ability to generate force or muscle power. This  
119 originates from physiological, mechanical and psychological modifications (Stirling, Von  
120 Tscherner, Fletcher, & Nigg, 2012) and a reduction of performance, which has been  
121 described as a conservative response to maintain tissue integrity (Millet et al., 2011).  
122 Previous work considering fatigue in badminton players has shown that dynamic postural  
123 control and the quality of athletes' performance is lower in a post fatigue state (Sarshin,  
124 Mohammadi, Shahrabad, & Sedighi, 2011). Players' perceived fatigue may be assessed  
125 using the rating of perceived exertion scale (Borg, 1982a), which has been shown to be  
126 valid for the assessment of exercise intensity during badminton matches (Fernández, de  
127 la Aleja, Moya, Cabello, & Méndez, 2013).

128

129 Previous investigations into sports related tasks have shown plantar pressure is an  
130 important method of quantifying the magnitude and location of the force applied beneath  
131 the foot, which may be measured using in shoe pressure systems (Falda-Buscaiot, Hintzy,  
132 Rougier, Lacouture, & Coulmy, 2017; Navarro, Zahonero, Huertas, Vera, & Barrios,  
133 2012). Fu, Liu & Wei (2009) studied badminton lunge tasks, and found the maximum  
134 peak pressure was distributed under the forefoot with lower pressures under the midfoot.  
135 Conversely, Hu, Li, Hong & Wang (2015) found lower pressures under the forefoot with  
136 the maximum pressure under the heel, indicating either differences in movement strategy  
137 or test protocol. Changes in distribution of foot pressure, for example midfoot loading,  
138 has been associated with foot pronation and patellofemoral pain (Thijs, Van Tiggelen,  
139 Roosen, De Clercq, & Witvrouw, 2007; Powers, 2003). In addition, the static assessment  
140 of foot posture using the Foot Posture Index (Redmond, Crosbie, & Ouvrier, 2006) has  
141 been shown to be important in the prediction of clinical subgroups in people with  
142 patellofemoral pain (Selfe et al., 2016). Therefore, the use of foot pressure may allow an  
143 assessment of changes in loading strategy and dynamic postural control on the trail and  
144 lead limbs which could be performed in the competition arena. This could be useful in  
145 the assessment of training and injury prevention, or when considering when to return to  
146 sport after an injury.

147

148 The aims of the present study were to investigate the differences in plantar pressure under  
149 the trail and lead foot between two lunge tasks to the net, and to explore how fatigue  
150 affects the plantar pressure patterns whilst performing movements before and after a  
151 competitive match. It was hypothesised that lunge tasks to the dominant side (LD) and

152 lunge tasks to the non-dominant side (LND) would show different foot loading strategies  
153 and that players would show changes in plantar pressure patterns in a fatigue state.

## 154 **Methods**

### 155 *Participants*

156 The inclusion criteria for both genders were; players in the 1<sup>st</sup> Spanish badminton league  
157 who played at least 3 times a week, with no injuries to the upper and lower limbs in the  
158 previous 6 months. In addition, all participants had no history of surgery or traumatic  
159 injury to the lower extremities or lower back, and no history of medical conditions that  
160 limit physical activity. Exclusion criteria included; presence of neuromuscular or  
161 vestibular conditions, visual impairment or back pain.

162

163 Thirteen right-handed badminton players (5 males and 8 females) participated in the  
164 study. Anthropometric measurements of height and weight were recorded; age  $25.93 \pm$   
165  $10.05$  years and bodyweight  $64.30 \pm 8.66$  kg. Hand laterality was assess using a  
166 previously validated questionnaire (Chapman & Chapman, 1987), which includes  
167 questions such as *which hand do you use to throw a ball* or *which foot do you use to kick*  
168 *a ball*, which has been used in previous studies (Brophy, Silvers, Gonzales, &  
169 Mandelbaum, 2010; English, Brannock, Chik, Eastwood, & Uhl, 2006). In addition, Foot  
170 Posture Index (FPI), a clinical tool that measures foot type between +12 (pronated) and -  
171 12 (supinated) was recorded (Redmond, Crosbie, & Ouvrier, 2006). This study was  
172 approved by the Valencia Catholic University San Vicente Mártir Ethics Committee and  
173 all data collection conformed to the Declaration of Helsinki. Volunteers gave written  
174 informed consent and parental consent for the four participants who were minors was  
175 obtained prior to participation.

176

### 177 *Equipment*

178 In shoe plantar pressure data were recorded using the Biofoot-IBV in-shoe system  
179 (Valencia, Spain), which consists of 64 sensors of 0.5mm thickness and 5mm diameter  
180 and has been previously validated and used to assess sports tasks (Martínez, Hoyos,  
181 Brizuela, Ferrús, & González, 1988; Marhuenda, Fuentes, Costa, Ferrús, & González,  
182 2011). Not normalised peak and mean pressure data were used according to previous

183 studies (Patrick, & Donovan, 2018; Taylor, Nguyen, Griffin, & Ford, 2018). In addition,  
184 the regions of interest were normalised to foot size following Oliveira, Sousa, Santos,  
185 & Tavares (2012) with values for foot shape proposed by Hu et al. (2015).

186

### 187 *Procedure*

188 In order to familiarise the players, submaximal lunge tasks were performed to the right  
189 and left sides, LD and LND respectively for a right-handed player (figure 1). During the  
190 lunge, the role of the non-stepping limb is to support the bodyweight during the forward  
191 movement of the lead limb (Hofmann, Holyoak, & Juris, 2017) and reaches a maximum  
192 knee flexion during landing, this is followed by a movement backwards in order to  
193 recover to the initial starting position (Kuntze et al., 2010). The lunge tasks were  
194 performed at 45° to the net in the defensive position (Gibbs, 1988), and were defined as  
195 controlled movements of the knee such that the knee did not move in front of the ankle  
196 joint. The most natural start position for the lunge task was identified for each player in  
197 order to hit a shuttlecock that was hung using a fine thread at a height of 165cm, 10 cm  
198 from the net (figure 2). Prior to data collection, a standardised 10 minute warm-up was  
199 performed, which included active stretching of the quadriceps and hamstring muscles  
200 (Lam et al., 2017), specifically this involved five repetitions of 30 seconds per muscle;  
201 and a familiarization period which involved the participants performing as many  
202 repetitions of the lunge tasks as they needed to feel comfortable (Gribble, Hertel, &  
203 Plisky, 2012).

204

205 [Figures 1 and 2 near here]

206

207 Pressure sensors were then placed in both shoes by fixing them to the insole to avoid them  
208 moving within the shoe. Changes in foot pressure data were recorded at a sampling  
209 frequency of 265Hz. in directions. Each lunge task trial consisted of a lunge to the net,  
210 hitting the shuttlecock with a top-spin shot and moving back to the start position as fast  
211 as possible to simulate a match shot. Approximately 5 minutes after participants had  
212 played a competition match the lunge tests were repeated. In addition, the level of match  
213 intensity was assessed using the Rated Perceived Exertion (RPE) Scale (Borg, 1982a).  
214 This determined the perceived intensity of the exercise, from 0 (nothing at all) to 10 (very,  
215 very heavy) (Borg, 1982b).

216

217 The plantar surface of the foot was divided into 9 areas previously reported by Navarro  
218 et al. (2012) (figure 3), these included; hallux, 2<sup>nd</sup> and 3<sup>rd</sup> phalanges and 4<sup>th</sup> and 5<sup>th</sup>  
219 phalanges, 1<sup>st</sup> metatarsal, 2<sup>nd</sup> and 3<sup>rd</sup> metatarsals and 4<sup>th</sup> and 5<sup>th</sup> metatarsals, medial  
220 midfoot and lateral midfoot, and calcaneus. The peak pressure (PP) and average pressure  
221 (PMEAN) of the whole foot were recorded and an average value from 5 repetitions was  
222 found for each parameter for each movement direction for both the lead and trail feet.

223

224 [Figure 3 near here]

225

### 226 *Statistical Analysis*

227

228 Based on previous papers by Lam et al. (2017) and Park et al. (2017) and an alpha level  
229 of 0.05 and an 80% power, a sample size of at least 13 was found to be required to explore  
230 the differences between sides and fatigue state. The data were checked for normality using  
231 the Shapiro-Wilk test and found to be suitable for parametric testing. In addition, partial  
232 eta squared ( $\eta^2$ ) was computed to determine the effect size which was interpreted as  
233 small 0.1, medium 0.3, and large 0.5. Statistical analysis was performed with SPSS 21.0  
234 (IBM, Armonk, NT, USA).

235

236 A 2x2 repeated ANOVA found significant differences between the two tasks and  
237 between pre and post match (fatigued state).

### 238 **Results**

239 The players had a mean RPE after playing the competition match of 7.54 (SD 2.10), with  
240 a range of perception of fatigue between strong and extremely strong. The average match  
241 length was 26 minutes 29 seconds with a standard deviation of 8 minutes and 9 seconds.  
242 The FPI showed mean values of 1.17 (SD 1.79) for the lead foot and 1.50 (SD 1.72) for  
243 the trail foot, which corresponds to a neutral foot posture (Redmond, Crosbie, & Ouvrier,  
244 2006). All players were at a similar level, and were all Spanish 1<sup>st</sup> league competitors and  
245 were playing for the Championship.

246



247 Significant main effects were seen between pre and post fatigue on the lead foot. These  
248 revealed significant differences under the 4th and 5th Phalangeal areas between pre and  
249 post fatigue for the peak and mean pressure ( $p=0.035$ ,  $\eta^2=0.32$ ;  $p=0.031$ ,  $\eta^2=0.33$ )  
250 respectively, with lower values in a fatigue state. In addition, a reduction of lead foot peak  
251 pressure under the lateral side was seen with a corresponding increase in peak pressure  
252 under the medial side of the midfoot, although the latter was not statistically significant  
253 (table 1). A significant interaction was seen between the factors of lunge task and fatigue  
254 state under the 2nd and 3rd Metatarsals ( $p=0.011$ ,  $\eta^2=0.43$ ). Further post hoc analysis  
255 explored differences between pre and post fatigue for each lunge task separately, which  
256 showed an increase in peak pressure post fatigue for the LD task and a decrease with the  
257 LND task (table 1). In addition, the calcaneus mean pressure for the lead foot in the LD  
258 task was lower than the LND task ( $p=0.032$ ,  $\eta^2=0.33$ ) (Table 2), indicating a different  
259 strategy during landing between lunge tasks.

260

261 [Tables 1 and 2 near here]

262

263 Significant differences were also seen under the 1st Metatarsal on the trail foot pre and  
264 post fatigue for the peak and mean pressure ( $p=0.048$ ,  $\eta^2=0.29$ ;  $p=0.046$ ,  $\eta^2=0.29$ )  
265 respectively, with a decrease in pressure post fatigue in both LD and LND tasks, and a  
266 corresponding significant increase in medial midfoot pressure. Finally, the medial  
267 midfoot showed an increase in peak and mean pressure post fatigue for both the LD and  
268 LND tasks ( $p=0.022$ ,  $\eta^2=0.37$ ;  $p=0.046$ ,  $\eta^2=0.29$ ) respectively (Tables 3 and 4), which  
269 would imply a shift in pressure to the medial midfoot as the players fatigue.

270

271 Significant main effects were seen between LD and LND tasks. These revealed  
272 differences in the peak and mean pressure under the Hallux ( $p=0.008$ ,  $\eta^2=0.45$ ;  $p=0.020$ ,  
273  $\eta^2=0.38$ ) respectively. This showed the Hallux pressure was lower in the LND task than  
274 the LD task in the trail foot (tables 3 and 4), with a corresponding lower pressure in the  
275 LND task versus the LD task for the peak and mean pressure under the 4th and 5th  
276 Phalangeal areas ( $p=0.026$ ,  $\eta^2=0.35$ ;  $p=0.017$ ,  $\eta^2=0.39$ ) respectively (tables 3 and 4).  
277 In addition, significant differences were found between the LD and LND tasks in the  
278 mean pressure under the Hallux ( $p=0.038$ ,  $\eta^2=0.31$ ) (table 4). Furthermore, a significant  
279 interaction was also seen for the peak pressure under the 2nd and 3rd Phalangeal areas in

280 the trail foot between lunge task and fatigue state ( $p=0.017$ ,  $\eta^2=0.39$ ), with a greater  
281 pressure being seen during the LD task, although this was not significant (Table 3). A  
282 further post hoc analysis revealed a significant difference in peak pressure between pre  
283 and post fatigue in the LD task on the trail foot only ( $p=0.045$ ,  $\eta^2=0.30$ ).

284

285 [Tables 3 and 4 near here]

286

## 287 **Discussion and Implications**

288 A fatigue state has been shown to reduce athletes' performance and can lead to poor joint  
289 control (Chang, 2015) and a decrease in dynamic postural control in badminton players  
290 (Sarshin et al., 2011). Furthermore, the biomechanics and movement patterns have been  
291 shown to be modified as a result of fatigue (Chang, 2015), which could lead to a  
292 subsequent increase in injury rate. Footwork manoeuvres are therefore extremely  
293 important for badminton players and the consideration of how landing strategies change  
294 on the different limbs after fatigue may help us to understand injury mechanisms  
295 (Phomsoupha & Laffaye, 2014). Diagonal lunge tasks have been previously shown to  
296 account for approximately 50% of on court manoeuvres in both male and female players  
297 (Valldecabres et al., 2017). This movement is required to allow the players to move to hit  
298 the shuttlecock, and the speed and reaction time are important to allow the player to  
299 recover a defensive court position to be ready for the next shot (Gibbs, 1988). Therefore,  
300 the aim of this study was to explore differences in foot contact pressures under the lead  
301 and trail foot during two badminton specific lunge tasks to the net, and to determine how  
302 plantar pressure patterns change as the players' fatigue.

303

304 The Foot Posture Index has been used to determine foot type in athletes in different sports  
305 including; basketball, handball and running (Martínez-Nova et al., 2014). Our results  
306 show a neutral foot type across the participants. However, when athletes fatigue, their  
307 foot posture tends to move towards a more pronated position (Cowley & Marsden, 2013),  
308 which could be an indicator of arch collapse leading to an increase of plantar pressure  
309 under the medial midfoot. Jørgensen & Winge (1990) reported that more than 30% of  
310 lower limb injuries are to the foot or ankle joint. This could be related to a flattening of  
311 the arch with a more pronated foot position (Lange, Chipchase, & Evans, 2004), leading  
312 to associated injuries (Barton, Bonanno, Levinger, & Menz, 2010; Beeson, Phillips, Corr,

313 & Ribbans, 2009; Graham, Jawrani, & Goel, 2011; Raissi, Cherati, Mansoori, & Razi,  
314 2009).

315

316 This study found an increase in pressure under the medial aspect of the lead foot,  
317 indicating a more pronated foot or a collapse of the arch post fatigue with the adoption of  
318 a flatter foot posture, which is in line with previous findings (Wei, Liu, Tian, & Fu, 2009).  
319 This would arguably increase the pronation and pronation velocity which have been  
320 previously identified as key factors in patellofemoral pain and patellar tendinopathy in  
321 runners (Powers, 2003; Thijs et al., 2007), the latter of which has been identified as an  
322 issue in 43% of badminton players (Shariff et al., 2009). In addition, the side-to-side  
323 differences found may help to explain the higher injury rates which have been reported  
324 on the non-dominant leg (Krajnc et al., 2010). One consideration to help mitigate this  
325 effect is the use of foot orthoses. These could be used to directly manage foot posture by  
326 supporting the arch and therefore decreasing the pronation and pronation velocity when  
327 athletes are in a fatigued state. This in turn may reduce the incidence of patellar  
328 tendinopathy (Mündermann, Nigg, Humble, & Stefanyshyn, 2003). However, more  
329 research is needed to explore the use of foot orthotics in badminton players, and their  
330 effect on potential injury mechanisms when athletes are in a fatigued state.

331

332 When comparing LD and LND tasks on lead foot, there are differences in pressure under  
333 the Hallux, a lower pressure under the 4th and 5th Phalangeal areas and a lower calcaneus  
334 mean pressure, which indicates a possible change in strategy during landing as Vauhnik  
335 et al. (2008) reported in other court sports. Lower pressure on the forefoot and lateral  
336 areas could be due to the involvement of pelvic rotation which has been reported by  
337 players who find dominant side movements easier than non-dominant side ones  
338 (Bazipoor, Shojaeddin, Shahhoseini, & Abdollahi, 2017). Further exploration of such  
339 compensations was beyond the scope of this current study

340

341 After fatigue, a significant decrease in mean pressure under the Hallux and 1st Metatarsal  
342 areas and a significant increase under medial midfoot were seen in both LD and LND  
343 tasks. This would support the shift in pressure to the medial midfoot and collapse of the  
344 arch when players reach a fatigued state which is in agreement with previous literature  
345 (Weist, Eils, & Rosenbaum, 2004), and supports that changes in plantar pressure  
346 distribution occur due to fatigue (Bisiaux & Moretto, 2008). This has implications to the

347 foot movement used to recover the initial position in the centre of the court with cutting  
348 and pivoting creating a higher tibia rotation torque (Oh, Kreinbrink, Wojtys, & Ashton-  
349 Miller, 2012) which has been linked with patella mal-alignment and an increased risk of  
350 patellofemoral pain (Sinclair & Dillon, 2016).

351

352 During both LND and LD lunge tasks the Hallux, 4th and 5th Metatarsals all showed  
353 lower mean and peak pressure on the trail limb (tables 3 and 4). The explanation for this  
354 could be different hip movement strategies when lunging towards the net, with movement  
355 into hip external rotation during the LD task, and a move into hip internal rotation when  
356 performing the LND task which has been previously reported by Valdecabres, de Benito,  
357 Littler & Richards (2018). In addition, the trail limb is in contact with the ground for  
358 longer and is responsible for the eccentric control as the person lunges forwards, which  
359 is similar to findings reported during fencing, where the trail/rear limb demonstrated  
360 lower pressures (Trautmann, Martinelli, & Rosenbaum, 2011).

361

362

363 This current study is the first to explore the plantar pressure patterns in the lead and trail  
364 foot. Previously published work by Hu et al. (2015) on plantar pressures during  
365 badminton movements has only taken into account the dominant/lead limb during lunge  
366 tasks to the net. This work offers a contribution to knowledge on the changes in  
367 movement strategies due to fatigue within a competition environment in elite players.  
368 However, more work is required to assess how fatigue affects pronation and pronation  
369 velocity, knee joint stability and compensations in pelvic rotation in badminton players.

370

371 This study was not without its limitations which included a large standard deviation in  
372 the age of the players recruited. A large standard deviation was seen in many of the  
373 parameters reported, this was due to variations in the magnitude of many of the  
374 parameters between the participants, however the direction of the changes seen were  
375 common among the participants which accounts for the significant differences seen, and  
376 supports the conclusion that a change in strategy occurs due to fatigue. In addition, no  
377 direct measures of the amount of pronation or pronation velocity were taken.  
378 Furthermore, greater fatigue has been previously reported as a competition progresses,  
379 however this current study did not report how many matches were played at the time of

380 assessment, although the match duration was similar to that reported by Abián-Vicén,  
381 Castanedo, Abián, & Sampedro (2013).

382

### 383 **Conclusion**

384 In conclusion, this study found that players have different strategies when moving to the  
385 dominant and non-dominant sides during lunge to the net tasks. Under a fatigue state the  
386 plantar pressure shifts to the medial aspect of the midfoot in the trail limb indicating a  
387 reduction in control of the midfoot and collapse of the arch. This could account for the  
388 higher injury risk in the non-dominant trail limb which has been previously reported in  
389 badminton players, therefore further work should consider both the lead and trail foot.  
390 These results provide new insights into the changes in foot function in a fatigued state,  
391 which could possibly be managed using foot orthoses.

392

### 393 **Disclosure statement**

394 There is no conflict of interest reported by authors.

395

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400

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407

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## 672 **Supporting information**

673 S1 Fig. Non-dominant and dominant lunge to the net movement

674 S2 Fig. Net and shuttlecock position during test

675 S3 Fig. Pressure zone distribution and sensor configuration

676 S1 Table. Peak pressure in kilopascals (Kpa) for lead foot

677 S2 Table. 2 Mean pressure in kilopascals (Kpa) for lead foot

678 S3 Table. Peak pressure in kilopascals (Kpa) for trail foot

679 S4 Table. Mean pressure in kilopascals (Kpa) for foot trail foot

680



Table 1 Peak pressure in kilopascals (Kpa) for lead foot

Parameter	LD task		LND task		<i>p</i> -value Interaction	<i>p</i> -value Pre - Post	$\eta_p^2$	<i>p</i> -value Lunge Dom	$\eta_p^2$
	Mean (Kpa) $\pm$ SD		Mean (Kpa) $\pm$ SD						
	Pre	Post	Pre	Post					
Hallux	2450.9 $\pm$ 901.6	2520.6 $\pm$ 1127.4	2702.4 $\pm$ 570.4	2315.6 $\pm$ 1117.1	0.170	0.460	0.05	0.913	0.00
2 <sup>nd</sup> 3 <sup>rd</sup> Phal	2503.1 $\pm$ 818.5	2257.9 $\pm$ 1328.3	2584.6 $\pm$ 793.7	2269.5 $\pm$ 1150.3	0.731	0.284	0.10	0.716	0.01
4 <sup>th</sup> 5 <sup>th</sup> Phal *	1698.5 $\pm$ 1190.7	851.6 $\pm$ 1022.5	1548.3 $\pm$ 993.5	1206. $\pm$ 1132.4	0.268	<b>0.035</b>	<b>0.32</b>	0.457	0.05
1 <sup>st</sup> Met	1887.9 $\pm$ 911.9	1966.7 $\pm$ 1006.0	2209.0 $\pm$ 829.7	2135.30 $\pm$ 841.1	0.475	0.991	0.000	0.058	0.27
2 <sup>nd</sup> 3 <sup>rd</sup> Mets ‡	1616.1 $\pm$ 779.3	1858.1 $\pm$ 919.5	1981.0 $\pm$ 922.8	1435,6 $\pm$ 742.2	<b>0.011</b>	0.595	0.02	0.799	0.01
4 <sup>th</sup> 5 <sup>th</sup> Mets	1053.7 $\pm$ 1076.9	1198.1 $\pm$ 1283.7	1261.9 $\pm$ 1028.6	1212.74 $\pm$ 1215.7	0.301	0.857	0.00	0.317	0.08
Med-midfoot	1190.5 $\pm$ 1034.4	1318.5 $\pm$ 1170.2	1058.8 $\pm$ 852.4	1386.3 $\pm$ 944.6	0.569	0.393	0.06	0.796	0.01
Lat-midfoot	1548.9 $\pm$ 1034.9	1423.0 $\pm$ 1159.5	1290.0 $\pm$ 843.5	1660.2 $\pm$ 1295.1	0.146	0.618	0.02	0.893	0.00
Calcaneus	1960.4 $\pm$ 931.5	1770.9 $\pm$ 916.8	2043.9 $\pm$ 797.5	1827.2 $\pm$ 968.6	0.893	0.306	0.09	0.309	0.09

\* significant difference between Pre and Post † significant difference between Lunge Dominance

‡ significant interaction between Pre and post and Lunge Dominance

Table 2 Mean pressure in kilopascals (Kpa) for lead foot

Parameter	LD task		LND task		<i>p</i> -value Interaction	<i>p</i> -value Pre - Post	$\eta_p^2$	<i>p</i> -value Lunge Dom	$\eta_p^2$
	Mean (Kpa) $\pm$ SD		Mean (Kpa) $\pm$ SD						
	Pre	Post	Pre	Post					
Hallux	867.8 $\pm$ 507.2	790.8 $\pm$ 490.5	783.9 $\pm$ 297.1	719.6 $\pm$ 517.1	0.920	0.432	0.05	0.303	0.09
2 <sup>nd</sup> 3 <sup>rd</sup> Phal	636.1 $\pm$ 518.1	541.19 $\pm$ 397.2	615.0 $\pm$ 391.25	532.5 $\pm$ 374.6	0.883	0.380	0.07	0.736	0.01
4 <sup>th</sup> 5 <sup>th</sup> Phal *	966.4 $\pm$ 767.5	475.49 $\pm$ 613.9	956.9 $\pm$ 706.13	643.0 $\pm$ 609.1	0.496	<b>0.031</b>	<b>0.33</b>	0.394	0.06
1 <sup>st</sup> Met	670.8 $\pm$ 350.2	612.53 $\pm$ 355.6	750.2 $\pm$ 381.58	621.3 $\pm$ 310.8	0.354	0.331	0.08	0.374	0.07
2 <sup>nd</sup> 3 <sup>rd</sup> Mets	397.2 $\pm$ 206.4	361.56 $\pm$ 193.8	405.5 $\pm$ 159.04	305.8 $\pm$ 168.1	0.220	0.176	0.15	0.459	0.05
4 <sup>th</sup> 5 <sup>th</sup> Mets	227.8 $\pm$ 193.1	182.28 $\pm$ 168.7	256.5 $\pm$ 193.29	193.4 $\pm$ 185.3	0.667	0.225	0.12	0.419	0.06
Med-midfoot	298.1 $\pm$ 245.9	317.93 $\pm$ 281.9	258.9 $\pm$ 161.69	320.3 $\pm$ 198.3	0.645	0.479	0.04	0.516	0.04
Lat-midfoot	267.8 $\pm$ 180.2	233.94 $\pm$ 195.3	254.7 $\pm$ 185.42	266.6 $\pm$ 202.5	0.249	0.797	0.01	0.638	0.02
Calcaneus †	635.2 $\pm$ 389.9	538.08 $\pm$ 276.8	661.6 $\pm$ 386.04	596.2 $\pm$ 319.4	0.532	0.327	0.08	<b>0.032</b>	<b>0.33</b>

\* significant difference between Pre and Post † significant difference between Lunge Dominance

‡ significant interaction between Pre and post and Lunge Dominance

Table 3 Peak pressure in kilopascals (Kpa) for trail foot

Parameter	LD task		LND task		<i>p</i> -value Interaction	<i>p</i> -value Pre - Post	$\eta^2$	<i>p</i> -value Lunge Dom	$\eta^2$
	Mean (Kpa) $\pm$ SD		Mean (Kpa) $\pm$ SD						
	Pre	Post	Pre	Post					
Hallux1 †	2347.9 $\pm$ 806.9	1984.4 $\pm$ 1161.8	2116.3 $\pm$ 840.5	1619.1 $\pm$ 1052.7	0.671	0.083	0.23	<b>0.008</b>	<b>0.45</b>
2 <sup>nd</sup> 3 <sup>rd</sup> Phal ‡	1749.7 $\pm$ 965.0	1347.5 $\pm$ 837.0	1250.5 $\pm$ 837.0	1535.8 $\pm$ 1051.3	<b>0.017</b>	0.460	0.05	0.615	0.02
4 <sup>th</sup> 5 <sup>th</sup> Phal †	1040.5 $\pm$ 851.5	764.2 $\pm$ 745.7	673.2 $\pm$ 723.9	492.6 $\pm$ 588.0	0.463	0.198	0.13	<b>0.026</b>	<b>0.35</b>
1 <sup>st</sup> Met *	2382.0 $\pm$ 915.2	1948.0 $\pm$ 1036.1	2211.8 $\pm$ 1070.1	1870.6 $\pm$ 874.2	0.757	<b>0.048</b>	<b>0.29</b>	0.473	0.04
2 <sup>nd</sup> 3 <sup>rd</sup> Mets	1365.3 $\pm$ 993.5	1123.2 $\pm$ 653.8	1413.7 $\pm$ 1034.5	1203.5 $\pm$ 755.8	0.863	0.204	0.13	0.542	0.03
4 <sup>th</sup> 5 <sup>th</sup> Mets	1627.2 $\pm$ 1038.0	1265.5 $\pm$ 1082.4	1336.8 $\pm$ 1179.0	1102.1 $\pm$ 986.1	0.575	0.084	0.23	0.106	0.20
Med-midfoot *	576.3 $\pm$ 371.3	967.2 $\pm$ 608.7	595.6 $\pm$ 558.2	998.0 $\pm$ 726.4	0.966	<b>0.022</b>	<b>0.37</b>	0.837	0.00
Lat-midfoot	910.6 $\pm$ 916.8	875.0 $\pm$ 855.3	1146.9 $\pm$ 1220.1	735.1 $\pm$ 692.4	0.191	0.288	0.09	0.702	0.01
Calcaneus	638.4 $\pm$ 415.3	456.1 $\pm$ 279.2	583.5 $\pm$ 332.7	563.4 $\pm$ 376.0	0.095	0.167	0.15	0.659	0.02

\* significant difference between Pre and Post † significant difference between Lunge Dominance

‡ significant interaction between Pre and post and Lunge Dominance

Table 4 Mean pressure in kilopascals (Kpa) for foot trail foot

Parameter	LD task		LND task		<i>p</i> -value Interaction	<i>p</i> -value Pre - Post	$\eta_p^2$	<i>p</i> -value Lunge Dom	$\eta_p^2$
	Mean (Kpa) $\pm$ SD		Mean (Kpa) $\pm$ SD						
	Pre	Post	Pre	Post					
Hallux * †	649.8 $\pm$ 318.4	488.5 $\pm$ 302.2	560.85 $\pm$ 245.9	425.06 $\pm$ 329.0	0.811	<b>0.020</b>	<b>0.38</b>	<b>0.038</b>	<b>0.31</b>
2 <sup>nd</sup> 3 <sup>rd</sup> Phal	336.8 $\pm$ 219.9	221.7 $\pm$ 159.3	291.76 $\pm$ 239.0	254.67 $\pm$ 190.2	0.101	0.067	0.25	0.806	0.01
4 <sup>th</sup> 5 <sup>th</sup> Phal †	564.6 $\pm$ 453.3	408.7 $\pm$ 383.6	376.04 $\pm$ 395.08	280.43 $\pm$ 312.5	0.349	0.175	0.15	<b>0.017</b>	<b>0.39</b>
1 <sup>st</sup> Meta *	804.1 $\pm$ 439.2	645.1 $\pm$ 501.3	721.71 $\pm$ 353.45	576.00 $\pm$ 286.0	0.869	<b>0.046</b>	<b>0.29</b>	0.312	0.09
2 <sup>nd</sup> 3 <sup>rd</sup> Meta	354.8 $\pm$ 233.7	284.2 $\pm$ 161.2	406.64 $\pm$ 240.6	323.44 $\pm$ 172.7	0.711	0.113	0.20	0.120	0.19
4 <sup>th</sup> 5 <sup>th</sup> Meta	300.9 $\pm$ 192.7	271.3 $\pm$ 264.2	246.46 $\pm$ 163.32	223.26 $\pm$ 198.4	0.791	0.449	0.05	0.130	0.18
Med-midfoot *	155.3 $\pm$ 79.8	225.7 $\pm$ 122.5	138.82 $\pm$ 103.71	216.72 $\pm$ 147.7	0.889	<b>0.046</b>	<b>0.29</b>	0.623	0.02
Lat-midfoot	174.5 $\pm$ 135.5	162.9 $\pm$ 146.5	195.1 $\pm$ 170.17	128.49 $\pm$ 114.1	0.138	0.177	0.15	0.619	0.02
Calcaneus	229.0 $\pm$ 139.1	208.0 $\pm$ 154.1	236.27 $\pm$ 150.6	237.8 $\pm$ 182.8	0.378	0.813	0.01	0.372	0.07

\* significant difference between Pre and Post † significant difference between Lunge Dominance

‡ Significant interaction between Pre and post and Lunge Dominance

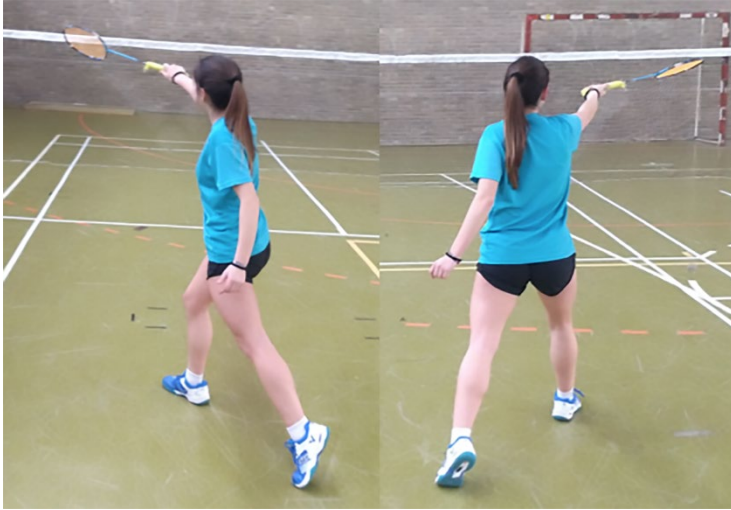


Figure 1. Non-dominant and dominant lunge to the net movement



Figure 2. Net and shuttlecock position during test

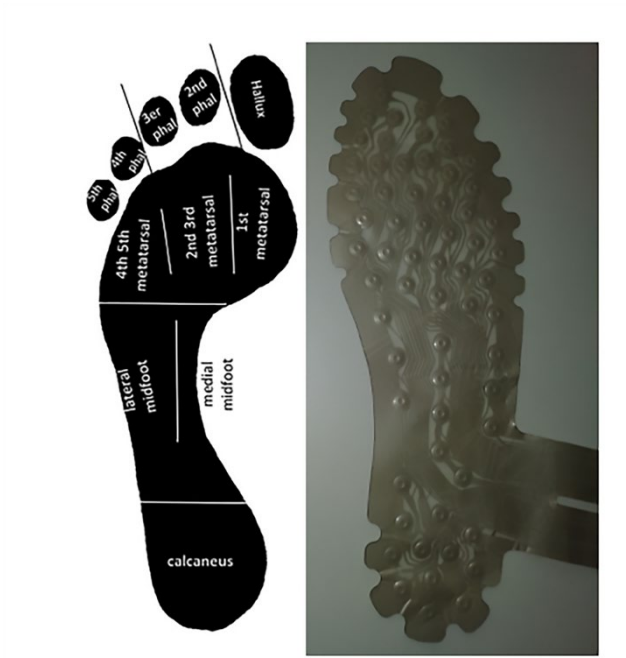


Figure 3. Pressure zone distribution and sensor configuration