

**Please cite the Published Version**

Thomas, Christopher, Dos'Santos, Thomas , Warmenhoven, John and Jones, Paul Anthony (2022) Between-Limb Differences During 180 Turns in Female Soccer Players: Application of Statistical Parametric Mapping. *Journal of Strength and Conditioning Research*, 36 (11). pp. 3136-3142. ISSN 1064-8011

**DOI:** <https://doi.org/10.1519/jsc.0000000000004022>

**Publisher:** Lippincott, Williams & Wilkins

**Version:** Accepted Version

**Downloaded from:** <https://e-space.mmu.ac.uk/627591/>

**Additional Information:** This is an Author Accepted Manuscript of an article published in *Journal of Strength and Conditioning Research*.

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**Between-limb differences during 180° turns in female soccer players: Application  
of Statistical Parametric Mapping**

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38 **Abstract**

39 This study was exploratory in nature, and investigated the ability of statistical parametric  
40 mapping (SPM) to assess between-limb differences in lower-extremity movement change  
41 of direction. Fourteen female soccer players (mean  $\pm$  SD; age =  $20.6 \pm 0.6$  years; height  
42 =  $1.65 \pm 0.07$  m; body mass =  $56.04 \pm 6.20$  kg). For comparisons between preferred and  
43 non-preferred limbs, vertical (Fz) and horizontal (Fx) GRFs were determined along with  
44 hip, knee, and ankle angles and moments in the sagittal plane during weight acceptance  
45 during the final contact. Additionally, frontal plane knee abduction angles and moments  
46 were calculated during the final contact. SPM software was then used to assess for  
47 differences between the entire weight acceptance phase of preferred and non-preferred  
48 limbs. There were no differences between limbs in all variables using SPM. These results  
49 demonstrate that female soccer players exhibit little side-to-side differences in certain  
50 lower-limb biomechanics when performing a turn manoeuvre. These findings can be  
51 utilised by practitioners and clinicians when developing injury prevention and  
52 rehabilitation programmes.

53

54 **Keywords:** deceleration; knee abduction moment, change of direction ability,  
55 side-to-side differences

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62 **INTRODUCTION**

63 A between-limb difference is a change in performance or function of one limb with  
64 respect to the other (35) pertaining to muscle strength, movement coordination, and  
65 movement timing (i.e. kinetics and kinematics); such examples may include isokinetic  
66 peak torque difference between left and right limbs (7), or difference in change of  
67 direction time between left and right limbs) (13). Due to laterality, humans will  
68 preferentially use one side of the body when performing a motor task, typically resulting  
69 in more skillful and therefore become the preferred side (26), thus it is unsurprising that  
70 athletes tend to display limb dominance. Indeed, between-limb differences may be  
71 developmental, or functional in specific sporting contexts (35), potentially due to the  
72 chronic exposure to repeated asymmetrical sport-specific actions (29). Specifically, any  
73 sport which has a preferred limb for a particular skill is preferentially recruited for the  
74 activity, and this is why between-limb differences arise in kicking actions in soccer (1)  
75 and Australian rules football (17). Thus, understanding the between-limb biomechanics  
76 underlying a turn task is essential for mitigating injury risk and facilitating performance.

77

78 Limb preference has been suggested to play a sex-based role in non-contact anterior  
79 cruciate ligament injury, specifically in soccer players (5). Indeed, 74% (20/27 cases) of  
80 males sustained a greater number of non-contact anterior cruciate ligament (ACL) injuries  
81 to the dominant limb, compared to 32% (10/31 cases) in females. Thus, female soccer  
82 players were more likely to injure their ACL in the non-dominant limb (support/stance)  
83 limb, whereas males demonstrated the opposite. These injuries most likely occur due to  
84 the high joint loads when adopting postures such as lateral trunk flexion (10), knee valgus  
85 (9), limited knee flexion (24), wide lateral foot plant (21), and high ground reaction forces  
86 (24). Several attempts have been made to explore differences in lower-limb biomechanics

87 during change of direction manoeuvres (12); these studies typically compare preferred  
88 push-off and non-preferred push-off limbs, dominant (stronger) and nondominant  
89 (weaker) limbs, and kicking and non-kicking limbs. The general aim of these studies has  
90 been to better understand the potential role of between-limb differences in injury  
91 prevention and rehabilitation programs. To date there has been little agreement on the  
92 role of between-limb differences, with studies demonstrating findings in favor of greater  
93 injury risk (8,15,27,28) and against risk of injury (3,6,32). However, with the exception  
94 of Marshall et al. (27), these investigations have compared limb differences at discrete  
95 points (i.e. average and peak values) and may play a limited role to aid in the  
96 understanding of the overall performance and movement patterns of interest. Very little  
97 is currently known about between-limb differences when analyzing the entire waveform  
98 for variables during change of direction. Therefore, given that anterior cruciate ligament  
99 injuries occur early and often with the knee extended and hip flexed early in ground  
100 contact, possibly in slight valgus (knee abduction) alignment (25); it might be worth  
101 exploring whether side-to side differences are present that relate to these critical positions  
102 early in ground contact rather than global peak magnitudes which could occur at different  
103 points during ground contact.

104

105 One method for comparing lower-limb kinetics and kinematics over an entire movement  
106 sequence is statistical parametric mapping (SPM) (31,34). SPM is based on random field  
107 theory and calculates a critical threshold for each test, considering both the magnitude  
108 and shape of the entire data set for each curve. SPM has been used to evaluate GRF data  
109 and joint kinetics and kinematics in athletic populations (33,36). Furthermore, SPM has  
110 been used to examine biomechanical differences between limbs in patients with anterior  
111 cruciate ligament injury 9 months after reconstruction during change of direction (22,23)

112 and during running and landing in multiple populations (19). In each of these prior cases,  
113 SPM enabled a more in-depth evaluation of movement throughout various tasks and  
114 identified additional limb differences that were found with traditional discrete analyses  
115 alone. Furthermore, SPM removes the need for potentially biasing discretization, whilst  
116 allowing for non-directed hypotheses. To date, the few studies investigating the  
117 differences in between-limb biomechanics during change of direction have only included  
118 discrete analyses and potential differences between full waveforms (i.e. one-dimensional  
119 or 1D analysis) are yet to be fully explored. The aim of this study therefore, was  
120 exploratory in nature and designed to examine the differences in preferred and non-  
121 preferred limb GRFs, and lower-limb sagittal and frontal plane joint angles and moments  
122 over the entire waveform, using SPM during change of direction. The intention of this  
123 study is also to provide a valid hypothesis to be tested as a part of future 1D testing in  
124 future research.

## 125 **METHODS**

### 126 Experimental Approach to the Problem

127 Fourteen female soccer players (mean  $\pm$  SD; age =  $20.6 \pm 0.6$  years; height =  $1.65 \pm 0.07$   
128 m; body mass =  $56.04 \pm 6.20$  kg) participated in the study. All subjects were registered  
129 with soccer clubs playing in the second tier of English Women's Soccer. At the time of  
130 testing, subjects were performing 4–5 sport-specific sessions, plus 3 resistance training  
131 sessions per week. All subjects had  $>8$  years' competitive experience and  $>3$  years'  
132 resistance training experience. All subjects met the inclusion criteria: (1) fully active (i.e.,  
133 3 sessions per week) in female soccer competition, (2) did not suffer from an ACL injury  
134 and (3) did not suffer from any other lower limb injury within the last 6 months before  
135 data collection. Written informed consent was attained from all subjects and approval for  
136 the study was provided by the Institutional Review Board. The study was conducted in

137 accordance with the Declaration of Helsinki.

138

139 Procedures

140 All subjects were fitted with appropriate size compression tops (Champion Vapor,  
141 Champion, Winston-Salem, NC, USA) and indoor shoes (Balance W490, New Balance,  
142 Boston, MA, USA). The leg which a player preferred to turn with was noted as the  
143 preferred limb. Testing took place on an indoor synthetic running surface (Mondo,  
144 SportsFlex, 10 mm; Mondo America Inc., Mondo, Summit, NJ, USA). All subjects  
145 performed a 180° turn task, turning off the preferred and non-preferred limbs, considered  
146 to be representative of the nature of competitive soccer match-play (14). All subjects  
147 performed a standardised progressive warm-up directed by the investigator including  
148 various bodyweight lunges and squats, interspersed with footwork and sprint mechanics  
149 drills, replicating the athlete's standardised warm-ups before training. This was followed  
150 by practice trials of the 180° turn (3 on each limb). The 180° turn involved running  
151 towards a single force platform, used to measure GRFs from the final foot contact.  
152 Subjects were instructed to sprint to a line marked on the central portion of the force  
153 platform, 5 m from the start, planting their preferred or non-preferred foot on the line,  
154 turn 180° and sprint back 5 m through the finish. During the test session, all subjects  
155 performed a minimum of 6 acceptable trials turning off each limb (preferred and non-  
156 preferred) in a randomized order and counterbalanced between subjects. Subjects were  
157 instructed to perform trials with maximum effort whilst contacting the central portion of  
158 the force platform during final contact to ensure a homogeneous distance of travel  
159 between trials and without prior stuttering or prematurely turning prior to final contact.  
160 Verbal feedback was provided to rectify any of the abovementioned aspects on  
161 subsequent trials. Each subject was allowed time prior to data collection to identify their

162 exact starting point to ensure an appropriate force platform contact. Brower timing lights  
163 (Brower Timing Systems, Draper, UT, USA) were set at approximate hip height for all  
164 participants. The mean of the 3 fastest trials were retained for further analysis.

165 The procedures have been reported previously (20), thus only a brief overview is provided  
166 here. Reflective markers (14 mm spheres) were placed on the following body landmarks;  
167 mid-clavicle, 7<sup>th</sup> cervical vertebrae, right and left; shoulder, iliac crest, anterior superior  
168 iliac spine, posterior superior iliac spine, greater trochanter, medial epicondyle, lateral  
169 epicondyle, lateral malleoli, medial malleoli, heel, 5<sup>th</sup>, 2<sup>nd</sup> and 1<sup>st</sup> metatarsal heads  
170 using double-sided adhesive tape. Subjects wore 'cluster sets' (4 reflective markers  
171 attached to a lightweight rigid plastic shell) attached using Velcro elasticated wraps on  
172 the right and left thigh and shin to approximate the motion of these segments during  
173 dynamic trials. The pelvis and trunk cluster sets were attached using an elasticated belt  
174 and compression top, respectively. Three dimensional motions of these markers were  
175 collected whilst performing the turning using 10 Qualisys 'Oqus 7' (Model no. MCU  
176 240) infrared cameras (240 Hz) operating through Qualisys Track Manager software  
177 (version 2.14). Ground reaction forces were collected from a single AMTI (Model no.  
178 600900) force platform (1200 Hz) embedded into the indoor surface.

179 From a standing trial, a 6-degree-of-freedom model of the lower extremity and trunk was  
180 created for each participant, including trunk, pelvis, thigh, shank and foot using Visual3D  
181 software (C-Motion, version 3.90.21). This kinematic model was used to quantify the  
182 motion at the hip, knee and ankle joints using Cardan angle sequence (16). The local  
183 coordinate system was defined at the proximal joint centre for each segment. The static  
184 trial position was designated as the subject's neutral (anatomical zero) alignment, and  
185 subsequent kinematic measures were related back to this position. Lower limb joint  
186 moments were calculated using an inverse dynamics approach (37) through Visual3D

187 software and are defined as external moments. Segmental inertial characteristics were  
188 estimated for each participant (11). The model utilised a CODA pelvis orientation (2) to  
189 define the location of the hip joint centre. The knee and ankle joint centres were defined  
190 as the mid-point of the line between lateral and medial markers. The trials were time  
191 normalised to 100 data points, each representing 1% of the weight acceptance phase for  
192 each subject of the turn task. Initial contact was defined as the instant after ground contact  
193 that the vertical GRF was higher than 20 N and end of contact was defined as the point  
194 where the vertical GRF subsided past 20 N for the final contact. The weight acceptance  
195 phase of ground contact was defined as from the instant of initial contact to the point of  
196 maximum knee flexion during ground contact, as used previously (18,20). Joint  
197 coordinate and force data were smoothed in Visual3D with a Butterworth low pass digital  
198 filter with cut-off frequencies of 12 and 25 Hz, respectively. Cut off frequencies were  
199 selected based on a residual analysis (37) and visual inspection of the data.

200 For comparisons between preferred and non-preferred limbs, vertical ( $F_z$ ) and horizontal  
201 ( $F_x$ ) GRFs were determined along with hip, knee, and ankle angles and moments in the  
202 sagittal plane during weight acceptance during the final contact. Additionally, frontal  
203 plane knee abduction angles and moments were calculated during the final contact. Joint  
204 moment data were normalised to body mass (Nm/kg).

205

## 206 Statistical Analyses

207 For the waveform analyses, force and lower-limb angles and moments were registered to  
208 101 nodes. Open-source SPM software (30) was then used to assess for differences  
209 (paired t-test) between the entire weight acceptance phase of preferred and non-preferred  
210 limbs. Differences in performance time between limbs were examined using standardized  
211 differences (effect size, ES [ $\pm$  95% confidence interval]), based on Cohen's effect size

212 principle.

## 213 **RESULTS**

214 There were unclear differences in performance times between limbs (ES = 0.30 [-0.13 to  
215 0.73]). There were no significant differences between limbs in vertical and horizontal  
216 GRF during weight acceptance (Figure 1). Sagittal plane hip, knee, and ankle angles and  
217 moments revealed no differences between limbs (Figure 2). Similarly, no between-limb  
218 differences were found in frontal plane knee abduction angles and moments (Figure 3).

## 219 **DISCUSSION**

220 Although several reports have investigated between-limb differences in lower-limb  
221 biomechanics during change of direction tasks (12), few have explored differences using  
222 1D approaches. Understanding lower-limb biomechanics during turning is key to injury  
223 prevention and rehabilitation programming due to the braking demands and body  
224 alignment, which is associated with increased loading, and therefore, surrogates of injury  
225 risk. While few studies have explored lower-limb biomechanical differences between  
226 limbs in cutting using full waveform analyses (12), this exploratory study is the first to  
227 examine the differences during a turn manoeuvre. After analysing GRFs and lower-limb  
228 sagittal and frontal plane joint angles and moments, no between-limb differences were  
229 detected for change of direction biomechanics during turning in female soccer players.  
230 Thus for the current study, it appears that there are no differences in lower-limb joint  
231 angles and moments at critical instances during weight acceptance between preferred and  
232 non-preferred limbs.

233 The results of this study did not show any significant differences between limbs in lower-  
234 limb biomechanics during a turn manoeuvre. Specifically, vertical and horizontal GRFs,

235 sagittal plane hip, knee, and ankle moments, and frontal plane knee abduction angles and  
236 moments failed to demonstrate any between-limb differences when turning off the  
237 preferred and non-preferred limbs. In these cases, SPM was able to provide information  
238 the full waveform of the weight acceptance phase regarding differences (or lack of) in  
239 movement patterns and overall performance. SPM enables a more comprehensive  
240 understanding of differences in movement patterns and overall performance between  
241 limbs that could better inform clinical and training interventions, decision making, and  
242 rehabilitation targeted at these specific regions of difference (22). However, in this  
243 experiment, SPM did not identify any between-limb differences, despite differences  
244 between limbs being identified in previous studies for vertical GRF (15,27), peak knee  
245 flexion angle (15), peak knee flexion moment (28), and peak knee abduction moment  
246 (8,28). It is difficult to explain this result, but it might be related to the fact with the  
247 exception of Marshall et al (27), the aforementioned studies compared between-limb  
248 differences based on discrete point analyses; potentially leading to regional focus bias  
249 and does not provide information regarding temporal differences. This form of analysis  
250 could also lead to a large proportion of potentially valuable and meaningful information  
251 of the full waveform being left unexamined. Another possible explanation for this is that  
252 as SPM does have a multiple comparison correction built in, the threshold for statistical  
253 significance is higher with SPM than with discrete analysis (null hypothesis significance  
254 testing). There is abundant room for further progress in determining between-limb  
255 differences in change of direction biomechanics using SPM. Future studies on the current  
256 topic are therefore recommended.

257 SPM has been used to compare differences between limbs in lower-extremity movement  
258 during running (19). Previous work has also used full waveform analyses to evaluate  
259 between-limb biomechanics during a 75°cut in male international rugby players (27).

260 Using these approaches, prior studies have provided additional information regarding  
261 between-limb differences that are not available using discrete point analyses. For  
262 example, when using discrete analyses, Marshall et al. (27) found only 1 variable of 28  
263 (ankle internal rotation moment) to demonstrate statistical significance between limbs for  
264 male rugby players. Moreover, full waveform analysis between limbs revealed additional  
265 limb differences that were not observed during discrete analyses on measures such as  
266 ankle dorsi-flexion angle, knee abduction angle, knee internal rotation moment, knee  
267 flexion angle, and vertical GRF. Similarly, Hughes-Oliver et al. (19) found SPM to  
268 provide clinically meaningful movement differences between limbs during running in  
269 healthy and anterior cruciate ligament reconstruction patients. Subsequently, the current  
270 study adds to our understanding about lower-limb biomechanics in female soccer players  
271 during a turn manoeuvre, using SPM. This study includes SPM findings in healthy female  
272 soccer players during turning to broaden the base of information regarding the use of  
273 SPM to evaluate between-limb kinetic and kinematic differences.

274 Although this study does provide novel information regarding between-limb differences  
275 in change of direction biomechanics, there are several limitations to this study. First, the  
276 pre-planned execution of the turn manoeuvre, whereas unanticipated change of direction  
277 has shown to elevate knee joint loads during cutting (4). Another limitation is that some  
278 differences (with respect to knee abduction angles and moments) may be concealed by  
279 the preferred limb displaying greater values than the non-preferred limb, and vice versa  
280 (i.e. some athletes will be higher risk for the preferred limb and some high-risk for the  
281 non-preferred). It is unknown whether individual analyses might actually reveal some  
282 athletes display a temporal pattern which indicate a particular limb may be a heightened  
283 risk of injury. Future research on this topic is therefore warranted. Notwithstanding these  
284 limitations, the results of this study demonstrate SPM can be used to assess between-limb

285 differences in lower-limb kinetics and kinematics of female soccer players during turning.  
286 Although this method provides additional information about between-limb differences  
287 than the evaluation of discrete measures alone, SPM may require larger sample sizes to  
288 be sufficiently powered to detect all between-limb differences. In addition, SPM may  
289 provide a method for determining clinically meaningful movement differences between  
290 limbs that could be used in the development of change of direction intervention programs.  
291 The use of SPM for determining between limb differences should be further investigated  
292 in additional sporting populations and change of direction tasks (i.e. sidestep cutting).  
293 Finally, given that no differences in lower-limb kinetics and kinematics were noted as a  
294 part of this exploratory analysis, no unique 1D hypotheses were framed as a part of future  
295 research. Despite this, future explorations asymmetries in female populations should  
296 incorporate larger samples and evaluation of temporal differences across movement  
297 cycles.

298

## 299 **PRACTICAL APPLICATIONS**

300 The results of this exploratory study show that no differences exist in lower-limb kinetics  
301 and kinematics between the preferred and non-preferred limbs during turning in female  
302 soccer players. As such, coaches and practitioners should consider these findings when  
303 assessing and monitoring between-limb differences in lower-limb kinetics and kinematics  
304 during turning maneuvers. Specifically, whether a particular limb is of heightened risk of  
305 injury when female soccer players perform a turn maneuver, practitioners should aim to  
306 reduce high risk postures and knee joint loads in both the preferred and non-preferred  
307 limbs, and potentially adopt an individual approach.

308

309

310 **ACKNOWLEDGEMENTS**

311 The authors would like to thank all participants for taking part in the study.

312

313 **Declaration of Interest**

314 The authors report no conflict of interest

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