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**HORIZONTAL FORCE PRODUCTION AND MULTI-SEGMENT FOOT  
KINEMATICS DURING THE ACCELERATION PHASE OF BEND SPRINTING**

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1 **Abstract**

2 This paper investigated horizontal force production, foot kinematics and metatarsophalangeal  
3 (MTP) joint push-off axis use during acceleration in bend (anti-clockwise) and straight-line  
4 sprinting. It was hypothesised that bend sprinting would cause the left step push-off to occur  
5 about the oblique axis, resulting in a decrease in propulsive force. Three-dimensional  
6 kinematic and ground reaction force data were collected from nine participants during  
7 sprinting on the bend (36.5 m radius) and straight. Anteroposterior force was reduced at 38-  
8 44% of stance during bend sprinting compared with the straight. This coincided with an  
9 increase in mediolateral force for the majority of the stance phase (3-96%) on the bend  
10 compared with the straight. In addition, a lower propulsive impulse was reported on the bend  
11 compared with the straight. Analysis of multi-segment foot kinematics provides insight into  
12 the possible mechanisms behind these changes in force production. Mean mediolateral centre  
13 of pressure position was more lateral in relation to the second metatarsal head in the left step  
14 on the bend compared with the straight, indicating the oblique axis was used for push-off at  
15 the MTP joint. Greater peak joint angles of the left foot were also reported, in particular, an  
16 increase in left step midfoot eversion and internal ankle rotation. It is possible these changes  
17 in joint kinematics are associated with the observed decrease in propulsive force. Therefore,  
18 practitioners should seek to strengthen muscles such as tibialis posterior in frontal and sagittal  
19 planes and ensure specificity of training which may aid in addressing these force reductions.

20 **Key words:** 200 m, three-dimensional, athletics, curve, impulse, SPM

21

22

## 23 **Introduction**

24           During maximal velocity treadmill sprinting, faster speeds are associated with higher  
25 peak vertical forces<sup>1</sup>. However, rather than solely producing greater peak forces, faster speeds  
26 are more dependent on the ability to produce these forces rapidly, meaning the production of  
27 high vertical force over a short contact time is crucial<sup>1</sup>. During anti-clockwise bend sprinting,  
28 left step contact times are longer than straight-line sprinting<sup>2-5</sup>. As forces are only produced  
29 when the foot is in contact with the ground, it could be postulated that the associated ground  
30 reaction forces are affected.

31           During maximal velocity bend sprinting, lower peak resultant and vertical forces have  
32 been reported for the left step on the bend than the straight<sup>6</sup>. Additionally, inward forces were  
33 greater on the bend than the straight, with the left limb producing a greater peak inward force  
34 compared with the right on the bend<sup>6</sup>. This limb asymmetry in force production could hold  
35 important insights in understanding bend sprinting performance. Furthermore, the maximal  
36 velocity phase does not reflect the full requirements of a 200 m or 400 m race and  
37 consideration of the acceleration phase bend sprinting is required.

38           Similar to maximum speed<sup>1</sup>, straight-line acceleration performance is not simply  
39 reliant upon the production of large forces, but rather producing greater horizontal force as a  
40 proportion of the total amount of force applied<sup>7,8</sup>. Thus, 'ratio of force' has been proposed as a  
41 useful measure of performance during the acceleration phase of straight-line sprinting,  
42 placing emphasis on the orientation of force rather than magnitude<sup>7-9</sup>. The necessity to  
43 generate centripetal force during bend sprinting might also affect the magnitude of vertical  
44 and anteroposterior forces, and thus ratio of force, however, this is yet to be investigated.  
45 Therefore, ratio of force might provide important insight into performance changes between  
46 bend and straight sprinting.

47 Bojsen-Moller<sup>10</sup> observed the metatarsophalangeal joint (MTP) has two axes about  
48 which the foot can push off: transverse and oblique. The transverse axis runs through the  
49 heads of the first and second metatarsals (MTH1, MTH2), whereas the oblique axis runs  
50 through the second to fifth metatarsal heads (MTH5)<sup>10</sup>. Push-off at higher walking speeds  
51 uses the transverse axis, thus it is deemed more effective than the oblique axis at generating  
52 propulsive force in the direction of progression<sup>10</sup>. Churchill, Trewartha, Bezodis, Salo<sup>6</sup>  
53 purported the inward lean of athletes during bend sprinting might promote the use of the  
54 oblique axis for the left ground contact (but the transverse axis for the right ground contact).  
55 Therefore, it is probable athletes are less effective at generating propulsive force when using  
56 the oblique axis, which has been suggested as a limiting factor in bend sprinting<sup>6</sup>. Indeed, the  
57 MTP joint has been highlighted as making an important contribution to performance in  
58 straight line sprinting<sup>11,12</sup> and warrants investigation during bend sprinting.

59 If MTP joint push-off mechanics are influenced by sprinting on the bend, as a  
60 consequence the more proximal ankle joint also employ different compensatory mechanisms,  
61 as described by Bojsen-Moller<sup>10</sup>. Kinematic adaptations have been reported elsewhere in the  
62 lower extremity, for example, both Alt, Heinrich, Funken, Potthast<sup>2</sup> and Churchill, Salo,  
63 Trewartha<sup>3</sup> reported an increase in peak left hip adduction on the bend compared with the  
64 straight at submaximal<sup>2</sup> and maximal speeds<sup>3</sup>. Alt, Heinrich, Funken, Potthast<sup>2</sup> also reported  
65 greater peak left ankle eversion during bend sprinting. During the stance phase in sprinting,  
66 the foot is in a fixed position, thus motion at the foot and ankle is thought to pass proximally  
67 as part of a closed kinematic chain to the tibia, fibula and femur<sup>13</sup>. Therefore, adaptations  
68 occurring proximally in the kinematic chain during bend sprinting are likely associated with  
69 adaptations at the foot. Furthermore, asymmetric differences in strength of the muscle groups  
70 of the foot<sup>14</sup> and high incidences of injuries to the foot<sup>15</sup> have been reported in bend sprinting

71 athletes. Hence, better understanding the motion of the foot during bend sprinting might  
72 provide insight for practitioners to aid injury prevention strategies.

73 In summary, force adaptations during the bend sprinting acceleration are likely and  
74 might contribute towards a decrease in sprint performance. Furthermore, these changes could  
75 be associated with kinematic adaptations of the foot and ankle. Therefore, this study aimed to  
76 investigate horizontal force production, foot kinematics and MTP axis use during sprinting on  
77 the bend compared with the straight. A secondary aim was to evaluate between limb  
78 differences to identify the existence of any asymmetry during bend sprinting. It was  
79 hypothesised the oblique axis would be used by the left foot for push-off during bend  
80 sprinting, resulting in a decrease in propulsive force (and therefore sprint performance) in  
81 comparison with the straight.

## 82 **Methods**

### 83 *Participants*

84 Following institutional ethical approval, nine male sprinters (mean age  $22 \pm 4$  years;  
85 body mass  $71.48 \pm 9.47$  kg; stature  $1.81 \pm 0.06$  m) volunteered to participate in this study. All  
86 athletes were experienced bend sprinters (200 and/or 400 m) and the inclusion criteria  
87 required a 200 m personal best of 23.5 s or faster (mean  $22.70 \pm 0.49$  s, range 21.8 - 23.43 s)  
88 to standardise ability with previous research (Alt, Heinrich, Funken, Potthast<sup>2</sup>  $22.60 \pm 0.33$  s;  
89 Churchill, Salo, Trewartha<sup>3</sup>  $22.15 \pm 0.93$  s). At the time of data collection, all athletes were  
90 injury free and active in training. The study procedures were fully explained to participants  
91 who subsequently provided written informed consent.

92

93

94 ***Experimental set-up***

95           The experimental set-up is demonstrated in figure 1. Kinematic data were collected  
96 using a 15-camera optoelectronic motion capture system (13 x Raptor model and 2 x Eagle  
97 model, Motion Analysis Corporation (MAC), Santa Rosa, CA, USA) sampling at 200 Hz. A  
98 right-handed lab coordinate system was defined using a rigid L-frame with four markers at  
99 known locations. Athletes ran primarily in the direction of the positive  $x$ -axis, where the  
100 positive  $y$ -axis was directed vertically upwards and the positive  $z$ -axis was mediolateral,  
101 pointing to the athletes' right. The calibration volume (7 m long, 3 m wide and 1.5 m high)  
102 was located tangentially to the apex of the curve to record data through the 10 - 17 m section  
103 of the 30 m sprints.

104 **\*\*\* Figure 1 near here \*\*\***

105           A modified Vicon Plug-in Gait (PiG) marker set (lower limb and trunk<sup>16</sup>) was used to  
106 model the torso, pelvis, thighs, shanks and feet segments (toebox, forefoot, rearfoot). Retro-  
107 reflective markers (12.7 mm) were placed on the following anatomical landmarks: lateral  
108 malleolus, medial malleolus, shank (lower lateral 1/3), thigh (lower lateral 1/3 surface of the  
109 thigh), lateral femoral epicondyle, medial femoral epicondyle, greater trochanter, posterior  
110 superior iliac spine, anterior superior iliac spine, C7, T10, suprasternal notch, xiphoid  
111 process. Shoe-mounted markers (posterior, medial and lateral calcaneus, 1<sup>st</sup> and 5<sup>th</sup> metatarsal  
112 bases, MTH1, MTH2, MTH5 and head of the 2<sup>nd</sup> toe) were used to represent the movement  
113 of the underlying structure of the foot. Further details of marker placement can be found in  
114 Judson, Churchill, Barnes, Stone, Brookes, Wheat <sup>17</sup>.

115           Kinetic data were collected using a Kistler force plate (Model: 9287BA, 900 x 600  
116 mm) sampling at 1000 Hz. The force plate was embedded into the track surface and covered



117 with a secured piece of synthetic track. The force platform was configured to produce a  
118 rising(/falling) edge 5 V signal at the onset of data collection, which was sampled by the  
119 motion capture system and used to temporally synchronise the kinematic and kinetic data.

## 120 ***Protocol***

121 Data were collected on a flat standard indoor track surface with a reconstructed bend  
122 replicating lane 1 (radius 36.5 m) of a standard 400 m running track (IAAF, 2008). Straight-  
123 line trials were completed on a 30 m section of straight track. The order of experimental  
124 conditions were randomised to minimise order effects. Results from Morin, Slawinski, Dorel,  
125 de Villareal, Couturier, Samozino, Brughelli, Rabita<sup>18</sup> suggest the production of propulsive  
126 impulse in the first 20 m determines acceleration performance. Thus, it was decided to limit  
127 analysis to the 0 - 20 m section. Therefore, kinematic data were collected at 10-17 m within  
128 the present study to enable comparison with previous research. Furthermore, only one study  
129 has examined the acceleration phase of bend sprinting, analysing data at 12 m<sup>19</sup>, so the force  
130 plate was located at approximately 12 m.

131 Participants completed their typical competition warm-up before performing a  
132 maximum of six trials (three left, three right) at maximal effort for 30 m in each condition  
133 (bend and straight). Starting blocks were used alongside an '*on your marks, set, go*' signal to  
134 maintain the experimental representativeness of the protocol. For force data, a minimum of  
135 one successful right and left step on the bend and one successful right and left step on the  
136 straight were achieved within these trials. A successful trial was defined as contact being  
137 made with the force plate without changes to running gait caused by 'targeting'. To achieve  
138 this, one researcher modified the start location up to a maximum of one metre of the athletes  
139 based upon warm-up trials. Therefore, force data were collected in the range of 11 - 13 m. To

140 further reduce the likelihood of targeting, participants were not informed of the force plate  
141 location. Approximately eight minutes were allowed between trials to avoid the onset of  
142 fatigue<sup>3</sup>. Participants wore their own sprint spikes for the testing session.

### 143 *Data processing*

144 Raw 3D marker coordinate data were analysed using Cortex software (version 5.3,  
145 Motion Analysis Corporation, Santa Rosa, CA, USA). Automatic gap filling, using a cubic  
146 spline, was performed. All gaps were <10 frames. A low-pass, fourth order recursive  
147 Butterworth filter was applied to raw marker positions. Residual analysis was used to  
148 determine the cut-off frequency (18 Hz). Visual 3D (version 6, C-Motion, Rockville, MD,  
149 USA) was used to define and construct segments, local coordinate systems and joint centres.  
150 Where possible, International Society of Biomechanics (ISB) guidelines<sup>20,21</sup> were adhered to.  
151 However, the joint coordinate system for the multi-segment foot was defined in accordance  
152 with Cappozzo, Catani, Della Croce, Leardini<sup>22</sup>. For centre of mass (CoM) calculations,  
153 body segment parameters were estimated from de Leva<sup>23</sup> and adjusted by 150 to 189 g  
154 representing the mass of individual participants' spiked shoe according to manufacturer  
155 specification. Previous work established using a lower limb and trunk model was appropriate  
156 for whole body CoM calculations<sup>16</sup>. Kinetic data were analysed using Matlab (v2017a,  
157 Mathworks, Natick, USA). Force data were filtered with a low-pass, fourth order recursive  
158 Butterworth filter 150 Hz cut-off frequency, chosen with the use of residual analysis.

159 For force data, one successful trial per condition and per participant was analysed, as  
160 was the case with Churchill, Trewartha, Bezodis, Salo<sup>6</sup>. Two participants were not able to  
161 record force data for one condition, so their force data was removed from the analysis. For  
162 kinematic data, a mean of three trials was calculated for both the left and right foot on the

163 bend and straight. *Touchdown* and *take-off events* were identified using the mean plus two  
164 standard deviations of the last three seconds of vertical ground reaction force data (where  
165 there was zero load on the force plate) as a threshold<sup>24</sup>. For trials where force plate data were  
166 not available, the mean plus two standard deviations of the vertical coordinates of MTH5 in  
167 the static trial were used as a threshold for touchdown and take-off<sup>24</sup>. All variables were  
168 calculated separately for the left and right step. Left and right steps were defined by the foot  
169 that initiated the step. *Absolute speed* was calculated using the first central difference  
170 technique from the horizontal distance travelled by the CoM of the lower limb and trunk  
171 model. *Contact time* was calculated at the time from touchdown to take-off.

172 For both bend and straight trials, horizontal forces in the global coordinate system  
173 were transformed into an instantaneous, body-fixed reference system. The body-fixed system  
174 was defined at each time point, oriented such that the *x*-axis pointed in the direction of the  
175 instantaneous centre of mass velocity vector, the *y*-axis pointed vertically upwards and the *z*-  
176 axis pointed to the participant's right<sup>25</sup> and expressed relative to body weight. Therefore,  
177 anteroposterior force was defined as the *x*-component of external force in the body-fixed  
178 coordinate system. Centre of mass data were upsampled from 200 to 1000 Hz using a cubic  
179 spline to enable the rotation of forces. *Braking and propulsive impulses* were calculated from  
180 absolute values and expressed relative to body mass. *Ratio of force* was calculated as the  
181 mean ratio of force in the direction of forward progression (relative to the direction of travel  
182 of the athlete's CoM) to resultant force during ground contact.

183 Adapted from Smith, Lake, Lees, Worsfold<sup>26</sup>, *MTP push-off axis* was determined  
184 using centre of pressure (CoP) data. CoP data were first aligned with a local foot coordinate  
185 system. The mediolateral position of the CoP and MTH2 marker was then extracted during  
186 the propulsive phase of stance for each condition. The distance of the CoP from the MTH2

187 was then calculated for each frame, followed by calculation of the mean CoP position during  
188 the propulsive phase of stance and thus providing the *mean mediolateral CoP position*  
189 *relative to MTH2*. For ease of interpretation, data for the left foot were multiplied by -1, so a  
190 positive value indicated CoP was lateral to MTH2 and represented the oblique axis for both  
191 the left and right foot. Consequently, a negative value represents the use of the transverse axis  
192 (figure 2).

193 \*\*\* **Figure 2 near here** \*\*\*

194 *Joint orientation angles* during the stance phase were defined as the distal segment  
195 relative to the proximal segment, using the joint coordinate system convention<sup>27</sup>. The analysis  
196 focussed on frontal and transverse plane variables since previous bend sprinting research has  
197 demonstrated that kinematic adaptations occur predominantly in the non-sagittal planes<sup>2</sup>. The  
198 following joint angles were chosen for analysis to allow assessment of the influence of foot  
199 position on force production: midfoot inversion and eversion, ankle inversion and eversion,  
200 ankle internal and external rotation. Values for the left limb were multiplied by -1 for ease of  
201 interpretation. MTP angular velocity was included since Krell, Stefanyshyn<sup>11</sup> have shown a  
202 relationship between sprint performance and higher maximal rates of MTP extension.

203 Minimum detectable difference (MDD) indicates the magnitude of change required to  
204 be considered 'real'. Where the difference between conditions exceeds the MDD, it can be  
205 considered a change due to experimental condition and not natural athlete variance or  
206 protocol error. Therefore, peak angles and spatiotemporal variables were interpreted with  
207 reference to the MDD evaluated in the bend sprinting, identified by Judson, Churchill,  
208 Barnes, Stone, Brookes, Wheat<sup>17</sup>.

209

## 210 *Statistical analysis*

211 Normal distribution of the data for each variable was confirmed by the Shapiro-Wilk  
212 normality test ( $P > 0.05$ ).

213 For discrete variables, two way repeated measures ANOVAs were performed where  
214 condition (bend vs. straight) x limb (left vs. right) were analysed ( $P > 0.05$ ). Due to a small  
215 sample size, the study may be statistically underpowered and so the chance of detecting a true  
216 effect was reduced. Therefore results were also interpreted using Hedges'  $g$ , which includes a  
217 correction for small sample sizes. Cohen<sup>28</sup> guidelines were used for the interpretation of  
218 effect size, where  $d < 0.20$  represents a trivial difference,  $0.20 \geq 0.50$  indicating a small  
219 difference,  $0.50 \geq 0.80$  a moderate difference and  $\geq 0.80$  a large difference between means.

220 Statistical Parametric Mapping (SPM<sup>29</sup>) was used to statistically compare force  
221 production across the entire stance phase between conditions. Force data were first  
222 normalised to 101 data points, representing 0-100% of the stance phase. An SPM repeated  
223 measures two way ANOVA was then performed separately at each of the 101 time points  
224 resulting in the output of a statistical parametric map (SPM{F}). If SPM{F} exceeded the  
225 critical threshold, forces at these specific nodes could be considered different. A collection of  
226 consecutive nodes exceeding the threshold and considered significant is termed a 'supra-  
227 threshold cluster'. Following methods used by Colyer, Nagahara, Salo<sup>30</sup>, clusters of fewer  
228 than five nodes were considered unlikely to be meaningful. SPM analyses were implemented  
229 using open source SPM code (SPM1D open-source package, [spm1d.org](http://spm1d.org)) in MATLAB  
230 (v2017a, Mathworks, Natick, USA).

## 231 **Results**

### 232 **Performance descriptors**

233           There was a 2% reduction in absolute speed on the bend compared with the straight  
234 for the left step ( $g = 0.52$ , Table 1). During bend sprinting, absolute speed was faster during  
235 the right step than the left step ( $g = 0.48$ , Table 1). However, there was no significant main  
236 effect for condition,  $F_{(1, 8)} = 0.574$ ,  $P = 0.47$  or limb  $F_{(1, 8)} = 2.994$ ,  $P = 0.122$ . For contact  
237 time, there was a significant main effect for condition,  $F_{(1, 8)} = 6.111$ ,  $P = 0.039$  ( $g = 1.50$  left  
238 step;  $0.27$  right step), with contact being longer on the bend than straight. A significant  
239 condition x limb interaction was also reported,  $F_{(1, 8)} = 7.801$ ,  $P = 0.023$  showing the increase  
240 in contact time on the bend was greater in the left step compared with the right step ( $d =$   
241  $0.56$ ).

242 \*\*\* **Table 1 near here** \*\*\*

#### 243 **Anteroposterior, mediolateral force and ratio of force**

244           The profiles of anteroposterior force signals during straight-line and bend sprinting  
245 were similar for the majority of the stance phase (Figure 3). However, one supra-threshold  
246 cluster (37-44%) exceeded the critical threshold of  $F = 17.238$  for the main effect of  
247 condition, where anteroposterior force was lower on the bend compared with the straight in  
248 both the left and right steps. The probability that a supra-threshold cluster of this size would  
249 be observed in repeated random samplings was  $P < 0.001$ .

250           One supra-threshold cluster exceeded the critical threshold ( $F = 15.309$ ) for main  
251 effect of condition when comparing mediolateral force on the bend and straight (3-96%,  $P <$   
252  $0.001$ ). This was due to an increase in mediolateral force production across the majority of  
253 the stance phase on the bend (see Figure 4). There was also a significant main effect for limb,  
254 with two supra-threshold clusters found at 1-12% and 75-100% of stance. At 1-12%,

255 mediolateral force was greater in the right step than left, whilst at 75-100% of stance, the left  
256 step was greater than the right.

257 \*\*\* **Figure 3 near here** \*\*\*

258 \*\*\* **Figure 4 near here** \*\*\*

259         There was a main effect for condition on propulsive impulse  $F_{(1,6)} = 8.53$ ,  $P = 0.02$  ( $g$   
260  $= 0.93$  left step;  $0.78$  right step, Table 2), with the straight resulting in a greater propulsive  
261 impulse than the bend. However, there was no condition x limb interaction,  $F_{(1,6)} = 0.708$ ,  $P$   
262  $= 0.433$ . For braking impulse, a 27% increase with large effect size ( $g = 1.29$ , Table 2) was  
263 reported in the left step on the bend relative to the straight. However, the main effect for  
264 condition was not significant,  $F_{(1,6)} = 6.272$ ,  $P = 0.05$ . For mean ratio of force there was a  
265 significant main effect for condition,  $F_{(1,6)} = 11.647$ ,  $P = 0.014$  ( $g = 1.72$  left step;  $1.16$  right  
266 step, Table 2), with the straight resulting in a higher mean ratio of force than the bend. There  
267 was no condition x limb interaction for mean ratio of force ( $F_{(1,6)} = 2.628$ ,  $P = 0.156$ ).

268 \*\*\* **Table 2 near here** \*\*\*

269

#### 270 **MTP push-off axis and multi-segment foot kinematics**

271         There was a significant condition x limb interaction for COP position,  $F_{(1,6)} =$   
272  $127.878$ ,  $P < 0.001$ . The mean mediolateral COP position was more lateral in the left step on  
273 the bend compared with the straight (Figure 5). This indicates the oblique axis was in use  
274 during the left step on the bend, while the transverse axis was used for all other conditions.

275 \*\*\***Figure 5 near here**\*\*\*

276           There was a significant condition x limb interaction for peak ankle internal rotation,  
277  $F_{(1, 8)} = 17.091, P = 0.003$ . Left step peak ankle internal rotation was greater on the bend,  
278 compared with the straight ( $g = 1.70$ ) and the right step on the bend ( $g = 1.95$ ). Left step peak  
279 ankle eversion was 55% greater on the bend than straight ( $g = 0.88$ ), however, no significant  
280 main effect for condition was reported,  $F_{(1, 8)} = 1.247, P = 0.297$ . For peak ankle inversion,  
281 there was a significant condition x limb interaction,  $F_{(1, 8)} = 12.707, P = 0.007$ , due to a  
282 decrease in left step peak ankle inversion on the bend compared with the straight. For peak  
283 midfoot eversion, there was a significant condition x limb interaction ( $F = 11.768, P = 0.009$ )  
284 due to an increase in the left step on the bend compared with the straight ( $g = 0.79$ ), and a  
285 decrease in the right step on the bend compared with the straight ( $g = 0.72$ ). A significant  
286 main effect for limb in peak midfoot eversion ( $F_{(1, 8)} = 9.166, P = 0.016, g = 1.73$ ) was also  
287 reported.

288           A significant condition x limb interaction was reported for peak midfoot inversion,  $F_{(1, 8)} = 6.238, P = 0.037$ , due to an increase in right step peak midfoot inversion on the bend  
289 relative to the straight and the left step on the bend ( $g = 0.90$ ). There was no significant  
290 condition x limb interaction for MTP angular velocity ( $F_{(1, 8)} = 1.672, P = 0.232$ ), however a  
291 moderate effect size between the left step on the bend and straight was reported ( $g = 0.50$ ).

293 **\*\*\* Table 3 near here \*\*\***

## 294 **Discussion and Implications**

295           The aim of this research was to investigate horizontal force production, foot  
296 kinematics and MTP joint axis use during sprinting in the acceleration phase on the bend  
297 compared to the straight. The left foot was found to use the oblique axis for push-off at the  
298 MTP joint. This coincided with a decrease in anteroposterior force and propulsive impulse



299 and an increase in peak eversion of the midfoot and ankle. These findings support the study's  
300 hypothesis. Moreover, although non-statistically significant, a small (2%,  $g = 0.52$ ) reduction  
301 in left step absolute speed on the bend compared with the straight was observed. The decrease  
302 in absolute speed is lower than the 4.7% reduction reported by Churchill, Salo, Trewartha<sup>3</sup>  
303 during maximal speed, suggesting the effect of the bend during the acceleration phase  
304 accumulates and results in a greater loss of speed during the later maximal speed phase.

305 A decrease in propulsive force on the bend compared with the straight was observed,  
306 with the supra-threshold cluster occurring at 37-44% of the stance phase. Colyer, Nagahara,  
307 Salo<sup>30</sup> found better performances in straight-line sprinting were associated with the  
308 production of high amounts of propulsive force during the mid-late propulsive phase of the  
309 eighth step (55-85% of stance). As the sprint distance increased, these associations occurred  
310 earlier in the stance phase (nineteenth step: 19 - 64% of stance<sup>30</sup>). Therefore it is reasonable  
311 to assume that associations with sprint performance and propulsive force at the tenth or  
312 eleventh step as measured in the present study will occur earlier in the stance phase than the  
313 55-85% reported by Colyer, Nagahara, Salo<sup>30</sup> at the eighth step. Thus, the results of the  
314 present study suggest the ability to produce propulsive force is reduced on the bend and  
315 occurs at a crucial time point during the stance phase which might impact upon acceleration  
316 performance.

317 In addition to the reduction in propulsive force, there was a decrease in propulsive  
318 impulse, particularly during the left step where a large effect size was found ( $g = 0.93$ ). Right  
319 step propulsive impulse was also reduced on the bend compared to the straight. However, the  
320 moderate effect size suggests this was not to the same extent (propulsive impulse  $g = 0.78$ ).  
321 Morin, Slawinski, Dorel, de Villareal, Couturier, Samozino, Brughelli, Rabita<sup>18</sup> discussed

322 how acceleration capability in faster sprinters was characterised by 'pushing more' but not  
323 necessarily 'braking less'. This concept suggests producing higher propulsive impulse is of  
324 greater importance than producing lower braking impulse, particularly in the first twenty  
325 metres of acceleration. This is supported by Colyer, Nagahara, Salo<sup>30</sup> who observed a  
326 positive association between better performances and higher amounts of anteroposterior force  
327 during the mid-late propulsion phase of stance. During bend sprinting, the ability to produce  
328 propulsive impulse was restricted, and although a significant effect was not reported for  
329 braking impulse, large effect sizes were observed when comparing left step on the bend and  
330 straight ( $g = 1.29$ ). This suggests a greater braking impulse was experienced in the left step  
331 on the bend in comparison to the straight. Unlike Morin, Slawinski, Dorel, de Villareal,  
332 Couturier, Samozino, Brughelli, Rabita<sup>18</sup>, acceleration performance during bend sprinting is  
333 characterised by 'pushing less' and 'braking more' than the straight, particularly with the left  
334 foot. Therefore, propulsive force production of the left foot may be a limiting factor for  
335 acceleration performance on the bend.

336           However, these reductions in propulsive force observed during bend sprinting are a  
337 necessary consequence of the additional requirement to produce centripetal force. In order to  
338 achieve this requirement, and stay in the correct lane, mediolateral force was greater on the  
339 bend compared to the straight for the majority (3-96%) of the stance phase. Whilst necessary  
340 for bend sprinting, it is possible the introduction of mediolateral force is a contributing factor  
341 for the decrease in ratio of force found during bend sprinting. In addition, use of SPM  
342 revealed mediolateral force during bend sprinting was greater in the right step compared to  
343 the left during 1-12% of the stance phase, whereas later in stance (75-100%), mediolateral  
344 force was greater in the left step than right, thus further establishing the left foot as fulfilling a  
345 different role to the right foot during bend sprinting. These asymmetries demonstrate the

346 benefit of SPM analysis which has provided insight that may have been lost with the analysis  
347 of discrete values.

348 In comparison with straight-line sprinting, bend sprinting elicited an 11% and 22%  
349 decrease in mean ratio of force for the left and right steps, respectively. A higher ratio of  
350 force has been associated with better acceleration performance<sup>9</sup>. This reinforces the notion  
351 that athletes apply propulsive force less effectively during bend sprinting and therefore the  
352 generation and orientation of force appear a limiting factor to acceleration performance on  
353 the bend when compared with straight-line sprinting. It appears this may be due to the  
354 combination of a reduction in propulsive force and an essential increase in mediolateral force.  
355 Whilst the right step experienced a decrease in ratio of force on the bend, right step ratio of  
356 force was 8% greater than the left step on the bend ( $g = 0.88$ ). Thus, there appear to be  
357 asymmetries in force production of the left and right limb during bend sprinting, with the  
358 right being more effective at propulsive force production.

359 Ratio of force analysis provides an overview of force orientation and a reduction was  
360 reported in both left and right steps on the bend compared with the straight. This finding is  
361 reinforced when considering impulse, which as the product of force and time acts as a metric  
362 to evaluate force application. Reductions in the magnitude of force despite longer contact  
363 times resulted in a decrease in propulsive impulse that was greater in the left step. Therefore,  
364 it appears the decrease in acceleration performance at approximately 12 m is largely due to  
365 changes in left step force orientation and application.

366 A mechanism behind the reported changes in force production during bend sprinting  
367 might be the use of different MTP joint push-off axes. Results showed that left step mean  
368 mediolateral COP position was more lateral on the bend than the straight, suggesting the

369 oblique axis is used to push-off with the left step during bend sprinting, supporting the  
370 hypothesis put forward by Churchill, Trewartha, Bezodis, Salo<sup>6</sup>. The oblique axis is  
371 considered less effective for push-off at high speeds<sup>10</sup>. However, during bend sprinting,  
372 oblique axis use seems a necessary adaptation (dictated by the need to produce centripetal  
373 force and change in the segmental arrangement of the lower limb) required to enable the  
374 change of direction. The mean mediolateral COP position for the right step on the bend was  
375 more medial than the straight, thus transverse axis was in use. This reinforces the notion that  
376 the right step and left steps perform different functions during bend sprinting. Furthermore,  
377 results suggest there may be a decrease in MTP joint angular velocity during the left step on  
378 the bend compared to the straight. Krell, Stefanyshyn<sup>11</sup> established that faster male sprinters  
379 elicited higher maximal rates of MTP extension. Therefore, decreased MTP joint angular  
380 velocity might contribute to the decrease in sprint performance found on the bend. Further  
381 research is required to strengthen this conclusion.

382 Bend sprinting also induced kinematic adaptations in the multi-segment foot. In  
383 particular, there was an increased left step peak midfoot eversion combined with increased  
384 left step peak internal ankle rotation on the bend compared to the straight. Although there was  
385 no significant main effect, a large effect size suggests a trend towards an increase in left step  
386 peak ankle eversion angle ( $g = 0.88$ ). Eversion occurs during the first 15% of stance due to  
387 the eccentric contraction of invertors such as tibialis posterior and anterior<sup>13</sup>. As bi-planar  
388 muscles, whilst they are predominantly invertors they also have a role to play in  
389 plantarflexion of the foot and ankle<sup>31</sup>. Simulations<sup>32</sup> and later experimental data<sup>33</sup> suggested  
390 kinetics of the ankle joint play a dominant role in the acceleration of the centre of mass  
391 during the stance phases of early acceleration in straight-line sprinting. Therefore, as  
392 previously supposed by Chang, Kram<sup>34</sup>, a joints capacity to contribute to the production of

393 propulsive forces in the sagittal plane may be restricted by the frontal and transverse plane  
394 adaptations reported. It appears the increased left step eversion and ankle internal rotation  
395 place the foot in a disadvantageous position, compromising the ability to produce propulsive  
396 force.

397 Hamill, Murphy, Sussman<sup>35</sup> theorised the left limb would most likely suffer injuries  
398 such as plantar fasciitis or post-tibialis tendonitis as a consequence of bend running and  
399 repeated exposure to stress in the frontal and transverse planes. The results of the current  
400 study support these possible injury aetiologies. Repetitive loading and excessive eversion are  
401 considered a risk factor for plantar fasciitis<sup>36</sup>. The increased eversion of the left midfoot and  
402 ankle found during bend sprinting may place additional stress on tibialis anterior which  
403 provides a 'stirrup' for the arch under the foot<sup>31</sup> and may, therefore be a contributing factor in  
404 the onset of plantar fasciitis.

405 It is acknowledged the use of shoe-mounted markers to represent movement of the  
406 underlying bones of the foot could be associated with some inaccuracies of joint kinematics,  
407 as observed by Sinclair<sup>37</sup> during running. However, sprint spikes tend to have a tight fit  
408 which helped minimise this risk. Furthermore, this approach ensured a more representative  
409 experimental design (see Pinder, Davids, Renshaw, Araujo<sup>38</sup>) in comparison to other options  
410 such as bone-mounted markers. Whilst cutting holes in shoes enables skin-mounted markers,  
411 this compromises the integrity of the shoe and prevents athletes from wearing their own  
412 spikes. In addition, although in line with previous bend sprinting literature<sup>2,3,6</sup>, the sample  
413 size is small. Therefore, as Knudson<sup>39</sup> suggest, replication studies are encouraged to further  
414 advance our findings.

415

## 416 **Perspectives**

417           The results demonstrate a reduction in the ability to produce anteroposterior force  
418 during bend sprinting. There was also an increase in mediolateral force, resulting in a lower  
419 average ratio of force, suggesting athletes apply force less effectively during bend sprinting.  
420 In the left step, the oblique axis was used for push-off at the MTP joint, combined with  
421 increased midfoot eversion and ankle internal rotation. Therefore, it appears athletes are  
422 restricted by their ability to produce force in the non-sagittal planes due to a complex  
423 interaction of adaptations at the joints of the ankle and foot. Practitioners should, therefore,  
424 seek to strengthen muscles in frontal and sagittal planes which may aid in addressing these  
425 reductions. In addition, as highlighted by Churchill, Salo, Trewartha<sup>3</sup>; Churchill, Trewartha,  
426 Salo<sup>40</sup>, undertaking sprint training on the bend to ensure specificity, is essential. Finally, it is  
427 possible that repeated stress in these planes may be a precursor to injury. Thus, strengthening  
428 muscles, such as the tibialis posterior and tibialis anterior may have implications for injury  
429 prevention as well as performance improvements.

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544

**Table 1** Group mean values ( $\pm$  standard deviation) and effect sizes (% difference) for performance measures of the left and right step.

	Straight		Bend		Effect size (g) (% difference)			
	Left	Right	Left	Right	Left vs right straight	Left vs right bend	Straight vs bend left	Straight vs bend right
<b>Absolute speed (m/s)</b>	7.96 $\pm$ 0.23	8.00 $\pm$ 0.20	7.81 $\pm$ 0.30	7.89 $\pm$ 0.34	0.12 (0%)	0.48 (2%)	0.52 (2%)	0.05 (0%)
<b>Contact time (s)</b>	0.107 $\pm$ 0.007	0.111 $\pm$ 0.012	0.119 $\pm$ 0.007	0.114 $\pm$ 0.008	0.34 (4%)	0.57 (4%)	1.50 (11%)	0.27 (3%)

**Table 2** Group mean values ( $\pm$  standard deviation), effect sizes (% difference) for anteroposterior force variables of the left and right step.

	Straight		Bend		Effect size (g) (% difference)			
	Left	Right	Left	Right	Left vs. right straight	Left vs. right bend	Straight vs. bend left	Straight vs. bend right
<b>Relative braking impulse (m/s)</b>	-0.08 $\pm$ 0.02	-0.09 $\pm$ 0.03	-0.11 $\pm$ 0.01	-0.10 $\pm$ 0.03	0.15 (6%)	0.27 (7%)	1.29 (27%)	0.37 (15%)
<b>Relative propulsive impulse (m/s)</b>	0.59 $\pm$ 0.06	0.65 $\pm$ 0.12	0.55 $\pm$ 0.06	0.58 $\pm$ 0.06	0.65 (10%)	0.45 (5%)	0.93 (7%)	0.78 (12%)
<b>Mean ratio of force (%)</b>	19.13 $\pm$ 1.30	23.50 $\pm$ 5.52	16.94 $\pm$ 1.12	18.44 $\pm$ 2.03	1.03 (19%)	0.88 (8%)	1.72 (11%)	1.16 (22%)

**Table 3** Group mean values ( $\pm$  standard deviation) and effect sizes (% difference) for centre of pressure and midfoot kinematics of the left and right step.

Peak angle (°)	Straight		Bend		Effect size (g) (% difference)			
	Left	Right	Left	Right	Left vs right straight	Left vs right bend	Straight vs bend left	Straight vs bend right
<b>Midfoot inversion</b>	-7 $\pm$ 5	-7 $\pm$ 5	-5 $\pm$ 4	-12 $\pm$ 4	0.03 (6%)	1.48 (63%)	0.30 (41%)	0.90 (69%)
<b>Midfoot eversion</b>	0.3 $\pm$ 5	-0.3 $\pm$ 5	4 $\pm$ 3	-4 $\pm$ 4	0.13 (209%)	1.73 (184%)	0.79 (956%)	0.72 (1271%)
<b>Ankle inversion</b>	14 $\pm$ 9	10 $\pm$ 9	11 $\pm$ 9	12 $\pm$ 9	0.34 (48%)	0.06 (6%)	0.22 (33%)	0.19 (16%)
<b>Ankle eversion</b>	-2 $\pm$ 9	-4 $\pm$ 10	-5 $\pm$ 9	-3 $\pm$ 10	0.15 (36%)	0.12 (23%)	0.88 (55%)	0.02 (8%)
<b>Ankle internal rotation</b>	2 $\pm$ 4	3 $\pm$ 5	12 $\pm$ 7	1 $\pm$ 7	0.25 (44%)	1.95 (562%)	1.70 (346%)	0.46 (108%)
<b>Ankle external rotation</b>	-10 $\pm$ 5	-10 $\pm$ 3	-5 $\pm$ 5	-9 $\pm$ 5	0.13 (9%)	0.85 (42%)	0.95 (50%)	0.20 (6%)
<b>MTP angular velocity (°/s)</b>	776 $\pm$ 239	732 $\pm$ 120	694 $\pm$ 168	704 $\pm$ 176	0.25 (6%)	0.06 (2%)	0.50 (11%)	0.15 (4%)

**Figure 1:** Plan view of experimental set-up (not to scale).

**Figure 2:** Right foot representation of the transverse (solid line **—**) and oblique (dashed line **- - -**) axes of the foot. Where T2 represents marker at the second toe and MTH1, 2 and 5 the first, second and fifth metatarsal heads, respectively.

**Figure 3:** Group mean anteroposterior force for the left (red) and right (black) steps on the bend (dashed line **- - -**) and straight (solid line **—**). Shaded areas represent supra-threshold clusters indicating a significant main effect for condition.

**Figure 4:** Group mean mediolateral force for the left (red) and right (black) steps on the bend (dashed line **- - -**) and straight (solid line **—**). Shaded areas represent supra-threshold clusters indicating a significant main effect for condition (left figure) and limb (right figure). A negative force represents inward force on the bend and lateral force on the straight.

**Figure 5:** Mean mediolateral centre of pressure position relative to second metatarsal head during the propulsive phase.

