Force production during maximal effort bend sprinting : theory versus reality

CHURCHILL, Sarah M <http://orcid.org/0000-0001-9542-3812>,
TREWARTHA, Grant, BEZODIS, Ian N and SALO, Aki I T

Published version

Force production during maximal effort bend sprinting: theory versus reality

SARAH M. CHURCHILL[1,2], GRANT TREWARTHA[1],

IAN N. BEZODIS[3] AND AKI I.T. SALO[1,a]

[1] Sport, Health and Exercise Science, University of Bath, Bath, UK

[2] Academy of Sport and Physical Activity, Sheffield Hallam University, Sheffield, UK

[3] Cardiff School of Sport, Cardiff Metropolitan University, Cardiff, UK

Running Head: Force production during bend sprinting

[a] Corresponding author:

Dr Aki I. T. Salo

Sport, Health and Exercise Science

Applied Biomechanics Suite 1.309

University of Bath

BATH, BA2 7AY

UNITED KINGDOM

Tel. +44-1225-383569

Email: A.Salo@bath.ac.uk

Force production during maximal effort bend sprinting: theory versus reality

ABSTRACT

This study investigated whether the 'constant limb force hypothesis' can be applied to bend sprinting on an athletics track and to understand how force production influences performance on the bend compared with the straight. Force and three-dimensional video analyses were conducted on seven competitive athletes during maximal effort sprinting on the bend (radius 37.72 m) and straight. Left step mean peak vertical and resultant force decreased significantly by 0.37 BW and 0.21 BW, respectively, on the bend compared with the straight. Right step force production was not compromised in the same way, and some athletes demonstrated substantial increases in these variables on the bend. More inward impulse during left (39.9 ± 6.5 Ns) than right foot contact (24.7 ± 5.8 Ns) resulted in 1.6° more turning during the left step on the bend. There was a 2.3% decrease in velocity from straight to bend for both steps. The constant limb force hypothesis is not entirely valid for maximal effort sprinting on the bend. Also, the force requirements of bend sprinting are considerably different to straight-line sprinting and are asymmetrical in nature. Overall, bend-specific strength and technique training may improve performance during this portion of 200 m and 400 m races.

Introduction

22

23   Force production during maximal effort sprinting on the bend, on the surfaces and at radii

24   typical of athletic sprint events, is not well understood. This is despite the fact that during

25   200 m and 400 m track and field sprint events more than 50% of the race is run on the bend

26   section of the track. Utilising information from Greene (1985) and Weyand et al. (2000),

27   Usherwood and Wilson (2006) adopted the 'constant limb force hypothesis' for their

28   mathematical model of bend sprinting. This model assumes that athletes running on the bend

29   would generate the same constant maximum resultant force as on the straight. Thus, with the

30   additional requirement to generate centripetal force to turn on the bend (and stay within the

31   lane), it was postulated by Usherwood and Wilson (2006) that athletes would increase the

32   time spent in ground contact in order to produce the necessary vertical and inward impulses.

33   This consequently would reduce the sprinting speed. On the other hand, Gaudet (2014), when

34   creating a mathematical model for sprinting, speculated that athletes do not apply maximum

35   force during the bend running, although the author did not provide any empirical evidence for

36   this statement.

37

38   In contrast to the above, empirical research into maximal effort sprinting on bends of very

39   small radii (1-6 m) has found athletes to be unable to achieve the resultant and vertical forces

40   on the bend that they were capable of during straight-line sprinting (Chang & Kram, 2007).

41   Even during slower running (approximately 6 m/s) on larger radii typical of an athletics track,

42   vertical force production has been observed to be reduced compared with straight-line

43   running (Hamill et al., 1987).

44

45   There is reason to believe that left and right legs may have different roles in force production

46   and in keeping the athletes on the appropriate curved path during bend sprinting. Chang and

47 Kram (2007) found that during sprinting on bends with radii of 1-6 m, the right leg produced

48 greater peak lateral forces than the left leg. In contrast, Hamill et al. (1987) found that at a

49 bend radius of 31.5 m, larger peak lateral forces were produced by the left leg than the right

50 leg when running at approximately 6 m/s. Churchill et al. (2015) reported that, during

51 maximal effort sprinting on a track bend radius of 37.72 m, more turning was achieved

52 during the left ground contact than the right. This suggests that when sprinting maximally at

53 radii typical of an athletics track, the left leg may produce greater inward force than the right

54 leg. However, empirical measurement is required to confirm this.

55

56 Although Usherwood and Wilson (2005) demonstrated that the constant limb force

57 hypothesis fails for greyhounds (limb forces increase on the bend), this theory has never been

58 appropriately and empirically tested on sprinters running on an athletics track. Thus, the main

59 aim of this study was to empirically investigate whether the constant limb force hypothesis is

60 valid in maximal effort bend sprinting. In order to test this, force production characteristics

61 were compared between bend and straight line sprinting with a view to understand how any

62 potential changes in force production contribute to changes in performance descriptors. Based

63 on the empirical literature of smaller radii running, it was hypothesised that athletes would

64 produce less maximum resultant and vertical force on the bend than the straight. The second

65 hypothesis was that more inward impulse, and thus turning, would be generated during the

66 left ground contact than the right.

67

68 **Methods**

69 *Participants*

70 Considering that all participants were required to be experienced in bend sprinting (200 m

71 and/or 400 m) and competed at national or international level, and the fact that such athletes

72   are often reluctant to take part in research (Kearney, 1999), an opportunistic sampling of

73   seven male sprinters from a limited pool of appropriate athletes volunteered for the study.

74   The mean age, mass and height of the participants were 22.6 ± 4.2 years, 70.7 ± 9.2 kg and

75   1.76 ± 0.06 m, respectively, with the mean 200 m personal best time $= 22.04 \pm 0.74$ s (range

76    $= 20.89$ s to 22.90 s). The study procedures were approved by the local research ethics

77   committee and all athletes provided written informed consent.

78

79   *Data collection*

80   Athletes undertook maximal effort sprints on the bend and straight in an indoor athletics

81   centre. For the bend trials, markings were made on the track surface across the flat infield to

82   fully replicate 60 m of lane 2 of a standard outdoor track (radius: 37.72 m). Bend trials were

83   completed entirely around the bend and straight trials entirely on the straight. Two 0.90 m by

84   0.60 m force plates (9287BA, Kistler Instruments Ltd, Switzerland) operating at 1000 Hz

85   were located contiguously in an area where the bend and straight lanes overlapped (Fig. 1).

86   The force plates were isolated from the track foundations and surrounding track surface, and

87   were covered with a piece of firmly-secured synthetic track surface which was flush with the

88   rest of the track. Two video cameras (HVR-Z5E, Sony Corporation, Japan) operating at 200

89   Hz, with a shutter speed of 1/600 s, recorded a whole step starting from touchdown on the

90   force plate and finishing with the touchdown of the contralateral leg. The separation angle of

91   the two cameras' optical axes was approximately 95° (Fig. 1).

92

93   ***Fig. 1 near here***

94

95   An 18-point structure was used to calibrate a three-dimensional (3D) activity volume (6.00 m

96   long × 1.60 m wide × 2.00 m high). The positive y-axis of the global coordinate system

97   (GCS) was aligned with the positive y-axis of the force plates (the primary direction of travel

98   of the athlete within the activity volume), the positive x-axis was to the right and positive z-

99   axis was vertically upwards.

100

101   Athletes completed their typical competition warm up before undertaking up to six 60 m

102   maximal effort sprints to achieve one successful left step and one successful right step on the

103   bend and one successful left step and one successful right step on the straight. A step was

104   assigned as left or right based on the leg producing the force on the initial contact with the

105   force plate and for the following airborne phase. A successful trial was when the athlete's

106   foot made contact within the force plate area without any visible alteration to the step pattern.

107   All athletes achieved the required four different steps within the agreed maximum of six runs.

108   This was helped by one investigator modifying the starting location of athletes based on a

109   warm-up run and consequent trials after spotting the locations of the steps on the force plate

110   area. In order to reduce the likelihood of force plate targeting, athletes were not informed of

111   the location of the force plates, nor were they easily visible. All athletes had at least 40 m

112   run-up, before the filming area. Recovery time between trials was approximately eight

113   minutes.

114

115   *Data processing*

116   All trials were manually digitised using Vicon Motus software (Version 9.2, Vicon, Oxford,

117   UK) at a resolution of 720 × 576 pixels with a 2 × zoom function increasing the effective

118   resolution of the screen to 1440 × 1152 pixels. Two sets of synchronised 20-LED displays

119   were triggered during each trial to allow the video streams and the force data to be

120   synchronised to the nearest 1 ms.

121

122   Digitised trial video clips included 10 fields before the touchdown on the force plate and 10

123   fields after the next touchdown to mitigate against end-point errors in the data conditioning

124   process (Smith, 1989). The digitised 20-point model of the human body consisted of the top

125   of the head, the joint centres of the neck (C7 level), shoulders, elbows, wrists, hips, knees,

126   ankles, second metatarsophalangeal (MTP) joints and the tips of the middle finger and

127   running shoe. Six video fields of the calibration structure were digitised in each camera view

128   to provide 11 DLT parameters (Abdel-Aziz & Karara, 1971). The raw 3D coordinates and the

129   force data were exported to a custom written Matlab script (v7.9.0, The MathWorks, USA)

130   for further processing. Position data were filtered with a low-pass, 2nd order, zero lag,

131   recursive Butterworth filter (Winter, 2009) with a cut-off frequency of 20 Hz. Force data

132   were filtered with a 150 Hz cut-off frequency, chosen based on previous sprint research under

133   similar testing conditions (Bezodis et al., 2014).

134

135   A 16-segment kinematic model of the human body was created. A standard 14-segment body

136   model, with inertia data from de Leva (1996), had the feet additionally split into rearfeet and

137   forefeet based on the average ratio of the male data obtained for Bezodis et al. (2012). The

138   mass of a typical spiked sprinting shoe (0.2 kg; Hunter et al., 2004) was added to the mass of

139   each foot with 85% and 15% added to the rearfeet and forefeet, respectively (Churchill et al.

140   2015). The ratios of the total mass for all segment masses were, thus, adjusted accordingly.

141

142   Gait events (touchdown and take off) were determined using a combination of force plate and

143   kinematic data. Touchdown and take-off on the force plate were defined using a two standard

144   deviation threshold of the mean zero-load vertical force. An alternative first touchdown event

145   was also determined from the peak vertical acceleration of the touchdown MTP point

146   (Bezodis et al., 2007) and used only for the purpose of calculating step time. Second

147 touchdown, which occurred off the force plate, was identified solely from this peak vertical

148 acceleration of the touchdown MTP.

149

150 *Calculation of variables*

151 All variables were measured separately for the left and right steps. A number of ground

152 reaction force variables were calculated and expressed relative to body weight (BW).

153 Impulses were calculated in absolute terms and also expressed relative to body mass.

154 Variables were selected based on force variables that have been shown to be important for

155 performance in the straight-line sprinting literature and in the limited bend sprinting

156 literature. These included peak values in horizontal, vertical and resultant directions, and the

157 mean values and impulses over ground contact in each direction. Force data were aligned

158 with the GCS for straight trials. During the bend trials, the horizontal forces in the GCS were

159 rotated relative to the direction of travel of the athlete using a finite difference method based

160 on the horizontal displacement of the Centre of Mass (CoM; Glaister et al., 2007).

161

162 Additionally, performance descriptors were selected based on those that have been shown to

163 be affected by sprinting on the bend (Churchill et al., 2015). Full details of the methods of

164 calculation of race velocity (the athletes' performance with respect to the official race

165 distance), race step length (the length of the race distance covered by each step), step

166 frequency and turn of the CoM during ground contact (the change in trajectory of the CoM

167 during contact to follow the curved path in the bend trials) can be found in Churchill et al.

168 (2015). In the present study, ground contact time was calculated as the time from touchdown

169 to take off, as identified using force plate data. Flight time was calculated as step time (based

170 on MTP acceleration data) minus ground contact time.

171

172   *Statistical analysis*

173   Paired samples t-tests were used to identify significant differences between left and right

174   steps for variables within the straight and bend conditions separately, and between the

175   straight and bend for the left and right steps separately. Based on Perneger (1998) and

176   additionally in order to limit the risk of a type II error, no adjustment was made to the alpha

177   level ($P < 0.05$). All statistical analyses were performed using IBM SPSS Statistics software

178   (v19.0, SPSS Inc., USA). Cohen's *d* effect sizes (Cohen, 1988) are provided in the results

179   section as additional contextualisation of the meaning of the results. Magnitudes less than or

180   equal to 0.20 represent a small difference, *d* greater than 0.20 but less than 0.80 a moderate

181   difference and *d* greater than or equal to 0.80 a large difference, between the two means.

182

183   **Results**

184   Mean peak resultant force during the left step was lower on the bend (3.61 ± 0.45 BW) than

185   the straight (3.82 ± 0.53 BW; $P = 0.044$, $d = 0.45$, Table 1). For the right step, however, mean

186   peak resultant force was greater on the bend (4.19 ± 1.29 BW) than the straight ($3.66 \pm$

187   0.29 BW; $P = 0.248$, $d = 0.57$, Table 1), although this result was markedly influenced by one

188   athlete producing a peak resultant force of 7.02 BW during the right step on the bend,

189   compared with 4.11 BW for the right step on the straight.

190

191   ***Table 1 near here***

192

193   Typical ground reaction force-time curves for the left and right steps on the bend and straight

194   are provided in Fig. 2. There was a 19% increase in braking impulse ($P = 0.012$, $d = 0.72$)

195   and the duration of braking (13% increase, $P = 0.003$, $d = 1.25$) for the left step on the bend

196   when compared with the left step on the straight (Table 2). Additionally, there was greater

197 braking impulse (33% increase, $P = 0.001$, $d = 1.34$) and duration of braking (30% increase,

198 $P < 0.0005$, $d = 2.84$) for the left compared with the right step on the bend. Mean peak inward

199 force and net inward impulse were higher during the left step than the right step on the bend

200 ($P = 0.018$, $d = 0.85$ and $P = 0.001$, $d = 2.46$, respectively, Table 3).

201

202 ***Fig. 2 near here***

203 ***Tables 2 and 3 near here***

204

205 Mean race velocity was 2.3% lower on the bend compared with the straight for both the left

206 step ($P = 0.012$, $d = 0.48$) and right step ($P = 0.001$, $d = 0.47$; Table 4). The mean right race

207 step length reduced from 2.12 ± 0.08 m on the straight to 2.02 ± 0.07 m on the bend

208 ($P = 0.030$, $d = 1.31$). This was accompanied by a slight increase in mean right step

209 frequency from 4.49 ± 0.22 Hz on the straight to 4.59 ± 0.23 Hz on the bend ($P = 0.225$,

210 $d = 0.47$). There were non-significant reductions (0.03 m) in left race step length ($P = 0.148$,

211 $d = 0.67$) and left step frequency (0.02 Hz decrease, $P = 0.404$, $d = 0.13$) from straight to

212 bend. A slight decrease in left step frequency and the increase in right step frequency on the

213 bend did, however, result in a significant difference between left and right steps on the bend

214 for this variable (right step frequency 0.15 Hz higher, $P = 0.024$, $d = 0.67$, Table 4), which

215 was not seen on the straight. Additionally, there was more turning (change of CoM trajectory)

216 achieved during the left step ($4.2 \pm 0.9°$) than the right step ($2.6 \pm 0.7°$) on the bend

217 ($P = 0.025$, $d = 1.99$, Table 4).

218

219 ***Table 4 near here***

220

221

222 **Discussion**

223 To the authors' knowledge this is the first full study to empirically investigate force

224 production in maximal effort sprinting on a radius and surface typical of outdoor athletic

225 competition. We investigated both whether the constant limb force hypothesis can be applied

226 to bend sprinting and how force production on the bend influences performance. Firstly, we

227 found that the constant limb force hypothesis is not fully valid in bend sprinting. Secondly,

228 there are clear disparities in force production and function between left and right legs, which

229 affect bend sprinting performance differently.

230

231 A reduction in left step peak vertical (9.8%) and resultant forces (5.7%) on the bend

232 compared with the straight confirms our study's first hypothesis, at least for the left step, that

233 lower vertical and resultant forces would be generated on the bend than on the straight. The

234 0.21 BW reduction in peak resultant force production in the present study for the left step on

235 the bend compared with the straight runs counter to Usherwood and Wilson's (2006) use of

236 the constant limb force assumption which suggested that athletes will generate a maximum

237 resultant force on the bend equal to that generated on the straight. Our finding, however,

238 concurs with the ground reaction force results of Chang and Kram (2007).

239

240 The bend did not appear to compromise vertical or resultant force production during the right

241 step (Table 1), thus the study's first hypothesis is rejected for the right step. In fact, peak

242 resultant force increased from 3.66 ± 0.29 BW on the straight to 4.19 ± 1.29 BW on the bend

243 for the right step (Table 1). This increase was, however, influenced by an exceptionally large

244 (more than seven times body weight) peak resultant force produced during the right step on

245 the bend by one athlete. These very large forces produced by this one athlete seems to have

246 been due to an individualised technique, as the athlete produced higher forces than any other

247 athlete in each of the conditions, even once normalised to body weight. This athlete was

248 running at the second highest velocity within that condition (9.66 m/s) and the ground contact

249 time for that step was the shortest at 0.097 s. When that athlete's result for peak resultant

250 force during the right step was removed, the group mean was 3.58 ± 0.23 BW on the straight

251 and 3.72 ± 0.37 BW on the bend. Although this was not statistically significant, the 14%

252 increase in right step peak resultant force on the bend compared with the straight, and

253 considering the substantial increase in force on the bend for some athletes, these results

254 demonstrate that the constant limb force hypothesis may not be valid for the right leg either.

255 Usherwood and Wilson (2006) were able to use their mathematical model effectively to

256 match indoor competition results based on the outdoor sprinting speeds. However, it is clear

257 the constant limb force hypothesis is not a valid assumption for humans sprinting maximally

258 on an outdoor athletics track, especially when specific information about force production is

259 required.

260

261 Naturally, the horizontal (anteroposterior) force production is also very important in

262 sprinting. As this study was conducted at the perceived maximum velocity phase, the net

263 anteroposterior impulse by default is very close to zero (just enough positive to counteract the

264 air resistance of the sprinter). Thus, we could not expect large differences in anteroposterior

265 forces between the conditions. However, there was a statistically significant difference in

266 anteroposterior propulsive impulse between straight and bend for the right step. This was

267 mainly due to one athlete as explained above. Gaudet (2014), using a mathematical model

268 containing several assumptions, speculated that during Berlin 2009 World Championships,

269 Usain Bolt applied 97.3% of the horizontal forces in the curve of the 200 m final in

270 comparison with his 100 m final in the same championships. In the current study, the left step

271 peak anteroposterior propulsive force on the bend was 93.0% of that on the straight. The

272   respective value for the right step was 106.3%. However, as our forces are actual measured

273   forces during a step and Gaudet's (2014) value is an estimation over a longer period of race,

274   we need to be careful of drawing any meaningful comparisons from the values.

275

276   Kinematic analysis of maximal (Churchill et al., 2015) and submaximal (Alt et al., 2015)

277   effort bend sprinting has shown that inward lean during bend sprinting results in greater

278   adduction of the left hip during the ground contact phase of bend sprinting compared with

279   straight-line sprinting. On the other hand, Churchill et al. (2015) reported that the right hip

280   abduction/adduction angle at touchdown was not significantly affected by the bend and that

281   peak adduction was less on the bend compared with the straight. The inward lean and

282   adduction/abduction angles could also influence why there were statistically significant

283   differences in horizontal braking impulses between left and right step on the bend (left step

284   braking larger) and between the straight and bend conditions for the left leg (bend condition

285   larger). It seems that due to inward lean, left leg has 'less room' (in relation to CoM) to

286   produce the pull-back action in the air and consequently makes contact earlier producing

287   larger and longer braking phases.

288

289   Some of the muscles that are involved in hip and knee flexion or extension are also involved

290   in controlling hip abduction or adduction (Palastanga et al., 2006). Thus, it is possible that

291   alterations to joint positions in the frontal plane may have an impact on those muscles' ability

292   to generate forces in the sagittal plane. Indeed, it has been suggested that the ability to sustain

293   forces in the frontal plane, whilst generating force in the sagittal plane, may be the limiting

294   factor to bend running performance (Chang & Kram, 2007). Measurement of 3D joint

295   moments whilst bend sprinting at track specific radii is lacking in the literature and is a

296   potential area for further investigation in order to establish whether frontal plane joint

297   moments are, in fact, limiting factors to bend running performance. These measures may also

298   explain the reduced vertical and resultant ground reaction forces observed for the left step and

299   why the right step force production appeared to be less affected in the present study.

300

301   In addition to the above, the position of the foot during the push off may have influenced the

302   force generation during the left and right steps on the bend. Although not directly measured

303   in the present study, Bojsen-Møller (1979) described the foot as being capable of using two

304   alternative axes for push off: the transverse and oblique axes. The transverse axis runs

305   through the first and second metatarsal heads, whereas the oblique axis runs through the

306   second to the fifth metatarsal heads (Bojsen-Møller, 1979). The use of these two axes affects

307   the congruency of the calcaneocuboid joint and the effectiveness of the windlass mechanism

308   of the plantar aponeurosis, which in turn affects the stability of the foot and so its

309   effectiveness for propulsion is likely superior when push off is about the transverse axis

310   rather than the oblique axis (Bojsen-Møller, 1979). It is probable that inward lean of the

311   athletes during bend running means that in the ground phase, the left foot contact is more

312   lateral and the right foot contact is more medial. This would mean the left foot would be more

313   likely to employ the oblique axis during the push off phase so may account for the reduction

314   in vertical force production during the left step on the bend compared with the straight. It

315   may also explain the significantly greater inward impulse generated on the left step compared

316   with the right step on the bend. In contrast, the right foot would be more likely to employ the

317   transverse axis, which may have contributed to maintenance of vertical and anteroposterior

318   propulsive force generation, but may not be conducive for inward force generation.

319

320   The present results for the left step do provide partial support for Usherwood and Wilson's

321   (2006) mathematical model, as a significant 10 ms increase in ground contact time was

322 observed for the left step on the bend compared with the straight (Table 4). Usherwood and

323 Wilson (2006) suggested, based on the research of Weyand et al. (2000), that the maximum

324 force an athlete is able to produce is already achieved during straight-line sprinting. They

325 postulated that ground contact time and the proportion of stride time spent in ground contact

326 during bend running would be increased in order to generate the centripetal force required to

327 follow the curved path. They suggested that swing time would remain constant and, therefore,

328 step frequency would decrease. The increased left step ground contact time in the present

329 study is in line with previously reported increases of 11 ms in left step ground contact time

330 during maximal effort bend sprinting (Churchill et al., 2015). Alt et al. (2015) revealed a

331 much smaller increase in contact time of the left step from straight to bend sprinting (2.6 ms).

332 Right step ground contact time decreased, although not significantly, on the bend compared

333 with the straight, again counter to the assumptions of Usherwood and Wilson (2006). The

334 reduction was less than in Alt et al. (2015) who found right ground contact time reduced

335 significantly on the bend compared with the straight. The observed differences between the

336 studies may be due to the fact that Alt et al. (2015) analysed matching velocities in two

337 conditions rather than maximal effort trials, allowing their athletes to have a relatively longer

338 contact time on the straight. The increased ground contact time in the current study enabled

339 maintenance of vertical impulse (only a 0.7 Ns reduction) for the left step on the bend

340 compared with the straight in the presence of significantly reduced mean vertical forces (0.11

341 BW). For the right step, vertical impulse results were similar between conditions, yet there

342 was a significant decrease in right step flight time (by 0.012 s), which had the effect of

343 significantly reducing right race step length (by 0.010 m). A reduction in right step length on

344 the bend compared with the straight has previously been shown in both the acceleration phase

345 (Stoner & Ben-Sira, 1979) and the maximum speed phase of bend sprinting (Churchill et al.,

346 2015).

347

348   The net inward impulse was significantly greater (61.2%) during the left step than the right

349   on the bend, resulting in 1.6° more turning of the CoM being achieved during the left than

350   right ground contact (Table 4). This greater inward impulse was produced via a combination

351   of both an increased contact time and a higher mean inward force (impulse divided by contact

352   time) being generated for the left step than the right step. This finding supports our second

353   hypothesis and suggests that there are functional differences between the left and right steps

354   in terms of force generation during bend sprinting. This finding is in line with our previous

355   kinematics study on a different participant group which also showed more turning was

356   achieved during the left step than the right (Churchill et al., 2015). Furthermore, the present

357   results contradict previous research that found the outer (right) leg generated greater peak

358   inward forces than the inside leg during maximal effort sprinting on radii of up to 6 m (Chang

359   & Kram, 2007) and during running (~5 m/s) on a curved path of 5 m radius on turf (Smith et

360   al., 2006). The tightness of the radii may account for the differences between those studies

361   (Chang & Kram, 2007; Smith et al., 2006) and the present study. Thus, the turning method

362   employed by sprinters running at maximal effort in athletic events appears to be different to

363   that of cutting actions, or of turning on very small radii. While the amount of turning of the

364   CoM is the consequence of the net impulse, there are various internal/external rotations

365   within joints and segments in bend sprinting. Regarding these rotational elements, Alt et al.

366   (2015) provided further insight into the functional differences between the legs. For example,

367   their results showed that the peak external rotation of the right ankle was three times more

368   than in the left ankle, although the overall external rotation from initial contact to peak

369   external rotation was similar in both ankles.

370

371 Mean peak inward forces during bend trials were over two-fold higher than the observed

372 mediolateral forces during straight trials (Table 3). These values were even larger than the

373 mean peak anteroposterior propulsive forces observed and may have potential implications

374 for strength training of athletes. Coupled with differences in frontal plane kinematics on the

375 bend compared with the straight, including leaning into the bend and hip abduction/adduction

376 angles (Alt et al., 2015; Churchill et al., 2015) and likely changes in frontal plane joint

377 moments on the bend when compared with the straight (Chang & Kram, 2007), these aspects

378 should be a consideration in both strength and technique training for athletes. For example,

379 athletes should ensure that they undertake some maximum-speed training on the bend in

380 order that the high forces whilst leaning are not only experienced during a competition

381 setting. This means that when the focus of the training is the bend, the starting positions

382 should, at times, be such that a substantial proportion of the maximum-speed phase occurs on

383 the bend. Additionally, the use of ropes or harnesses may allow athletes to be supported in a

384 leaning position during strength training and/or plyometric training. Moreover, the demands

385 of the left and right steps on the bend appear to be functionally different, but care should be

386 taken to avoid introducing asymmetries, such as strength imbalances, that might be

387 detrimental to the straight-line portion of the race.

388

389 The straight line velocities, step lengths and step frequencies achieved in the present study

390 (Table 4) were similar to those reported in previous studies of the maximal phase of straight

391 line sprinting in athletes of similar calibre (Bezodis et al., 2008; Churchill et al., 2015; Mero

392 & Komi, 1986). Furthermore, the athletes in the present study were able to achieve vertical

393 and anteroposterior ground reaction forces on the straight which were similar to previously

394 reported values. For example, Korhonen et al. (2010) reported peak vertical, braking and

395 anteroposterior propulsive ground reaction forces of 3.35 BW, 1.43 BW and 0.74 BW,

396   respectively, for athletes sprinting on the straight at a similar velocity (9.5 m/s). These

397   findings confirm that the athletes in our study were typical competitive athletes performing

398   normally. However, a limitation of the present study is that the number of trials was limited

399   to a maximum of six per athlete in total, as the quality of runs may not be maintained at

400   maximal effort beyond that, highlighting challenges when investigating competitive sprinters

401   in ecologically valid situations. This meant that only one successful foot strike on the force

402   plate was achieved for each foot under each condition for each athlete. Force data from

403   multiple steps have been collected in sprinting (e.g. Belli et al., 2002; Korhonen et al., 2010;

404   Mero & Komi, 1986; Morin et al., 2011, 2012). However, these have been carried out either

405   on instrumented treadmills (Morin et al., 2011, 2012), which is not applicable to track bend

406   sprinting, or on long multiple force plates (Belli et al., 2002; Korhonen et al., 2010; Mero &

407   Komi, 1986) that are not readily available. Data collection on separate occasions would have

408   facilitated multiple trials per foot per condition, but this would have increased variation due

409   to data being collected on different days and would likely have increased participant drop-

410   out. It is acknowledged that there was a relatively limited sample size in this study. However,

411   this was due to the requirement to have high calibre athletes who were experienced in bend

412   sprinting and competing regularly so that any differences found could be confidently

413   attributed to the running condition rather than the novelty of the task. Despite being a limited

414   sample, statistically significant results were found, and differences in force production

415   between the bend and straight were still identified.

416

417   **Perspectives**

418   We believe this is the first investigation of the kinetics of maximal effort bend sprinting on a

419   surface and radius typical of an outdoor athletics track. Overall force production reduced on

420   the left step on the bend resulting in lower velocity, contrary to the assumptions of

421   Usherwood and Wilson's (2006) mathematical model. The decrease in velocity was due to

422   decreased step length and frequency similar to Alt et al. (2015) and Churchill et al. (2015).

423   However, the left step contributed more than the right step to the generation of inward

424   impulses and turning, contradicting studies of small radii (Chang & Kram, 2007; Smith et al.,

425   2006). Resultant force increased during the right foot contact, although step velocity reduced

426   due to shorter step length. This was possibly due to difficulties in repositioning the left leg for

427   the subsequent contact leading to an abbreviated step. Force requirements of bend sprinting

428   were considerably different to those of straight-line sprinting with asymmetries between left

429   and right steps observed on the bend. Therefore, bend specific strength and technique training

430   performed at high velocity may improve athletes' ability to meet the requirements of bend

431   sprinting, thus improving performance during this portion of a race.

432

435   **References**

436   Abdel-Aziz YI, Karara HM. Direct linear transformation from comparator coordinates into

437   object space coordinates in close range photogrammetry. American Society of

438   Photogrammetry Symposium on Close-Range Photogrammetry, Falls Church, VA:

439   American Society of Photogrammetry; 1971: 1-18.

440

441   Alt T, Heinrich K, Funken J, Potthast W. Lowerextremity kinematics of athletics curve

442   sprinting. J Sports Sci 2015: 33: 552-560.

443

444   Belli A, Kyröläinen H, Komi PLV. Moment and power of lower limb joints in running. Int J

445   Sports Med: 2002: 23: 136-141.

446

447   Bezodis I, Thomson A, Gittoes M, Kerwin D. Identification of instants of touchdown and

448   take-off in sprint running using an automatic motion analysis system. In: Proceedings

449   of the XXV International Symposium on Biomechanics in Sports. Ouro Preto, Brazil:

450   International Society of Biomechanics in Sports, 2007: 501-504.

451

452   Bezodis IN, Kerwin DG, Salo, AIT. Lower-limb mechanics during the support phase of

453   maximum-velocity sprint running. Med Sci Sports Exerc 2008: 40: 707-715.

454

455   Bezodis NE, Salo AIT, Trewartha G. Modeling the Stance Leg in Two-Dimensional

456   Analyses of Sprinting: Inclusion of the MTP Joint Affects Joint Kinetics. J Appl

457   Biomech 2012: 28: 222-227

458

459   Bezodis, NE, Salo, AIT, Trewartha G. Lower limb joint kinetics during the first stance phase

460   in athletics sprinting: three elite athlete case studies. J Sports Sci 2014: 32: 738-746.

461

462   Bojsen-Møller F. Calcaneocuboid joint and stability of the longitudinal arch of the foot at

463   high and low gear push off. J. Anat 1979: 129: 165-176.

464

465   Chang YH, Kram R. Limitations to maximum running speed on flat curves. J Exp Biol 2007:

466   210: 9719-82.

467

468   Churchill SM, Salo AIT, Trewartha G. The effect of the bend on technique and performance

469   during maximal effort sprinting. Sport Biomech 2015: 14: 106-121.

470

471   Cohen J. Statistical Power Analysis for the Behavioral Sciences. Hillsdale, NJ: Lawrence

472   Erlbaum Associates, 1988.

473

474   de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech

475   1996: 29: 1223-1230.

476

477   Gaudet S. A physical model of sprinting. J Biomech 2014: 47: 2933-2940.

478

479   Glaister BC, Orendurff MS, Schoen JA, Klute GK. Rotating horizontal ground reaction

480   forces to the body path of progression. J Biomech 2007: 40: 3527-3532.

481

482   Greene PR. Running on flat turns: Experiments, theory and applications. J Biomech Eng-T

483   ASME 1985: 107: 96-103.

484

485

486 Hamill J, Murphy M, Sussman D. The effects of track turns on lower extremity function. Int J

487   Sport Biomech 1987: 3: 276-286.

488

489 Hunter JP, Marshall RN, McNair PJ. Interaction of step length and step rate during sprint

490   running. Med Sci Sports Exerc 2004: 36: 261-271.

491

492 Kearney JT. Sport performance enhancement:design and analysis of research. Med Sci Sports

493   Exerc 1999:31: 755-756.

494

495 Korhonen MT, Suominen H, Viitasalo JT, Liikavainio T, Alen M, Mero AA. Variability and

496   symmetry of force platform variables in maximum-speed running in young and older

497   athletes. J Appl Biomech 2010: 26: 357-366.

498

499 Mero A, Komi PV. Force-, EMG-, and elastic-velocity relationships at submaximal, maximal

500   and supramaximal running speeds in sprinters. Eur J Appl Physiol 1986: 55: 553-561.

501

502 Morin J-B, Edouard P, Samozino P. Technical ability of force application as a determinant

503   factor of sprint performance. Med Sci Sports Exerc 2011:43: 1680-1688.

504

505 Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR. Mechanical

506   determinants of 100-m sprint running performance. Eur J Appl Physiol 2012:112:

507   3921-3930.

508

509   Palastanga N, Field D, Soames R. Anatomy and human movement: Structure and function.

510   Philadelphia: Elsevier, 2006.

511

512   Perneger TV. What's wrong with Bonferroni adjustments. Brit Med J 1998: 316: 1236-1238

513

514   Smith G. Padding point extrapolation techniques for the Butterworth digital-filter. J Biomech

515   1989: 22: 967-971.

516

517   Smith N, Dyson R, Hale T, Janaway L. Contributions of the inside and outside leg to

518   maintenance of curvilinear motion on a natural turf surface. Gait Posture 2006: 24:

519   453-458.

520

521   Stoner LJ, Ben-Sira D. Sprinting on the curve. In: Terauds J, Dales GG, editors. Science in

522   Athletics. Del Mar, CA: Academic Publishers, 1979: 167-173.

523

524   Usherwood JR, Wilson AM. No force limit on greyhound sprint speed. Nature 2005: 438:

525   753-754.

526

527   Usherwood JR, Wilson AM. Accounting for elite indoor 200 m sprint results. Biol Letters

528   2006: 2: 47-50.

529

530   Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved

531   with greater ground forces not more rapid leg movements. J Appl Physiol 2000: 89:

532   1991-1999.

533

534   Winter DA. Biomechanics and motor control of human movement. Hoboken, New Jersey:

535   John Wiley & Sons, Inc., 2009.

Table 1. Left and right step group mean values (± SD) and significant differences for vertical and resultant force variables on the straight and bend.

	Straight		Bend		Significant differences			
					Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right
	Left	Right	Left	Right				
Peak vertical force (BW)	3.80 ± 0.52	3.64 ± 0.29	3.43 ± 0.41	4.13 ± 1.27			#	
Mean vertical force (BW)	2.13 ± 0.25	2.05 ± 0.14	2.02 ± 0.20	2.09 ± 0.20			#	
Vertical impulse (Ns)	82.0 ± 18.2	76.9 ± 13.0	81.3 ± 17.4	78.4 ± 18.0				
Relative vertical impulse (m/s)	1.16 ± 0.21	1.09 ± 0.07	1.15 ± 0.20	1.11 ± 0.18				
Peak resultant force (BW)	3.82 ± 0.53	3.66 ± 0.29	3.61 ± 0.45	4.19 ± 1.29			*	
Mean resultant force (BW)	2.23 ± 0.26	2.14 ± 0.15	2.18 ± 0.21	2.22 ± 0.20				

* significant at $P < 0.05$; # significant at $P < 0.01$

Table 2. Left and right step group mean values (± SD) and significant differences for anteroposterior force variables on the straight and bend.

	Straight		Bend		Significant differences			
					Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right
	Left	Right	Left	Right				
Peak braking force (BW)	1.43 ± 0.39	1.31 ± 0.26	1.41 ± 0.34	1.31 ± 0.22				
Braking impulse (Ns)	14.0 ± 3.7	13.2 ± 3.8	16.6 ± 3.5	12.4 ± 2.8		#	*	
Relative braking impulse (m/s)	0.20 ± 0.04	0.18 ± 0.04	0.23 ± 0.02	0.17 ± 0.02		§	*	
Duration of braking (s)	0.046 ± 0.006	0.044 ± 0.007	0.052 ± 0.004	0.040 ± 0.004		§	#	
Peak anteroposterior propulsive force (BW)	0.81 ± 0.09	0.73 ± 0.07	0.76 ± 0.09	0.77 ± 0.07	*			
Anteroposterior propulsive impulse (Ns)	18.3 ± 3.7	16.8 ± 3.7	19.1 ± 2.8	18.7 ± 3.9				*
Relative anteroposterior propulsive impulse (m/s)	0.26 ± 0.02	0.24 ± 0.03	0.27 ± 0.02	0.26 ± 0.03				*
Duration of anteroposterior propulsion (s)	0.061 ± 0.004	0.064 ± 0.006	0.064 ± 0.003	0.064 ± 0.005			#	

* significant at $P < 0.05$; # significant at $P < 0.01$; § significant at $P < 0.001$

Table 3. Left and right step group mean values (± SD) and significant differences for mediolateral force variables on the straight and bend.

	Straight		Bend		Significant differences			
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right
Peak medial force (BW)	0.41 ± 0.11	0.41 ± 0.11						
Peak lateral force (BW)	0.22 ± 0.14	0.25 ± 0.06						
Net mediolateral impulse (Ns) [1]	3.2 ± 5.0	5.3 ± 2.1						
Relative net lateral impulse (m/s)	0.05 ± 0.08	0.08 ± 0.03						
Peak inward force (BW)			1.07 ± 0.22	0.86 ± 0.25		*		
Net inward impulse (Ns)			39.9 ± 6.5	24.7 ± 5.8		#		
Relative net inward impulse (m/s)			0.56 ± 0.05	0.35 ± 0.06		#		

[1] A positive value indicates a net lateral impulse (away from the midline of the body); * significant at $P < 0.05$; # significant at $P < 0.01$

Table 4. Left and right step group mean values (± SD) and significant differences for performance descriptors on the straight and bend.

	Straight		Bend		Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right
	Left	Right	Left	Right				
Race velocity (m/s)	9.56 ± 0.46	9.51 ± 0.47	9.34 ± 0.43	9.29 ± 0.47			*	#
Race step length (m)	2.14 ± 0.05	2.12 ± 0.08	2.11 ± 0.05	2.02 ± 0.07		*		*
Step frequency (Hz)	4.46 ± 0.23	4.49 ± 0.22	4.44 ± 0.25	4.59 ± 0.23		*		
Ground contact time (s)	0.107 ± 0.008	0.108 ± 0.008	0.117 ± 0.006	0.104 ± 0.005		§	#	
Flight time (s)	0.116 ± 0.019	0.120 ± 0.014	0.118 ± 0.011	0.108 ± 0.016				*
Turn of CoM (°)			4.2 ± 0.9	2.6 ± 0.7		*		

* significant at $P < 0.05$; # significant at $P < 0.01$; § significant at $P < 0.001$
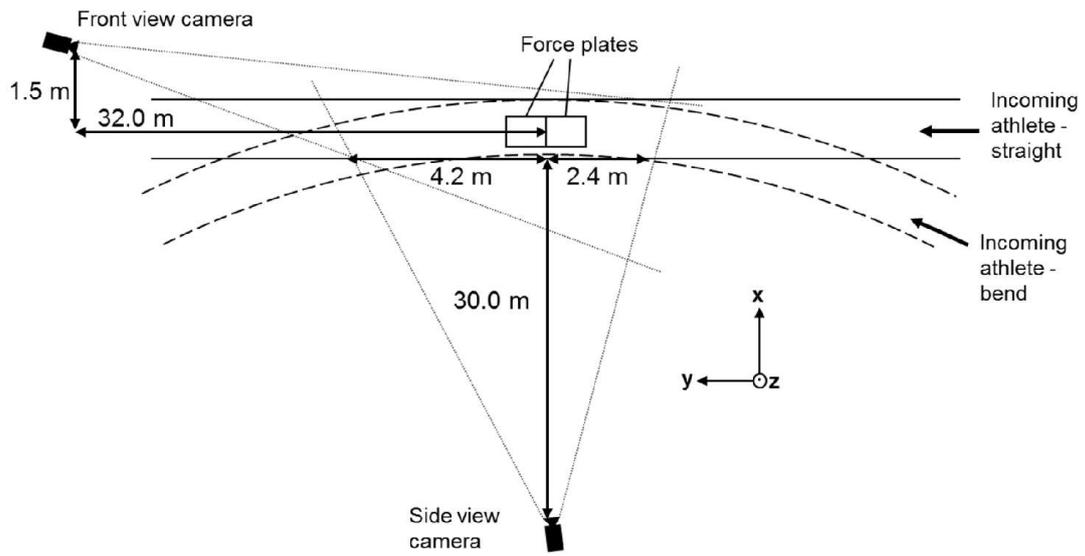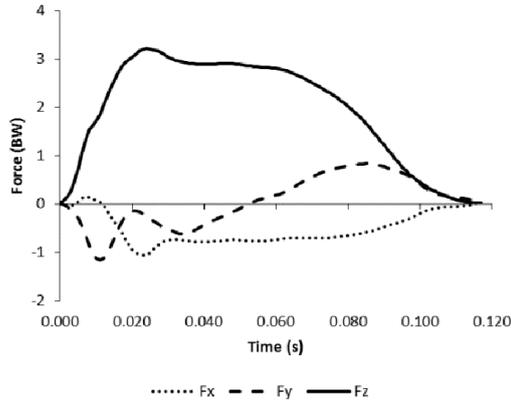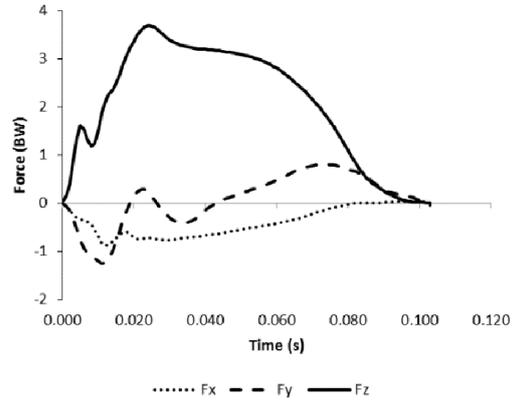
Fig 1. Camera set-up for bend and straight trials (not to scale).
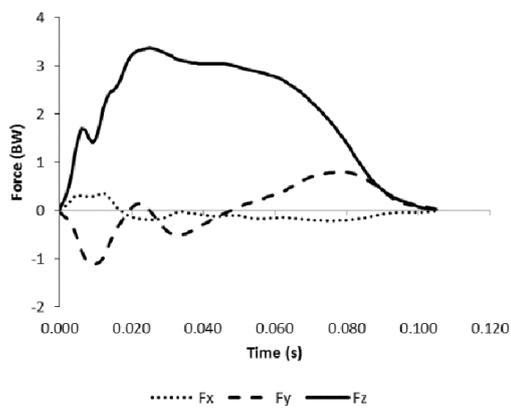
(a) Bend – Left step

(b) Bend – Right step

(c) Straight – Left step
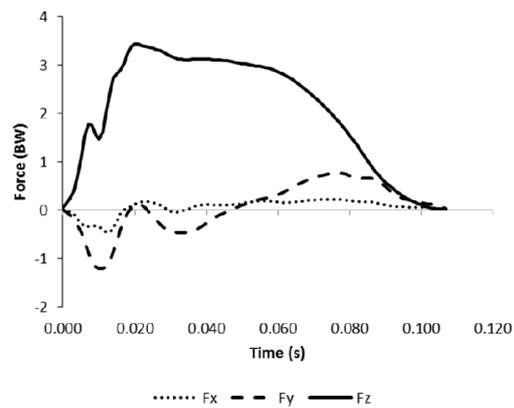

(d) Straight – Right step

Fig 2. Ground reaction forces for one participant's left and right steps on the bend and straight. Negative Fx on the bend represents inward force; Negative and positive Fx for the left step on the straight represents lateral and medial force, respectively; Negative and positive Fx for the right step on the straight represents medial and lateral force, respectively. Negative and positive Fy represents braking and anteroposterior propulsive force, respectively. Positive Fz represents upwards vertical force.