

The effect of the bend on technique and performance during maximal effort sprinting

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

Available from Sheffield Hallam University Research Archive (SHURA) at:

<https://shura.shu.ac.uk/10043/>

This document is the

Citation:

CHURCHILL, Sarah M., SALO, Aki I.T. and TREWARTHA, Grant (2015). The effect of the bend on technique and performance during maximal effort sprinting. *Sports Biomechanics*, 14 (1), 106-121. [Article]

Copyright and re-use policy

See <http://shura.shu.ac.uk/information.html>

**THE EFFECT OF THE BEND ON TECHNIQUE AND PERFORMANCE
DURING MAXIMAL EFFORT SPRINTING**

Sarah M. Churchill^{a, b}, Aki I.T. Salo^{a, 1} and Grant Trewartha^a

^{a)} Sport, Health and Exercise Science, University of Bath, Bath, United Kingdom

^{b)} Department of Sport, Sheffield Hallam University, Sheffield, United Kingdom

¹ Corresponding author:

Dr Sarah M. Churchill

Sport, Health and Exercise Science

Applied Biomechanics Suite

University of Bath

BATH, BA2 7AY

UNITED KINGDOM

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

Dr Grant Trewartha

Sport, Health and Exercise Science

Applied Biomechanics Suite 1.306

University of Bath

BATH, BA2 7AY

UNITED KINGDOM

Tel. +44-1225-383055

Email: G.Trewartha@bath.ac.uk

b) Dr Churchill has moved to Department of Sport, Collegiate Hall A115, Sheffield Hallam University, Collegiate Crescent, SHEFFIELD, S10 2BP, UNITED KINGDOM, Tel. +44-114-225-5921, Email: S.Churchill@shu.ac.uk

1 **THE EFFECT OF THE BEND ON TECHNIQUE AND PERFORMANCE**
2 **DURING MAXIMAL EFFORT SPRINTING**

3
4 **Abstract**

5 This study investigated changes in performance and technique that occur during maximal
6 effort bend sprinting compared to straight-line sprinting under typical outdoor track
7 conditions. Utilising a repeated measures design, three-dimensional video analysis was
8 conducted on seven male sprinters in both conditions (bend radius: 37.72 m). Mean race
9 velocity decreased from 9.86 m/s to 9.39 m/s for the left step ($p = 0.008$) and from 9.80 m/s
10 to 9.33 m/s for the right step ($p = 0.004$) on the bend compared to the straight, a 4.7%
11 decrease for both steps. This was due mainly to a 0.11 Hz ($p = 0.022$) decrease in step
12 frequency for the left step and a 0.10 m ($p = 0.005$) reduction in race step length for the right
13 step. The left hip was 4.0° ($p = 0.049$) more adducted at touchdown on the bend than the
14 straight. Furthermore, the bend elicited significant differences between left and right steps in
15 a number of variables including ground contact time, touchdown distance and hip
16 flexion/extension and abduction/adduction angles. The results indicate that the roles of the
17 left and right steps may be functionally different during bend sprinting. This specificity
18 should be considered when designing training programmes.

19 (Word count: 198)

20
21 Keywords: Three-dimensional kinematics, track and field, 200 m race, curve, lean

24 **Introduction**

25 Winning margins in athletic sprint events can be a fraction of a second. This means that even
26 relatively small improvements in performance can have meaningful effects on an athlete's
27 finishing position in a race. As such, numerous biomechanical analyses of sprinting have
28 focussed on understanding and improving performance during straight-line sprint running
29 (e.g. Kunz & Kaufmann, 1981; Mann, 1985; Bezodis, Kerwin & Salo, 2008). During sprint
30 events longer than 100 m on a standard outdoor track, athletes are required to run more than
31 half the race around the bend (International Association of Athletics Federations, 2008). It is
32 generally accepted that the necessity to generate centripetal acceleration in order to follow the
33 curved path on the bend has a detrimental effect on running speed (Usherwood and Wilson,
34 2006). However, bend sprinting has received relatively little attention compared with
35 straight-line sprinting in the research literature, despite the bend portion of the race being a
36 potentially important source of performance improvement.

37

38 The aim of a sprint race is for competitors to cover the given horizontal distance in the
39 shortest possible time. As such, horizontal velocity is ultimately the most important factor in
40 terms of success. Maximal effort velocity has been shown to decrease on bends of small radii
41 compared with straight-line sprinting (Chang & Kram, 2007), but bends of small radii are not
42 representative of typical outdoor tracks used in athletic sprint events. Experimental studies of
43 bend running conducted on radii specific to outdoor athletic tracks have been limited to
44 submaximal effort running (~6 m/s; Hamill, Murphy, & Sussman, 1987), to the acceleration
45 phase of sprinting (Stoner & Ben-Sira, 1979), or have been performed on surfaces dissimilar
46 to a standard track surface (Green, 1985). Thus, the effect of the bend on the maximal speed
47 phase of sprinting has not been adequately examined.

48

49 Horizontal velocity is the product of step length and step frequency, which are themselves
50 influenced by a number of further determinants including ground contact time and flight time
51 (Hay, 1993). Stoner and Ben-Sira (1979) reported significant decreases in step length during
52 the acceleration phase of sprinting on the bend compared with straight-line acceleration.
53 Further analysis of the results presented by Stoner and Ben-Sira (1979) demonstrate a
54 reduction in step frequency for the left step and an increase in step frequency for the right
55 step on the bend, suggesting the effect of the bend may be asymmetrical. A mathematical
56 model to predict indoor 200 m race times suggested that velocity decreases on the bend were
57 due to an increase in ground contact time which leads to a reduction in step frequency
58 (Usherwood & Wilson, 2006). However, this model did not permit changes in step length and
59 did not provide experimental data to evaluate it. Empirical studies of maximal bend sprinting
60 are needed in order to fully understand the effect of the bend on the determinants of velocity.

61

62 Previous kinematic studies of bend sprinting have generally been concerned with differences
63 in whole body performance descriptors (Stoner & Ben-Sira, 1979; Usherwood & Wilson,
64 2006), such as velocity, step length and step frequency. A number of straight-line sprint
65 studies have conducted sagittal-view two-dimensional (2D) video analyses of segment
66 kinematics (Mann & Hagy, 1980; Kunz & Kaufmann, 1981; Mann & Herman, 1985;
67 Hamilton, 1993; Bushnell & Hunter, 2007; Bezodis, Salo, & Trewartha, 2012). Although a
68 reasonable assumption for straight-line sprinting, a 2D analysis is inappropriate for bend
69 sprinting, due to the additional importance of actions in the non-sagittal planes, such as
70 inward lean. Despite the potential importance of non-sagittal motion, a three-dimensional
71 (3D) kinematic analysis is missing from the bend sprinting literature.

72

73 In order to improve bend sprinting performance in track and field sprint events, it is important
74 to understand how bend sprinting differs from straight-line sprinting utilising appropriate
75 bend radii and surfaces. This would provide a focus for athletes and coaches to improve
76 bend-specific technique. With this in mind, the aim of this experimental repeated measures
77 study was to understand the changes in performance and technique that occur during maximal
78 effort bend sprinting compared to straight-line sprinting under typical outdoor track
79 conditions. Specifically, the following research questions were addressed: (1) how do
80 selected performance descriptors and 3D technique variables change on the bend compared to
81 the straight and (2) does the bend have an asymmetrical effect on performance and
82 technique? It was hypothesised that the bend would have a detrimental effect on performance
83 descriptors and that changes in technique from straight to bend would be asymmetrical in
84 nature.

85

86 **Methods**

87 *Participants*

88 Seven male sprinters (mean age: 23.6 ± 1.9 years, mass: 80.5 ± 9.2 kg, height: 1.81 ± 0.07 m)
89 volunteered for the study. All were experienced in bend sprinting (200 m and/or 400 m) and
90 all competed regularly at national or international level. Mean personal best time in the 200 m
91 was 22.15 ± 0.93 s (range from 21.18 s to 23.90 s). The study procedures were approved by
92 the Bath Local Research Ethics Committee, England, and following an explanation of the
93 study procedures and risks and benefits of participation, all athletes provided written
94 informed consent.

95

96 *Data collection*

97 Bend sprinting and straight-line sprinting data were collected on a standard outdoor 400 m

98 track during two consecutive track sessions (no more than 3 days apart) for each participant
99 (bend and straight trials were completed in separate sessions). The athletes completed a
100 coach-prescribed warm up before being asked to undertake three 60 m maximal effort sprints
101 running in lane 2 (the radius on the bend was 37.72 m). Recovery time between trials was
102 approximately eight minutes.

103

104 Two high speed video cameras (MotionPro HS-1, Redlake, USA) recorded the athletes at the
105 40.00-47.50 m section of the 60 m, enabling two consecutive steps to be analysed (Figure 1).
106 The cameras were focussed, operated with a 200 Hz frame rate and shutter speed of 1/1000 s,
107 and recorded images with a resolution of 1280 × 1024 pixels. An 18-point 3D calibration
108 volume (6.50 m long × 1.60 m wide × 2.00 m high) was recorded prior to the athletes' trials
109 taking place. The global coordinate system (GCS) followed the right-hand rule and was
110 aligned such that, within the activity volume, athletes travelled primarily in the direction of
111 the positive y-axis, the positive z-axis was vertically upwards and the positive x-axis was
112 orthogonal to the other two axes (Figure 1).

113

114 ***Figure 1 near here***

115

116 ***Data processing***

117 All trials were manually digitised using Peak Motus software (Version 8.5, Vicon, UK) with
118 a 2 × zoom function increasing the effective resolution of the screen to 2560 × 2048 pixels.
119 Two sets of synchronised 20 LED displays (Wee Beasty Electronics, UK) were placed with
120 one in each camera view during data collection. Sequential illumination of LEDs at 1 ms
121 intervals allowed the digitised data from the two video streams to be synchronised to the
122 nearest 1 ms within the Peak Motus software.

123

124 Due to one athlete not completing a third trial as well as some recording and synchronisation
125 issues that were visible only after the data collection session has finished, one athlete had
126 only one usable bend trial available and two further athletes had two bend trials available for
127 further analysis. All other athletes had all three bend trials available for digitising and all
128 athletes had three straight trials available.

129

130 Six video frames of the calibration structure were digitised in each camera view to provide
131 the relevant DLT parameters required for coordinate reconstruction (Abdel-Aziz & Karara,
132 1971). Video clips were cropped to include two complete steps plus 10 frames before the first
133 touchdown of interest and 10 frames after the final touchdown of interest. This ensured the
134 trial sequence was longer than the required data to mitigate against end-point errors in the
135 data conditioning process (Smith, 1989). Gait events (touchdown and take-off) were
136 determined by visual inspection of the video from the front-view camera.

137

138 For the running trials, a 20-point model of the human body was digitised consisting of the top
139 of the head, the joint centres of the neck (C7 level), shoulders, elbows, wrists, hips, knees,
140 ankles, second metatarsophalangeal (MTP) joints and the tips of the middle finger and
141 running spikes. An 11-parameter 3D-DLT (Abdel-Aziz & Karara, 1971) reconstruction
142 enabled 3D coordinates to be calculated and then exported to a custom written Matlab script
143 (v 7.9.0, The MathWorks, USA) for further processing. Raw 3D coordinates were filtered
144 with a low-pass, 2nd order, recursive Butterworth filter (effectively a 4th order zero lag
145 Butterworth filter; Winter, 2009) with a cut-off frequency of 20 Hz.

146

147 A 16-segment kinematic model of the human body was created: head, trunk, and left and
148 right upper arms, forearms, hands, thighs, shanks, rearfeet and forefeet. For calculation of
149 segmental centre of mass positions, filtered coordinates were combined with the body
150 segment inertia data of de Leva (1996). The feet were split into forefoot and rearfoot
151 segments based on the average ratio of the male data obtained for Bezodis et al. (2012). The
152 mass of a typical spiked sprinting shoe (0.2 kg; Hunter, Marshall & McNair, 2004) was added
153 to the mass of each foot, with 15% and 85% of the shoe mass added to the forefoot and
154 rearfoot segments, respectively, in line with the ratio of the mass of the foot for these
155 segments. The ratio of the total mass for all segment masses was adjusted accordingly. Whole
156 body CoM location was determined using the segmental approach (Winter, 1993). From the
157 filtered coordinates, two virtual coordinates were also calculated: mid-hip (the halfway point
158 between right and left hips) and mid-shoulder (the halfway point between right and left
159 shoulders). To assess reliability of digitising, a bend trial and a straight trial were selected at
160 random and each was redigitised a total of eight times across the digitising process. The
161 standard deviation from the mean of the eight trials was then calculated for each of the
162 outcome variables measured.

163

164 ***Calculation of variables***

165 All variables were measured separately for left and right steps and are based on typical
166 variables seen in sprinting literature (e.g. Kunz & Kaufmann, 1981; Mann, 1985; Hunter et
167 al., 2004). Some of the variables in the literature were modified to accommodate the bend
168 condition. A step was defined from touchdown of one foot to the next touchdown of the
169 contralateral foot. Left and right steps were determined according to the leg that initiated the
170 step. For example, left step refers to touchdown of the left foot to the next touchdown of the
171 right foot.

172

173 *Absolute speed* was calculated as the athletes' actual horizontal speed using first central
174 difference equations (Miller & Nelson, 1973) from the cumulative horizontal distance
175 travelled by the CoM. The mean of the instantaneous speeds, from the first frame of ground
176 contact to the last frame of flight, was calculated to give the absolute speed over the step.
177 *Race velocity* was calculated as the athletes' performance in terms of official race distance.
178 For straight trials, first central difference equations were used to calculate horizontal velocity
179 from the displacement of the CoM in the global y-direction at each time point. For bend
180 trials, measurements were made relative to the curved race line (a line 0.20 m from the inside
181 of the lane, along which race distance is measured; International Association of Athletics
182 Federations, 2014) to provide instantaneous tangential velocities. For both bend and straight
183 trials, race velocity was calculated as the mean of the instantaneous velocities of the CoM,
184 from the first frame of ground contact to the last frame of flight of the step.

185

186 *Directional step length* was calculated relative to the CoM direction of travel (regardless of
187 whether the direction of travel was along the race line). A vector was created between the
188 horizontal positions of the contact-limb MTPs during successive ground contacts. Similarly, a
189 second vector was created between the horizontal positions of CoM from the start of the first
190 contact to the start of the second contact. Directional step length was then calculated as the
191 scalar projection of the MTP vector onto the CoM vector. *Race step length* was calculated as
192 the length of the race distance covered by each step. This was the displacement of the
193 y-coordinates of the MTP during two consecutive contacts for straight trials, or the product of
194 the radius of the race line (37.92 m) and the angular distance (relative to the centre of the
195 origin of the bend radius) between the MTP during two consecutive contacts for bend trials.
196 *Step frequency* was calculated as race velocity divided by race step length. *Ground contact*

197 *time* was the time from touchdown to take-off. *Flight time* was calculated as the total step
198 time (touchdown to touchdown) minus ground contact time.

199

200 *Touchdown distance* was calculated as the horizontal displacement between the CoM and the
201 MTP at touchdown relative to the direction of travel of the CoM of the athlete at touchdown.

202 *Turn of the CoM during ground contact* was calculated for the bend trials as a measure of
203 how much turning ‘into’ the bend an athlete achieved during each ground contact. A linear
204 trend line was fitted to the raw CoM x-displacement as a function of the raw CoM
205 y-displacement for the three available flight phases. The change in angle of consecutive flight
206 displacement vectors gave the angle of turn of the CoM during the intervening contact phase.

207

208 *Three-dimensional hip and body lean angles* (Figure 2) were calculated using 3D orientation
209 angles based on the methods outlined by Yeadon (1990). For angles measured at times other
210 than touchdown (TD) and take-off (TO), the time at which they occurred was recorded.

211 Range of motion (ROM) from TD to TO was calculated for *body sagittal lean angle*. *Thigh*
212 *separation angle* was calculated at touchdown as a vector angle in the sagittal plane of the
213 athlete. *Flexion/extension angular velocities of the hip* were calculated from angular
214 displacement using the first central difference method. Additionally, the times at which peak
215 angular velocities occurred were recorded.

216

217 ***Figure 2 near here***

218

219 ***Statistical analysis***

220 An individual mean value for every variable in each condition was calculated for each athlete
221 from their available trials. This value was then used for further analyses. A number of

222 comparisons were made using paired-samples t-tests (SPSS for Windows, v 14.0, SPSS Inc.,
223 USA). The following pairs were compared for each variable: left on the bend to left on the
224 straight and right on the bend to right on the straight in order to determine changes between
225 straight versus bend conditions. The presence of asymmetries was assessed by comparing left
226 on the bend to right on the bend and left on the straight to right on the straight, for each
227 variable. Absolute values were used for comparison of left and right body lateral lean on the
228 straight.

229

230 No adjustments were made to the criterion alpha level ($p < 0.05$) despite multiple t-tests
231 being conducted. This was because each time the statistical test was run it was considered a
232 new analysis of that particular variable. For example the comparison of results for the bend
233 and straight for absolute speed during the left step was considered a separate analysis to the
234 comparison between the bend and straight for the right step absolute speed. Similarly, the
235 assessment of asymmetries was considered separately for the different conditions.
236 Furthermore, a compelling argument against adjusting for multiple comparisons is provided
237 by Perneger (1998). While adjusting the alpha level to be more conservative decreases the
238 chance of committing a Type I error, it increases the chances of committing a Type II error.
239 As there is such a paucity of research into bend sprinting, and so little information about
240 those variables which are particularly important to bend running, the priority was to reduce
241 the chances of false negatives.

242

243 The effect size between bend and straight for left and right steps and between left and right
244 on the bend was calculated for each variable using Cohen's d (Cohen, 1988). Relative
245 magnitude of the effect was assessed based on Cohen's guidelines with d less than or equal to

246 0.20 representing a small difference, greater than 0.20 but less than 0.80 a moderate
247 difference and greater than or equal to 0.80 a large difference between the two means.

248

249 **Results**

250 Overall, the redigitised results demonstrated low variation with a maximum standard
251 deviation (SD) of 0.02 m/s from the mean value for speed/velocity variables, 0.02 m for the
252 distance variables and a maximum of 0.03 Hz for the step frequency. Similarly, the maximum
253 SD for angular displacement variables was 2.5°. The only significant difference in angular
254 displacement that was smaller than 2.5° was peak hip adduction between straight and bend
255 for the right step (2.3°; Table II). However, the redigitising for peak hip adduction yielded a
256 SD of 1.4° on the straight and 1.0° on the bend.

257

258 Absolute speed and race velocity were significantly slower on the bend when compared to the
259 straight ($p < 0.05$, Table I), with both left and right steps showing a 4.7% decrease in mean
260 absolute speed, from 9.86 ± 0.55 m/s to 9.40 ± 0.42 m/s for the left step ($p = 0.014$, $d = 0.93$)
261 and from 9.80 ± 0.59 m/s to 9.34 ± 0.41 m/s for the right step ($p = 0.009$, $d = 0.90$, Table I).

262

263 Directional step length reduced by 0.04 m and 0.08 m for left and right steps, respectively, on
264 the bend compared to the straight (Table I). This represented a non-significant difference but
265 moderate effect size ($p = 0.294$, $d = 0.37$) for the left step and a significant difference and
266 moderate effect ($p = 0.030$, $d = 0.60$) for the right step. Race step length reduced by 0.06 m (p
267 $= 0.130$, $d = 0.51$) and 0.10 m ($p = 0.005$, $d = 0.79$) for left and right steps, respectively, on
268 the bend compared to the straight (Table I). Furthermore, mean left step frequency reduced
269 significantly from 4.50 ± 0.19 Hz on the straight to 4.39 ± 0.26 Hz on the bend ($p = 0.022$,

270 $d = 0.47$, Table I). There was no difference in step frequency between the bend and straight
271 on the right step, with mean values of 4.46 Hz for both conditions ($p = 0.973$, $d = 0.00$).

272

273 There was a significant increase of 0.011 s in mean left ground contact time on the bend
274 compared to the straight ($p = 0.001$, $d = 2.97$, Table I). Additionally, mean ground contact
275 time for the left step on the bend was significantly longer than right ground contact time on
276 the bend ($p = 0.019$, $d = 1.70$, Table I). Mean flight time was similar between the straight and
277 bend for the left step. There was, however, a significant decrease of 0.009 s in flight time
278 from the straight to the bend for the right step ($p = 0.021$, $d = 0.67$, Table I).

279

280 Asymmetrical movement patterns between left and right steps were apparent on the bend for
281 touchdown distance and body sagittal lean ROM variables, with the left step values being
282 greater for both. The left step values were also significantly larger on the bend compared to
283 the straight for both of these variables (Table II). Significant asymmetries between left and
284 right steps on the bend also included a larger thigh separation at left touchdown than right
285 touchdown on the bend (Table II), and significant differences between left and right hip
286 flexion/extension angles at take-off and at peak flexion which were not apparent during
287 straight-line sprinting. Additionally, the left hip was significantly more adducted (more
288 positive) at touchdown and at peak adduction than the right on the bend ($p < 0.05$; Table II).
289 More turning of the CoM occurred during left ground contact on the bend with mean values
290 of $4.1 \pm 0.7^\circ$ compared to $2.5 \pm 0.8^\circ$ during right ground contact ($p = 0.022$, $d = 2.12$).

291

292 ***Tables I and II near here***

293

294 **Discussion**

295 The purpose of the study was to understand the changes to performance that occur during
296 maximal speed sprinting on the bend when compared to the straight, and how differences in
297 technique on the bend contribute to these changes in performance. This study shows
298 experimentally that performance is decreased during the maximal speed phase on the bend
299 when compared to the straight at bend radii typical of those used in athletic outdoor sprint
300 events. Group mean absolute velocity during straight-line sprinting was 9.86 ± 0.55 m/s and
301 9.80 ± 0.59 m/s for the left and right steps, respectively, which compares well to the
302 velocities attained during maximal effort straight-line sprinting of trained athletes in the
303 literature. For example, a mean velocity of 9.80 ± 0.50 m/s was reported for four male
304 sprinters in the study by Bezodis et al. (2008), and a mean velocity of 9.78 ± 0.42 m/s was
305 achieved by a similar level of male sprinters in the study by Mero and Komi (1986).
306 Furthermore, the step lengths and step frequencies for the straight, in the present study, are
307 similar to the mean values of 2.21 ± 0.15 m and 4.46 ± 0.21 Hz, respectively, reported by
308 Bezodis et al. (2008). The bend elicited a 4.7% reduction in absolute speed to 9.40 ± 0.42 m/s
309 and 9.34 ± 0.41 m/s for the left and right steps, respectively. Since absolute speed measures
310 the actual performance of the athlete regardless of the path travelled, this is important
311 because it showed that there was a real decrease in performance on the bend and that
312 reductions in race velocities were not simply due to athletes following paths longer than the
313 race line. Race velocity on the bend was also reduced by 4.8% for both left and right steps
314 compared to the straight as a consequence. On an individual level, there were four athletes
315 whose race velocities were faster than their absolute speeds on the bend indicating the CoM
316 of those athletes followed a path inside, and thus shorter than, the race line producing a
317 beneficial effect. While these four athletes are clearly effective in their bend sprinting, to
318 understand why there were able to run inside the race line when others did not is beyond the
319 scope of the current paper.

320

321 On the left step, the reduction in race velocity was due to a significant 0.11 Hz reduction in
322 step frequency ($p = 0.022$, Table I) and a 0.06 m reduction in race step length, although the
323 latter finding was non-significant ($p = 0.130$). These results for the left step partially support
324 the mathematical model of bend sprinting proposed by Usherwood and Wilson (2006).
325 Previous research by Weyand, Sternlight, Bellizzi and Wright (2000) had suggested that that
326 the swing time and the distance travelled by the CoM during stance were constant and the
327 limiting factor to maximum speed is the amount of force that can be exerted by the stance
328 limb during contact. Usherwood and Wilson (2006) used these assumptions in their model
329 and proposed that during straight-line sprinting athletes exert the maximum limb force
330 possible, in order to oppose and overcome the acceleration due to gravity and propel
331 themselves into the next step. Thus, the need to generate centripetal acceleration during bend
332 running places an additional requirement in terms of force generation. Usherwood and
333 Wilson (2006) suggested that since the limb force is constant and cannot be increased further,
334 the only way this additional requirement can be met is to increase the amount of time over
335 which the force is applied, that is the ground contact time, to provide the necessary impulse.
336 Usherwood and Wilson (2006) suggested that increasing ground contact time, with swing
337 time remaining constant, reduced step frequency and thus velocity on the bend. Therefore, in
338 the present study, the mean increase in left ground contact time of 0.007 s on the bend which
339 had the effect of reducing left step frequency and thus had a detrimental effect on velocity, is
340 in support of Usherwood and Wilson's (2006) model.

341

342 However, there was also an increase in left touchdown distance and body sagittal lean ROM
343 on the bend compared to the straight (Table II). Larger touchdown distances (or larger
344 touchdown angle) have been shown to be related to slower sprint performance (Kunz &

345 Kaufmann, 1981; Mann & Herman, 1985). Furthermore, increased touchdown distance and
346 body sagittal lean ROM have both been shown to be related to increased ground contact time
347 in straight-line running (Hunter et al., 2004). Thus, it is likely that these detrimental technique
348 changes may have increased braking forces or at least increased the duration of braking, thus
349 contributing to the observed increase in ground contact time, and consequently increased step
350 frequency. Therefore, a need to increase ground contact time in order to generate centripetal
351 force during bend sprinting may not be the only explanation for the decrease in performance.
352 Studies of force production during maximal effort bend sprinting are required to confirm this.
353

354 During the right step there was no difference in mean step frequency between the bend and
355 straight. Instead, performance decreased due to a significant reduction in race and directional
356 step lengths of 0.10 m and 0.08 m, respectively ($p < 0.05$, Table I). These are changes which
357 are unaccounted for in the mathematical model of Usherwood and Wilson (2006), but are
358 consistent with the findings of Stoner and Ben-Sira (1979). The latter authors found that
359 mean right step length for a group of nine college athletes was approximately 0.09 m shorter
360 on the bend compared to the straight during the acceleration phase of sprinting. The decrease
361 in race and directional step lengths in the present study was due to a statistically significant
362 0.009 s reduction in flight time for the right step from straight to bend ($p = 0.021$). This is,
363 again, in agreement with the findings of Stoner and Ben-Sira (1979) who found left step
364 flight times on the bend and straight to be similar, but significantly shorter right step flight
365 times on the bend compared to the straight. This suggests that the athletes may not have been
366 able to generate the vertical impulse during ground contact required for longer flight times
367 and step lengths, possibly due to the requirement to generate centripetal force in order to
368 follow the curved path. Again, further research investigating force production during
369 maximal effort bend sprinting is required to confirm this. The reductions in absolute speed

370 and race velocity for both steps and the detrimental changes to left step frequency and right
371 step length support the study's first hypothesis that there would be a detrimental effect of the
372 bend on performance descriptors. However, these detriments for the left and right steps came
373 from different sources.

374

375 The greater reduction in right step length than left step length might be taken to suggest that
376 more centripetal force is generated during the right ground contact. Indeed, in a study of
377 curved running on very small bend radii (1-6 m), Chang and Kram (2007) found the right leg
378 (outside leg) generated in the region of 100-200 N larger peak lateral forces than the left.
379 However, the turn of the CoM results in the present study are somewhat contradictory, since
380 more turning of the CoM was achieved during the left step ($4.1 \pm 0.7^\circ$ change in flight
381 trajectory) than the right step ($2.5 \pm 0.8^\circ$). Our finding is in line with Hamill et al. (1987),
382 who found larger peak lateral forces and impulses were generated with the left leg than the
383 right during running at 6.31 m/s on a bend of 31.5 m radius, which is much closer to the
384 radius used in the present study than that used by Chang and Kram (2007). It appears that
385 bend radius is the discriminatory factor. For bend running on tight radii, it has been suggested
386 that the outside leg performs an action which is a very slight version of an open, or sidestep,
387 cutting manoeuvre, whereas the inside leg performs an action similar to a cross, or crossover,
388 cutting manoeuvre (Rand & Ohtsuki, 2000). Indeed, cutting studies have reported larger
389 vertical and mediolateral force production and greater muscle activation in open cutting
390 manoeuvres than in cross cutting manoeuvres (Ohtsuki & Yanase, 1989; Rand & Ohtsuki,
391 2000). However, during sprinting on radii typical of athletic events, a conference proceeding
392 by Churchill, Salo, Trewartha and Bezodis (2012) revealed that the left leg (inside leg)
393 generated a larger lateral impulse, which may explain the greater contribution of the left step
394 to turning in the present study.

395

396 During bend sprinting the athletes leant inwards (Table II). Generally, this inward lean
397 caused a tendency for the left hip to be more adducted on the bend compared to the straight,
398 but the right hip to be significantly more abducted at peak adduction on the bend than the
399 straight (Table II). Additionally, significant differences between left and right steps were
400 observed in a number of sagittal plane variables such as touchdown distance, thigh
401 separation, and hip flexion/extension angle at take-off and at peak flexion ($p < 0.05$). Thus,
402 the second hypothesis relating to asymmetrical technique changes was partially accepted,
403 given that there were a number of asymmetrical changes to technique (kinematic) variables
404 but not universally. It is possible that the observed asymmetries in sagittal plane kinematics
405 were a result of the asymmetrical nature of bend running in the frontal plane. Although not
406 directly measured in the current study, previous studies have shown that alterations to hip
407 muscular activity in the frontal plane can affect the activity of muscles working in the sagittal
408 plane (e.g. Coqueiro et al., 2005; Earl, Schmitz, & Arnold, 2001). Furthermore, muscles such
409 as gluteus maximus, tensor fascia lata, pectineus and gracilis, that are involved in abduction
410 or adduction of the hip are also involved in flexion or extension of the hip or knee
411 (Palastanga, Field, & Soames, 2006). Therefore, it is probable that the observed asymmetrical
412 effect of the bend on sagittal plane hip angles, such as the left hip being more extended at
413 take-off and more flexed at peak flexion than the right hip on the bend ($p < 0.05$, Table II),
414 were caused by altered orientation in the frontal plane. Additionally, the increased adduction
415 of the left hip on the bend may have meant the limb was positioned in a less advantageous
416 position to extend quickly, causing the reduction in left hip extension angular velocity during
417 contact observed on the bend compared to the straight (Table II), although systematic
418 analysis is required to confirm this speculation. Furthermore, measurement of muscle
419 activation during bend sprinting compared to straight-line sprinting to assess whether changes

420 in the frontal plane kinematics may be affecting activation of those muscles involved in
421 sagittal plane motion is an area for future research.

422

423 From a coaching perspective it appears that one of the problems affecting forward velocity of
424 athletes during bend sprinting is the increased left touchdown distance compared to the
425 straight, and this might be an area in which improvements can be made. For example,
426 exercises aimed at reducing touchdown distance should be undertaken on the bend and not
427 just on the straight. Furthermore, it has been suggested that strengthening the hip extensors to
428 enable the foot to be pulled backward relative to the CoM at touchdown may be beneficial for
429 reducing touchdown distance in straight-line sprinting (Mann, 1985). Undertaking hip
430 extension strengthening exercises whilst in the altered orientation induced by the lean may
431 improve touchdown distance on the bend. Additionally, the observed asymmetries between
432 the legs, and the fact that the left step contributed more to turning than the right step, indicate
433 that the roles of the left and right steps may be functionally different in bend sprinting. Thus,
434 training should apply the principle of specificity, meeting the different requirements for the
435 left and right limbs. This may include ensuring enough good-quality high speed training is
436 conducted on the bend as well as on the straight, as well as completion of strength and
437 conditioning exercises which befit the demands of bend sprinting. This would allow athletes
438 to experience the requirement to withstand and generate large forces whilst in the altered
439 frontal plane orientation, which includes a tendency towards adduction of the left hip and
440 abduction of the right hip, rather than focusing on training primarily in the sagittal plane.
441 Whilst it may be prudent to ensure training meets the differing demands of the left and right
442 limbs, care should be taken that asymmetries that may be detrimental to straight-line
443 performance (such as asymmetrical step lengths or frequencies) are not introduced. In
444 addition to this, it has been suggested that excessive training in an anti-clockwise direction on

445 tracks with small bend radii (17.5 m) can result in muscle strength imbalances of the hind-
446 foot invertor and evertor muscle groups, which may be a potential factor for injury
447 (Beukeboom, Birmingham, Forwell & Ohrling, 2000). Overall, care should be taken to avoid
448 asymmetries and strength imbalances occurring.

449

450 As shown in the results, the redigitising yielded very low variability for the key variables.
451 Maximum SD from the mean redigitised values was 0.02 m/s, 0.02 m and 0.03 Hz for
452 speed/velocity variables, distance variables and step frequency, respectively. These values are
453 much smaller than the significant differences between means reported in the results. For
454 example, of those comparisons found to be statistically significant, the smallest difference in
455 means for absolute speed/race velocity variables was 0.06 m/s (Table I). This is three times
456 larger than the maximum SD of the redigitising in these variables. Similarly, for step length
457 variables the smallest difference which achieved statistical significance (0.08 m; Table 1) is
458 four times larger than the aforementioned maximum SD in distance variables. Only in
459 angular displacement variables was there a significant difference that was smaller than the
460 maximum SD of 2.5° in the redigitised trials. As shown in the results, right step peak hip
461 adduction had a significant difference of 2.3° between straight and bend. However, this is still
462 1.6 times greater than the larger of the two redigitising SDs in this individual variable (1.4°
463 on the straight and 1.0° on the bend). The second smallest difference in angular
464 displacements, which was found to be significant, was 4.3°. The above reliability values are
465 similar or slightly better than the redigitising data reported in Salo and Grimshaw (1998),
466 which is the most similar study to the current one reporting variability data from 3D manual
467 digitisation (of 2 x 50 Hz cameras) in sprint hurdling. The other source of variability in the
468 results is the athletes' own performance. Salo, Grimshaw and Viitasalo (1997) found very
469 high reliability values for the mean results (from individual participants' eight trials). The

470 clear majority of variables revealed reliability R-values over 0.90. Although not totally
471 comparable with the situation in the current paper, the variables similar to those analysed
472 here generally yielded that one to three trials were enough to reach the reliability R-value
473 over 0.80. Taking this information together, in conjunction with the low redigitising
474 variability provides confidence in our approach and results.

475

476 There were certain limitations to the present study. One limitation of the angle calculation
477 method is that it was not possible to reconstruct knee and ankle joint angles in three
478 dimensions to correspond with anatomical axes of rotation as was possible for the hip. This
479 was due to a lack of independent points for segment orientation definition. It is likely that
480 some measure of 3D joint motion at these joints would be of interest during bend sprinting.
481 However, the methods employed to obtain such angles (e.g. automated 3D motion capture)
482 would have meant that the ecological validity of the present study would have been
483 compromised. The sample size of seven athletes in the present study was relatively small, but
484 was sufficient to return significant results on some key comparisons. To improve the
485 robustness of the statistical analysis and the overall results, we utilised only the mean value of
486 runs by each athlete. Whilst it may have been preferable to have more participants, the
487 inclusion criteria set and testing conditions were such that this was not possible. In order that
488 the effects measured could be confidently attributed to the influence of the bend rather than a
489 novel task, it was important that all athletes were experienced bend runners and regularly
490 competing in high-level events which contained a bend portion (200 m and/or 400 m).
491 Additionally, to ensure the quality of running, the data were collected during the competition
492 season, when it is more difficult to recruit athletes. Furthermore, the bend and straight trials
493 were conducted on consecutive track training sessions so that any differences measured were
494 not due to training effects. Athletes who were not available for two consecutive track sessions

495 had to be excluded from the study. Despite the above, some statistically significant results
496 combined with many moderate and large effect sizes were found giving a strong foundation
497 for future research to build upon.

498

499 Although the present study provides useful information as to the changes in technique caused
500 by the bend in comparison to straight-line sprinting, the effect of the bend on force generation
501 is not fully understood. It has been suggested by Chang and Kram (2007) that the necessity to
502 stabilise joints in the frontal plane during bend running may affect the ability of the athlete to
503 exert extensor forces and may be a limiting factor for performance on the bend. The current
504 study provides evidence for altered frontal plane kinematics during maximal speed bend
505 sprinting and the effect on force generation warrants further investigation. Additionally, only
506 one bend radius was investigated in the present study. Further research is required to
507 understand what changes occur to technique on bends of different radii typical of those
508 experienced in athletic sprint events. This may be an important issue for athletes, who are
509 required to run at different bend radii depending on lane allocation in races.

510

511 ***Conclusion***

512 We investigated the changes in performance and technique that occurred during maximal
513 effort bend sprinting compared to straight-line sprinting under typical outdoor track
514 conditions. Seven male sprinters undertook maximal effort sprints on the bend (radius:
515 37.72 m) and the straight. Several performance descriptors and 3D technique variables were
516 calculated for a left and right step in each condition. Results showed a decrease in sprinting
517 performance on the bend compared to the straight. This was due mainly to a decrease in step
518 length on the right step resulting from a decrease in flight time and due to reduced step
519 frequency on the left step because of an increased ground contact time. The necessity to lean

520 into the bend resulted in asymmetrical changes to technique. Training should apply the
521 principle of specificity so that the demands of bend sprinting, which are different to that of
522 straight-line sprinting, are met. Furthermore, results suggest that the execution of left and
523 right steps may be functionally different during bend sprinting, and training may need to
524 reflect this. However, care should be taken to ensure training does not introduce asymmetries
525 between left and right which may be detrimental to straight-line sprinting performance.

526

527 **Acknowledgement**

528 This research was partially supported by grants from UK Athletics.

529

530 **References**

531

532 Abdel-Aziz, Y. I., & Karara, H. M. (1971). Direct linear transformation from comparator
533 coordinates into object space coordinates in close range photogrammetry.
534 *Proceedings of the Symposium on Close-Range Photogrammetry* (pp. 1-18). Falls
535 Church, VA: American Society of Photogrammetry.

536 Beukeboom, C., Birmingham, T. B., Forwell, L. & Ohrling, D. (2000). Asymmetrical
537 strength changes and injuries in athletes training on a small radius curve indoor track.
538 *Clinical Journal of Sport Medicine*, 10, 245-250.

539 Bezodis, I. N., Kerwin, D. G., & Salo, A. I. T. (2008). Lower-limb mechanics during the
540 support phase of maximum-velocity sprint running. *Medicine and Science in Sports
541 and Exercise*, 40, 707-715.

542 Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2012). Modeling the stance leg in two-
543 dimensional analyses of sprinting: Inclusion of the MTP joint affects joint kinetics.
544 *Journal of Applied Biomechanics*, 28, 222-227.

545 Bushnell, T. & Hunter, I. (2007). Differences in technique between sprinters and distance runners
546 at equal and maximal speeds. *Sports Biomechanics*, 6, 261-268.

547 Chang, Y. H., & Kram, R. (2007). Limitations to maximum running speed on flat curves.
548 *Journal of Experimental Biology*, 210, 971-982.

549 Churchill, S. M., Salo, A. I. T., Trewartha, G., & Bezodis, I. N. (2012). Force production
550 during maximal effort sprinting on the bend. In E. J. Bradshaw, A. Burnett, & P.
551 A.Hume (Eds.), *Proceedings of XXX International Symposium on Biomechanics in*
552 *Sports* (pp. 119-122). Melbourne: Australian Catholic University.

553 Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, New
554 Jersey: Lawrence Erlbaum Associates.

555 Coqueiro, K. R. R., Bevilaqua-Grossi, D., Bérzin, F., Soares, A. B., Candolo, C., &
556 Monteiro-Pedro, V. (2005). Analysis on the activation of the VMO and VLL muscles
557 during semisquat exercises with and without hip adduction in individuals with
558 patellofemoral pain syndrome. *Journal of Electromyography and Kinesiology*, 15,
559 596-603.

560 de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters.
561 *Journal of Biomechanics*, 29, 1223-1230.

- 562 Earl, J. E., Schmitz, R. J., & Arnold, B. L. (2001). Activation of the VMO and VL during
563 dynamic mini-squat exercises with and without isometric hip adduction. *Journal of*
564 *Electromyography and Kinesiology*, 11, 381-386.
- 565 Greene, P. R. (1985). Running on flat turns: Experiments, theory, and applications. *Journal of*
566 *Biomechanical Engineering-Transactions of the ASME*, 107, 96-103.
- 567 Hamill, J., Murphy, M., & Sussman, D. (1987). The effects of track turns on lower extremity
568 function. *International Journal of Sport Biomechanics*, 3, 276-286.
- 569 Hamilton, N. (1993). Changes in sprint stride kinematics with age in master's athletes. *Journal of*
570 *Applied Biomechanics*, 9, 15-26.
- 571 Hay, J. G. (1993). *The biomechanics of sports techniques*. New Jersey: Prentice Hal
- 572 Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length and step rate
573 during sprint running. *Medicine and Science in Sports and Exercise*, 36, 261-271.
- 574 International Association of Athletics Federations (2008). IAAF Track and Field Facilities
575 Manual 2008 Edition - Marking Plan 400m Standard Track. Retrieved from
576 <http://www.iaaf.org/about-iaaf/documents/technical#manuals-guidelines>
- 577 International Association of Athletics Federations (2014). *Competition Rules 2014 -2015*.
578 Monaco: International Association of Athletics Federations.
- 579 Kunz, H. & Kaufmann, D. A. (1981). Biomechanical analysis of sprinting: Decathletes versus
580 champions. *British Journal of Sports Medicine*, 15, 177-81.

- 581 Mann, R. (1985). Biomechanical analysis of the elite sprinter and hurdler. In N. K. Butts, T.
582 T. Gushiken & B. Zarins (Eds.), *The Elite Athlete* (pp. 43-80). New York: Spectrum
583 Publications, Inc.
- 584 Mann, R. A. & Hagy, J. (1980). Biomechanics of walking, running, and sprinting. *American*
585 *Journal of Sports Medicine*, 8, 345-350.
- 586 Mann, R. & Herman, J. (1985). Kinematic analysis of Olympic sprint performance: Men's 200
587 meters. *International Journal of Sports Biomechanics*, 1, 151-162.
- 588 Mero, A. & Komi, P.V. (1986). Force-, EMG-, and elasticity-velocity relationships at
589 submaximal, maximal and supramaximal running speeds in sprinters. *European Journal*
590 *of Applied Physiology*, 55, 553-561.
- 591 Miller, D., & Nelson, R. (1973). *Biomechanics of Sport: A Research Approach*. Philadelphia,
592 PA: Lea and Febiger.
- 593 Ohtsuki, T., & Yanase, M. (1989). Mechanical verification of the effectiveness of the first
594 step for quick change of the forward running direction. In R. J. Gregor, R. F. Zernicke
595 & W. C. Whiting (Eds.), *Proceedings of XII International Congress of Biomechanics*
596 (pp. 1065). Los Angeles: International Society of Biomechanics.
- 597 Palastanga, N., Field, D., & Soames, R. (2006). *Anatomy and human movement: Structure*
598 *and function*. Philadelphia: Elsevier.

- 599 Perneger, T. V. (1998). What's wrong with Bonferroni adjustments. *British Medical Journal*,
600 316, 1236-1238.
- 601 Rand, M. K., & Ohtsuki, T. (2000). EMG analysis of lower limb muscles in humans during
602 quick change in running directions. *Gait & Posture*, 12, 169-183.
- 603 Salo, A. & Grimshaw, P. N. (1998). An examination of kinematic variability of motion
604 analysis in sprint hurdles. *Journal of Applied Biomechanics*, 14, 211-222.
- 605 Salo, A., Grimshaw, P. N. & Viitasalo, J. T. (1997). Reliability of variables in the kinematic
606 analysis of sprint hurdles. *Medicine and Science in Sports and Exercise*, 29, 383-389.
- 607 Smith, G. (1989). Padding point extrapolation techniques for the Butterworth digital-filter.
608 *Journal of Biomechanics*, 22, 967-971.
- 609 Stoner, L. J., & Ben-Sira, D. (1979). Sprinting on the curve. In J. Terauds & G. G. Dales
610 (Eds.), *Science in Athletics* (pp. 167-173). Del Mar, CA: Academic Publishers.
- 611 Usherwood, J. R., & Wilson, A. M. (2006). Accounting for elite indoor 200 m sprint results.
612 *Biology Letters*, 2, 47-50.
- 613 Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running
614 speeds are achieved with greater ground forces not more rapid leg movements.
615 *Journal of Applied Physiology*, 89, 1991-1999.

616 Winter, D. A. (1993). Estimations of the horizontal displacement of the total body centre of
617 mass: considerations during standing activities. *Gait & Posture*, 1, 141-144.

618 Winter, D. A. (2009). *Biomechanics and motor control of human movement*. Hoboken, New
619 Jersey: John Wiley & Sons, Inc.

620 Yeadon, M. R. (1990). The simulation of aerial movement - I: The determination of
621 orientation angles from film data. *Journal of Biomechanics*, 23, 59-66.

622 **Table I.** Left and right step group mean values (\pm SD) and significant differences for performance descriptors 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
Absolute speed (m/s)	9.86 \pm 0.55	9.80 \pm 0.59	9.40 \pm 0.42	9.34 \pm 0.41	*		*	#
Race velocity (m/s)	9.86 \pm 0.55	9.80 \pm 0.59	9.39 \pm 0.45	9.33 \pm 0.44	*		#	#
Directional step length (m)	2.20 \pm 0.10	2.20 \pm 0.12	2.16 \pm 0.11	2.12 \pm 0.14				*
Race step length (m)	2.20 \pm 0.10	2.20 \pm 0.12	2.14 \pm 0.11	2.10 \pm 0.14				#
Step frequency (Hz)	4.50 \pm 0.19	4.46 \pm 0.29	4.39 \pm 0.26	4.46 \pm 0.31			*	
Ground contact time (s)	0.105 \pm 0.003	0.105 \pm 0.008	0.116 \pm 0.004	0.109 \pm 0.005		*	#	
Flight time (s)	0.115 \pm 0.004	0.121 \pm 0.012	0.116 \pm 0.009	0.112 \pm 0.014				*

623 * Significant at $p < 0.05$; # significant at $p < 0.01$;

624

625 **Table II.** Left and right step group mean values (\pm SD) and significant differences for technique 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
Touchdown distance (m)	0.30 \pm 0.04	0.31 \pm 0.04	0.36 \pm 0.04	0.30 \pm 0.04		*	#	
Body sagittal lean range of motion ($^{\circ}$)	51.1 \pm 2.4	51.2 \pm 2.7	57.2 \pm 1.7	52.9 \pm 2.7		#	§	
Body lateral lean at touchdown ($^{\circ}$) ^{1,2}	3.5 \pm 1.2	-4.1 \pm 0.8	-10.3 \pm 2.3	-15.2 \pm 1.6		#	§	§
Body lateral lean at take-off ($^{\circ}$) ^{1,2}	3.4 \pm 1.2	-4.4 \pm 0.5	-8.2 \pm 2.2	-14.1 \pm 1.6	*	§	§	§
Thigh separation at touchdown ($^{\circ}$)	17.2 \pm 11.4	19.6 \pm 5.6	25.5 \pm 8.8	18.5 \pm 5.8		*	*	
Hip flexion/extension angle at take-off ($^{\circ}$)	207.6 \pm 3.8	203.7 \pm 6.8	209.7 \pm 5.6	204.4 \pm 3.1		*		
Hip flexion/extension angle at peak extension ($^{\circ}$)	209.4 \pm 5.2	205.1 \pm 7.0	211.5 \pm 4.8	206.8 \pm 3.2	*	*		
Time of hip peak extension (% of step time)	53.2 \pm 4.9	50.7 \pm 3.1	54.8 \pm 2.9	55.0 \pm 1.9				#
Hip flexion/extension angle at peak flexion ($^{\circ}$)	103.9 \pm 8.6	104.3 \pm 7.7	101.7 \pm 6.5	106.6 \pm 6.7		#		
Time of hip peak flexion (% of contralateral limb step time)	49.9 \pm 5.7	45.2 \pm 6.5	48.0 \pm 4.4	50.9 \pm 5.2				*
Hip abduction/adduction angle at touchdown ($^{\circ}$) ³	-3.4 \pm 2.9	-5.5 \pm 1.9	0.6 \pm 3.8	-7.1 \pm 3.3		#	*	
Hip peak abduction ($^{\circ}$) ³	-6.3 \pm 2.4	-7.5 \pm 1.2	-4.8 \pm 3.2	-8.9 \pm 3.5				
Time of hip peak abduction (% of contact)	56.3 \pm 28.3	44.2 \pm 31.5	88.7 \pm 11.4	26.7 \pm 28.4		#	*	

Hip peak adduction (°) ³	4.1 ± 2.6	3.3 ± 3.7	10.6 ± 4.1	1.0 ± 3.5	§	#	*
Time of hip peak adduction (% of contact)	38.0 ± 10.1	47.7 ± 15.8	38.2 ± 7.1	55.5 ± 24.1			
Hip abduction/adduction angle at take-off (°) ³	-4.6 ± 2.4	-5.0 ± 2.2	-4.3 ± 3.0	-4.2 ± 3.9			
Hip flexion/extension angular velocity at touchdown (°/s)	377 ± 114	440 ± 117	405 ± 106	348 ± 80			
Hip peak extension angular velocity during contact (°/s)	951 ± 119	885 ± 152	853 ± 119	874 ± 132			*
Time of peak extension angular velocity (% of contact phase)	63.8 ± 11.8	63.9 ± 7.9	60.4 ± 10.3	64.9 ± 12.1			
Peak hip flexion angular velocity during swing (°/s)	-974 ± 51	-898 ± 69	-1001 ± 83	-919 ± 91	#		
Time of peak hip flexion angular velocity (% of contralateral limb contact)	21.1 ± 17.4	21.7 ± 21.8	23.7 ± 10.3	28.2 ± 19.2			

626
627
628
629

* Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

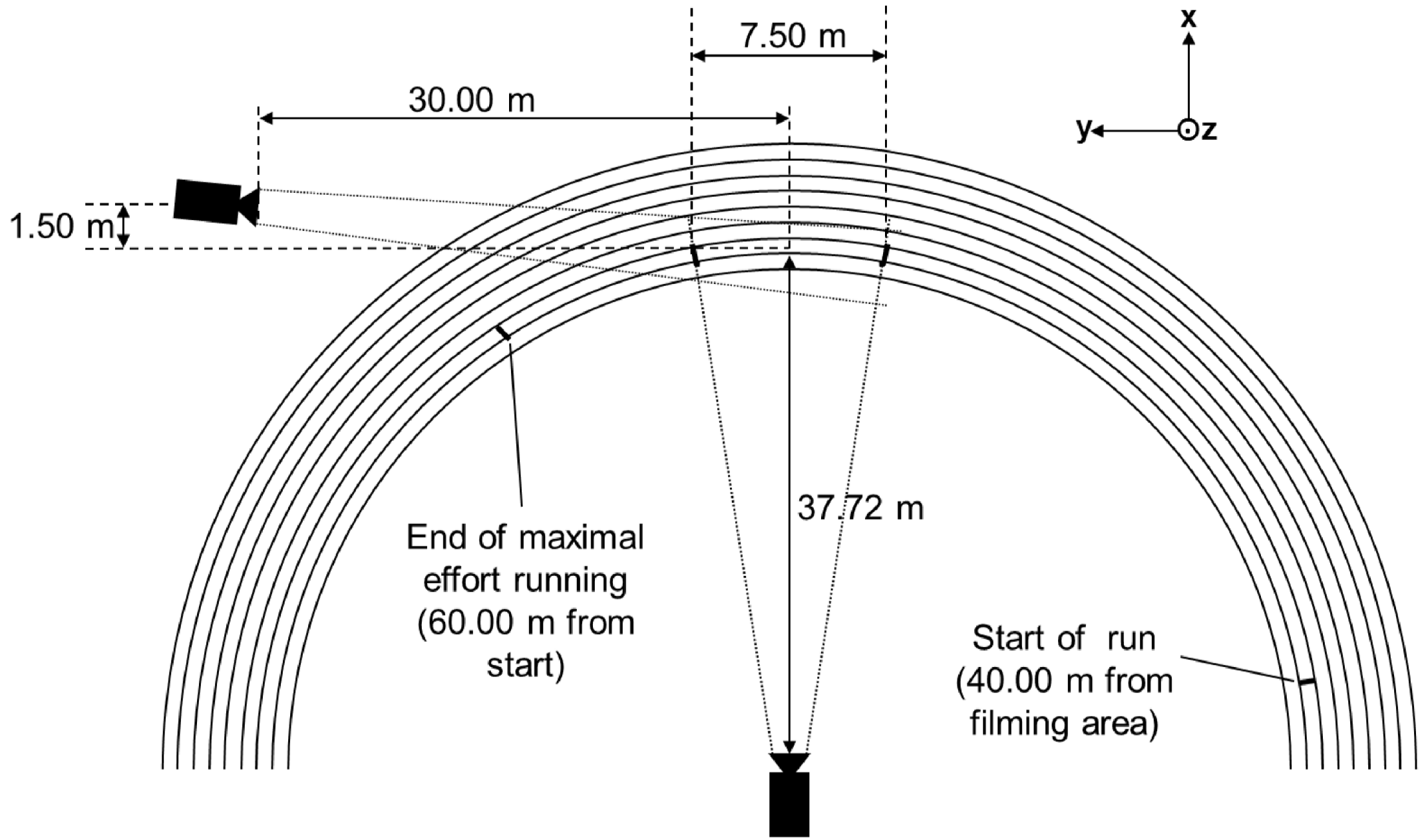
¹ Where left vs. right was compared on the straight by paired samples t-test absolute values were used for these variables; ² A negative value indicates lean to the left; ³ A negative value indicates abduction.

630 Figure captions:

631 **Figure 1.** Plan view of camera set-up for [a] bend trials (not to scale) and [b] straight trials
632 (not to scale).

633

634 **Figure 2.** a) Hip flexion/extension angle; b) Hip abduction/adduction angle [calculated
635 relative to the orientation of the trunk (represented here by the parallel dashed lines)]; c)
636 Body lateral lean angle; d) Body sagittal lean angle (used to calculate body sagittal lean range
637 of motion during contact).



a)



b)



c)



d)

