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CHURCHILL, Sarah M., SALO, Aki I.T. and TREWARTHA, Grant

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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

Dr Sarah M. Churchill

Sport, Health and Exercise Science

Applied Biomechanics Suite

University of Bath

BATH, BA2 7AY

UNITED KINGDOM

[1] 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

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

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

Abstract

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

(Word count: 198)

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

Introduction

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

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

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

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

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

Methods

Participants

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

Data collection

Bend sprinting and straight-line sprinting data were collected on a standard outdoor 400 m track during two consecutive track sessions (no more than 3 days apart) for each participant (bend and straight trials were completed in separate sessions). The athletes completed a coach-prescribed warm up before being asked to undertake three 60 m maximal effort sprints running in lane 2 (the radius on the bend was 37.72 m). Recovery time between trials was approximately eight minutes.

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

Figure 1 near here

Data processing

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

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

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

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

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

Calculation of variables

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

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

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

Touchdown distance was calculated as the horizontal displacement between the CoM and the MTP at touchdown relative to the direction of travel of the CoM of the athlete at touchdown. *Turn of the CoM during ground contact* was calculated for the bend trials as a measure of how much turning 'into' the bend an athlete achieved during each ground contact. A linear trend line was fitted to the raw CoM x-displacement as a function of the raw CoM y-displacement for the three available flight phases. The change in angle of consecutive flight displacement vectors gave the angle of turn of the CoM during the intervening contact phase.

Three-dimensional hip and body lean angles (Figure 2) were calculated using 3D orientation angles based on the methods outlined by Yeadon (1990). For angles measured at times other than touchdown (TD) and take-off (TO), the time at which they occurred was recorded. Range of motion (ROM) from TD to TO was calculated for *body sagittal lean angle*. *Thigh separation angle* was calculated at touchdown as a vector angle in the sagittal plane of the athlete. *Flexion/extension angular velocities of the hip* were calculated from angular displacement using the first central difference method. Additionally, the times at which peak angular velocities occurred were recorded.

Figure 2 near here

Statistical analysis

An individual mean value for every variable in each condition was calculated for each athlete from their available trials. This value was then used for further analyses. A number of comparisons were made using paired-samples t-tests (SPSS for Windows, v 14.0, SPSS Inc., USA). The following pairs were compared for each variable: left on the bend to left on the straight and right on the bend to right on the straight in order to determine changes between straight versus bend conditions. The presence of asymmetries was assessed by comparing left on the bend to right on the bend and left on the straight to right on the straight, for each variable. Absolute values were used for comparison of left and right body lateral lean on the straight.

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

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

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

Results

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

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

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

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

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

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

Tables I and II near here

Discussion

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

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

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

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

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

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

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

From a coaching perspective it appears that one of the problems affecting forward velocity of athletes during bend sprinting is the increased left touchdown distance compared to the straight, and this might be an area in which improvements can be made. For example, exercises aimed at reducing touchdown distance should be undertaken on the bend and not just on the straight. Furthermore, it has been suggested that strengthening the hip extensors to enable the foot to be pulled backward relative to the CoM at touchdown may be beneficial for reducing touchdown distance in straight-line sprinting (Mann, 1985). Undertaking hip extension strengthening exercises whilst in the altered orientation induced by the lean may improve touchdown distance on the bend. Additionally, the observed asymmetries between the legs, and the fact that the left step contributed more to turning than the right step, indicate that the roles of the left and right steps may be functionally different in bend sprinting. Thus, training should apply the principle of specificity, meeting the different requirements for the left and right limbs. This may include ensuring enough good-quality high speed training is conducted on the bend as well as on the straight, as well as completion of strength and conditioning exercises which befit the demands of bend sprinting. This would allow athletes to experience the requirement to withstand and generate large forces whilst in the altered frontal plane orientation, which includes a tendency towards adduction of the left hip and abduction of the right hip, rather than focusing on training primarily in the sagittal plane. Whilst it may be prudent to ensure training meets the differing demands of the left and right limbs, care should be taken that asymmetries that may be detrimental to straight-line performance (such as asymmetrical step lengths or frequencies) are not introduced. In addition to this, it has been suggested that excessive training in an anti-clockwise direction on tracks with small bend radii (17.5 m) can result in muscle strength imbalances of the hind-foot invertor and evertor muscle groups, which may be a potential factor for injury (Beukeboom, Birmingham, Forwell & Ohrling, 2000). Overall, care should be taken to avoid asymmetries and strength imbalances occurring.

As shown in the results, the redigitising yielded very low variability for the key variables. Maximum SD from the mean redigitised values was 0.02 m/s, 0.02 m and 0.03 Hz for speed/velocity variables, distance variables and step frequency, respectively. These values are much smaller than the significant differences between means reported in the results. For example, of those comparisons found to be statistically significant, the smallest difference in means for absolute speed/race velocity variables was 0.06 m/s (Table I). This is three times larger than the maximum SD of the redigitising in these variables. Similarly, for step length variables the smallest difference which achieved statistical significance (0.08 m; Table 1) is four times larger than the aforementioned maximum SD in distance variables. Only in angular displacement variables was there a significant difference that was smaller than the maximum SD of 2.5° in the redigitised trials. As shown in the results, right step peak hip adduction had a significant difference of 2.3° between straight and bend. However, this is still 1.6 times greater than the larger of the two redigitising SDs in this individual variable (1.4° on the straight and 1.0° on the bend). The second smallest difference in angular displacements, which was found to be significant, was 4.3°. The above reliability values are similar or slightly better than the redigitising data reported in Salo and Grimshaw (1998), which is the most similar study to the current one reporting variability data from 3D manual digitisation (of 2 x 50 Hz cameras) in sprint hurdling. The other source of variability in the results is the athletes' own performance. Salo, Grimshaw and Viitasalo (1997) found very high reliability values for the mean results (from individual participants’ eight trials). The clear majority of variables revealed reliability R-values over 0.90. Although not totally comparable with the situation in the current paper, the variables similar to those analysed here generally yielded that one to three trials were enough to reach the reliability R-value over 0.80. Taking this information together, in conjunction with the low redigitising variability provides confidence in our approach and results.

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

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

Conclusion

We investigated the changes in performance and technique that occurred during maximal effort bend sprinting compared to straight-line sprinting under typical outdoor track conditions. Seven male sprinters undertook maximal effort sprints on the bend (radius: 37.72 m) and the straight. Several performance descriptors and 3D technique variables were calculated for a left and right step in each condition. Results showed a decrease in sprinting performance on the bend compared to the straight. This was due mainly to a decrease in step length on the right step resulting from a decrease in flight time and due to reduced step frequency on the left step because of an increased ground contact time. The necessity to lean into the bend resulted in asymmetrical changes to technique. Training should apply the principle of specificity so that the demands of bend sprinting, which are different to that of straight-line sprinting, are met. Furthermore, results suggest that the execution of left and right steps may be functionally different during bend sprinting, and training may need to reflect this. However, care should be taken to ensure training does not introduce asymmetries between left and right which may be detrimental to straight-line sprinting performance.

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

* Significant at $p < 0.05$; $^{\#}$ significant at $p < 0.01$;

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

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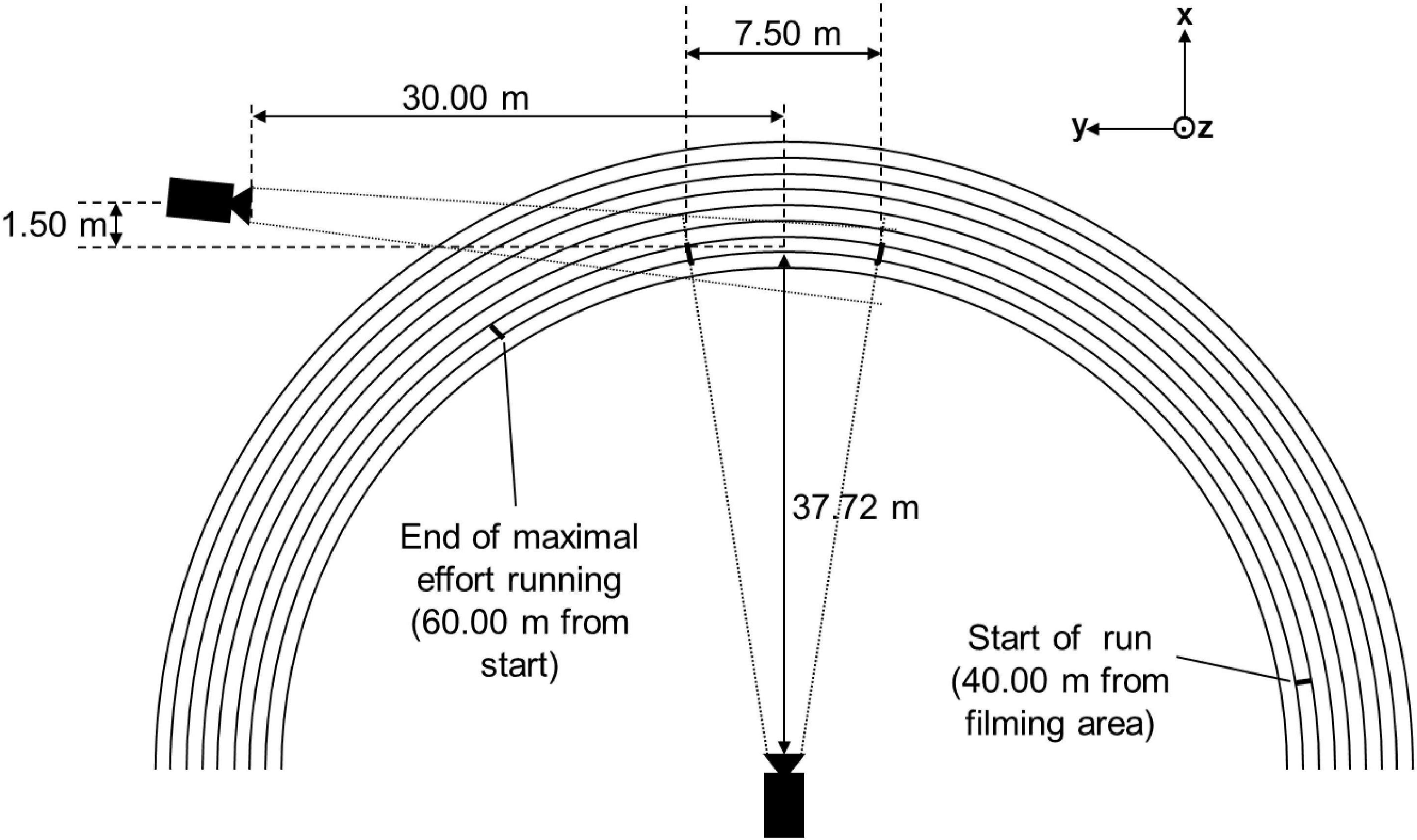
* Significant at $p < 0.05$; $^{\#}$ significant at $p < 0.01$; § significant at $p < 0.001$

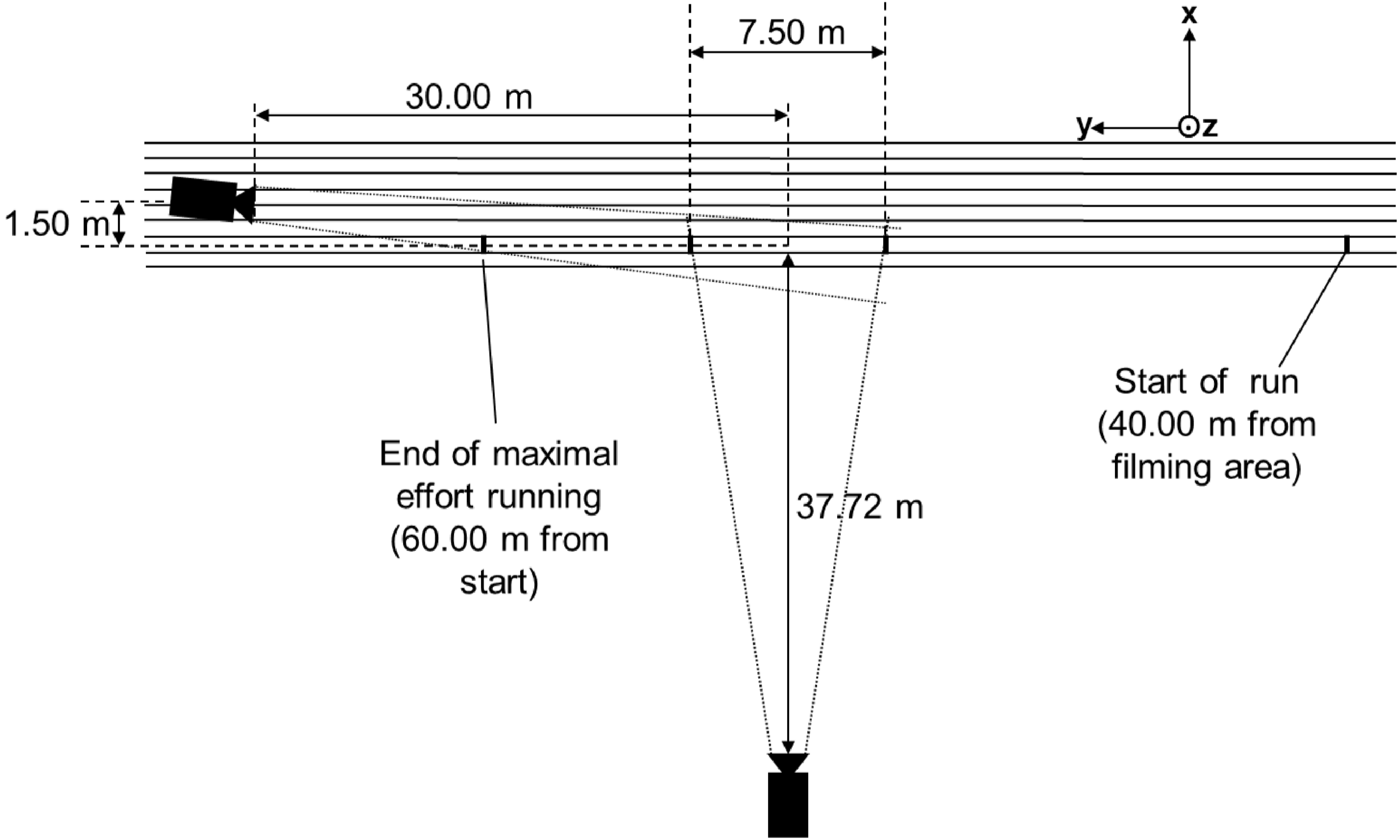
[1] Where left vs. right was compared on the straight by paired samples t-test absolute values were used for these variables; [2] A negative value indicates lean to the left; [3] A negative value indicates abduction.

Figure captions:

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

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


7.50 m
x
30.00 m
y
z
1.50 m
37.72 m
End of maximal effort running (60.00 m from start)
Start of run (40.00 m from filming area)



7.50 m
30.00 m
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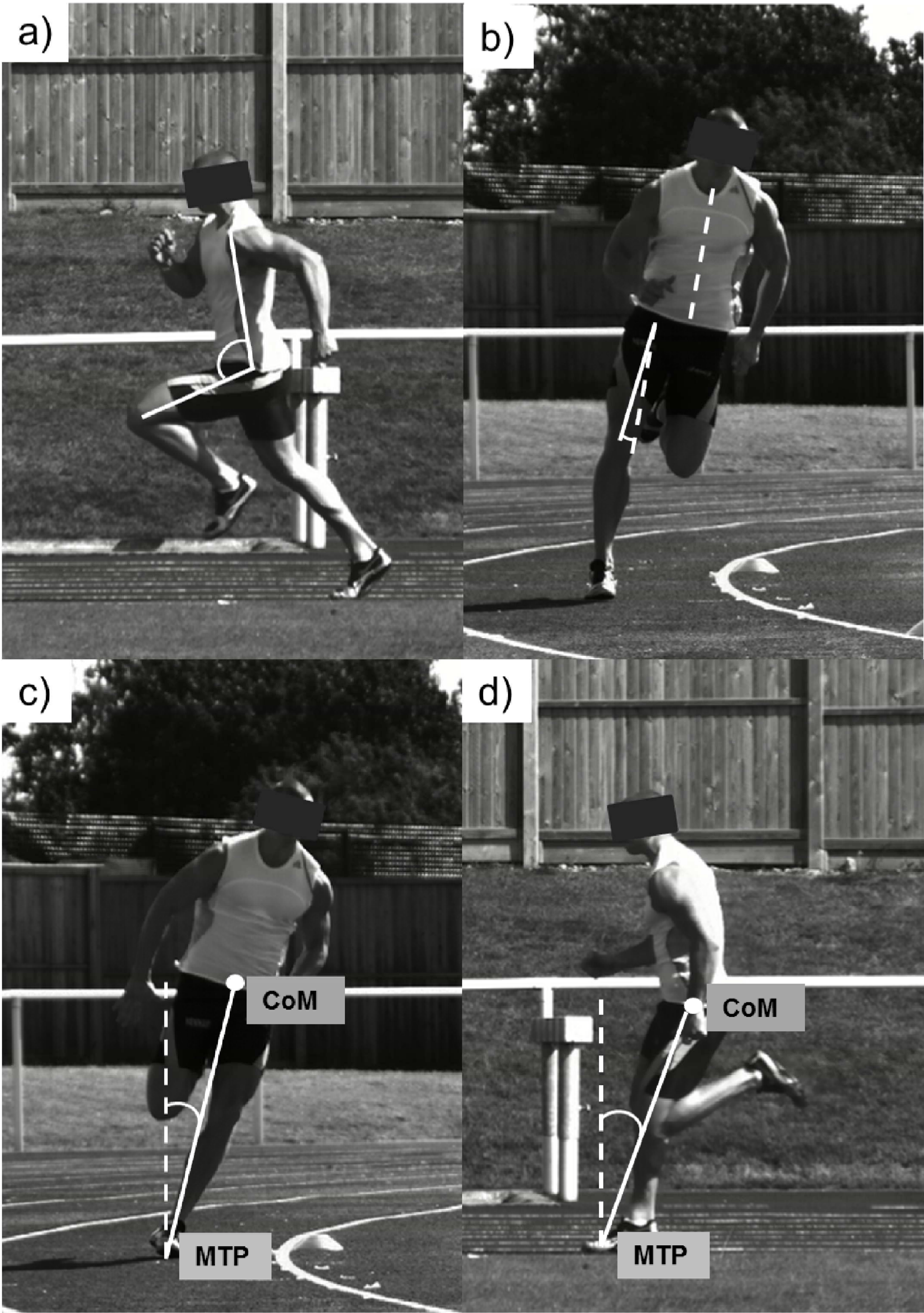
1.50 m
End of maximal effort running (60.00 m from start)
37.72 m
Start of run (40.00 m from filming area)


a)
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CoM
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d)
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