Force production during maximal effort bend sprinting: theory versus reality

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ABSTRACT

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

Keywords: Running gait, Mediolateral impulse, Limb asymmetry, Track and Field, 200 m, Curve, Constant limb force

Introduction

Force production during maximal effort sprinting on the bend, on the surfaces and at radii typical of athletic sprint events, is not well understood. This is despite the fact that during 200 m and 400 m track and field sprint events more than 50% of the race is run on the bend section of the track. Utilising information from Greene (1985) and Weyand et al. (2000), Usherwood and Wilson (2006) adopted the ‘constant limb force hypothesis’ for their mathematical model of bend sprinting. This model assumes that athletes running on the bend would generate the same constant maximum resultant force as on the straight. Thus, with the additional requirement to generate centripetal force to turn on the bend (and stay within the lane), it was postulated by Usherwood and Wilson (2006) that athletes would increase the time spent in ground contact in order to produce the necessary vertical and inward impulses. This consequently would reduce the sprinting speed. On the other hand, Gaudet (2014), when creating a mathematical model for sprinting, speculated that athletes do not apply maximum force during the bend running, although the author did not provide any empirical evidence for this statement.

In contrast to the above, empirical research into maximal effort sprinting on bends of very small radii (1-6 m) has found athletes to be unable to achieve the resultant and vertical forces on the bend that they were capable of during straight-line sprinting (Chang & Kram, 2007). Even during slower running (approximately 6 m/s) on larger radii typical of an athletics track, vertical force production has been observed to be reduced compared with straight-line running (Hamill et al., 1987).

There is reason to believe that left and right legs may have different roles in force production and in keeping the athletes on the appropriate curved path during bend sprinting. Chang and

Kram (2007) found that during sprinting on bends with radii of 1-6 m, the right leg produced greater peak lateral forces than the left leg. In contrast, Hamill et al. (1987) found that at a bend radius of 31.5 m, larger peak lateral forces were produced by the left leg than the right leg when running at approximately 6 m/s. Churchill et al. (2015) reported that, during maximal effort sprinting on a track bend radius of 37.72 m, more turning was achieved during the left ground contact than the right. This suggests that when sprinting maximally at radii typical of an athletics track, the left leg may produce greater inward force than the right leg. However, empirical measurement is required to confirm this.

Although Usherwood and Wilson (2005) demonstrated that the constant limb force hypothesis fails for greyhounds (limb forces increase on the bend), this theory has never been appropriately and empirically tested on sprinters running on an athletics track. Thus, the main aim of this study was to empirically investigate whether the constant limb force hypothesis is valid in maximal effort bend sprinting. In order to test this, force production characteristics were compared between bend and straight line sprinting with a view to understand how any potential changes in force production contribute to changes in performance descriptors. Based on the empirical literature of smaller radii running, it was hypothesised that athletes would produce less maximum resultant and vertical force on the bend than the straight. The second hypothesis was that more inward impulse, and thus turning, would be generated during the left ground contact than the right.

Methods

Participants

Considering that all participants were required to be experienced in bend sprinting (200 m and/or 400 m) and competed at national or international level, and the fact that such athletes are often reluctant to take part in research (Kearney, 1999), an opportunistic sampling of seven male sprinters from a limited pool of appropriate athletes volunteered for the study. The mean age, mass and height of the participants were 22.6 ± 4.2 years, 70.7 ± 9.2 kg and 1.76 ± 0.06 m, respectively, with the mean 200 m personal best time = 22.04 ± 0.74 s (range = 20.89 s to 22.90 s). The study procedures were approved by the local research ethics committee and all athletes provided written informed consent.

Data collection

Athletes undertook maximal effort sprints on the bend and straight in an indoor athletics centre. For the bend trials, markings were made on the track surface across the flat infield to fully replicate 60 m of lane 2 of a standard outdoor track (radius: 37.72 m). Bend trials were completed entirely around the bend and straight trials entirely on the straight. Two 0.90 m by 0.60 m force plates (9287BA, Kistler Instruments Ltd, Switzerland) operating at 1000 Hz were located contiguously in an area where the bend and straight lanes overlapped (Fig. 1). The force plates were isolated from the track foundations and surrounding track surface, and were covered with a piece of firmly-secured synthetic track surface which was flush with the rest of the track. Two video cameras (HVR-Z5E, Sony Corporation, Japan) operating at 200 Hz, with a shutter speed of 1/600 s, recorded a whole step starting from touchdown on the force plate and finishing with the touchdown of the contralateral leg. The separation angle of the two cameras' optical axes was approximately 95° (Fig. 1).

Fig. 1 near here

An 18-point structure was used to calibrate a three-dimensional (3D) activity volume (6.00 m long × 1.60 m wide × 2.00 m high). The positive y-axis of the global coordinate system

(GCS) was aligned with the positive y-axis of the force plates (the primary direction of travel of the athlete within the activity volume), the positive x-axis was to the right and positive z-axis was vertically upwards.

Athletes completed their typical competition warm up before undertaking up to six 60 m maximal effort sprints to achieve one successful left step and one successful right step on the bend and one successful left step and one successful right step on the straight. A step was assigned as left or right based on the leg producing the force on the initial contact with the force plate and for the following airborne phase. A successful trial was when the athlete's foot made contact within the force plate area without any visible alteration to the step pattern. All athletes achieved the required four different steps within the agreed maximum of six runs. This was helped by one investigator modifying the starting location of athletes based on a warm-up run and consequent trials after spotting the locations of the steps on the force plate area. In order to reduce the likelihood of force plate targeting, athletes were not informed of the location of the force plates, nor were they easily visible. All athletes had at least 40 m run-up, before the filming area. Recovery time between trials was approximately eight minutes.

Data processing

All trials were manually digitised using Vicon Motus software (Version 9.2, Vicon, Oxford, UK) at a resolution of 720 × 576 pixels with a 2 × zoom function increasing the effective resolution of the screen to 1440 × 1152 pixels. Two sets of synchronised 20-LED displays were triggered during each trial to allow the video streams and the force data to be synchronised to the nearest 1 ms.

Digitised trial video clips included 10 fields before the touchdown on the force plate and 10 fields after the next touchdown to mitigate against end-point errors in the data conditioning process (Smith, 1989). The digitised 20-point model of the human body consisted 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 shoe. Six video fields of the calibration structure were digitised in each camera view to provide 11 DLT parameters (Abdel-Aziz & Karara, 1971). The raw 3D coordinates and the force data were exported to a custom written Matlab script (v7.9.0, The MathWorks, USA) for further processing. Position data were filtered with a low-pass, 2nd order, zero lag, recursive Butterworth filter (Winter, 2009) with a cut-off frequency of 20 Hz. Force data were filtered with a 150 Hz cut-off frequency, chosen based on previous sprint research under similar testing conditions (Bezodis et al., 2014).

A 16-segment kinematic model of the human body was created. A standard 14-segment body model, with inertia data from de Leva (1996), had the feet additionally split into rearfeet and forefeet 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 et al., 2004) was added to the mass of each foot with 85% and 15% added to the rearfeet and forefeet, respectively (Churchill et al. 2015). The ratios of the total mass for all segment masses were, thus, adjusted accordingly.

Gait events (touchdown and take off) were determined using a combination of force plate and kinematic data. Touchdown and take-off on the force plate were defined using a two standard deviation threshold of the mean zero-load vertical force. An alternative first touchdown event was also determined from the peak vertical acceleration of the touchdown MTP point (Bezodis et al., 2007) and used only for the purpose of calculating step time. Second touchdown, which occurred off the force plate, was identified solely from this peak vertical acceleration of the touchdown MTP.

Calculation of variables

All variables were measured separately for the left and right steps. A number of ground reaction force variables were calculated and expressed relative to body weight (BW). Impulses were calculated in absolute terms and also expressed relative to body mass. Variables were selected based on force variables that have been shown to be important for performance in the straight-line sprinting literature and in the limited bend sprinting literature. These included peak values in horizontal, vertical and resultant directions, and the mean values and impulses over ground contact in each direction. Force data were aligned with the GCS for straight trials. During the bend trials, the horizontal forces in the GCS were rotated relative to the direction of travel of the athlete using a finite difference method based on the horizontal displacement of the Centre of Mass (CoM; Glaister et al., 2007).

Additionally, performance descriptors were selected based on those that have been shown to be affected by sprinting on the bend (Churchill et al., 2015). Full details of the methods of calculation of race velocity (the athletes' performance with respect to the official race distance), race step length (the length of the race distance covered by each step), step frequency and turn of the CoM during ground contact (the change in trajectory of the CoM during contact to follow the curved path in the bend trials) can be found in Churchill et al. (2015). In the present study, ground contact time was calculated as the time from touchdown to take off, as identified using force plate data. Flight time was calculated as step time (based on MTP acceleration data) minus ground contact time.

Statistical analysis

Paired samples t-tests were used to identify significant differences between left and right steps for variables within the straight and bend conditions separately, and between the straight and bend for the left and right steps separately. Based on Perneger (1998) and additionally in order to limit the risk of a type II error, no adjustment was made to the alpha level ($P < 0.05$). All statistical analyses were performed using IBM SPSS Statistics software (v19.0, SPSS Inc., USA). Cohen's d effect sizes (Cohen, 1988) are provided in the results section as additional contextualisation of the meaning of the results. Magnitudes less than or equal to 0.20 represent a small difference, d greater than 0.20 but less than 0.80 a moderate difference and d greater than or equal to 0.80 a large difference, between the two means.

Results

Mean peak resultant force during the left step was lower on the bend (3.61 ± 0.45 BW) than the straight (3.82 ± 0.53 BW; $P = 0.044$, $d = 0.45$, Table 1). For the right step, however, mean peak resultant force was greater on the bend (4.19 ± 1.29 BW) than the straight (3.66 ± 0.29 BW; $P = 0.248$, $d = 0.57$, Table 1), although this result was markedly influenced by one athlete producing a peak resultant force of 7.02 BW during the right step on the bend, compared with 4.11 BW for the right step on the straight.

Table 1 near here

Typical ground reaction force-time curves for the left and right steps on the bend and straight are provided in Fig. 2. There was a 19% increase in braking impulse ($P = 0.012$, $d = 0.72$) and the duration of braking (13% increase, $P = 0.003$, $d = 1.25$) for the left step on the bend when compared with the left step on the straight (Table 2). Additionally, there was greater braking impulse (33% increase, $P = 0.001$, $d = 1.34$) and duration of braking (30% increase, $P < 0.0005$, $d = 2.84$) for the left compared with the right step on the bend. Mean peak inward force and net inward impulse were higher during the left step than the right step on the bend ($P = 0.018$, $d = 0.85$ and $P = 0.001$, $d = 2.46$, respectively, Table 3).

Fig. 2 near here

Tables 2 and 3 near here

Mean race velocity was 2.3% lower on the bend compared with the straight for both the left step ($P = 0.012$, $d = 0.48$) and right step ($P = 0.001$, $d = 0.47$; Table 4). The mean right race step length reduced from 2.12 ± 0.08 m on the straight to 2.02 ± 0.07 m on the bend ($P = 0.030$, $d = 1.31$). This was accompanied by a slight increase in mean right step frequency from 4.49 ± 0.22 Hz on the straight to 4.59 ± 0.23 Hz on the bend ($P = 0.225$, $d = 0.47$). There were non-significant reductions (0.03 m) in left race step length ($P = 0.148$, $d = 0.67$) and left step frequency (0.02 Hz decrease, $P = 0.404$, $d = 0.13$) from straight to bend. A slight decrease in left step frequency and the increase in right step frequency on the bend did, however, result in a significant difference between left and right steps on the bend for this variable (right step frequency 0.15 Hz higher, $P = 0.024$, $d = 0.67$, Table 4), which was not seen on the straight. Additionally, there was more turning (change of CoM trajectory) achieved during the left step (4.2 ± 0.9°) than the right step (2.6 ± 0.7°) on the bend ($P = 0.025$, $d = 1.99$, Table 4).

Table 4 near here

Discussion

To the authors' knowledge this is the first full study to empirically investigate force production in maximal effort sprinting on a radius and surface typical of outdoor athletic competition. We investigated both whether the constant limb force hypothesis can be applied to bend sprinting and how force production on the bend influences performance. Firstly, we found that the constant limb force hypothesis is not fully valid in bend sprinting. Secondly, there are clear disparities in force production and function between left and right legs, which affect bend sprinting performance differently.

A reduction in left step peak vertical (9.8%) and resultant forces (5.7%) on the bend compared with the straight confirms our study's first hypothesis, at least for the left step, that lower vertical and resultant forces would be generated on the bend than on the straight. The 0.21 BW reduction in peak resultant force production in the present study for the left step on the bend compared with the straight runs counter to Usherwood and Wilson's (2006) use of the constant limb force assumption which suggested that athletes will generate a maximum resultant force on the bend equal to that generated on the straight. Our finding, however, concurs with the ground reaction force results of Chang and Kram (2007).

The bend did not appear to compromise vertical or resultant force production during the right step (Table 1), thus the study's first hypothesis is rejected for the right step. In fact, peak resultant force increased from 3.66 ± 0.29 BW on the straight to 4.19 ± 1.29 BW on the bend for the right step (Table 1). This increase was, however, influenced by an exceptionally large (more than seven times body weight) peak resultant force produced during the right step on the bend by one athlete. These very large forces produced by this one athlete seems to have been due to an individualised technique, as the athlete produced higher forces than any other athlete in each of the conditions, even once normalised to body weight. This athlete was running at the second highest velocity within that condition (9.66 m/s) and the ground contact time for that step was the shortest at 0.097 s. When that athlete's result for peak resultant force during the right step was removed, the group mean was 3.58 ± 0.23 BW on the straight and 3.72 ± 0.37 BW on the bend. Although this was not statistically significant, the 14% increase in right step peak resultant force on the bend compared with the straight, and considering the substantial increase in force on the bend for some athletes, these results demonstrate that the constant limb force hypothesis may not be valid for the right leg either. Usherwood and Wilson (2006) were able to use their mathematical model effectively to match indoor competition results based on the outdoor sprinting speeds. However, it is clear the constant limb force hypothesis is not a valid assumption for humans sprinting maximally on an outdoor athletics track, especially when specific information about force production is required.

Naturally, the horizontal (anteroposterior) force production is also very important in sprinting. As this study was conducted at the perceived maximum velocity phase, the net anteroposterior impulse by default is very close to zero (just enough positive to counteract the air resistance of the sprinter). Thus, we could not expect large differences in anteroposterior forces between the conditions. However, there was a statistically significant difference in anteroposterior propulsive impulse between straight and bend for the right step. This was mainly due to one athlete as explained above. Gaudet (2014), using a mathematical model containing several assumptions, speculated that during Berlin 2009 World Championships, Usain Bolt applied 97.3% of the horizontal forces in the curve of the 200 m final in comparison with his 100 m final in the same championships. In the current study, the left step peak anteroposterior propulsive force on the bend was 93.0% of that on the straight. The respective value for the right step was 106.3%. However, as our forces are actual measured forces during a step and Gaudet's (2014) value is an estimation over a longer period of race, we need to be careful of drawing any meaningful comparisons from the values.

Kinematic analysis of maximal (Churchill et al., 2015) and submaximal (Alt et al., 2015) effort bend sprinting has shown that inward lean during bend sprinting results in greater adduction of the left hip during the ground contact phase of bend sprinting compared with straight-line sprinting. On the other hand, Churchill et al. (2015) reported that the right hip abduction/adduction angle at touchdown was not significantly affected by the bend and that peak adduction was less on the bend compared with the straight. The inward lean and adduction/abduction angles could also influence why there were statistically significant differences in horizontal braking impulses between left and right step on the bend (left step braking larger) and between the straight and bend conditions for the left leg (bend condition larger). It seems that due to inward lean, left leg has 'less room' (in relation to CoM) to produce the pull-back action in the air and consequently makes contact earlier producing larger and longer braking phases.

Some of the muscles that are involved in hip and knee flexion or extension are also involved in controlling hip abduction or adduction (Palastanga et al., 2006). Thus, it is possible that alterations to joint positions in the frontal plane may have an impact on those muscles' ability to generate forces in the sagittal plane. Indeed, it has been suggested that the ability to sustain forces in the frontal plane, whilst generating force in the sagittal plane, may be the limiting factor to bend running performance (Chang & Kram, 2007). Measurement of 3D joint moments whilst bend sprinting at track specific radii is lacking in the literature and is a potential area for further investigation in order to establish whether frontal plane joint moments are, in fact, limiting factors to bend running performance. These measures may also explain the reduced vertical and resultant ground reaction forces observed for the left step and why the right step force production appeared to be less affected in the present study.

In addition to the above, the position of the foot during the push off may have influenced the force generation during the left and right steps on the bend. Although not directly measured in the present study, Bojsen-Møller (1979) described the foot as being capable of using two alternative axes for push off: the transverse and oblique axes. The transverse axis runs through the first and second metatarsal heads, whereas the oblique axis runs through the second to the fifth metatarsal heads (Bojsen-Møller, 1979). The use of these two axes affects the congruency of the calcaneocuboid joint and the effectiveness of the windlass mechanism of the plantar aponeurosis, which in turn affects the stability of the foot and so its effectiveness for propulsion is likely superior when push off is about the transverse axis rather than the oblique axis (Bojsen-Møller, 1979). It is probable that inward lean of the athletes during bend running means that in the ground phase, the left foot contact is more lateral and the right foot contact is more medial. This would mean the left foot would be more likely to employ the oblique axis during the push off phase so may account for the reduction in vertical force production during the left step on the bend compared with the straight. It may also explain the significantly greater inward impulse generated on the left step compared with the right step on the bend. In contrast, the right foot would be more likely to employ the transverse axis, which may have contributed to maintenance of vertical and anteroposterior propulsive force generation, but may not be conducive for inward force generation.

The present results for the left step do provide partial support for Usherwood and Wilson's (2006) mathematical model, as a significant 10 ms increase in ground contact time was observed for the left step on the bend compared with the straight (Table 4). Usherwood and Wilson (2006) suggested, based on the research of Weyand et al. (2000), that the maximum force an athlete is able to produce is already achieved during straight-line sprinting. They postulated that ground contact time and the proportion of stride time spent in ground contact during bend running would be increased in order to generate the centripetal force required to follow the curved path. They suggested that swing time would remain constant and, therefore, step frequency would decrease. The increased left step ground contact time in the present study is in line with previously reported increases of 11 ms in left step ground contact time during maximal effort bend sprinting (Churchill et al., 2015). Alt et al. (2015) revealed a much smaller increase in contact time of the left step from straight to bend sprinting (2.6 ms). Right step ground contact time decreased, although not significantly, on the bend compared with the straight, again counter to the assumptions of Usherwood and Wilson (2006). The reduction was less than in Alt et al. (2015) who found right ground contact time reduced significantly on the bend compared with the straight. The observed differences between the studies may be due to the fact that Alt et al. (2015) analysed matching velocities in two conditions rather than maximal effort trials, allowing their athletes to have a relatively longer contact time on the straight. The increased ground contact time in the current study enabled maintenance of vertical impulse (only a 0.7 Ns reduction) for the left step on the bend compared with the straight in the presence of significantly reduced mean vertical forces (0.11 BW). For the right step, vertical impulse results were similar between conditions, yet there was a significant decrease in right step flight time (by 0.012 s), which had the effect of significantly reducing right race step length (by 0.010 m). A reduction in right step length on the bend compared with the straight has previously been shown in both the acceleration phase (Stoner & Ben-Sira, 1979) and the maximum speed phase of bend sprinting (Churchill et al., 2015).

The net inward impulse was significantly greater (61.2%) during the left step than the right on the bend, resulting in 1.6° more turning of the CoM being achieved during the left than right ground contact (Table 4). This greater inward impulse was produced via a combination of both an increased contact time and a higher mean inward force (impulse divided by contact time) being generated for the left step than the right step. This finding supports our second hypothesis and suggests that there are functional differences between the left and right steps in terms of force generation during bend sprinting. This finding is in line with our previous kinematics study on a different participant group which also showed more turning was achieved during the left step than the right (Churchill et al., 2015). Furthermore, the present results contradict previous research that found the outer (right) leg generated greater peak inward forces than the inside leg during maximal effort sprinting on radii of up to 6 m (Chang & Kram, 2007) and during running (~5 m/s) on a curved path of 5 m radius on turf (Smith et al., 2006). The tightness of the radii may account for the differences between those studies (Chang & Kram, 2007; Smith et al., 2006) and the present study. Thus, the turning method employed by sprinters running at maximal effort in athletic events appears to be different to that of cutting actions, or of turning on very small radii. While the amount of turning of the CoM is the consequence of the net impulse, there are various internal/external rotations within joints and segments in bend sprinting. Regarding these rotational elements, Alt et al. (2015) provided further insight into the functional differences between the legs. For example, their results showed that the peak external rotation of the right ankle was three times more than in the left ankle, although the overall external rotation from initial contact to peak external rotation was similar in both ankles.

Mean peak inward forces during bend trials were over two-fold higher than the observed mediolateral forces during straight trials (Table 3). These values were even larger than the mean peak anteroposterior propulsive forces observed and may have potential implications for strength training of athletes. Coupled with differences in frontal plane kinematics on the bend compared with the straight, including leaning into the bend and hip abduction/adduction angles (Alt et al., 2015; Churchill et al., 2015) and likely changes in frontal plane joint moments on the bend when compared with the straight (Chang & Kram, 2007), these aspects should be a consideration in both strength and technique training for athletes. For example, athletes should ensure that they undertake some maximum-speed training on the bend in order that the high forces whilst leaning are not only experienced during a competition setting. This means that when the focus of the training is the bend, the starting positions should, at times, be such that a substantial proportion of the maximum-speed phase occurs on the bend. Additionally, the use of ropes or harnesses may allow athletes to be supported in a leaning position during strength training and/or plyometric training. Moreover, the demands of the left and right steps on the bend appear to be functionally different, but care should be taken to avoid introducing asymmetries, such as strength imbalances, that might be detrimental to the straight-line portion of the race.

The straight line velocities, step lengths and step frequencies achieved in the present study (Table 4) were similar to those reported in previous studies of the maximal phase of straight line sprinting in athletes of similar calibre (Bezodis et al., 2008; Churchill et al., 2015; Mero & Komi, 1986). Furthermore, the athletes in the present study were able to achieve vertical and anteroposterior ground reaction forces on the straight which were similar to previously reported values. For example, Korhonen et al. (2010) reported peak vertical, braking and anteroposterior propulsive ground reaction forces of 3.35 BW, 1.43 BW and 0.74 BW, respectively, for athletes sprinting on the straight at a similar velocity (9.5 m/s). These findings confirm that the athletes in our study were typical competitive athletes performing normally. However, a limitation of the present study is that the number of trials was limited to a maximum of six per athlete in total, as the quality of runs may not be maintained at maximal effort beyond that, highlighting challenges when investigating competitive sprinters in ecologically valid situations. This meant that only one successful foot strike on the force plate was achieved for each foot under each condition for each athlete. Force data from multiple steps have been collected in sprinting (e.g. Belli et al., 2002; Korhonen et al., 2010; Mero & Komi, 1986; Morin et al., 2011, 2012). However, these have been carried out either on instrumented treadmills (Morin et al., 2011, 2012), which is not applicable to track bend sprinting, or on long multiple force plates (Belli et al., 2002; Korhonen et al., 2010; Mero & Komi, 1986) that are not readily available. Data collection on separate occasions would have facilitated multiple trials per foot per condition, but this would have increased variation due to data being collected on different days and would likely have increased participant drop-out. It is acknowledged that there was a relatively limited sample size in this study. However, this was due to the requirement to have high calibre athletes who were experienced in bend sprinting and competing regularly so that any differences found could be confidently attributed to the running condition rather than the novelty of the task. Despite being a limited sample, statistically significant results were found, and differences in force production between the bend and straight were still identified.

Perspectives

We believe this is the first investigation of the kinetics of maximal effort bend sprinting on a surface and radius typical of an outdoor athletics track. Overall force production reduced on the left step on the bend resulting in lower velocity, contrary to the assumptions of

Usherwood and Wilson's (2006) mathematical model. The decrease in velocity was due to decreased step length and frequency similar to Alt et al. (2015) and Churchill et al. (2015). However, the left step contributed more than the right step to the generation of inward impulses and turning, contradicting studies of small radii (Chang & Kram, 2007; Smith et al., 2006). Resultant force increased during the right foot contact, although step velocity reduced due to shorter step length. This was possibly due to difficulties in repositioning the left leg for the subsequent contact leading to an abbreviated step. Force requirements of bend sprinting were considerably different to those of straight-line sprinting with asymmetries between left and right steps observed on the bend. Therefore, bend specific strength and technique training performed at high velocity may improve athletes' ability to meet the requirements of bend sprinting, thus improving performance during this portion of a race.

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

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

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

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

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

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

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

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

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

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

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

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

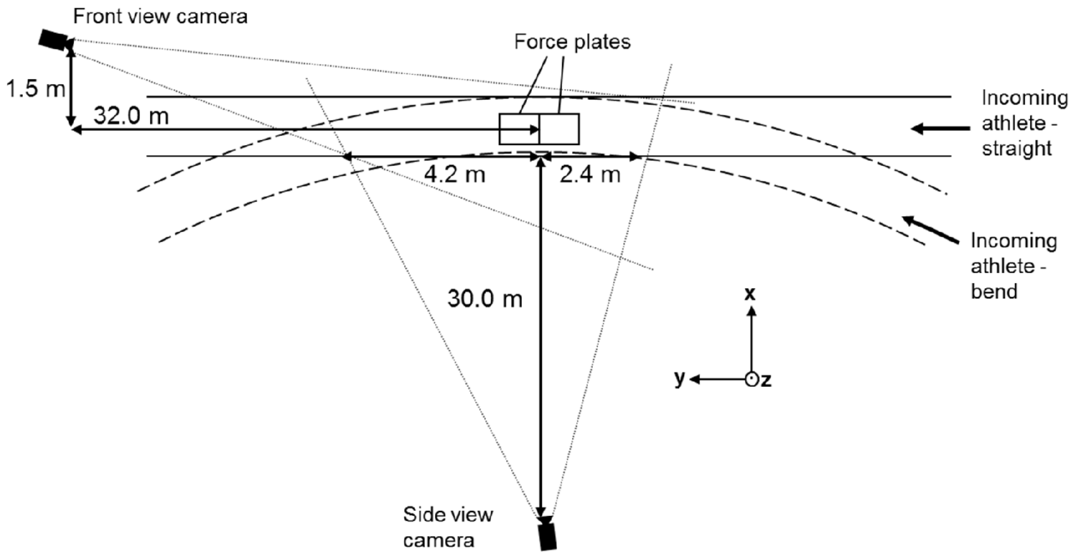
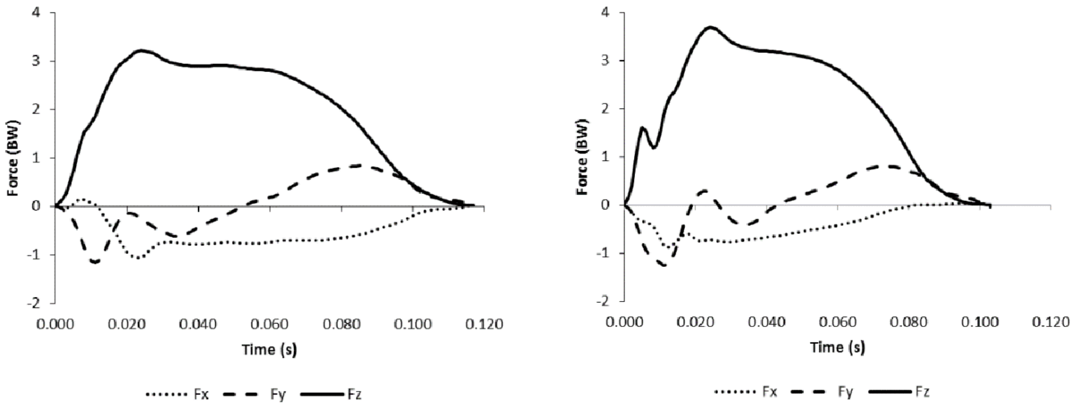


Fig 1. Camera set-up for bend and straight trials (not to scale).

(a) Bend – Left step (b) Bend – Right step



(c) Straight – Left step (d) Straight – Right step

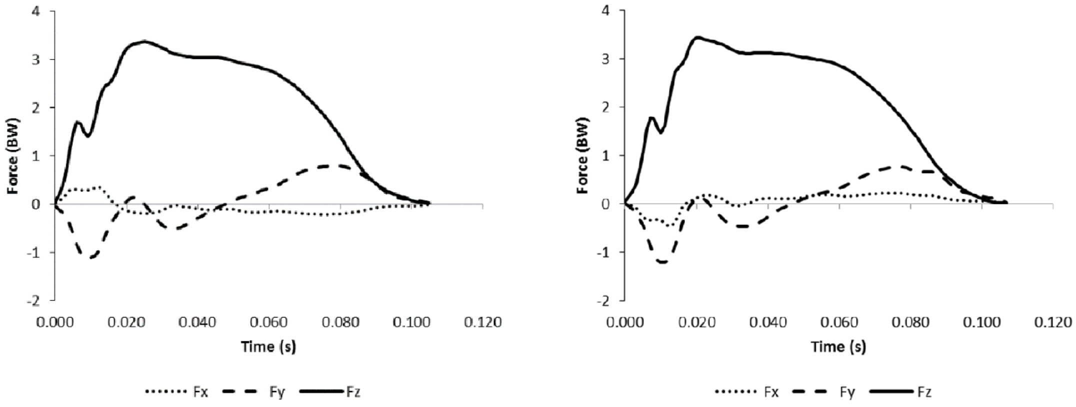


Fig 2. Ground reaction forces for one participant's left and right steps on the bend and straight. Negative Fx on the bend represents inward force; Negative and positive Fx for the left step on the straight represents lateral and medial force, respectively; Negative and positive Fx for the right step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