Horizontal force production and multi-segment foot kinematics during the acceleration phase of bend sprinting

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

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Abstract

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

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

Introduction

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

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

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

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

If MTP joint push-off mechanics are influenced by sprinting on the bend, as a consequence the more proximal ankle joint also employ different compensatory mechanisms, as described by Bojsen-Moller [10]. Kinematic adaptations have been reported elsewhere in the lower extremity, for example, both Alt, Heinrich, Funken, Potthast [2] and Churchill, Salo, Trewartha [3] reported an increase in peak left hip adduction on the bend compared with the straight at submaximal[2] and maximal speeds[3]. Alt, Heinrich, Funken, Potthast [2] also reported greater peak left ankle eversion during bend sprinting. During the stance phase in sprinting, the foot is in a fixed position, thus motion at the foot and ankle is thought to pass proximally as part of a closed kinematic chain to the tibia, fibula and femur[13]. Therefore, adaptations occurring proximally in the kinematic chain during bend sprinting are likely associated with adaptations at the foot. Furthermore, asymmetric differences in strength of the muscle groups of the foot[14] and high incidences of injuries to the foot[15] have been reported in bend sprinting athletes. Hence, better understanding the motion of the foot during bend sprinting might provide insight for practitioners to aid injury prevention strategies.

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

Methods

Participants

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

Experimental set-up

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

***** Figure 1 near here *****

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

Kinetic data were collected using a Kistler force plate (Model: 9287BA, 900 x 600 mm) sampling at 1000 Hz. The force plate was embedded into the track surface and covered with a secured piece of synthetic track. The force platform was configured to produce a rising(/falling) edge 5 V signal at the onset of data collection, which was sampled by the motion capture system and used to temporally synchronise the kinematic and kinetic data.

Protocol

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

Participants completed their typical competition warm-up before performing a maximum of six trials (three left, three right) at maximal effort for 30 m in each condition (bend and straight). Starting blocks were used alongside an '*on your marks, set, go*' signal to maintain the experimental representativeness of the protocol. For force data, a minimum of one successful right and left step on the bend and one successful right and left step on the straight were achieved within these trials. A successful trial was defined as contact being made with the force plate without changes to running gait caused by ‘targeting’. To achieve this, one researcher modified the start location up to a maximum of one metre of the athletes based upon warm-up trials. Therefore, force data were collected in the range of 11 - 13 m. To further reduce the likelihood of targeting, participants were not informed of the force plate location. Approximately eight minutes were allowed between trials to avoid the onset of fatigue[3]. Participants wore their own sprint spikes for the testing session.

Data processing

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

For force data, one successful trial per condition and per participant was analysed, as was the case with Churchill, Trewartha, Bezodis, Salo [6]. Two participants were not able to record force data for one condition, so their force data was removed from the analysis. For kinematic data, a mean of three trials was calculated for both the left and right foot on the bend and straight. *Touchdown* and *take-off events* were identified using the mean plus two standard deviations of the last three seconds of vertical ground reaction force data (where there was zero load on the force plate) as a threshold[24]. For trials where force plate data were not available, the mean plus two standard deviations of the vertical coordinates of MTH5 in the static trial were used as a threshold for touchdown and take-off [24]. All variables were calculated separately for the left and right step. Left and right steps were defined by the foot that initiated the step. *Absolute speed* was calculated using the first central difference technique from the horizontal distance travelled by the CoM of the lower limb and trunk model. *Contact time* was calculated at the time from touchdown to take-off.

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

Adapted from Smith, Lake, Lees, Worsfold [26], *MTP push-off axis* was determined using centre of pressure (CoP) data. CoP data were first aligned with a local foot coordinate system. The mediolateral position of the CoP and MTH2 marker was then extracted during the propulsive phase of stance for each condition. The distance of the CoP from the MTH2 was then calculated for each frame, followed by calculation of the mean CoP position during the propulsive phase of stance and thus providing the *mean mediolateral CoP position relative to MTH2*. For ease of interpretation, data for the left foot were multiplied by -1, so a positive value indicated CoP was lateral to MTH2 and represented the oblique axis for both the left and right foot. Consequently, a negative value represents the use of the transverse axis (figure 2).

***** Figure 2 near here *****

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

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

Statistical analysis

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

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

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

Results

Performance descriptors

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

***** Table 1 near here *****

Anteroposterior, mediolateral force and ratio of force

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

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

***** Figure 3 near here *****

***** Figure 4 near here *****

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

***** Table 2 near here *****

MTP push-off axis and multi-segment foot kinematics

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

*****Figure 5 near here*****

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

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

***** Table 3 near here *****

Discussion and Implications

The aim of this research was to investigate horizontal force production, foot kinematics and MTP joint axis use during sprinting in the acceleration phase on the bend compared to the straight. The left foot was found to use the oblique axis for push-off at the MTP joint. This coincided with a decrease in anteroposterior force and propulsive impulse and an increase in peak eversion of the midfoot and ankle. These findings support the study's hypothesis. Moreover, although non-statistically significant, a small (2%, $g = 0.52$) reduction in left step absolute speed on the bend compared with the straight was observed. The decrease in absolute speed is lower than the 4.7% reduction reported by Churchill, Salo, Trewartha [3] during maximal speed, suggesting the effect of the bend during the acceleration phase accumulates and results in a greater loss of speed during the later maximal speed phase.

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

In addition to the reduction in propulsive force, there was a decrease in propulsive impulse, particularly during the left step where a large effect size was found ($g = 0.93$). Right step propulsive impulse was also reduced on the bend compared to the straight. However, the moderate effect size suggests this was not to the same extent (propulsive impulse $g = 0.78$). Morin, Slawinski, Dorel, de Villareal, Couturier, Samozino, Brughelli, Rabita [18] discussed how acceleration capability in faster sprinters was characterised by 'pushing more' but not necessarily 'braking less'. This concept suggests producing higher propulsive impulse is of greater importance than producing lower braking impulse, particularly in the first twenty metres of acceleration. This is supported by Colyer, Nagahara, Salo [30] who observed a positive association between better performances and higher amounts of anteroposterior force during the mid-late propulsion phase of stance. During bend sprinting, the ability to produce propulsive impulse was restricted, and although a significant effect was not reported for braking impulse, large effect sizes were observed when comparing left step on the bend and straight (g = 1.29). This suggests a greater braking impulse was experienced in the left step on the bend in comparison to the straight. Unlike Morin, Slawinski, Dorel, de Villareal, Couturier, Samozino, Brughelli, Rabita [18], acceleration performance during bend sprinting is characterised by 'pushing less' and 'braking more' than the straight, particularly with the left foot. Therefore, propulsive force production of the left foot may be a limiting factor for acceleration performance on the bend.

However, these reductions in propulsive force observed during bend sprinting are a necessary consequence of the additional requirement to produce centripetal force. In order to achieve this requirement, and stay in the correct lane, mediolateral force was greater on the bend compared to the straight for the majority (3-96%) of the stance phase. Whilst necessary for bend sprinting, it is possible the introduction of mediolateral force is a contributing factor for the decrease in ratio of force found during bend sprinting. In addition, use of SPM revealed mediolateral force during bend sprinting was greater in the right step compared to the left during 1-12% of the stance phase, whereas later in stance (75-100%), mediolateral force was greater in the left step than right, thus further establishing the left foot as fulfilling a different role to the right foot during bend sprinting. These asymmetries demonstrate the benefit of SPM analysis which has provided insight that may have been lost with the analysis of discrete values.

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

Ratio of force analysis provides an overview of force orientation and a reduction was reported in both left and right steps on the bend compared with the straight. This finding is reinforced when considering impulse, which as the product of force and time acts as a metric to evaluate force application. Reductions in the magnitude of force despite longer contact times resulted in a decrease in propulsive impulse that was greater in the left step. Therefore, it appears the decrease in acceleration performance at approximately12 m is largely due to changes in left step force orientation and application.

A mechanism behind the reported changes in force production during bend sprinting might be the use of different MTP joint push-off axes. Results showed that left step mean mediolateral COP position was more lateral on the bend than the straight, suggesting the oblique axis is used to push-off with the left step during bend sprinting, supporting the hypothesis put forward by Churchill, Trewartha, Bezodis, Salo [6]. The oblique axis is considered less effective for push-off at high speeds[10]. However, during bend sprinting, oblique axis use seems a necessary adaptation (dictated by the need to produce centripetal force and change in the segmental arrangement of the lower limb) required to enable the change of direction. The mean mediolateral COP position for the right step on the bend was more medial than the straight, thus transverse axis was in use. This reinforces the notion that the right step and left steps perform different functions during bend sprinting. Furthermore, results suggest there may be a decrease in MTP joint angular velocity during the left step on the bend compared to the straight. Krell, Stefanyshyn [11] established that faster male sprinters elicited higher maximal rates of MTP extension. Therefore, decreased MTP joint angular velocity might contribute to the decrease in sprint performance found on the bend. Further research is required to strengthen this conclusion.

Bend sprinting also induced kinematic adaptations in the multi-segment foot. In particular, there was an increased left step peak midfoot eversion combined with increased left step peak internal ankle rotation on the bend compared to the straight. Although there was no significant main effect, a large effect size suggests a trend towards an increase in left step peak ankle eversion angle (g = 0.88). Eversion occurs during the first 15% of stance due to the eccentric contraction of invertors such as tibialis posterior and anterior[13]. As bi-planar muscles, whilst they are predominantly invertors they also have a role to play in plantarflexion of the foot and ankle[31]. Simulations[32] and later experimental data[33] suggested kinetics of the ankle joint play a dominant role in the acceleration of the centre of mass during the stance phases of early acceleration in straight-line sprinting. Therefore, as previously supposed by Chang, Kram [34], a joints capacity to contribute to the production of propulsive forces in the sagittal plane may be restricted by the frontal and transverse plane adaptations reported. It appears the increased left step eversion and ankle internal rotation place the foot in a disadvantageous position, compromising the ability to produce propulsive force.

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

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

Perspectives

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

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

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

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

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

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

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

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

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

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

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

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