FORCE PRODUCTION DURING MAXIMAL EFFORT SPRINTING ON THE BEND

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The force requirements of bend sprinting are not well understood. This study determined the forces produced and performance characteristics of seven male athletes during maximal effort sprinting on the bend and straight. There were asymmetrical changes in force production. Resultant force was reduced on the bend compared to the straight for the left step, but remained similar for the right step. Additionally, more mediolateral force was produced by the left step than the right step on the bend. Overall, we speculate that strength training should aim to meet the demands of bend running, although care should be taken to avoid introducing undesirable asymmetries into straight line sprinting.

KEY WORDS: mediolateral force, ground reaction force, impulse, athletics, 200 m.

INTRODUCTION: Maximal effort sprint performance is reduced on the bend compared to the straight (Churchill, Salo, & Trewartha, 2011). It has been suggested that this is due to changes in force production on the bend (Usherwood & Wilson, 2006; Chang & Kram, 2007). Athletes running the bend must generate sufficient centripetal force in order to follow the curved path and remain within their lane. This places additional force demands on the athlete, compared with straight line sprinting. There is, however, a paucity of literature concerning the forces produced during bend sprinting. Studies of force production on the bend have taken either a mathematical modelling approach (Usherwood & Wilson, 2006), have used very small bend radii (1-6 m; Chang & Kram, 2007) or investigated slower running (approx. 6.31 m/s; Hamill, Murphy & Sussman, 1987). Thus, our aim was to understand the changes that occur to force production and performance during maximal effort sprinting on the bend (radius ~38 m) compared to the straight.

METHODS: Data were collected at an indoor athletics arena (NIAC, Cardiff). Seven male sprinters (22.6 ±4.2 y, 70.7 ±9.2 kg, 1.76 ±0.06 m; 200 m personal best times ranging from 20.89 s to 22.90 s) gave written informed consent to participate in the study.
Data were collected using two force plates (1000 Hz; 9287BA, Kistler Instruments Ltd, Switzerland) embedded in the track and two video cameras (200 Hz, 1/600 s shutter speed; HVR-Z5E, Sony Corporation, Japan). The camera's fields of view covered a distance 6.60 m long in order that a whole step starting from touchdown on the force plate could be recorded. Camera A was positioned 30.00 m away from the inside edge of the lane (towards the curve centre). Camera B was positioned 'ahead' 32.00 m away from the centre of the force plates and 1.50 m to the side. An 18 point 3-D calibration volume (6.00 m long, 1.61 m wide and 2.02 m high) was used with the global coordinate system (GCS) aligned with the force plates. Athletes warmed up before undertaking 60 m maximal effort sprints. Successful left and right steps were obtained on the bend, in a marked-out lane replicating lane 2 (radius: 37.72 m) of a standard outdoor track (i.e. running anticlockwise), before a left and right step were obtained on the straight. From the maximum of six trials completed, all athletes managed to produce one successful foot strike in all four required conditions. The start position was adjusted to facilitate successful force plate strikes and all athletes had at least 40 m run-up before the videotaping area. Recovery time between trials was approximately eight minutes.
Video streams were synchronised using 1 ms interval LED displays visible in the fields of view. Upon triggering of the LEDs, a simultaneous analogue signal was recorded with the force data, on a spare channel, allowing synchronisation between the force and video data.
A 20-point, 16-segment, human model was manually digitised by estimating joint centres in both camera views using Vicon Motus software (Version 9.2, Vicon, Oxford, UK). A 3D-DLT allowed reconstruction of 3D coordinates which, along with force data, were subsequently

filtered with a low pass, 2nd order, recursive Butterworth filter (coordinates: 20 Hz cut-off, force: 150 Hz cut-off). Inertia data was adjusted from de Leva (1996), in order to include a two segment foot and to add 0.2 kg to each foot to account for the mass of the shoe.

Foot contact events of touchdown (TD) and take off (TO) were defined from vertical force data. Touchdowns (first and second) were also determined from the peak vertical acceleration of the touchdown MTP point for the purpose of calculating step time.

Performance descriptors were calculated, for left and right steps, under both bend and straight conditions. A step was defined as TD of one foot to contralateral limb TD e.g. left step was from left TD to right TD. The exact details of how these performance descriptors were defined and calculated are available in Churchill et al. (2011). An additional performance descriptor, *Turn of the CoM*, was calculated, for bend trials only, as the change in direction of travel of the CoM from the flight phases before and after contact.

The horizontal forces in the GCS were rotated relative to the direction of travel of the athlete for the bend trials. For straight trials force data was aligned with the GCS. The following force variables were then calculated, using the rotated or non-rotated forces as appropriate: *Peak braking force:* the largest negative force in the anteroposterior (AP) direction; *Peak propulsive force:* the largest positive force in the AP direction; *Peak medial force:* the largest force acting towards the midline of the body (straight trials only); *Peak lateral force:* the largest force acting away from the midline of the body (straight trials only); *Peak inward force:* the peak mediolateral (ML) force acting towards the inside of the bend (bend trials only); *Peak and average vertical force:* the maximum and mean force in the vertical direction; *Peak and average resultant force:* the maximum and mean of the resultant of the three components of the force; *Braking impulse:* the sum of negative AP impulse during contact; *Propulsive impulse:* the sum of positive AP impulse during contact; *Vertical impulse:* the vertical impulse minus the impulse due to body weight; *Net inward impulse:* the sum of ML impulses (bend trials only); *Duration of braking:* the duration for which there was a negative AP impulse; *Duration of propulsion:* the duration for which there was a positive AP impulse.

Paired sampled t-tests (IBM SPSS Statistics, v19.0, SPSS Inc., USA) identified significant differences between left and right for variables within a condition, and between the straight and bend for the left and right steps, separately. Significance was set at $p < 0.05$. Effect sizes were calculated using Cohen's d (Cohen, 1988). Relative magnitude of the effect was assessed based on Cohen's guidelines (small: $d \leq 0.20$; moderate: $d = 0.20-0.80$; large: $d \geq 0.80$).

RESULTS AND DISCUSSION: There was a significant 2.3% decrease in mean race velocity during both the left and right steps on the bend compared to the straight (Table 4). Left step race velocity reduced due to a small decrease in mean race SL and mean SF, on the bend compared to the straight (Table 4). Whilst these differences did not reach statistical significance, the effect size for race step length was moderate ($d = 0.67$). Right step race velocity decreased due to a significant 0.10 m reduction in race SL, which was contributed to by a significant decrease in flight time on the bend vs. the straight ($p < 0.05$; Table 4).

Usherwood and Wilson (2006) suggested that velocity on the bend decreases because swing time remains constant but ground contact time increases to meet the centripetal force requirements required to follow the curved path, thus SF decreases. The present study partially supports this theory in that there was indeed a significant 0.010 s increase in left ground contact time on the bend compared to the straight (Table 4). Left step peak vertical force reduced on the bend compared to the straight but vertical impulse was similar in both conditions (Table 5). Therefore, left ground contact time may have increased to maintain sufficient vertical impulse generation as well as to meet the centripetal demands of the bend. However, body sagittal lean ROM increased significantly ($p < 0.05$) and the increase of touchdown distance was not significant but the effect size was moderate ($d = 0.71$) and both of these variables may also have contributed to increased ground contact times (Table 1).

Ground contact time did not increase for the right step on the bend. Instead, there was a significant 0.012 s decrease in mean flight time which had the effect of significantly reducing right race SL (Table 4). The model of Usherwood and Wilson (2006) may partly explain changes to the left step, but it does not explain the changes, such as reduced flight time and SL, observed during the right step on the bend.

Table 4: Performance descriptor results (mean ±SD) for all four conditions.

	Straight		Bend	
	Left	Right	Left	Right
Race velocity (m/s)	9.56 ±0.46	9.51 ±0.47	9.34 ±0.43*	9.29 ±0.47$^{\&}$
Race SL (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$^{\&}$
Step contact factor	0.482 ±0.054	0.474 ±0.046	0.498 ±0.031	0.493 ±0.043
Touchdown distance (m)	0.37 ±0.07	0.37 ±0.06	0.41 ±0.05	0.33 ±0.05$^{\#}$
Sagittal lean ROM (°)	53.1 ±4.2	52.8 ±4.9	57.9 ±3.3*	52.0 ±3.7$^{\#}$
Lateral lean at TD (°)[1]	3.3 ±1.8	-2.6 ±0.8	-9.1 ±1.3*	-14.2 ±2.2$^{\&\,\#}$
Lateral lean at TO (°)[1]	3.6 ±2.3	-2.9 ±1.1	-7.8 ±1.1*	-13.2 ±2.0$^{\&\,\#}$
Turn of CoM (°)			4.2 ±0.9	2.6 ±0.7 $^{\#}$

Symbols: * significantly different to left on straight, $^{\&}$ significantly different to right on straight, $^{\#}$ significantly different to left on bend (p <0.05)
[1] Absolute values used for left vs right comparison by t-test on straight

On average 1.6° more turning of the CoM was achieved during the left ground contact than during the right ground contact (Table 4; p <0.05). This was due to a 15.2 Ns greater mean inward impulse being generated during the left ground contact compared to the right, on the bend (Table 5). This suggests that there are functional differences between the left and right steps in terms of force generation during bend running, with the left step contributing more to turning than the right step. As well as greater inward impulse, greater peak inward force was observed during the left step than the right step (Table 5). This contradicts the results of the study by Chang and Kram (2007) who found the outer (right) leg generated greater peak inward forces during maximal effort sprinting on radii of up to 6 m, although they did not report impulse. It is possible that at very tight radii, participants in that study performed an action more like cutting than the turning achieved during sprinting on bend radii typical of an outdoor running track (~38 m).

Mean peak inward forces, measured on the bend, were substantially larger than peak mediolateral forces on the straight (0.41 BW) with magnitudes of 1.07 BW and 0.86 BW observed for the left and right steps, respectively (Table 5). These values were also larger than the mean peak propulsive forces observed. These relatively large forces should not be overlooked. It has already 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). The present study supports this, showing the magnitude of the inward force to be substantial.

Chang and Kram (2007) suggested that athletes on the bend were not able to generate resultant forces as large as they could on the straight, although that study was conducted on bends of very small radii. The results of the present study appear to support this for the left step, where a statistically significant reduction in peak resultant force was seen on the bend compared to the straight (p <0.05; Table 5). The results for the right step, however, were more equivocal. Table 5 shows an increase in peak resultant force from 3.66 ±0.29 BW on the straight to 4.19 ±1.29 BW on the bend for the right step. The increase was, however, influenced by an exceptionally large peak resultant force produced by one athlete, of more than seven times body weight. When that athlete's results were removed, the mean peak resultant force for the right step was 3.58 ±0.23 BW on the straight and 3.72 ±0.37 BW on the bend. When tested with a paired samples t-test with the reduced n, the difference between the straight and bend was not significant (p=0.440).

It is possible that changes in frontal plane kinematics and the requirement to generate centripetal force on the bend results in a reduction in vertical force production, whilst facilitating inward force production during the left step. During the right step on the bend, propulsive and vertical force generation do not appear to be substantially compromised, and may even elicit larger force production than that seen on the straight in some athletes. However, in general shorter flight times limited right step length and led to a reduced velocity.

Table 5. Force variable results (mean values ±SD) for all four conditions.

	Straight		Bend	
	Left	Right	Left	Right
Peak braking force (BW)	-1.43 ±0.39	-1.31 ±0.26	-1.41 ±0.34	-1.31 ±0.22
Braking impulse (Ns)	-14.0 ±3.7	-13.2 ±3.8	-16.6 ±3.5*	-12.4 ±2.8#
Duration of braking (s)	0.046 ±0.006	0.044 ±0.007	0.052 ±0.004*	0.040 ±0.004#
Peak propulsive force (BW)	0.81 ±0.09	0.73 ±0.07*	0.76 ±0.09	0.77 ±0.07
Propulsive impulse (Ns)	18.3 ±3.7	16.8 ±3.7	19.1 ±2.8	18.7 ±3.9&
Duration of propulsion (s)	0.061 ±0.004	0.064 ±0.006	0.064 ±0.003*	0.064 ±0.005
Peak medial force (BW)	0.41 ±0.11	0.41 ±0.11		
Peak lateral force (BW)	0.22 ±0.14	0.25 ±0.06		
Peak inward force (BW)			1.07 ±0.22	0.86 ±0.25#
Net inward impulse (Ns)			39.9 ±6.5	24.7 ±5.8#
Peak vertical force (BW)	3.80 ±0.52	3.64 ±0.29	3.43 ±0.41*	4.13 ±1.27
Average 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
Peak resultant force (BW)	3.82 ±0.53	3.66 ±0.29	3.61 ±0.45*	4.19 ±1.29
Average resultant force (BW)	2.23 ±0.26	2.14 ±0.15	2.18 ±0.21	2.22 ±0.20

Symbols: * significantly different to left on straight, & significantly different to right on straight, # significantly different to left on bend (p <0.05)

CONCLUSION: There was an asymmetrical effect of the bend on force production during maximal effort sprinting. Left step resultant force production was reduced on the bend, in comparison to the straight. Left step ground contact time increased, probably to allow vertical impulse generation, which is in line with the model of Usherwood and Wilson (2006). Right step vertical force generation did not appear to be substantially compromised, but a reduction in flight time had a detrimental effect on SL. The left step produced more inward force and thus turning than the right step on the bend. Inward lean during bend sprinting is inevitable and probably contributes to athletes being able to produce sufficient inward force to turn effectively and follow the curved path. The effect of the bend on propulsive and vertical force production, as well as the substantial inward forces experienced, should, however, be an area for consideration amongst athletes and coaches. Athletes need to be able to generate large vertical and propulsive forces whilst leaning and stabilising in the frontal plane, and strength and sprint training should reflect this. 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 that might be detrimental to the straight line portion of the race.

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