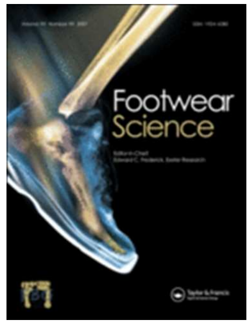

The influence of sprint spike bending stiffness on sprinting performance and metatarsophalangeal joint function

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1. Background

The metatarsophalangeal joint (MTPJ) has been highlighted by several authors to have an important role in the energetics of the lower limb during sprint running (Bezodis, Salo & Trewartha, 2012; Smith, Lake, Lees, & Worsfold, 2012; Stefanyshyn & Nigg, 1997). In fact, this joint appears to be a net dissipater of energy during stance. It has been speculated by several authors that altering the mechanical properties of running footwear, in particular the longitudinal bending stiffness, is one mechanism by which the kinetics of the MTPJ may be altered (Smith, Lake, & Lees, 2014; Stefanyshyn & Fusco, 2004; Toon, Hopkinson & Kane, 2008) potentially leading towards slightly improved sprint performance. In vertical jumping, stiffer running shoes have been shown to significantly reduce MTPJ energy loss and consequently improve jump height (Stefanyshyn & Nigg, 2000). Similarly in running at 3.5m/s, an increase in the midsole longitudinal bending stiffness both significantly reduced the energy loss and at the same time increased positive work performed (Willwacher, Konig, Potthast, & Bruggemann, 2013).

For maximal sprint running, the effect of sprinting footwear bending stiffness on sprinting performance remains to be fully agreed between researchers, as there is some conflicting evidence in the literature regarding the benefit of wearing stiffer sprint shoes. Stefanyshyn and Fusco (2004) reported a decrease of 0.02s in 20-40 m sprint time for a group of 34 elite national sprinters when stiff carbon insoles were inserted into their running spikes (42 $N{\cdot}mm^{-1}$ bending stiffness, measured using a three-point bending test). Conversely, Ding, Sterzing, Qin, and Cheung (2011) found no systematic influence of sprint spike stiffness upon 25 m acceleration performance for a group of young competitive athletes. When comparing barefoot sprinting to sprinting in sprint spikes, Smith et al. (2014) reported substantial changes in MTPJ function and potential improvements in performance-related parameters due to wearing spikes. Sprint spikes appeared to have a clear localised effect on the function of the MTPJ; increasing the work performed by lengthening the moment arm and likely contributing to the energy produced during push-off. Stefanyshyn and Fusco (2004) speculated that increasing the shoe bending stiffness would result in an anterior shift in the point of application of the ground reaction force, thereby increasing the moment arm. This would result in an increased MTPJ joint moment and energy production during late stance, therefore enabling a more effective push-off. Willwacher et al. (2013) also observed that increasing the midsole longitudinal bending stiffness seems to alter mechanical power generation capacities of the MTPJ plantar flexing muscle tendon units by changing ground reaction force leverage and decreasing plantar flexion angular velocity. Increasing the longitudinal bending stiffness altered the lever arms at the MTPJ and ankle joint, changing the gear ratio; the ratio of external GRF lever arm and internal lever arms of muscle tendon units acting at a joint, and therefore potentially permitting the muscle tendon units to generate higher joint moments (Willwacher at al., 2014). However, those authors pointed out that any energy return at the metatarsophalangeal joint would require both the elastic midsole and the toes to simultaneously perform a pronounced plantar flexion movement at the end of stance, therefore energy would need to be transferred to the sprinter at the right place and the right time.

In elite sprinters, reported variation in lower limb joint kinetics within groups of sprinters (Johnson & Buckley, 2001; Bezodis, Kerwin & Salo, 2008) suggests between-sprinter differences do exist. This variation in technique is important to consider in the context of elite sprinting, as even slight improvements in performance could affect finishing position within a sprint race (Bezodis, Salo, & Trewartha, 2014). Similarly, individual athletes may elicit different biomechanical and performance responses to changes in footwear, suggesting that shoe selection is specific to the functional requirements of individuals (Toon, Williams, Hopkinson & Kane, 2009) and might (among others) depend upon their ankle plantarflexor strength, force-length and force-velocity characteristics (Stefanyshyn & Fusco, 2004). Differences in responses to running shoes of varying stiffness coincide with runner's preferences and subjective perception (Kleindenst, Michel, & Krabbe 2005). It has been suggested that the only way to detect differences that exist between shoes is to employ a single-subject analysis (Bates, 1996). Furthermore, individual analysis has been advocated for future research to detecting differences between types of running shoes, based upon high variability of ground reaction forces reported in male and female groups of runners (Logan et al., 2010). Single subject analyses have been advocated in the research when a task could potentially elicit different responses / strategies in individuals and when the group mean does not necessarily describe well any individual subject response (Revill, Perry, Edwards, & Dickey, 2008).

Therefore the aim of this study was to first investigate the effect of sprint spike bending stiffness on sprinting performance and MTPJ motion in a group of sprinters. This experimental design was supplemented by a second investigation using the same footwear modifications during sprinting but utilising a single subject design and improved biomechanical data collection and analysis (Smith et al., 2012). It was hypothesised that group findings may mask some significant individual changes in foot function and sprint performance with sprint shoe stiffness.

2. Methods

This research comprised of two studies, a group study, followed by an individual case-study.

Experimental footwear

Commercially available sprint spikes (Puma Complete Theseus II) in two sizes (38.5 and 43 EUR) were provided by Puma SE, Germany and custom made insoles of varying longitudinal bending stiffnesses, made combining different layers of carbon and glass fibre, were inserted into the identical shoes. Additionally, Asics Hyper Sprint shoes of same sizes were used, serving as additional controls (A-control). The bending stiffness of the five sprint spike conditions of each size were measured mechanically: A-control and four Puma test conditions; P-control (no insole), P-low, P-medium, P-high (added stiffnesses with insoles). A two point bending test was used (Krumm, Schwanitz & Oldenwald, 2012; Smith et al., 2014) with 40 mm of bending at a constant velocity of 10 mm/s. A Servo hydraulic material testing machine was used (Zwick GmbH & Co. KG, Ulm, Germany, stroke 100 mm, load max. 10 kN) with a LVDT position sensor and a 10 kN load cell (Huppert GmbH Prüf- und Messtechnik, Herrenberg, Germany) with the sprint spikes placed in a mould and secured with a metal clamp on the forefoot. The average stiffness for a deformation of 0-40 mm dorsiflexion at the natural bending line was measured for three trials and then averaged per left and right shoe (Table 1).

Group Study

Twelve competitive athletes (club / regional level) participated in the group study; six male (mean age 22.0 ± 3.6 years, mean height 182.7 ± 4.5 cm, mean mass 73.8 kg ± 4.4 kg, mean 100 m personal best 11.3 ± 0.3 s). and six female (mean age 21.8 ± 4.8 years, mean height 167.0 ± 6.2 cm, mean mass 60.2 ± 4.2 kg, mean 100 m personal best 12.4 ± 0.3 s). Informed written consent was obtained in accordance with the Ethics Committee of Technische Universität Chemnitz. All participants fitted shoe size 43 or 38.5.

After their own warm up and two practice runs at 80% and 100% of their maximum velocity, sprinters performed eight maximal 40 m sprints from a standing start, along an indoor 100 m athletics track at Technische Universität Chemnitz. This consisted of two sprint trials in each Puma footwear condition (P-control, P-low, P-medium, and P-high) and athletes were asked to sprint maximally. The order of sprint spikes was randomised and counter-balanced and participants were blind to the footwear condition. Eight minutes rest between each maximal sprint was given, based upon pilot work examining fatigue over multiple sprint trials (Figure 1). 10 m split time was taken from 30 - 40 m using single beam timing cells. A high speed video camera (Exilim Pro Ex-F1, 600 Hz sample rate, 1/1000 s shutter speed) captured one foot contact 15 m into the sprint (acceleration phase). High speed videos were analysed in Quintic Biomechanics (Quintic Consultancy Ltd.) where the following points were manually digitised: the heel; the distal end of the hallux and the medial side of the first metatarsal head (MTH1). For two-dimensional analysis, a marker on MTH1 or MTH2 provides a better representation of MTPJ motion than a marker on MTH5 (see Smith et al., 2012). The MTPJ angle was therefore defined as the angle between the forefoot (MTH1 – hallux) and rearfoot (MTH1 - heel) segments. The raw kinematic data was smoothed using a 4th order Butterworth low pass digital filter with cut off frequencies of 60 Hz for the MTPJ angle and 30 Hz for the angular velocity.

Statistical analysis

A one-way repeated measures ANOVA was conducted to evaluate the intervention of sprint spikes stiffness (mean of two trials per condition) on sprint time, MTPJ range of motion, MTPJ maximum flexion and MTPJ peak angular velocities, both plantarflexion and dorsiflexion.

Individual case study

This aspect of the research work utilised a novel experimental design that aimed to tease out the likely small differences in sprint performance and lower limb function when sprinting in shoes of different stiffness. This part of the research work represents both an evolution to the study design and improvements to the biomechanical measurements taken, to gain further insight into individual responses in sprinting performance and MTPJ function to modified bending stiffness of sprint spikes. This study took place at a different testing location to enable the Biomechanical analysis.

Two additional trained, competitive sprinters took part in the individual study; one female 100 m sprinter / hurdler (aged 28 years, height 179cm, mass 68 kg, shoe size 38.5, 100 m sprint time 12.2 s) and one male 400 m specialist (aged 28 years, height 182cm, mass 73 kg, shoe size 43, 400 m best time 50.8 s). These two participants were chosen for the individual study as they were also experienced, well-trained track athletes, whose mean sprinting velocities at 35 m reflected the mean 30 - 40 m sprinting velocities of the group study (within one standard deviation). Informed written consent was obtained in accordance with the Ethics Committee of Liverpool John Moores University.

Each sprinter attended the lab three times, each time to test a different sprint spike stiffness (P-low, P-medium or P-high) condition in relation to A-control, therefore three stiffness conditions were tested in relation to control (Figure 1). The design included a balanced, presentation of the control shoe condition (A control) and a test shoe condition (P-low, P-medium or P-high) which minimises the error sources associated with presenting different test stimuli which are separated by a period of time (Gescheider, 1997). In each testing session, six sprinting trials per shoe were recorded, with the sprinter swapping shoes between each trial, e.g. A-control followed by P-low, repeated six times. Therefore, a total of twelve maximal sprints were collected per testing sessions, this number was based upon pilot testing of the number of sprints practically possible. The sprints were performed on a 70 m indoor sprint track at Liverpool John Moores University and the athletes accelerated for approximately 35 m before data collection. Athletes were instructed to sprint maximally to 40 m. A single left foot ground contact in the middle of a force platform (Kistler model 9287B, sampling at 1000 Hz) at approximately 35 m was used for analysis. A customized starting mark was used to aid the athlete in striking the force plate without the need to alter their stride pattern prior to force plate contact. Single beam timing cells were located 2.5 m either side of the force platform, therefore recording sprint times over 5 m as the athletes crossed the force platform. The athletes were still accelerating at this point.

Both participants underwent two DEXA scans to optimise the location of markers on the metatarsal heads (Smith et al., 2014). Kinematic data were collected using a 6 camera system (Pro-Reflex MCU 1000, Qualisys Inc., Sweden) sampling at 1000 Hz. Data were processed using Visual3D (C-Motion, Inc.) and a three-segment foot model was used for the kinematic analysis and kinetic analysis as detailed in Smith et al. (2012). In brief, the five MTPJ's were considered as a single joint rotating about an axis oblique to the sagittal plane defined by markers (11 mm diameter) on MTH1 and 5. Holes were cut out in the spikes for markers to be located on MTH1, MTH5 and MTH2. MTH2 was a virtual marker identified using a 3D pointer device (C-motion Inc., Canada). When the sprint spikes were swapped, a new standing calibration and pointer trial was performed. Joint positional and force data were smoothed using a fourth-order low pass Butterworth filter with a cut-off frequency (F_c) of 100 Hz. This was necessary to preserve the high frequency aspects of the signal previously identified and important for determining the presence of any positive joint power during the push-off phase (Smith et al. 2012). Force platform point of force application (PFA) measurements were determined above a vertical force threshold of 100 N for initial landing and 50 N at the end of ground contact, based upon visual inspection of PFA curves, as errors were greater at the start of foot contact where higher loading rates were experienced. Below these thresholds the PFA was distorted and in a position outside of the forefoot, due to low loading on the force platform. MTPJ joint moments and powers were calculated when the centre of pressure moved distally to its oblique axis during sprinting ground contact.

Statistical analysis

For each sprinter's within-subject statistical analysis, the Model Statistic was used. This approach was chosen to replicate previous single-subject studies assessing performance of sports shoes (Dufek & Bates, 1991). The Model Statistic is the single-subject equivalent of an independent t-test (Bates, James, & Dufek 2004) as using a repeated-measures approach in a single subject design is inappropriate, therefore the more appropriate approach is to treat trial values as independent measures and use the corresponding independent test procedure (Bates, 1996). The mean absolute differences between two conditions (for example MTPJ Moment in a stiff shoe minus MTPJ moment in the control condition) is calculated and compared to a critical difference. The critical difference is the product of the standard deviation (of all trials in each footwear condition) and a critical value based upon sample (trial) size from Bates et al., (2004). The critical value used in this study was 1.2408 for six trial comparisons (twelve trials in total) and $\alpha = 0.05$ level of significance. The interpretation of a mean absolute difference greater than the critical difference is that the difference is due to sampling error at a probability of α, therefore the null hypothesis is rejected. The single-subject, repeated trials design also accounts for any learning or fatigue during the testing session, as every trial in a stiffness condition is compared to the control (Figure 1).

3. Results

Group study

Thus, bending stiffness values of the sprint spikes used in this study indicate that, by adding the insoles, bending stiffness was increased considerably in comparison to the commercial sprint spike conditions used, P-high had almost three times greater stiffness (273%) than the A-control shoe (Table 1). Furthermore, four additional commercially available sprint spikes were mechanically tested and had average stiffnesses ranging from 190 ± 5.3 N/m to 256± 23.7 N/m.

Average 30 m to 40 m sprint time for all trials was 1.18 s (± 0.08 s), corresponding to a mean velocity of 8.50 m/s (± 0.57 m/s). There were no significant differences ($p < 0.05$) in mean sprinting velocity across the shoe stiffness conditions (Figure 2) ($p = 0.634$, $F = 0.427$).

Individual differences existed between sprinters with some sprinters appearing to perform slightly better in P-control and others possibly performing slightly better with stiff insoles (Figure 3). Observations of individual performance differences between shoe stiffness conditions did not appear to be related to overall sprinting ability. Both faster and slower sprinters demonstrated either increasing or decreasing sprint performances with increasing shoe bending stiffness (Figure 3).

There were no significant differences in the metatarsophalangeal range of motion during stance with mean values of 40.5 ° (± 3.0 °), 38.1 ° (± 4.5 °), 38.3 ° (± 2.8 °) and 37.5 ° (± 4.7 °) for P-control, P-low, P-medium and P-high respectively ($p = 0.277$, $F = 1.510$). Nor were there any statistically significant differences in maximum dorsiflexion ($p = 0.600$ $F = 0.654$) or plantarflexion ($p = 0.819$, $F = 0.109$) angular velocities across the four conditions.

Individual case study

The female participant achieved highest mean sprinting velocities in the P-medium and P-high, however the only significant difference, to A-control, was found for P-high, which resulted in a 2% increase in measured velocity (Table 3). The male participant achieved highest mean sprinting velocities in P-medium shoe, however there were no significant differences in velocities between any of the P stiffness conditions and A-control (Table 2). Tables 2 and 3 show individualised differences in MTPJ kinematics and kinetics between the conditions.

The female participant exhibited significantly higher resultant MTPJ moments in all three P stiffness conditions, in comparison to A-control (Table 3). In P-high the joint moment was increased by approximately 8.9 N·m (a 15 % increase). P-low and P-high significantly increased power production during the push-off phase of sprinting, although there were no favourable reductions in energy loss with the stiffened shoe conditions. Similarly, the male participant demonstrated significant differences in work performed at the MTPJ with significantly higher joint moments in all P stiffness conditions, in comparison to A-control, with P-high condition resulting in the highest joint moment (Figure 4). The MTPJ was a net absorber of energy during stance with up to 42.0 J lost during the energy absorption phase in the A-control (Table 2). All three P shoe conditions significantly reduced the amount of energy lost, compared to A-control. The largest reduction was in P-medium with 8.2 J (23%) difference in energy loss compared to A-control. A significantly increased positive energy was created during the push-off phase at the end of stance in P-low, producing 3.3 J energy, compared to 2.2 J energy in the A-control.

4. Discussion and Conclusion

This study found that increased sprint shoe bending stiffness was generally not linked with improved sprinting performance for a group of trained sprinters. The small improvement in performance reported by Stefanyshyn and Fusco (2004) may be due to a larger number of subjects used (34 sprinters) and a more homogeneous group of older elite athletes. However, the authors argued that performance enhancements of 0.7% are quite large, and therefore worthwhile, in elite sprinting, possibly making a difference in finishing position in a race. The lack of group mean shoe differences seen in the group study may be the result of high variability in individual results. The number of subjects (n = 12) and trials used in this study was not dissimilar to, or greater than previous biomechanical studies using trained sprinters (Bezodis et al., 2008; Ding et al., 2011; Gittoes & Wilson, 2010; Johnson & Buckley, 2001; Stefanyshyn & Nigg, 1997), although it is acknowledged that the sprinters in this study were younger and not world-class. The results from this study do, however, agree with the suggestion that the stiffness each athlete requires to produce maximal performance is subject-specific (Stefanyshyn & Fusco, 2004). Therefore, it is suggested that an athlete's optimal sprint shoe stiffness is individualised and likely dependent upon their perceptions and previous experiences (Kleindenst, Michel & Krabbe, 2005) forefoot structure or stiffness (Oleson, Adler & Goldsmith, 2005), and arch stiffness (Butler, Davis & Hamill, 2006).

In the individual case studies, the female participant demonstrated significantly improved sprinting performance in P-high stiffness condition, whilst improvements in sprinting speed for the male participant were not significant. For both participants, stiffer sprint spikes did appear to have a controlling effect over the MTPJ kinematics, significantly reducing the range of motion and also reducing the extent and rate of MTPJ dorsiflexion during stance and plantarflexion after push-off. This reaffirms, on an individual level, the restrictive influence that stiffened footwear seems to have on the normal bending of the MTPJ during stance, possibly influencing the effectiveness of the Windlass mechanism (Hicks, 1954), although this would likely be dependent upon the individual's foot dynamic stiffness. However, the controlling effect over the behaviour of the foot, does not appear to adversely affect energy production of the joint (Smith et al., 2014) and both athletes were able to produce energy within the foot/shoe complex during the push-off phase of sprinting. This is in agreement with Lin et al., (2013) who demonstrated that for walking, carbon fibre insoles effectively reduced the windlass effect, but also facilitated storage of energy that can be used for efficient gait propulsion without needing to dorsiflex the MTPJ to a great extent.

The results of this study suggest that stiffer sprint spikes may increase the loading applied on the central forefoot and may also facilitate greater anterior progression of the centre of pressure, as evidenced by a greater moment arm, to enable increased propulsion during push off. Values for MTPJ moments and a substantial net loss of energy at this joint are similar to those reported in other studies for sprinting (Smith et al., 2014; Stefanyshyn & Nigg, 1997; Toon et al., 2009). It is clear that the longitudinal stiffness of sprint spikes have a clear localised effect on the MPTJ, increasing the work performed on the joint, lengthening the moment arm and producing small amounts of energy during push-off, in agreement with Smith et al., 2014. However, it is also likely that the range of motion, joint moment and resultant power at the ankle joint will also be altered by forefoot bending stiffness (Chen et al. 2014). Wilwacher et al., (2014) demonstrated increasing the longitudinal bending stiffness in running shoes led to a significant anterior shift of all lower limb lever arms, this effect greater at the more distal joints In particular, higher ankle joint moments might be beneficial for increasing storage and return of energy in the Achilles Tendon, particularly in elite sprinters who are likely to have higher strength potential of the plantar flexor muscle tendon units.

It is impossible to compare the bending stiffness to other studies, due to different methods of quantifying longitudinal bending stiffness, plus the unknown stiffness of sprinters' own sprinting shoes. However, in this current study, the mechanical stiffness of the whole sprint spike system was determined mechanically and every stiffness condition was quantified and compared to a range of commercially available sprint spikes. It is also acknowledged that the testing protocol was modified from the group study to the individual case-study. However, this was done so in order to improve both the study design (number of testing session trials and conditions), and biomechanical measurements (MTPJ kinetics) possible for exploring individual responses to sprint spike stiffness in greater detail.

The high bending stiffness of the sprint spikes may allow the athletes to push off but still achieve substantial rigidity from the foot and shoe as a system. This concurs with the findings of Willwacher et al. (2013) for lower-velocity running; an increase in shoe stiffness around the MTPJ provides better working conditions for plantarflexing muscle tendon units, increasing the push-off duration. Participant one exhibited higher ranges of motion than participant two, indicating differences between the participants in their natural range of motion and flexibility within the foot and differing inherent foot stiffness or foot structures (e.g. high / low arch, plantar fascia stiffness). This is concurrent with the wide range of arch stiffness reported in high arch (1993.8 ± 1112.1 kg/arch height index) and low arch (788.0 ± 407.0 kg/arch height index) runners (Butler et al., 2006) Participant two experienced larger reductions in angular motion and peak angular velocities with the stiffer sprint spikes, suggesting greater responses to shoe stiffness. Both participants demonstrated increased joint moments with increased stiffness of sprint spike. Energy production during the last 10 milliseconds of stance was also increased by a stiffer sprint shoe.

The two participants in this study exhibited different responses to the footwear conditions, this may be due to anatomical differences and neurological responses (performance strategies). The participant's response has been suggested to depend on their recognition / perception of the perturbation, which in turn will be a function of the individual's past experiences (Bates, 1996). Response patterns vary along a continuum (from a Newtonian response whereby the perturbation is completely ignored to a fully accommodating response). Individual performance strategies are likely to be the norm rather than the exception, due to the complexity of the human machine and its numerous associated functional degrees, along with the different experiences, perceptions and expectations of the participants (Bates, 1996).

The individual responses exhibited in this study suggest that sprinting performance may be improved by implementation of relevant shoe mechanical characteristics. It appears that shoe selection may be specific to the functional requirements of individual athletes and athletes will likely respond differently to footwear modifications. Future work should identify key anatomical or biomechanical factors that influence foot function during maximal sprinting. For example, the influence of the natural stiffness of the human forefoot, and the strength and velocity characteristics of the ankle plantarflexors and toe flexors, are morphological factors which may influence foot function during sprinting and may dictate appropriate shoe selection. Besides changes to the overall longitudinal bending stiffness, other mechanical characteristics of sprint spike design, such as the toe spring angle warrant future investigation. The importance of appropriately modelling the position and orientation of the MTPJ has been previously established (Smith et al., 2012), therefore the location of the natural bending line of the sprint spikes in relation to the anatomical joint axis will likely affect the resultant motion at the foot.

Overall, the findings suggest that high variability in individual responses to sprint shoe bending stiffness manipulations can be masked by group mean findings and a single-subject approach appears warranted to further investigate whether shoe bending stiffness can be optimised to improve individual sprint performance.

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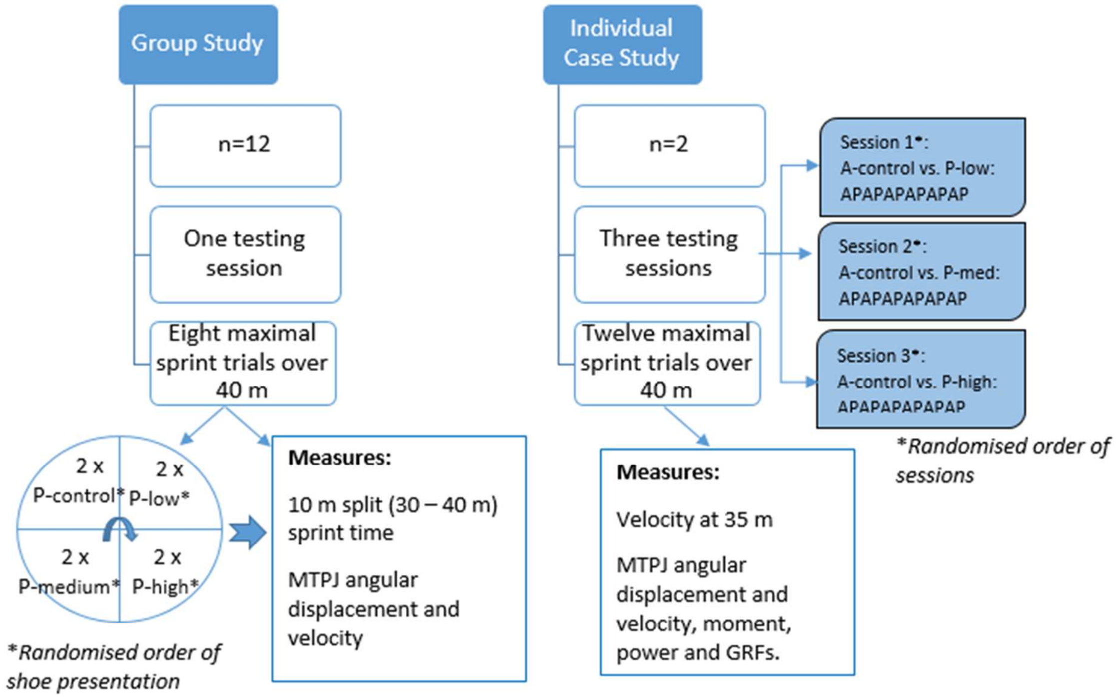

Figure 1. Schematic demonstrating study design and protocol for the Group Study and Individual Case Study

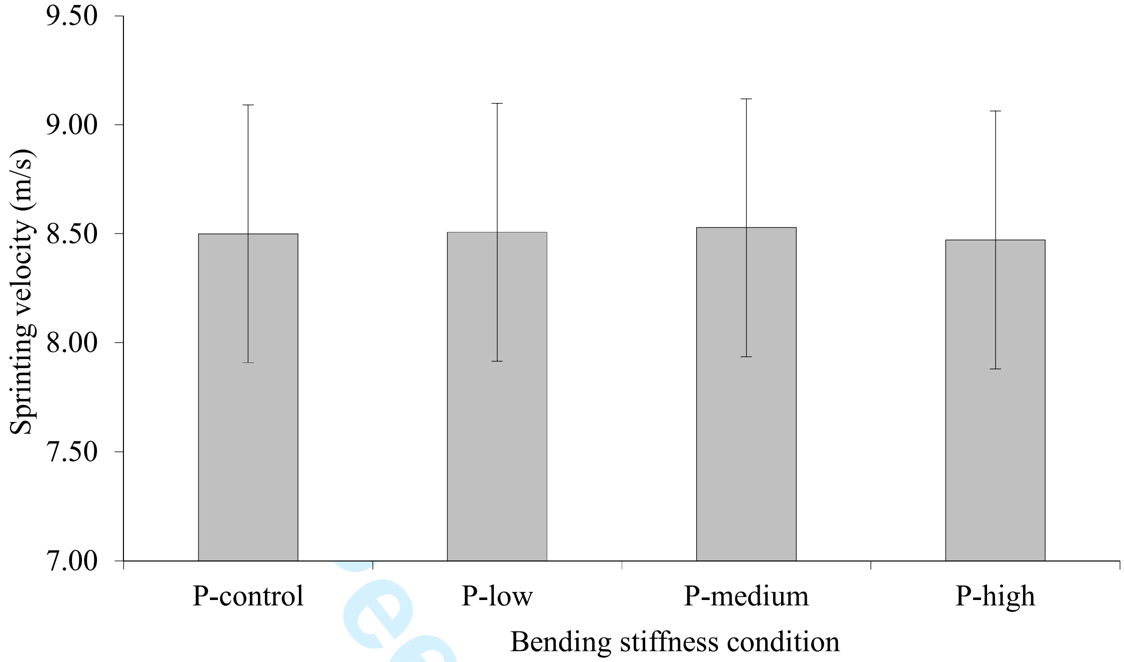

Figure 2. Mean (SD) sprinting velocity for twelve sprinting subjects performing two sprints in four sprint spike stiffness conditions.

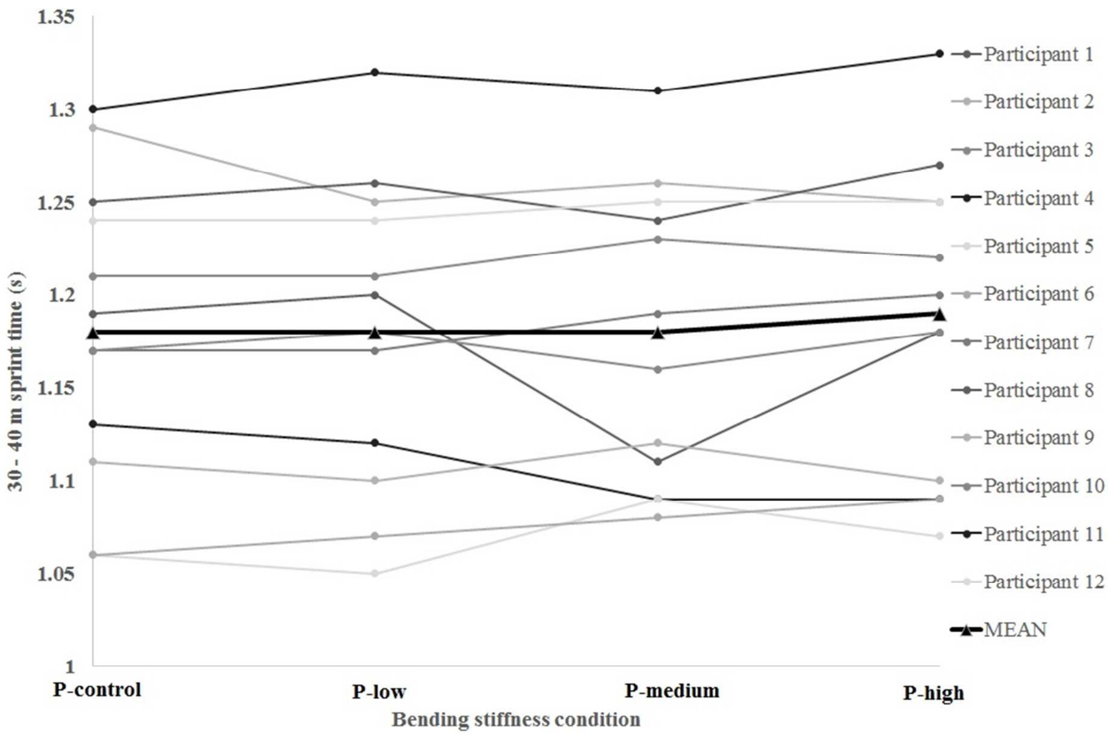

Figure 3. 10 m split (30 – 40m) sprint time for twelve sprinting participants performing two sprints each in four sprint spike bending stiffness conditions. Each line represents a different sprinter.

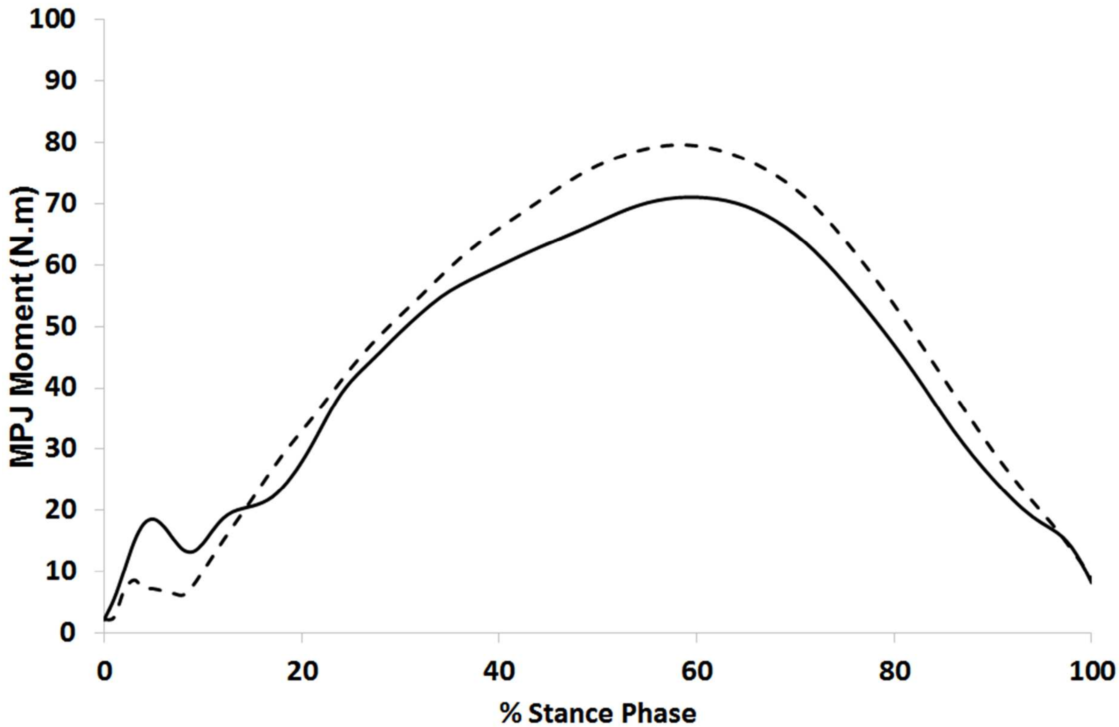

Figure 4. Mean resultant MTPJ moment during the stance phase of sprinting for male sprinter in the individual case study, for condition A-control; solid line, and P-medium; dashed line. Peak moment was significantly ($p < 0.05$) different between the two bending stiffness conditions.

Table 1. Average stiffness (and stiffness normalised to the Puma no insole condition) of the sprint spike conditions used in the study, left and right shoes.

Shoe condition	Shoe size 38.5 Average Mechanical stiffness (N/m) of left and right shoe and Normalised stiffness to condition 0 (%)	Shoe size 43 Average Mechanical stiffness (N/m) of left and right shoe and Normalised stiffness to condition 0(%)
Puma no insole	254.6 ± 22.7 (100%)	297.4 ± 7.6 (100%)
Puma low stiffness insole (low)	314.6 ± 7.8 (124%)	343.1 ± 6.0 (115%)
Puma medium stiffness insole (medium)	367.0 ± 19.7 (144%)	408.6 10.5 (± 137%)
Puma high stiffness insole (high)	501.7 ± 43.6 (197%)	472.1 ± 31.6 (159%)
Asics Baseline	183.66 ± 6.25 (72%)	197.9 ± 29.6 (67%)

Table 2. Male sprinter's mean sprinting velocity and selected MTPJ kinematic and kinetic variables for low, medium and high stiffness conditions to corresponding baseline conditions (Asics baseline). * denotes a significant difference to the corresponding baseline measure ($p<0.05$).

Stiffness	Asics baseline	Low	Asics baseline	Medium	Asics baseline	High
Speed (m/s)	7.66 (± 0.22)	7.60 (± 0.15)	8.05 (± 0.27)	8.12 (± 0.27)	7.94 (± 0.21)	7.90 (± 0.24)
MTPJ Range of Motion (◦)	37.1 (± 1.4)	31.6* (± 1.5)	37.8 (± 1.2)	28.5* (± 2.0)	36.5 (± 1.6)	30.3* (2.5)
Peak Dorsiflexion angular velocity (°/s)	844.2 (± 49.1)	703.3* (± 84.2)	773.6 (± 74.3)	534.4* (± 46.4)	783.8 (± 44.8)	697.2* (±68.5)
Peak Plantarflexion angular velocity (°/s)	-2359.0 (± 95.0)	-2146.8* (± 107.0)	-2507.4 (± 175.4)	-2150.2* (± 187.9)	-2288.0 (± 392.7)	-2120.2* (±331.5)
Peak vertical force Fz (N)	2261.9 (±60.0)	2194.5* (±79.5)	2271.7 (± 36.9)	2345.6* (±72.1)	2253.2 (±98.6)	2324.9 (± 89.1)
Peak plantar flexor moment (N·m)	83.1 (± 2.4)	87.6* (± 2.9)	72.1 (± 5.0)	79.7* (± 3.3)	75.8 (± 4.6)	87.6* (± 6.6)
Peak Positive Power (W) generated during plantarflexion	220.3 (± 23.9)	292.3 (± 73.5)	241.9 (± 24.2)	241.8 (±22.0)	265.5 (±52.3)	386.5* (±128.5)
Peak Negative Power (W) generated during dorsiflexion	-1053.7 (± 78.1)	-976.2* (± 97.6)	-963.8 (± 102.4)	-678.2* (±88.2)	-927.2 (± 78.2)	-916.2 (±121.0)
Total Energy generated (J) during plantarflexion	0.6 (± 0.4)	0.4 (± 0.2)	0.2 (± 0.2)	0.2 (± 0.2)	0.5 (±0.2)	0.8 (± 0.6)
Total Energy absorbed (J) during dorsiflexion	-42.0 (± 2.3)	-35.8* (± 3.0)	-35.0 (± 4.1)	-26.3* (± 1.3)	-37.8 (± 2.0)	-34.2* (± 3.3)
Total energy generated (J) during push-off	2.2 (± 0.3)	3.3* (± 0.6)	2.4 (± 0.4)	2.7 (± 0.4)	2.8 (± 0.7)	3.2 (± 0.6)

Table 3. Female sprinter's mean sprinting velocity and selected MTPJ kinematic and kinetic variables for low, medium and high stiffness conditions and corresponding baseline conditions (Asics baseline). * denotes a significant difference to the corresponding baseline measure (p<0.05).

Stiffness	Asics baseline	Low	Asics baseline	Medium	Asics baseline	High
Speed (m/s)	8.15 (± 0.23)	8.14 (± 0.14)	8.07 (± 0.18)	8.20 (± 0.08)	8.04 (± 0.14)	8.20* (± 0.09)
Metatarsophalangeal Range of Motion (◦)	37.9 (± 3.8)	42.3* (± 3.1)	41.1 (± 2.5)	39.2 (± 1.2)	46.8 (± 2.0)	41.3* (3.0)
Peak Dorsiflexion angular velocity (°/s)	1182.7 (± 314.4)	1228.3 (± 156.7)	1128.2 (± 158.1)	1068.5 (±184.8)	1334.2 (± 261.3)	1197.8 (± 66.0)
Peak Plantarflexion angular velocity (°/s)	-3071.0 (± 143.1)	-2729.3* (± 209.7)	-3472.0 (± 272.9)	-3008.5* (± 280.1)	-3080.8 (± 48.7)	-2476.5* (± 170.2)
Peak vertical force Fz (N)	2057.8 (± 36.3)	2144.0* (±36.7)	2083.2 (±39.1)	2136.1* (±36.6)	2037.2 (±34.8)	2078.1* (± 29.3)
Peak Plantarflexor moment (N.m)	53.7 (± 5.6)	64.0* (± 5.9)	56.0 (± 4.4)	72.7* (± 7.8)	58.7 (± 9.1)	67.6* (± 11.5)
Peak Positive Power (W) generated during plantarflexion	201.2 (± 100.0)	292.3 (± 73.5)	183.7 (± 81.0)	253.3 (±33.9)	333.9 (±148.9)	266.5 (±57.7)
Peak Negative Power (W) generated during dorsiflexion	-691.7 (± 61.2)	-867.0 (± 55.0)	-777..4 (± 90.9)	-855.1 (±90.6)	-1000.2 (± 169.2)	-927.9 (±50.0)
Total Energy generated (J) during plantarflexion	1.4 (± 1.1)	0.5* (± 0.2)	1.3 (± 1.0)	0.9 (± 0.5)	2.0 (± 1.5)	1.3 (± 0.9)
Total Energy absorbed (J) during dorsiflexion	-30.6 (± 2.3)	-33.3 (± 2.0)	-31.2 (± 2.8)	-36.4* (± 3.9)	-34.1 (± 4.3)	-36.9 (± 6.6)
Total energy generated (J) during push-off	0.3 (± 0.1)	2.3* (± 0.6)	1.6 (± 0.7)	2.1 (± 0.4)	0.9 (± 0.4)	2.1* (± 0.5)