Author(s): Grace Smith ; Mark Lake ; Adrian Lees

Title: Metatarsophalangeal joint function during sprinting: A comparison of barefoot and sprint spike shod foot conditions

Date: April 2014

Originally published in: Journal of Applied Biomechanics

Example citation: Smith, G., Lake, M., & Lees, A. (2014). Metatarsophalangeal joint function during sprinting: A comparison of barefoot and sprint spike shod foot conditions. *Journal of Applied Biomechanics*, *30*(2), 206-212. http://dx/doi.org/ 10.1123/jab.2013-0072

Version of item: Authors' post-print as accepted for publication

Metatarsophalangeal joint function during sprinting: A comparison of barefoot and sprint spike shod foot conditions.

Grace Smith,[1] Mark Lake,[2] and Adrian Lees.[2]

[1]Department of Sport and Exercise Sciences, University of Chester, Chester, UK

[2]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK

Funding: None

Conflict of Interest Disclosure: None

Correspondence Address: Dr. Grace Smith, Department of Sport and Exercise Sciences, University of Chester, Parkgate Road, Chester, CH1 4BJ, UK.

Abstract

The metatarsophalangeal joint is an important contributor to lower limb energetics during sprint running. This study compared the kinematics, kinetics and energetics of the metatarsophalangeal joint during sprinting barefoot and wearing standardised sprint spikes. The aim of this investigation was to determine whether standard sprinting footwear alters the natural motion and function of the metatatarsophalangeal joint exhibited during barefoot sprint running. Eight trained sprinters performed maximal sprints along a runway, four sprints in each condition. Three dimensional high speed (1000 Hz) kinematic and kinetic data were collected at the 20 m point. Joint angle, angular velocity, moment, power and energy were calculated for the metatarsophalangeal joint. Sprint spikes significantly increase sprinting velocity (0.3 m/s average increase), yet limit the range of motion about the metatarsophalangeal joint (17.9 % average reduction) and reduce peak dorsiflexion velocity (25.5 % average reduction), thus exhibiting a controlling affect over the natural behaviour of the foot. However, sprint spikes improve metatarsophalangeal joint kinetics by significantly increasing the peak metatarsophalangeal joint moment (15 % average increase) and total energy generated during the important push-off phase (0.5 J to 1.4 J). The results demonstrate substantial changes in metatarsophalangeal function and potential improvements in performance-related parameters due to footwear.

Keywords: biomechanics, sport, performance, footwear

Word Count: 4328

Introduction

An athlete's foot strike pattern depends on many factors, including amongst others: the footwear condition or stiffness of the footwear; running surface; running speed and individual anatomical or morphological characteristics.[1-6] Numerous studies[1-6] have reported clear kinematic and kinetic differences between barefoot and shod running, such as increased ankle plantarflexion and reduced loading rates during barefoot running. However, there is no conclusive evidence from controlled trials, to support the claim that barefoot running improves either simulated or real competitive performance. For sprinting, the effect of sprinting footwear upon normal patterns of foot behaviour, and subsequently on sprinting performance, is not well understood. Comparing how the foot functions in sprint spikes relative to barefoot sprinting, with particular consideration on the function of the metatarsophalangeal joint, may enhance understanding of sprinting performance.

Stefanyshyn and Nigg[7] highlighted the importance of metatarsophalangeal joint motion to sprinting and found the metatarsophalangeal joint to be a large dissipater of energy during stance. The energy absorbed as the athlete rolled onto the forefoot was dissipated in the shoe and foot structures, with almost no positive work produced during stance. Based upon the minimisation of energy loss concept, the authors[7] suggested that a reduction in the energy loss at the metatarsophalangeal joint during stance should improve performance. In subsequent studies,[8,9] increased running shoe stiffness caused a reduction in negative work and energy loss at the metatarsophalangeal joint and resulted in improved performance during running and jumping, despite no differences reported in energy generation. It may therefore be possible to create conditions under which energy loss at the metatarsophalangeal joint is reduced, energy production at push-off is increased, or energy storage and return at the metatarsophalangeal joint can occur, all of which may be potentially beneficial to sprinting performance.

More recently, the mechanical properties of sprint spikes have been demonstrated to influence sprinting performance, with 20 m sprint times significantly reduced when moderate stiffness carbon fibre plates were inserted into athletes own sprint spikes.[10] The authors[10] speculated that increasing the shoe bending stiffness would result in a change in the point of application of ground reaction force, moving the centre of pressure anteriorly and increasing the joint's moment arm. However, this speculation has not been supported by kinetic data for sprint running as, to date, no researchers have investigated this and therefore the biomechanical mechanism responsible for improved performance in stiff sprint spikes remains unknown.

Toon et al.[11] demonstrated that sprint spikes compromise the angular range at the metatarsophalangeal joint during maximal sprinting, compared to barefoot sprinting, therefore potentially affecting an athlete's energy generation ability during push-off. They[11] noted that 'performance-related parameters' such as metatarsophalangeal joint dorsiflexion and dorsiflexion velocity were significantly reduced by sprint spikes, although a better understanding of these parameters is needed to understand their effect on sprinting performance. Their study[11] was limited by a small group of only four sprinters and a rather simple representation of the metatarsophalangeal joint, which may not be realistic. The current investigation will provide a more in-depth study of such parameters during sprinting, combining kinematic data with joint kinetics and energetics to provide evidence of the mechanisms through which a stiff sprint spike may improve sprint performance.

Overall, little work has examined the effect of sprinting footwear on metatarsophalangeal joint function during sprinting. Therefore, the current study was designed to explore the effect of sprint spikes upon typical kinematics and kinetics, in comparison to a baseline condition completely absent of any effect of footwear. Bosjen-Moller[12] suggested that the natural (barefoot) foot function, specifically the motion around metatarsophalangeal joint axes, is compromised by footwear, however no clear evidence for this has been presented in the research for sprinting.

The aim of the current study was to determine whether standard sprinting footwear alters the natural motion and function of the metatarsophalangeal joint, specifically the kinematics, kinetics and energetics of the joint, exhibited during barefoot sprint running (in the absence of any effect of footwear). It was hypothesised that in comparison to the barefoot condition, sprint spikes would: 1) reduce the range of motion and dorsiflexion velocity at the metatarsophalangeal joint, 2) increase the resultant joint moment, 3) reduce the energy absorbed at the joint during metatarsophalangeal joint dorsiflexion, and 4) increase the amount of energy produced during push off.

Methods

Eight competitive athletes (club / regional level) were recruited using convenience sampling for the study; three female (mean age 22.0 ± 4.8 years, mean height 172.3 ± 9.9 cm, mean mass 64.0 ± 6.9 kg) and five male (mean age 22.7 ± 3.5 years, mean height 186 ± 4.7 cm, mean mass 77.2 ± 3.5 kg). All athletes were trained sprinters who specialised in sprints or heptathlon / decathlon and were forefoot strikers when sprinting. Informed written consent was obtained from all participants in accordance with the University's Ethics Committee.

Each subject underwent two dual-energy X-ray absorptiometry scans, used as an aid for placing lead covered reflective markers onto the metatarsal heads 1, 2 and 5 and metatarsal bases 1 and 5. Markers were placed on the foot then the first scanned the foot in a flat position, the second the metatarsophalangeal joint was flexed against a triangle support object with an angle of approximately 60 degrees (similar to the maximum flexion angle of the metatarsophalangeal joint recorded in barefoot sprinting during pilot testing). These scans were used to optimise the location of the metatarsal head and base markers relative to the underlying bones, any adjustments needed to the marker positions were made following the first or second scan, then the marker positions were marked on the athletes' left foot. Prior to the sprinting trials, the athletes performed a standing trial, where they stood still on the force platform with foot flat and tibia at 90 degrees, in each condition.

Eight maximal sprinting trials were collected for each sprinter, four barefoot and four wearing sprint spikes (order of conditions randomized). Participants had at least 5 minutes rest between trials in order to reduce the effect of fatigue. Each subject wore the same entry level Nike Zoom Mazcat sprint spikes (but sized for the individual athlete). This shoe was chosen based upon mid-level price, popularity and mechanical stiffness, in comparison to similar commercially available sprint spikes on the market. Bending stiffness of four different pairs of sprint spikes in size US 9.5 were previously measured mechanically, using a two point bending test. 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). The sprint spikes underwent 40 mm of bending at a constant velocity of 10 mm/s. These values were chosen based upon the angular displacement and velocities of the MPJ in previous work.[13] Mean mechanical stiffness for a deformation of 0 - 40 mm (left and right shoe, three trials per shoe) for the Nike Zoom Mazcat was 256.1 N·m ± 23.7 N·m, in comparison to Adidas Techstar Meteor Sprint: 190.5 N·m ± 5.3 N·m, Asics Hypersprint: 197.9 N·m ± 29.6 N·m and Puma Complete Theseus II: 297.4 N·m ± 7.6 N·m.

Sprints were performed on a 55 m indoor runway with an indoor synthetic track surface. They were instructed and encouraged to run maximally with a single left foot ground contact in the middle of a force platform (Kistler model 9287B) at 20 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. Timing gates were located 2.5 m on either side of the force platform, therefore recording sprint times over 5 m as the athletes crossed the force platform. Kinematic data were collected using a 6 camera system (Pro-Reflex MCU 1000, Qualisys Inc., Sweden) sampling at 1000 Hz. Force data were also sampled at 1000 Hz. In order to avoid using correction algorithms, foot contacts towards the edges of the force plate were discounted due to the higher centre of pressure inaccuracies around load cell locations and when necessary, athletes performed additional trials to obtain four successful trials in each condition.[14]

Data were processed using Visual3D (C-Motion, Inc). A foot model, with toe and forefoot segments, was used for the kinematic analysis with segments defined similarly to Oleson et al.[15] Reflective markers (11 mm diameter) placed on the 1st and 5th metatarsal bases, along with the 1st and 5th metatarsal heads defined the forefoot segment. Markers on the 1st and 5th metatarsal heads and on the head of the second toe at the distal end of the toe box defined the toe segment. A virtual marker was created for the second metatarsal head, defined using a C-motion digitising pointer (C-Motion Inc.) in the standing trial, whereby an anatomical landmark can be created without placing a marker at that location and this was used only as a tracking marking for the forefoot segment. Markers were placed on the skin for barefoot conditions (dorsal surface) using the marked locations from the dual-energy X-ray absorptiometry scans. For the sprint spike condition, holes were cut out in the spikes for markers metatarsal heads 1, 2 (virtual marker) and 5, with the markers placed onto the skin (Figure 1). The remaining markers were placed on top the sprint spike, which was tightly fastened. The inertial effect of the phalanges was considered to be negligible.[7] The five joints were considered as a single joint rotating about an axis oblique to the sagittal plane defined by markers on the first and fifth metatarsal heads (Figure 1). The black line represents the oblique axis through the first and fifth metatarsal heads. The metatarsophalangeal joint angle was defined as the angle between the toe and forefoot segments in relation to a standing calibration for normalization. Metatarsophalangeal joint range of motion was defined as from minimum to maximum peak angle during stance phase.

Joint positional and force data were smoothed using a fourth-order low pass Butterworth filter with a cut-off frequency of 100 Hz, due to the importance of using the same cut off frequency for both kinematic and kinetic data when investigating high speed movements / impacts.[13,16] To minimise errors in the center of pressure data and following visual inspection, thresholds of 100 N and 50 N were used at the start and end of ground contact respectively, as errors were greater at the start of foot contact where higher loading rates were experienced. Below these thresholds the centers of pressure was distorted and were in a position outside of the forefoot, due to low loading on the force platform.[17] Relative propulsive impulse was calculated based on all positive horizontal force data during stance and relative braking impulse on all negative horizontal force data during stance, both expressed relative to body mass. Joint moments, powers and energies were calculated according to Winter.[18] The two dimensional analysis assumed the resultant forces and moments at the metatarsophalangeal joint were zero until the ground reaction force acted distal to the joint and that the inertial effect of the phalanges was negligible.[7] Metatarsophalangeal joint plantarflexor moments (defined as positive) therefore resulted from the ground reaction forces acting distally to the metatarsophalangeal joint line, with the horizontal (X) moment arm calculated as the perpendicular distance from the x and y centre of pressure coordinates to the metatarsophalangeal joint line, a straight line through the x and y coordinates of the first and fifth metatarsal heads for the oblique axis definition.[15]

Data were normally distributed, so paired samples t-tests were performed to compare mean differences in metatarsophalangeal joint kinematic and kinetic variables between barefoot and sprint spike conditions. The level of significance was set at $\alpha = .05$. Effect sizes were calculated using Cohen's *d*, with $d \sim 0.20$ indicating a small effect size, $d \sim 0.50$

indicating a medium effect size and *d* ~ 0.80 indicating a large effect size.[19] Effect size correlation *r* was also calculated.

Results

Mean sprinting velocities were significantly faster ($p = .003$) in the sprint spikes condition (7.80 m/s ± 0.55 m/s) compared to the barefoot condition (7.50 m/s ± 0.65 m/s) with all sprinters demonstrating faster sprint times when wearing sprint spikes. The athletes were still accelerating at the 20 m point, as the relative propulsive impulses (positive) were greater ($p < .001$) than braking impulses (negative) in both conditions (barefoot: 0.31 m/s ± 0.05 m/s and -0.16 ± 0.04 m/s, sprint spikes: 0.34 m/s ± 0.05 m/s and -0.16 ± 0.05 m/s). There was no reduction in sprint speed over the eight trials; demonstrating fatigue was not a factor in this study. There was no significant difference ($p = .606$) in mean stance times between conditions, which were 0.125 s ± 0.010 s for barefoot and 0.127 s ± 0.009 s for sprint spikes.

The metatarsophalangeal joint underwent rapid dorsiflexion during midstance followed by plantarflexion during the last 10-20 ms of stance, demonstrating that the toes did begin to push-off during stance (push-off phase), although plantarflexion continued after the point of take-off (Figure 2). Metatarsophalangeal joint range of motion was significantly reduced ($p = .012$) in the sprint spikes condition compared to barefoot, with an average reduction of 9.2 ° (Table 1, large effect size). Mean metatarsophalangeal joint dorsiflexion velocities were also significantly lower ($p = .023$) wearing sprint spikes (Table 1, large effect size).

Despite faster sprinting velocities for the sprint spike trials, there was no difference ($p = .671$) in peak vertical forces with mean values of 2184.9 N ± 263.2 N and 2169.8 N ± 216.0 N for the barefoot and sprint spike conditions respectively. Mean horizontal propulsive forces were slightly greater for the sprint spike conditions than the barefoot conditions with peak values of 622.0 N ± 158.0 N and 570.8 N ± 154.1 N respectively, although the difference was not significant ($p = .369$). There were no significant differences in relative propulsive impulse ($p = .060$), relative braking impulse ($p = .981$) or net horizontal propulsive impulse (p = .257) between conditions.

Resultant peak moments ranged from 51 to 85 N·m for the eight participants wearing sprint spikes. The metatarsophalangeal joint moments were significantly higher ($p = .028$) in the sprint spikes condition compared to the barefoot condition (Figure 3). Seven out of eight participants demonstrated higher joint moments in the sprint spike condition (Table 1: average increase 8.3 N·m, medium effect size). At the time of peak moment, horizontal moment arms were greater ($p < .001$) in the sprint spikes condition with lever distances of 0.041 m ± 0.004 m, compared to 0.027 m ± 0.004 m in the barefoot condition when metatarsophalangeal joint peak moments were achieved (Table 1, large effect size).

There was no difference ($p = .334$) in the negative power during stance, however the barefoot condition produced more positive power ($p = .033$) throughout stance. All participants demonstrated a large energy absorption phase during stance with only a small amount of energy produced during push-off. There was no significant difference ($p = .521$) in the total energy absorbed at the metatarsophalangeal joint during stance; therefore sprint spikes did not significantly reduce the total energy loss. The sprint spikes condition produced significantly greater energy ($p = .013$) during push-off, albeit a small amount. During this phase, the peak horizontal moment arms were significantly greater ($p = .008$) for the sprint spikes condition with lever distances of 0.064 m ± 0.007 m, compared to 0.054 m ± 0.004 m in the barefoot condition (medium effect size).

Typical intra-subject variation in the kinematic and kinetic variables for one participant demonstrates coefficients of variation ranging from 5.3% to 25.5% (Table 2). Despite this variation, the magnitude of the significant differences between barefoot and sprint spike conditions in the kinematics and kinetics were high. Where significant differences were found, calculated effect sizes (Table 1) for the kinematic and kinetic variables were moderate to large (Cohen's *d*) suggesting a meaningful localised effect on the function of the MPJ.

Discussion

The main purpose of this study was to quantify the effect of standardised, commercially available, entry-level, sprint spikes on the kinematics and energetics of the metatarsophalangeal joint exhibited during barefoot sprinting. The results of this study suggest substantial changes in metatarsophalangeal joint function and performance related parameters between barefoot sprinting and sprinting wearing standardised sprint spikes.

This study demonstrates that sprint spikes have a controlling effect over the barefoot kinematics of the metatarsophalangeal joint, by limiting the range of motion and reducing peak dorsiflexion velocity, accepting the hypothesis (1). Previous researchers have obtained their metatarsophalangeal joint range of motion results from manually digitising the lateral or medial aspect of the metatarsophalangeal joint from high-speed two-dimensional video, [11, 20] instead of a more anatomically correct oblique or dual axis representation of the joint.[13] Furthermore, typical sampling and filtering procedure underestimate metatarsophalangeal joint motion and suppress high frequency transients of motion.[13] Using a low cut-off frequency of 8 Hz has been reported to not only distort vital data after landing, but also severely underestimate the rate of dorsiflexion of the joint.[13] Therefore, the importance of using an appropriate axis representation, alongside appropriate kinematic data sampling and filtering, is paramount to obtaining accurate angular data. The oblique axis representation of the joint used in this investigation also ensures resultant moment arms and joint moments are not overestimated by oversimplifying the modelling of the metatarsophalangeal joint, as shown by Smith et al. who compared the effect of three metatarsophalangeal joint axes definitions on kinematics and kinetics of the joint during sprinting. [13]

The mean metatarsophalangeal joint range of motion values in this study (51.5 º ± 3.5 º barefoot and 42.3 º ± 5.7 º) were slightly higher than those reported in the previous research. Stefanyshyn et al.[20] reported average peak dorsiflexion at the metatarsophalangeal joint from medial and lateral aspects combined of 36.5 º and 37.7 º for male and female Olympic sprinters respectively at the 50 m point. Toon et al.[11] reported peak metatarsophalangeal joint (medial aspect) dorsiflexion values of 43 º ± 3 º for barefoot sprinting and 31 º ± 3 º wearing standardised sprint spikes for four sprinters at the 50 m point. These differences may be due to the relatively low stiffness of standard sprint spike used, the phase of the sprint or, more likely, due to different methodologies, mentioned above, employed to measure metatarsophalangeal joint angular movement. Peak metatarsophalangeal joint dorsiflexion velocities for this study of 1172 º/s ± 310 º/s barefoot and 873 º/s ± 155 º/s are similar to Krell and Stefanyshyn,[21] who reported peak velocities for the medial aspect of the metatarsophalangeal joint of between 900 and 1300 º/s for 100 m Olympic athletes, but are higher than Toon et al.,[11] who reported values of 531 º/s to 737 º/s for barefoot and sprint spikes respectively, as they used the mean of the medial and lateral aspects of the metatarsophalangeal joint. The motion calculated by manually digitising the lateral aspect of the metatarsophalangeal joint, however, is both substantially lower and more variable than that experienced of the medial aspect,[11] therefore it is questionable whether combining these aspects for calculating the resultant range of motion and angular velocity of the metatarsophalangeal joint is accurate.

This study provides evidence for the inherent controlling effect of the sprint spikes, which act as a velocity dampener during metatarsophalangeal joint dorsiflexion. Sprint spikes resulted in a significant reduction in the range of motion at the metatarsophalangeal joint as well as the dorsiflexion velocity, compared to the barefoot trials. The metatarsophalangeal joint began to plantarflex during push-off, consequently providing an opportunity to generate energy, disagreeing with Stefanyshyn and Nigg,[7] who stated that the toes remain dorsiflexed, thus generating no or very little energy at take-off. This was likely due to the low cut frequency of 8 Hz they employed.

The sprint spikes resulted in significantly greater resultant joint moments, in comparison to the barefoot condition, accepting the hypothesis (2), by significantly increasing the length of the moment arm. Sprinting footwear elicits an anterior shift in the point of force application during the push off phase of sprinting, which in turn increases the amount of work performed at the joint. This is the first investigation to provide substantial evidence to support this mechanism during sprint running. It is expected that the increased moment arm is primarily due to the longitudinal bending stiffness of the sprint spikes, along with the possible effect of the toe spring design, whereby the upward curvature of the shoe sole in the forefoot region may promote forefoot contact and perhaps increase metatarsophalangeal joint dorsiflexion. In order to cope with an increased lever arm and rigid link of a stiff footwear condition, the plantarflexors (in particular the triceps surae) need to produce more work, if this additional force can be translated this may result in a more effective transfer of energy and lead to an improvement in sprinting performance.

The metatarsophalangeal joint was a large energy absorber and produced little energy during push-off. Although the sprint spikes resulted in reduced energy loss at the metatarsophalangeal joint, compared to the barefoot condition, this was not significant; therefore the hypothesis (3) was rejected. The increased lever length in the sprint spike condition did not amplify the energy absorption at the metatarsophalangeal joint, in fact the increased plantarflexion moment of the metatarsophalangeal joint during the barefoot condition led to increased (although not significant) energy absorption. The sprint spikes did, however, result in increased energy production during push-off, due to a greater moment arm, thus the hypothesis (4) was accepted. Consequently, the stiffer sprint spike condition, compared to the barefoot condition, seemed to increase the effective lever length of the foot about the metatarsophalangeal joint during push-off, which may facilitate effective propulsion. Therefore, sprint spikes appear to enhance metatarsophalangeal joint kinetics, by increasing the total energy generated during the push-off phase. Combined with the restriction of the range of motion at the metatarsophalangeal joint, these two factors may contribute to the improved sprinting performance demonstrated in the sprint spike condition. Despite the controlling influences of the sprint spikes over the angular motion at the metatarsophalangeal joint, it appears that sprint spikes do not reduce the effectiveness of the windlass mechanism and the efficiency of the foot as a lever for propulsion. Conversely, the athletes created more energy during push-off wearing sprint spikes, despite reduced dorsiflexion range of motion at the metatarsophalangeal joint, which suggests substantial rigidity was achieved from the foot and shoe as a system.

As active plantarflexion of the toes occurs during the push-off phase of sprinting, the metatarsophalangeal joint should not be ignored in strength and conditioning training. It is suggested that strengthening exercises should not only target the extrinsic foot/ankle muscles (e.g. triceps surae, flexor hallucis longus, flexor digitorum longus), but also include the intrinsic foot muscles (e.g. abductor hallucis and flexor digitorum brevis). Potthast et al.[22] demonstrated that a training footwear intervention could initiate biopositive adaptations within the foot, including significantly increased toe flexor strength and reduced metatarsophalangeal joint dorsiflexion in walking gait. These adaptations could potentially be advantageous to sprinting performance, through stiffening of the metatarsophalangeal joint, thereby decreasing deformation of the foot and helping the athlete to propel forwards.

Limitations of this study include the possible effects of the midsole height and the toe spring of the sprint spike condition, which were unknown and beyond the scope of the study, as were the effects of individual foot geometry or anatomical factors. Speed was a confounding factor as athletes exhibited faster sprinting velocities wearing sprint spikes. It is acknowledged that besides metatarsophalangeal joint function, the traction provided by the sprint spike condition may have influenced the foot function, in particular increasing the friction upon landing and around the instant of take-off. It is likely that sprint spikes may promote more localised pressure distribution in the forefoot, further facilitating push-off. However, as there were no significant differences in the vertical and horizontal propulsive / braking forces and stance times, this could indicate that traction and pressure distribution were less influential than the moment produced at the metatarsophalangeal joint. It is believed, that the differences between the joint kinematics, kinetics and energetics reported between the two different conditions were primarily due to the greater stiffness of the sprint shoe increasing the lever arm distances and the work produced at the metatarsophalangeal joint. The use of skin mounted and externally placed markers to reflect bone kinematics may introduce some minimal soft tissue artefact, although marker placement was improved by the use of dual-energy X-ray absorptiometry scans to locate anatomical locations, holes cut in the sprint spikes and finally the use of a virtual marker. It is recommended that future investigation is needed to assess the effect of different sprint spike stiffness’s upon metatarsophalangeal joint function, the windlass mechanism and sprinting performance, possibly using a very low stiffness shoe as a baseline condition.

In summary, this study has demonstrated performance-related differences in metatarsophalangeal joint kinematics and kinetics between barefoot sprinting and when sprinting in spikes. Whilst several factors could have influenced these results, it is believed that the metatarsophalangeal joint had a significant effect upon sprinting performance in barefoot and sprint spike conditions. The metatarsophalangeal joint is clearly a large absorber of energy as the joint dorsiflexes during stance, sprint spikes appear to aid in propulsion of the sprinter, by creating a rigid lever for push-off and producing some, albeit small, energy as the toes begin to plantarflex prior to the instant of take-off. It is clear from the considerable range of motion undergone at the metatarsophalangeal joint during sprinting, along with the additional requirement of energy loss, that researchers should not ignore this joint in future analyses of sprinting biomechanics. Sprint spikes appear to have a clear localised effect on the function of the metatarsophalangeal joint, increasing the work performed at the joint by lengthening the moment arm and enabling a more effective, energy-producing push-off.

Acknowledgements

None

References

1. De Wit B, De Clercq D. Aerts P. Biomechanical analysis of the stance phase during barefoot and shod running. *J Biomech.* 2001;33(3):269-278.

2. De Clerq D, Aerts P, Kunnon M. The mechanical characteristics of the heel pad during foot strike in running: an in vivo cineradiographic study. *J Biomech.* 1994;27(10)*:*1213–1222.

3. De Koning JJ, Nigg BM. Kinematic factors affecting peak vertical ground reaction forces in running. *J Biomech.* 1994;27(6):673.

4. Dickinson JA, Cook SD, Leinhardt TM. The measurement of shock waves following heel strike while running. *J Biomech.* 1985;18(5):415–422.

5. Hartveld A, Chockalingam N. Shock absorption during jumping barefoot and in shoes. *Int J Podiatric Biomech.* 2003;1*:*16–20.

6. Griffin JR, Mercer JA, Dufek JS. (2007). Kinematic comparison of running barefoot and in the barefoot shoe Free 5.0. *Med Sci Sports Exercise*. 2007;39(S5):73.

7. Stefanyhysn DJ, Nigg BM. Mechanical energy contribution of the metatarsophalangeal joint to running and sprinting. *J Biomech.* 1997; 30(11):1081-1085.

8. Roy JPR, Stefanyshyn DJ. Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Med Sci Sport Exercise.* 2006;38(3):562-569.

9. Stefanyshyn DJ, Nigg BM. Influence of midsole bending stiffness on joint energy and jump height performance. *Med Sci Sport Exercise.* 2000:32(2);471-476.

10. Stefanyshyn DJ, Fusco C. Increased shoe bending stiffness increases sprint performance. *Sport Biomech*. 2004;3(1):55-66.

11. Toon D, Williams B, Hopkinson N, Caine M. A comparison of barefoot and sprint spike conditions in sprinting. *J Sports Eng and Tech; Proceedings of the Institute of Mechanical Engineers, Part P.* 2009;223(2):77-87.

12. Bosjen-Moller F. The human foot a two speed construction. In: Asmussen E, Jorgensen K, eds. *International Series of Biomechanics, VI*. Baltimore: University Park Press; 1978:26.1-2

13. Smith GE. Lake ML, Lees A, Worsfold P. Measurement procedures effect the interpretation of metatarsophalangeal joint function during accelerated sprinting. *J Sport Sci.* 2012;30(14):1521-1527.

14. Kistler**.** *Multicomponent Measuring Force Plate for Biomechanics Type 9287A* **(**Operating Instructions**),** Kistler**:** Switzerland. 2003.

15. Oleson M, Adler D, Goldsmith P. A comparison of forefoot stiffness in running and running bending stiffness. *J Biomech.* 2005;38(9):1886-1894.

16. Bisseling RW, Hof LA. Handling of impact forces in inverse dynamics. *J Biomech.* 2006;39(13):2438-2444.

17. Nigg BM. Force, In: Nigg BM, Herzog W, eds. *Biomechanics of the Musculo-skeletal system,* 3rd ed. Chichester, UK: Wiley. 2007:311-323.

18. Winter DA. (1983). Moments of force and mechanical power in jogging. *J Biomech.* 1983;16(1):91-97.

19. Cohen J. *Statistical power analysis for the behavioural sciences,* 2nd ed. Mahwah, NJ: Lawrence Erlbaum Associates; 1988.

20. Stefanyshyn DJ, Krell JR, Chow DL. Metatarsophalangeal joint movement in Olympic sprinters. *Med Sci Sports Exercise.* 2002;34(5):16.

21. Krell JB, Stefanyshyn DJ. The relationship between extension of the metatarsophalangeal joint and sprint time for 100m Olympic athletes. *J Sports Sci.* 2006;24(2):175-180.

22. Potthast W, Niehoff A, Braunstein J, et al. Changes in Morphology and Function of Toe flexor muscles are related to training footwear. *In: Proceedings of the VIIth ISB Footwear Biomechanics Symposium. July 27-29.* Cleveland, Ohio. 2005.

Figures

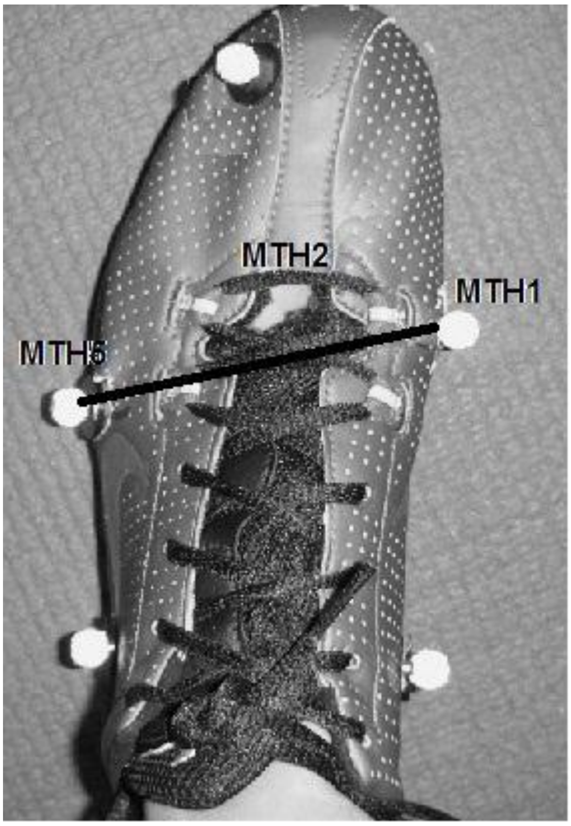

Figure 1 - Image of the left foot demonstrating marker location and axes of the metatarsophalangeal joint.

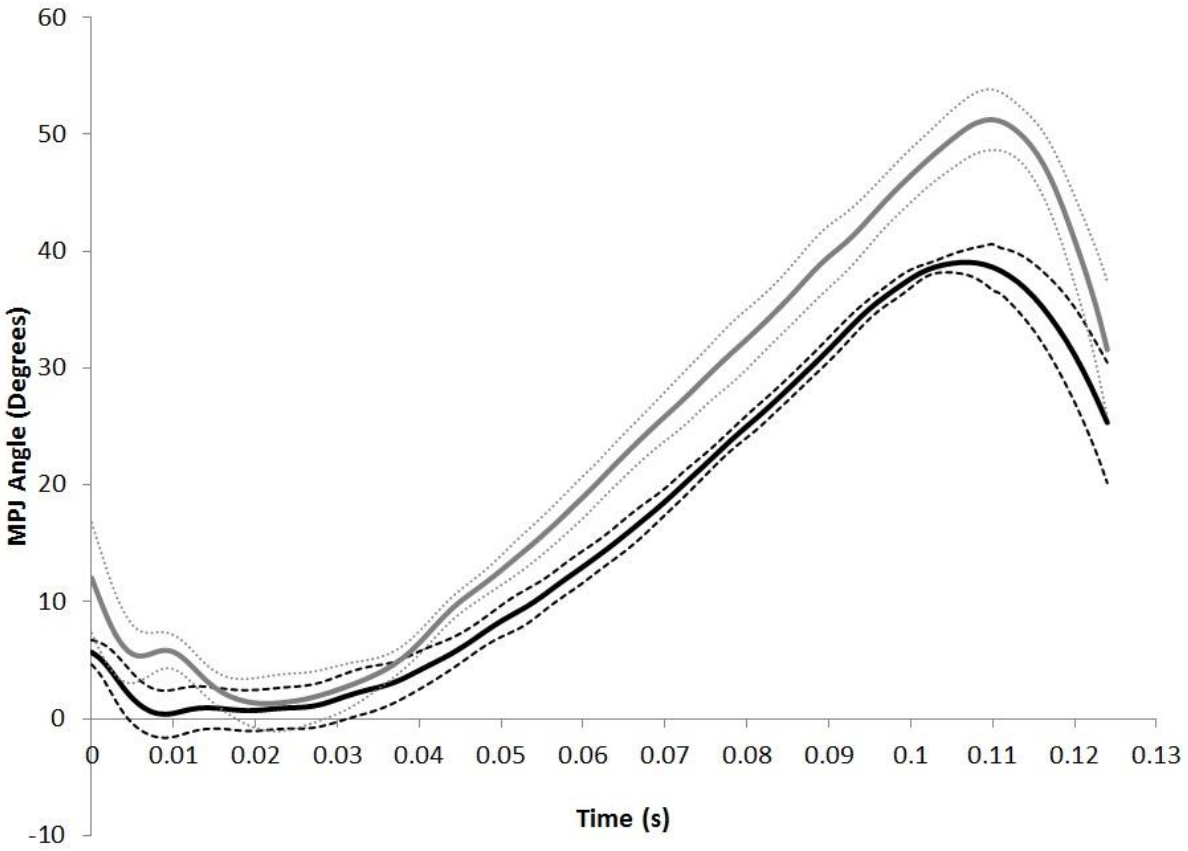

Figure 2 – Average metatarsophalangeal joint angle throughout the stance phase of sprinting, mean trace (± *SD* lines – dashed) for one female participant sprinting wearing sprint spikes (black line) and barefoot (grey line).

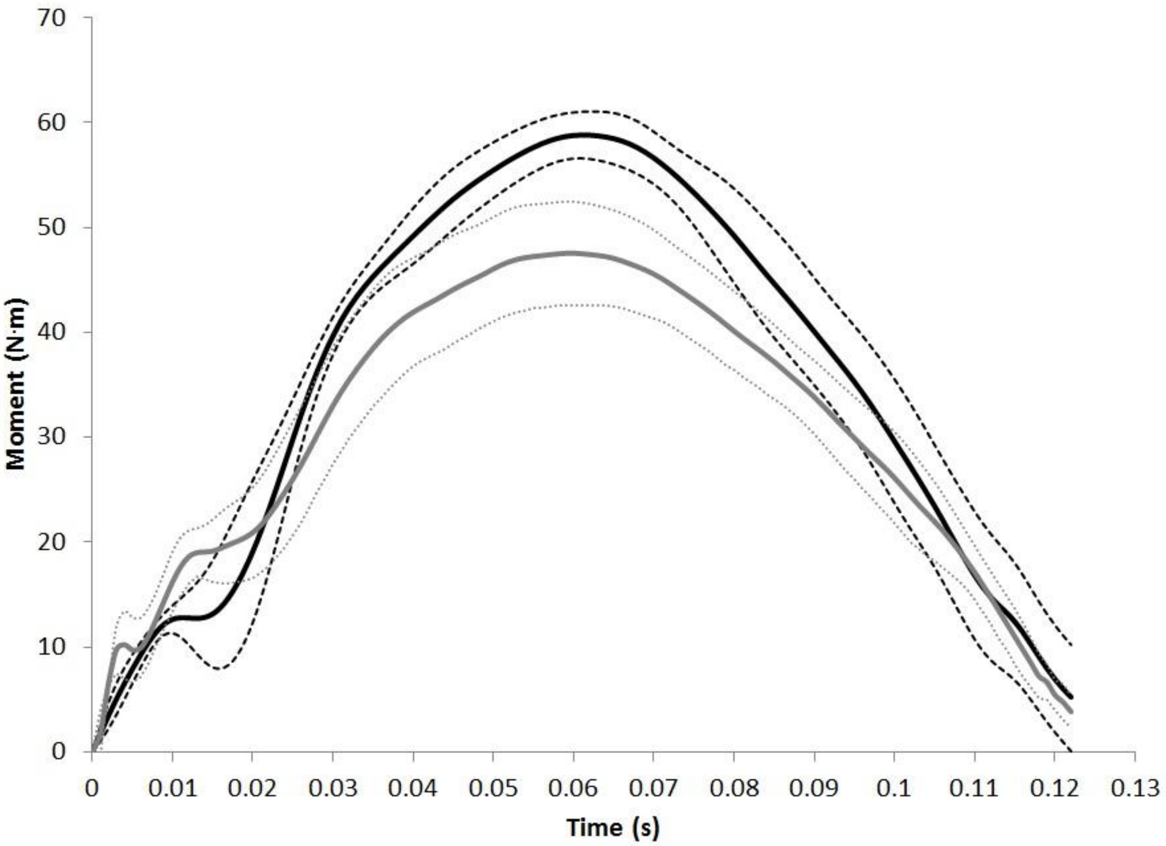

Figure 3 – Average metatarstophalangeal joint moment during stance for one female participant, mean trace (± *SD* lines – dashed lines) sprinting wearing sprint spikes (black line) and barefoot (grey line). Joint moment is positive (plantarflexor) during the entire stance phase as the center of pressure was in front of the metatarsophalangeal joint axis throughout.

Tables

Table 1 Metatarsophalangeal joint kinematics and kinetics for barefoot versus shod conditions, mean ± *SD*.

Condition	Barefoot (n=8)	Sprint Spikes (n=8)	*P* value	Cohen's *d* (effect size *r*)
Angular ROM (°)	51.5 ± 3.5	42.3 ± 5.7	.012	1.945 (.697)
Peak dorsiflexion velocity (°/s)	1172.2 ± 309.8	873.1 ± 154.9	.023	1.221 (.521)
Peak plantar flexor moment (N·m)	55.6 ± 11.3	63.9 ± 14.9	.028	0.628 (.300)
Peak Positive Power (W)	300.0 ± 202.5	140.9 ± 106.3	.033	0.984 (.441)
Peak Negative Power (W)	-712.7 ±207.2	-780.1 ±228.7	.334	0.309 (.152)
Total Energy generated (J) after touchdown	2.8 ± 2.1	1.3 ± 1.0	.028	0.912 (.415)
Total Energy absorbed (J)	-31.3 ± 7.7	-29.9 ± 7.7	.521	0.182 (.009)
Total energy generated (J) during push-off	0.5 ± 0.5	1.4 ± 1.0	.013	1.138 (.495)
Horizontal moment arm (m) at Peak plantar flexor moment	0.027 ± 0.004	0.041 ± 0.004	<.001	3.500 (.868)
Horizontal moment arm (m) during push-off	0.054 ± 0.004	0.064 ±0.007	.008	1.754 (.503)

Table 2 Intra-subject variability: Mean ± SD and Coefficient of Variation (CoV) for metatarsophalangeal joint kinematic and kinetic variables for one typical participant, barefoot and sprint conditions, four sprint trials per condition.

Condition	Barefoot mean ± SD	Barefoot CoV (%)	Spikes mean ±SD	Spikes CoV(%)
Angular ROM (°)	50.1 ± 2.7	5.3	39.1 ± 2.2	5.7
Peak dorsiflexion velocity (°/s)	1417.1 ± 160.7	11.3	919.7 ± 132.0	14.3
Peak plantar flexor moment (N·m)	47.6 ± 4.8	10.3	56.1 ± 5.8	10.4
Peak Positive Power (W)	251.3 ± 27.4	10.9	139.4 ± 13.1	9.3
Peak Negative Power (W)	-530.0 ±35.2	6.6	-615.0 ± 77.6	12.6
Total Energy generated (J) after touchdown	2.2 ± 0.5	22.7	1.9 ± 0.4	18.8
Total Energy absorbed (J)	-29.1 ± 3.4	11.6	-25.8 ± 3.2	12.5
Total energy generated (J) during push-off	0.8 ± 0.2	23.7	1.3 ± 0.3	25.5