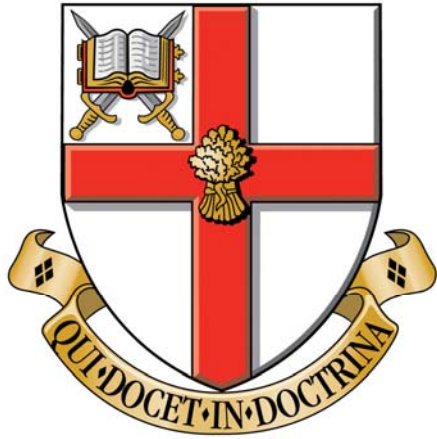


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Metatarsophalangeal joint function during sprinting: A comparison of barefoot and sprint spike shod foot conditions.

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1 **Abstract**

2 The metatarsophalangeal joint is an important contributor to lower limb energetics during
3 sprint running. This study compared the kinematics, kinetics and energetics of the
4 metatarsophalangeal joint during sprinting barefoot and wearing standardised sprint spikes.
5 The aim of this investigation was to determine whether standard sprinting footwear alters the
6 natural motion and function of the metatarsophalangeal joint exhibited during barefoot
7 sprint running. Eight trained sprinters performed maximal sprints along a runway, four sprints
8 in each condition. Three dimensional high speed (1000 Hz) kinematic and kinetic data were
9 collected at the 20 m point. Joint angle, angular velocity, moment, power and energy were
10 calculated for the metatarsophalangeal joint. Sprint spikes significantly increase sprinting
11 velocity (0.3 m/s average increase), yet limit the range of motion about the
12 metatarsophalangeal joint (17.9 % average reduction) and reduce peak dorsiflexion velocity
13 (25.5 % average reduction), thus exhibiting a controlling affect over the natural behaviour of
14 the foot. However, sprint spikes improve metatarsophalangeal joint kinetics by significantly
15 increasing the peak metatarsophalangeal joint moment (15 % average increase) and total
16 energy generated during the important push-off phase (0.5 J to 1.4 J). The results demonstrate
17 substantial changes in metatarsophalangeal function and potential improvements in
18 performance-related parameters due to footwear.

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21 **Keywords:** biomechanics, sport, performance, footwear

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25 **Word Count: 4328**

Introduction

27 An athlete's foot strike pattern depends on many factors, including amongst others: the
28 footwear condition or stiffness of the footwear; running surface; running speed and individual
29 anatomical or morphological characteristics.¹⁻⁶ Numerous studies¹⁻⁶ have reported clear
30 kinematic and kinetic differences between barefoot and shod running, such as increased ankle
31 plantarflexion and reduced loading rates during barefoot running. However, there is no
32 conclusive evidence from controlled trials, to support the claim that barefoot running
33 improves either simulated or real competitive performance. For sprinting, the effect of
34 sprinting footwear upon normal patterns of foot behaviour, and subsequently on sprinting
35 performance, is not well understood. Comparing how the foot functions in sprint spikes
36 relative to barefoot sprinting, with particular consideration on the function of the
37 metatarsophalangeal joint, may enhance understanding of sprinting performance.

38 Stefanyshyn and Nigg⁷ highlighted the importance of metatarsophalangeal joint
39 motion to sprinting and found the metatarsophalangeal joint to be a large dissipater of energy
40 during stance. The energy absorbed as the athlete rolled onto the forefoot was dissipated in
41 the shoe and foot structures, with almost no positive work produced during stance. Based
42 upon the minimisation of energy loss concept, the authors⁷ suggested that a reduction in the
43 energy loss at the metatarsophalangeal joint during stance should improve performance. In
44 subsequent studies,^{8,9} increased running shoe stiffness caused a reduction in negative work
45 and energy loss at the metatarsophalangeal joint and resulted in improved performance during
46 running and jumping, despite no differences reported in energy generation. It may therefore
47 be possible to create conditions under which energy loss at the metatarsophalangeal joint is
48 reduced, energy production at push-off is increased, or energy storage and return at the
49 metatarsophalangeal joint can occur, all of which may be potentially beneficial to sprinting
50 performance.

51 More recently, the mechanical properties of sprint spikes have been demonstrated to
52 influence sprinting performance, with 20 m sprint times significantly reduced when moderate
53 stiffness carbon fibre plates were inserted into athletes own sprint spikes.¹⁰ The authors¹⁰
54 speculated that increasing the shoe bending stiffness would result in a change in the point of
55 application of ground reaction force, moving the centre of pressure anteriorly and increasing
56 the joint's moment arm. However, this speculation has not been supported by kinetic data for
57 sprint running as, to date, no researchers have investigated this and therefore the
58 biomechanical mechanism responsible for improved performance in stiff sprint spikes
59 remains unknown.

60 Toon et al.¹¹ demonstrated that sprint spikes compromise the angular range at the
61 metatarsophalangeal joint during maximal sprinting, compared to barefoot sprinting,
62 therefore potentially affecting an athlete's energy generation ability during push-off. They¹¹
63 noted that 'performance-related parameters' such as metatarsophalangeal joint dorsiflexion
64 and dorsiflexion velocity were significantly reduced by sprint spikes, although a better
65 understanding of these parameters is needed to understand their effect on sprinting
66 performance. Their study¹¹ was limited by a small group of only four sprinters and a rather
67 simple representation of the metatarsophalangeal joint, which may not be realistic. The
68 current investigation will provide a more in-depth study of such parameters during sprinting,
69 combining kinematic data with joint kinetics and energetics to provide evidence of the
70 mechanisms through which a stiff sprint spike may improve sprint performance.

71 Overall, little work has examined the effect of sprinting footwear on
72 metatarsophalangeal joint function during sprinting. Therefore, the current study was
73 designed to explore the effect of sprint spikes upon typical kinematics and kinetics, in
74 comparison to a baseline condition completely absent of any effect of footwear. Bosjen-
75 Moller¹² suggested that the natural (barefoot) foot function, specifically the motion around

76 metatarsophalangeal joint axes, is compromised by footwear, however no clear evidence for
77 this has been presented in the research for sprinting.

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

86

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Methods

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

94 Each subject underwent two dual-energy X-ray absorptiometry scans, used as an aid
95 for placing lead covered reflective markers onto the metatarsal heads 1, 2 and 5 and
96 metatarsal bases 1 and 5. Markers were placed on the foot then the first scanned the foot in a
97 flat position, the second the metatarsophalangeal joint was flexed against a triangle support
98 object with an angle of approximately 60 degrees (similar to the maximum flexion angle of
99 the metatarsophalangeal joint recorded in barefoot sprinting during pilot testing). These scans
100 were used to optimise the location of the metatarsal head and base markers relative to the

101 underlying bones, any adjustments needed to the marker positions were made following the
102 first or second scan, then the marker positions were marked on the athletes' left foot. Prior to
103 the sprinting trials, the athletes performed a standing trial, where they stood still on the force
104 platform with foot flat and tibia at 90 degrees, in each condition.

105 Eight maximal sprinting trials were collected for each sprinter, four barefoot and four
106 wearing sprint spikes (order of conditions randomized). Participants had at least 5 minutes
107 rest between trials in order to reduce the effect of fatigue. Each subject wore the same entry
108 level Nike Zoom Mazcat sprint spikes (but sized for the individual athlete). This shoe was
109 chosen based upon mid-level price, popularity and mechanical stiffness, in comparison to
110 similar commercially available sprint spikes on the market. Bending stiffness of four different
111 pairs of sprint spikes in size US 9.5 were previously measured mechanically, using a two
112 point bending test. A Servo hydraulic material testing machine was used (Zwick GmbH &
113 Co. KG, Ulm, Germany, stroke 100 mm, load max. 10 kN) with a LVDT position sensor and
114 a 10 kN load cell (Huppert GmbH Prüf- und Messtechnik, Herrenberg, Germany). The sprint
115 spikes underwent 40 mm of bending at a constant velocity of 10 mm/s. These values were
116 chosen based upon the angular displacement and velocities of the MPJ in previous work.¹³
117 Mean mechanical stiffness for a deformation of 0 - 40 mm (left and right shoe, three trials per
118 shoe) for the Nike Zoom Mazcat was $256.1 \text{ N}\cdot\text{m} \pm 23.7 \text{ N}\cdot\text{m}$, in comparison to Adidas
119 Techstar Meteor Sprint: $190.5 \text{ N}\cdot\text{m} \pm 5.3 \text{ N}\cdot\text{m}$, Asics Hypersprint: $197.9 \text{ N}\cdot\text{m} \pm 29.6 \text{ N}\cdot\text{m}$ and
120 Puma Complete Theseus II: $297.4 \text{ N}\cdot\text{m} \pm 7.6 \text{ N}\cdot\text{m}$.

121 Sprints were performed on a 55 m indoor runway with an indoor synthetic track
122 surface. They were instructed and encouraged to run maximally with a single left foot ground
123 contact in the middle of a force platform (Kistler model 9287B) at 20 m was used for
124 analysis. A customized starting mark was used to aid the athlete in striking the force plate
125 without the need to alter their stride pattern prior to force plate contact. Timing gates were

126 located 2.5 m on either side of the force platform, therefore recording sprint times over 5 m
127 as the athletes crossed the force platform. Kinematic data were collected using a 6 camera
128 system (Pro-Reflex MCU 1000, Qualisys Inc., Sweden) sampling at 1000 Hz. Force data
129 were also sampled at 1000 Hz. In order to avoid using correction algorithms, foot contacts
130 towards the edges of the force plate were discounted due to the higher centre of pressure
131 inaccuracies around load cell locations and when necessary, athletes performed additional
132 trials to obtain four successful trials in each condition.¹⁴

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

151 calibration for normalization. Metatarsophalangeal joint range of motion was defined as from
152 minimum to maximum peak angle during stance phase.

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

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

176 indicating a medium effect size and $d \sim 0.80$ indicating a large effect size.¹⁹ Effect size
177 correlation r was also calculated.

178 **Results**

179 Mean sprinting velocities were significantly faster ($p = .003$) in the sprint spikes
180 condition ($7.80 \text{ m/s} \pm 0.55 \text{ m/s}$) compared to the barefoot condition ($7.50 \text{ m/s} \pm 0.65 \text{ m/s}$)
181 with all sprinters demonstrating faster sprint times when wearing sprint spikes. The athletes
182 were still accelerating at the 20 m point, as the relative propulsive impulses (positive) were
183 greater ($p < .001$) than braking impulses (negative) in both conditions (barefoot: $0.31 \text{ m/s} \pm$
184 0.05 m/s and $-0.16 \pm 0.04 \text{ m/s}$, sprint spikes: $0.34 \text{ m/s} \pm 0.05 \text{ m/s}$ and $-0.16 \pm 0.05 \text{ m/s}$).
185 There was no reduction in sprint speed over the eight trials; demonstrating fatigue was not a
186 factor in this study. There was no significant difference ($p = .606$) in mean stance times
187 between conditions, which were $0.125 \text{ s} \pm 0.010 \text{ s}$ for barefoot and $0.127 \text{ s} \pm 0.009 \text{ s}$ for
188 sprint spikes.

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

197 Despite faster sprinting velocities for the sprint spike trials, there was no difference (p
198 $= .671$) in peak vertical forces with mean values of $2184.9 \text{ N} \pm 263.2 \text{ N}$ and $2169.8 \text{ N} \pm 216.0$
199 N for the barefoot and sprint spike conditions respectively. Mean horizontal propulsive forces

200 were slightly greater for the sprint spike conditions than the barefoot conditions with peak
201 values of $622.0 \text{ N} \pm 158.0 \text{ N}$ and $570.8 \text{ N} \pm 154.1 \text{ N}$ respectively, although the difference was
202 not significant ($p = .369$). There were no significant differences in relative propulsive impulse
203 ($p = .060$), relative braking impulse ($p = .981$) or net horizontal propulsive impulse ($p = .257$)
204 between conditions.

205 Resultant peak moments ranged from 51 to 85 N·m for the eight participants wearing
206 sprint spikes. The metatarsophalangeal joint moments were significantly higher ($p = .028$) in
207 the sprint spikes condition compared to the barefoot condition (Figure 3). Seven out of eight
208 participants demonstrated higher joint moments in the sprint spike condition (Table 1:
209 average increase 8.3 N·m, medium effect size). At the time of peak moment, horizontal
210 moment arms were greater ($p < .001$) in the sprint spikes condition with lever distances of
211 $0.041 \text{ m} \pm 0.004 \text{ m}$, compared to $0.027 \text{ m} \pm 0.004 \text{ m}$ in the barefoot condition when
212 metatarsophalangeal joint peak moments were achieved (Table 1, large effect size).

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

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

230 Discussion

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

236 This study demonstrates that sprint spikes have a controlling effect over the barefoot
237 kinematics of the metatarsophalangeal joint, by limiting the range of motion and reducing
238 peak dorsiflexion velocity, accepting the hypothesis (1). Previous researchers have obtained
239 their metatarsophalangeal joint range of motion results from manually digitising the lateral or
240 medial aspect of the metatarsophalangeal joint from high-speed two-dimensional video,^{11, 20}
241 instead of a more anatomically correct oblique or dual axis representation of the joint.¹³
242 Furthermore, typical sampling and filtering procedure underestimate metatarsophalangeal
243 joint motion and suppress high frequency transients of motion.¹³ Using a low cut-off
244 frequency of 8 Hz has been reported to not only distort vital data after landing, but also
245 severely underestimate the rate of dorsiflexion of the joint.¹³ Therefore, the importance of
246 using an appropriate axis representation, alongside appropriate kinematic data sampling and

247 filtering, is paramount to obtaining accurate angular data. The oblique axis representation of
248 the joint used in this investigation also ensures resultant moment arms and joint moments are
249 not overestimated by oversimplifying the modelling of the metatarsophalangeal joint, as
250 shown by Smith et al. who compared the effect of three metatarsophalangeal joint axes
251 definitions on kinematics and kinetics of the joint during sprinting.¹³

252 The mean metatarsophalangeal joint range of motion values in this study ($51.5^\circ \pm 3.5$
253 $^\circ$ barefoot and $42.3^\circ \pm 5.7^\circ$) were slightly higher than those reported in the previous research.
254 Stefanyshyn et al.²⁰ reported average peak dorsiflexion at the metatarsophalangeal joint from
255 medial and lateral aspects combined of 36.5° and 37.7° for male and female Olympic
256 sprinters respectively at the 50 m point. Toon et al.¹¹ reported peak metatarsophalangeal joint
257 (medial aspect) dorsiflexion values of $43^\circ \pm 3^\circ$ for barefoot sprinting and $31^\circ \pm 3^\circ$ wearing
258 standardised sprint spikes for four sprinters at the 50 m point. These differences may be due
259 to the relatively low stiffness of standard sprint spike used, the phase of the sprint or, more
260 likely, due to different methodologies, mentioned above, employed to measure
261 metatarsophalangeal joint angular movement. Peak metatarsophalangeal joint dorsiflexion
262 velocities for this study of $1172^\circ/\text{s} \pm 310^\circ/\text{s}$ barefoot and $873^\circ/\text{s} \pm 155^\circ/\text{s}$ are similar to Krell
263 and Stefanyshyn,²¹ who reported peak velocities for the medial aspect of the
264 metatarsophalangeal joint of between 900 and 1300 $^\circ/\text{s}$ for 100 m Olympic athletes, but are
265 higher than Toon et al.,¹¹ who reported values of 531 $^\circ/\text{s}$ to 737 $^\circ/\text{s}$ for barefoot and sprint
266 spikes respectively, as they used the mean of the medial and lateral aspects of the
267 metatarsophalangeal joint. The motion calculated by manually digitising the lateral aspect of
268 the metatarsophalangeal joint, however, is both substantially lower and more variable than
269 that experienced of the medial aspect,¹¹ therefore it is questionable whether combining these
270 aspects for calculating the resultant range of motion and angular velocity of the
271 metatarsophalangeal joint is accurate.

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

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

293 The metatarsophalangeal joint was a large energy absorber and produced little energy
294 during push-off. Although the sprint spikes resulted in reduced energy loss at the
295 metatarsophalangeal joint, compared to the barefoot condition, this was not significant;
296 therefore the hypothesis (3) was rejected. The increased lever length in the sprint spike

297 condition did not amplify the energy absorption at the metatarsophalangeal joint, in fact the
298 increased plantarflexion moment of the metatarsophalangeal joint during the barefoot
299 condition led to increased (although not significant) energy absorption. The sprint spikes did,
300 however, result in increased energy production during push-off, due to a greater moment arm,
301 thus the hypothesis (4) was accepted. Consequently, the stiffer sprint spike condition,
302 compared to the barefoot condition, seemed to increase the effective lever length of the foot
303 about the metatarsophalangeal joint during push-off, which may facilitate effective
304 propulsion. Therefore, sprint spikes appear to enhance metatarsophalangeal joint kinetics, by
305 increasing the total energy generated during the push-off phase. Combined with the
306 restriction of the range of motion at the metatarsophalangeal joint, these two factors may
307 contribute to the improved sprinting performance demonstrated in the sprint spike condition.
308 Despite the controlling influences of the sprint spikes over the angular motion at the
309 metatarsophalangeal joint, it appears that sprint spikes do not reduce the effectiveness of the
310 windlass mechanism and the efficiency of the foot as a lever for propulsion. Conversely, the
311 athletes created more energy during push-off wearing sprint spikes, despite reduced
312 dorsiflexion range of motion at the metatarsophalangeal joint, which suggests substantial
313 rigidity was achieved from the foot and shoe as a system.

314 As active plantarflexion of the toes occurs during the push-off phase of sprinting, the
315 metatarsophalangeal joint should not be ignored in strength and conditioning training. It is
316 suggested that strengthening exercises should not only target the extrinsic foot/ankle muscles
317 (e.g. triceps surae, flexor hallucis longus, flexor digitorum longus), but also include the
318 intrinsic foot muscles (e.g. abductor hallucis and flexor digitorum brevis). Potthast et al.²²
319 demonstrated that a training footwear intervention could initiate biopositive adaptations
320 within the foot, including significantly increased toe flexor strength and reduced
321 metatarsophalangeal joint dorsiflexion in walking gait. These adaptations could potentially be

322 advantageous to sprinting performance, through stiffening of the metatarsophalangeal joint,
323 thereby decreasing deformation of the foot and helping the athlete to propel forwards.

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

345 In summary, this study has demonstrated performance-related differences in
346 metatarsophalangeal joint kinematics and kinetics between barefoot sprinting and when

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

358 **Acknowledgements**

359 None

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361

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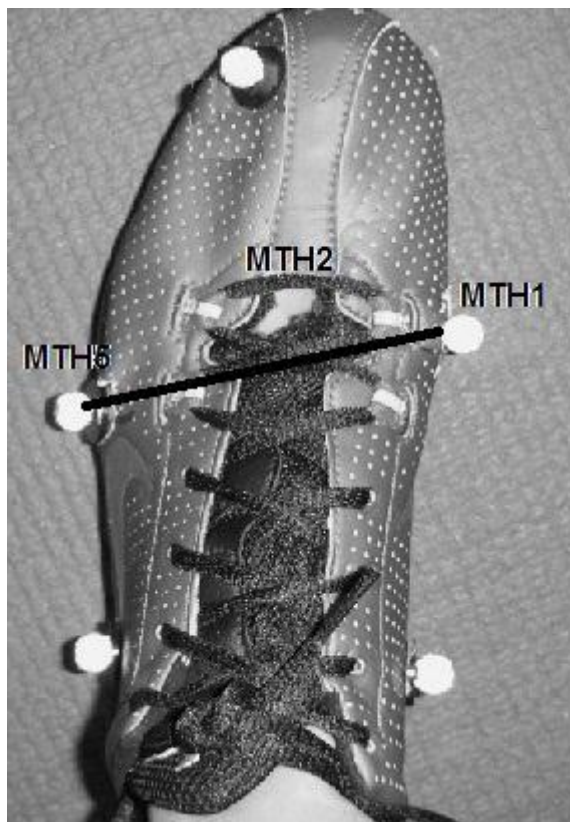
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Figures

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

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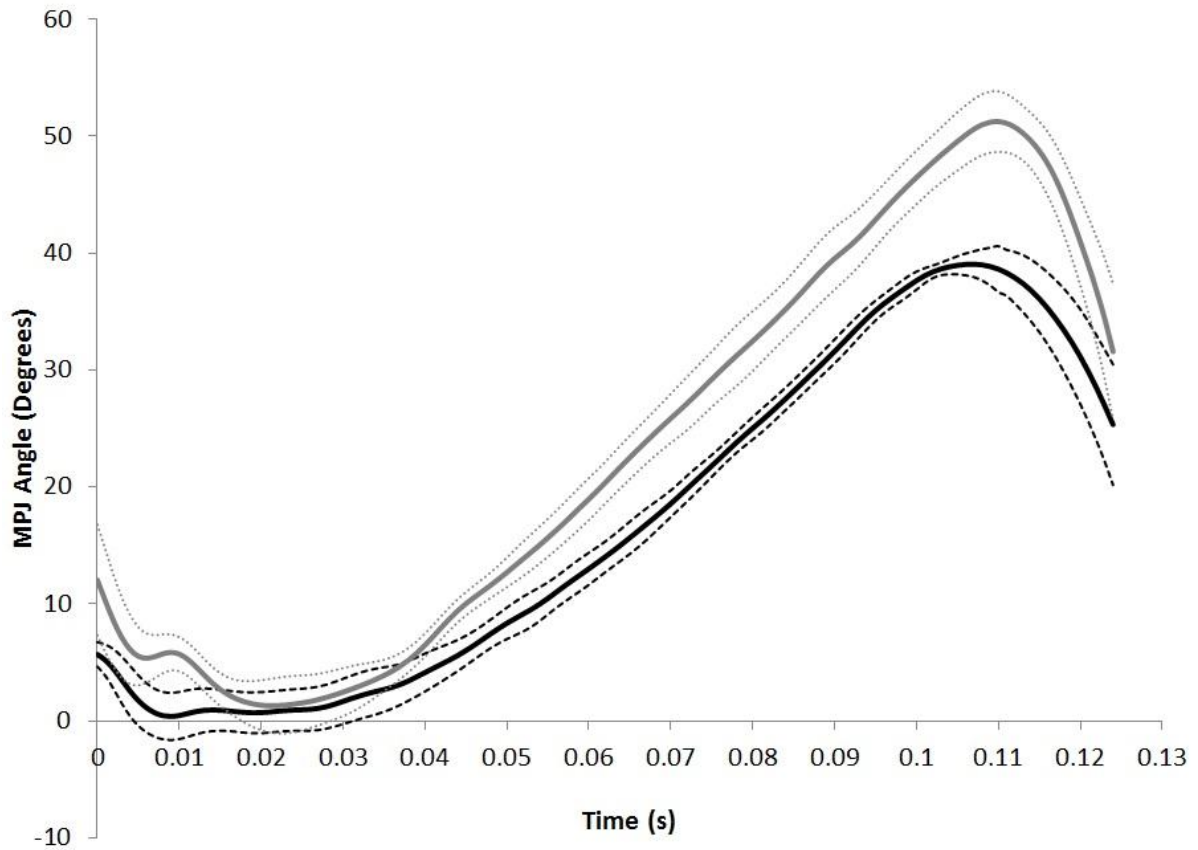
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425 **Figure 2** – Average metatarsophalangeal joint angle throughout the stance phase of sprinting,
 426 mean trace (\pm *SD* lines – dashed) for one female participant sprinting wearing sprint spikes
 427 (black line) and barefoot (grey line).

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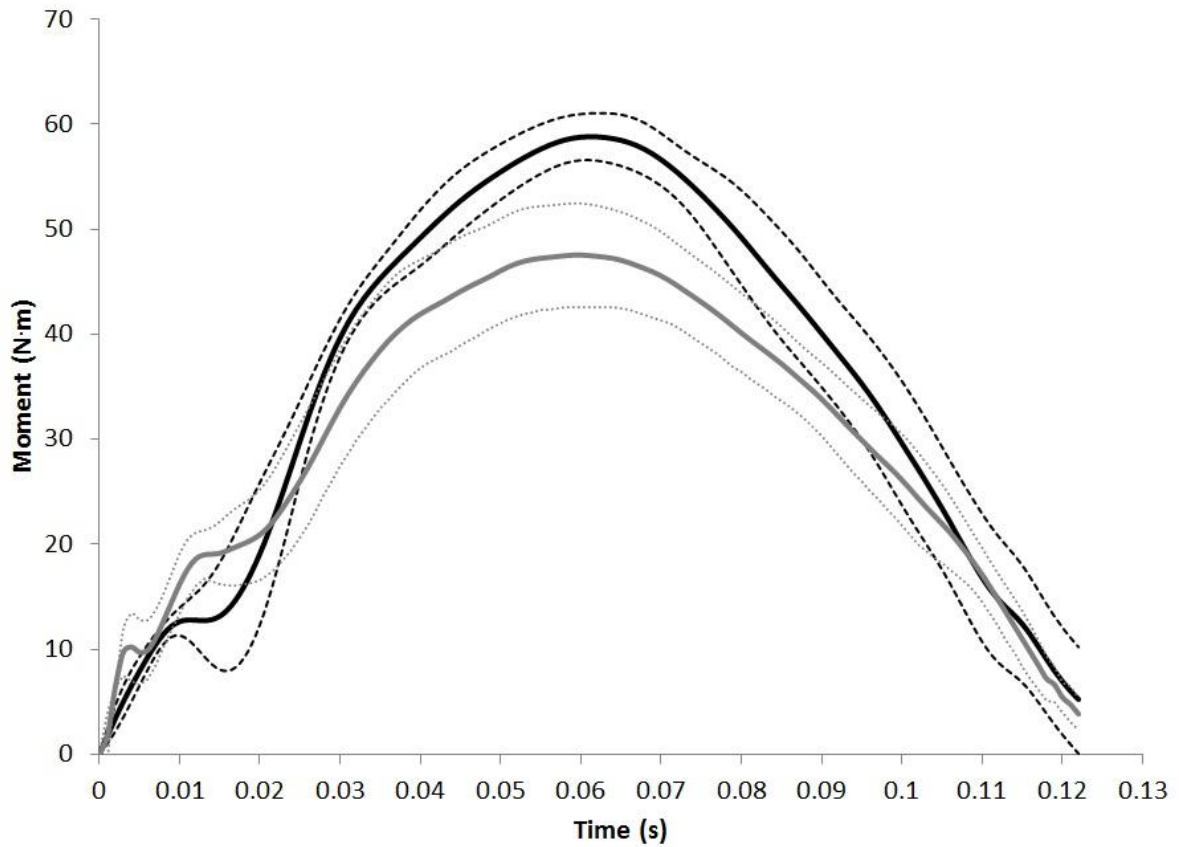
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434 **Figure 3** – Average metatarsophalangeal joint moment during stance for one female
 435 participant, mean trace (\pm *SD* lines – dashed lines) sprinting wearing sprint spikes (black line)
 436 and barefoot (grey line). Joint moment is positive (plantarflexor) during the entire stance
 437 phase as the center of pressure was in front of the metatarsophalangeal joint axis throughout.
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447 **Table 1** Metatarsophalangeal joint kinematics and kinetics for barefoot versus shod
 448 conditions, mean \pm *SD*.

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

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

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

