1 # Effects of barefoot and shod running on lower extremity joint loading, a

2 # musculoskeletal simulation study.

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16 **Abstract**

17 *PURPOSE:* The aim of the current investigation was to utilize a musculoskeletal simulation

18 based approach, to examine the effects of barefoot and shod running on lower extremity joint

19 loading during the stance phase.

METHODS: Twelve male runners, ran over an embedded force plate at 4.0 m/s, in both barefoot and shod conditions. Kinematics of the lower extremities were collected using an eight camera motion capture system. Lower extremity joint loading was also explored using a musculoskeletal simulation and mathematical modelling approach, and differences between footwear conditions were examined using paired samples t-tests.

RESULTS: Peak Achilles tendon force was significantly larger (P=0.039) when running barefoot (6.85 BW) compared to shod (6.07 BW). In addition, both medial (P=0.013) and lateral (P=0.007) tibiofemoral instantaneous load rates were significantly larger in the barefoot (medial = 289.17 BW/s & lateral = 179.59 BW/s) in relation to the shod (medial = 167.57 BW/s & lateral = 116.40 BW/s) condition. Finally, the barefoot condition (9.70 BW) was associated with a significantly larger (P=0.037) peak hip force compared to running shod (8.51 BW).

CONCLUSIONS: The current investigation indicates that running barefoot may place runners at increased risk from the biomechanical factors linked to the aetiology of chronic lower extremity pathologies. However, future analyses using habitual barefoot runners, are required before more definitive affirmations regarding injury predisposition can be made.

Introduction

Running is an extremely popular exercise modality. It has been projected that as many as 2 million people in the UK utilize running as a mode of exercise (1). There is an overwhelming body of evidence, which has emphasized the physiological and psychological benefits of physical activity and exercise (2). However, despite the plethora of physical benefits

42   associated with regular running, it is also associated with a high incidence of chronic

43   pathologies. Each year, up to 80 % of runners will suffer an overuse injury (3).

44

45   The knee joint is most susceptible to chronic pathology in runners (3). Specifically,

46   patellofemoral pain syndrome is the most frequent overuse injury encountered in runners (4),

47   characterized by pain at or anterior to the patella aggravated by physical activities that load

48   the patellofemoral joint (5). Pain symptoms are related to excessive patellofemoral loading

49   and typically persist for many years (6). A recent epidemiological analysis has shown that

50   there may be a link between patellofemoral pain in younger adults and subsequent

51   osteoarthritis at this joint (7). Furthermore, tibiofemoral pathologies are also common chronic

52   running injuries; associated with up to 16.8% of all knee injuries (8). The medial aspect of the

53   tibiofemoral joint is known to be significantly more prone to osteoarthritic degeneration than

54   the lateral compartment (9). The causes of tibiofemoral chronic pathologies relate to the

55   magnitude of the stress loading of the joint (10), which is considered to be the mechanical

56   parameter most strongly associated with the onset and progression of knee osteoarthritis. The

57   mechanism responsible for this is thought to be the increased joint contact forces experienced

58   by the medial compartment of the tibiofemoral joint during locomotion (11). Finally, Achilles

59   tendinopathies are also frequently occurring chronic musculoskeletal disorders in runners,

60   accounting for approximately 8–15% of all injuries (12). The pathogenesis of Achilles

61   tendinopathy is considered to be associated with habitual and excessive mechanical loading

62   of the tendon itself, which creates microscopic tears in the tendons' collagen fibres (13).

63

64   An array of different treatment/ preventative modalities, have therefore been investigated in

65   an attempt to attenuate the risk of running injuries. An extremely popular conservative

66   strategy is to select running trainers with appropriate biomechanical properties, as running

67   shoes are proposed as a mechanism by which the rate of chronic injuries can be controlled

68   (14). Recently however, it has been proposed that running using traditional running shoes

69   may place runners at increased risk from the biomechanical factors linked to the aetiology of

70   chronic running injuries (15). This led to a new proposal in footwear research, that running

71   barefoot footwear may be associated with a reduced incidence of chronic running injuries

72   (15). Based on this hypothesis, a number of runners are now choosing to run barefoot or in

73   minimalist footwear (16, 17).

74

75   In recent years, barefoot running has received considerable research attention in

76   biomechanical literature. Using a mathematical modelling approach driven by sagittal plane

77   external joint torques and knee kinematics, both Bonacci et al., (18) and Sinclair, (19) showed

78   that running barefoot significantly reduced patellofemoral joint loading during the stance

79   phase of running. Furthermore, using external joint torques and ankle joint kinematics,

80   Sinclair, (19) revealed that barefoot running was associated with significantly increased

81   Achilles tendon forces in comparison to running shod. Finally, Sinclair et al., (16) and

82   Sinclair et al., (17) found that barefoot running significantly increased the loading rate of the

83   external vertical ground reaction force. Previous analyses concerning the biomechanical

84   differences between barefoot and shod running, have utilized either the external ground

85   reaction force or joint torque driven mathematical modelling approaches to explore the loads

86   experienced by the musculoskeletal system. However, the external ground reaction force and

87   joint torques represent global indices of joint loading, and therefore are not representative of

88   localized joint loading (20). Herzog et al., (21) showed that muscles are the primary

89   contributors to lower extremity joint loading. Yet the complex role of muscles in controlling

90   joint biomechanics during human movement has received insufficient attention within the

91   literature, possibly due to difficulties in calculating muscle kinetics.

92

93   However, advances in musculoskeletal modelling have led to the development of bespoke

94   software which allows skeletal muscle force distributions to be simulated during movement

95   using motion capture based data (22). To date, such approaches have not yet been utilized to

96   explore biomechanical differences between barefoot and shod running. Therefore, the aim of

97   the current investigation was to examine the effects of barefoot and shod running on lower

98   extremity joint loading using a musculoskeletal simulation based approach. A study of this

99   nature may provide further insight into the biomechanical differences between barefoot and

100   shod running; particularly with regards to runners' susceptibility to chronic pathologies.

101

102   **Methods**

103   *Participants*

104   Twelve healthy male runners, volunteered to take part in this study. All were identified as

105   recreational runners who trained 3 times/week, completing a minimum of 35 km. The

106   participants provided written informed consent in accordance with the principles outlined in

107   the Declaration of Helsinki. The mean characteristics of the participants were; age 24.33 $\pm$

108   4.09 years, height 1.77 $\pm$ 0.09 cm and body mass 75.44 $\pm$ 6.58 kg. The procedure utilized for

109   this investigation was approved by the University of Central Lancashire, Science,

110   Technology, Engineering and Mathematics, ethical committee.

111

Procedure

Participants ran at 4.0 m/s (±5%), striking an embedded piezoelectric force platform (Kistler, Kistler Instruments Ltd., Alton, Hampshire) with their right foot. Running velocity was monitored using infrared timing gates (Newtest, Oy Koulukatu, Finland). The stance phase was delineated as the duration over which 20 N or greater of vertical force was applied to the force platform (23). Runners completed a minimum of five successful trials in both barefoot and shod conditions. The shod condition (New Balance 1260 v2) had an average mass of 0.285 kg, heel thickness of 25 mm and a heel drop of 14 mm. The order that participants ran in each footwear condition was counterbalanced. Kinematics and ground reaction forces data were synchronously collected. Kinematic data was captured at 250 Hz via an eight camera motion analysis system (Qualisys Medical AB, Goteburg, Sweden). Dynamic calibration of the motion capture system was performed before each data collection session.

To define the anatomical frames of the thorax, pelvis, thighs, shanks and feet retroreflective markers were placed at the C7, T12 and xiphoid process landmarks and also positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine (ASIS), posterior super iliac spine (PSIS), medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanter, calcaneus, first metatarsal and fifth metatarsal. Carbon-fibre tracking clusters comprising of four non-linear retroreflective markers were positioned onto the thigh and shank segments. In addition to these the foot segments were tracked via the calcaneus, first metatarsal and fifth metatarsal, the pelvic segment was tracked using the PSIS and ASIS markers and the thorax segment was tracked using the T12, C7 and xiphoid markers. The shod condition was modified by cutting windows into the experimental footwear at the calcaneus, first metatarsal and fifth metatarsal locations in accordance with

136 Shultz & Jenkyn (24). This allowed the anatomical markers at these positions to be placed

137 onto the skin in order to match the barefoot condition (25). Static calibration trials were

138 obtained with the participant in the anatomical position in order for the positions of the

139 anatomical markers to be referenced in relation to the tracking clusters/markers. A static trial

140 was conducted with the participant in the anatomical position in order for the anatomical

141 positions to be referenced in relation to the tracking markers, following which those not

142 required for dynamic data were removed.

143

144 *Processing*

145 Dynamic trials were digitized using Qualisys Track Manager in order to identify anatomical

146 and tracking markers then exported as C3D files to Visual 3D (C-Motion, Germantown, MD,

147 USA). All data were normalized to 100 % of the stance phase. Ground reaction force and

148 kinematic data were smoothed using cut-off frequencies of 50 and 12 Hz with a low-pass

149 Butterworth 4th order zero lag filter (26). All net joint force parameters throughout were

150 normalized by dividing by bodyweight (BW). Kinematic measures from the hip, knee, ankle

151 which were extracted for statistical analysis were 1) angle at footstrike, 2) peak flexion/

152 dorsiflexion during the stance phase and 3) angular range of motion (ROM) from footstrike to

153 peak angle.

154

155 Data during the stance phase were exported from Visual 3D into OpenSim 3.3 software

156 (Simtk.org). A validated musculoskeletal model with 12 segments, 19 degrees of freedom

157 and 92 musculotendon actuators (27) was used to estimate extremity joint forces. The model

158 was scaled for each participant to account for the anthropometrics of each athlete. As muscle

159 forces are the main determinant of joint compressive forces (21), muscle kinetics were

160 quantified using a static optimization in accordance with Steele et al., (28). Compressive

161 medial/ lateral tibiofemoral and hip joint forces were calculated via the joint reaction analyses

162 function using the muscle forces generated from the static optimization process as inputs.

163 Furthermore, medial and lateral tibiofemoral contact stresses (MPa) were quantified by

164 dividing the tibiofemoral force by the medial and lateral contact areas estimated using the

165 data of Kettelkamp and Jacobs, (29). From the above processing, peak medial tibiofemoral

166 force, peak lateral tibiofemoral force, peak hip force, peak medial tibiofemoral stress and

167 peak lateral tibiofemoral stress were extracted for statistical analyses. In addition medial/

168 lateral tibiofemoral and hip instantaneous load rates (BW/s) were also extracted by obtaining

169 the peak increase in force between adjacent data points.

170

171 Patellofemoral loading during the stance phase of running was quantified using a model

172 adapted from van Eijden et al., (30) in accordance with the protocol of Willson et al., (31). A

173 key drawback of this model is that co-contraction of the knee flexor musculature is not

174 accounted for. Taking this into account, summed hamstring and gastrocnemius forces derived

175 from the static optimization procedure were multiplied by their estimated knee joint muscle

176 moment arms as a function of knee flexion angle (32), and then added together to determine

177 the knee flexor torque during the stance phase. In addition to this, the knee extensor torque

178 was also calculated by dividing the summed quadriceps forces by this muscle groups' knee

179 joint muscle moment arms as a function of knee flexion angle (30). The knee flexor and

180 extensor torques were then summed and subsequently divided by the quadriceps muscle

181 moment arm to obtain quadriceps force adjusted for co-contraction of the knee flexor

182 musculature. Patellofemoral force was quantified by multiplying the derived quadriceps force

183 by a constant which was obtained by using the data of Eijden et al., (30). Finally,

184 patellofemoral joint stress (MPa) was quantified by dividing the patellofemoral force by the

185 patellofemoral contact area. Patellofemoral contact areas were obtained by fitting a

186 polynomial curve to the sex specific data of Besier et al., (33), who estimated patellofemoral

187 contact areas as a function of the knee flexion angle using MRI. From the above processing,

188 peak patellofemoral force and peak patellofemoral stress were extracted for statistical

189 analyses. In addition, patellofemoral instantaneous load rate (BW/s) was also extracted by

190 obtaining the peak increase in force between adjacent data points.

191

192 Finally, Achilles tendon forces were estimated in accordance with the protocol of

193 Almonroeder et al., (34), by summing the muscle forces of the medial gastrocnemius, lateral,

194 gastrocnemius, and soleus muscles. From the above processing, peak Achilles tendon force

195 and Achilles tendon instantaneous load rate (BW/s) were extracted for statistical analyses.

196

197 Running barefoot has been shown to alter the step length/ stance time during running (35),

198 which may affect the number of footfalls required to complete a set distance. We therefore

199 firstly calculated integral of the hip, tibiofemoral, patellofemoral and Achilles tendon forces

200 during the stance phase, using a trapezoidal function. In addition to this, we also estimated

201 the total force per mile (BW) by multiplying these parameters by the number of steps

202 required to run a mile. The number of steps required to complete one mile was quantified

203 using the step length (m), which was determined by taking the difference in the horizontal

204 position of the foot centre of mass between the right and left legs at footstrike.

205

206 *Statistical analyses*

207 Means, standard deviations (SD) and 95 % confidence intervals (*95% CI*) were calculated for

208 each outcome measure for both footwear conditions. The data was screened for normality

209 using Shapiro-Wilk tests which confirmed that the normality assumption was met.

210 Differences between footwear conditions were examined using paired samples t-tests, and

211 effect sizes were calculated using partial eta^2 (pη^2). Statistical actions were conducted using

212 SPSS v23.0 (SPSS, USA).

213

214 **Results**

215 *Joint kinematics*

216 The hip was significantly (P=0.017, pη^2 = 0.42) more flexed at footstrike in the shod

217 condition. In addition, peak hip flexion was significantly (P=0.018, pη^2 = 0.41) greater in the

218 shod condition.

219

220 The ankle was significantly (P=0.001, pη^2 = 0.66) more dorsiflexed at footstrike in the shod

221 condition. In addition, peak dorsiflexion was significantly (P=0.0004, pη^2 = 0.69) larger in

222 the shod condition, and ankle ROM was significantly (P=0.032, pη^2 = 0.35) greater in the

223 barefoot condition.

224

225 $@@@$ **TABLE 1 NEAR HERE** $@@@$

226 $@@@$ **FIGURE 1 NEAR HERE** $@@@$

227

228 *Temporal parameters*

229   **@@@ TABLE 2 NEAR HERE @@@**

230

231 Step length was significantly (P=0.001, $p\eta^2 = 0.65$) greater during shod running (Table 2). In

232 addition, the number of steps per mile was significantly (P=0.001, $p\eta^2 = 0.65$) lower in the

233 shod condition (Table 2).

234

235 *Tibiofemoral kinetics*

236 Medial tibiofemoral force instantaneous load rate was significantly larger (P=0.013, $p\eta^2 =$

237 0.33) in the barefoot condition (Table 3). In addition, lateral tibiofemoral force instantaneous

238 load rate was significantly larger (P=0.007, $p\eta^2 = 0.50$) in the barefoot condition (Table 3).

239

240 *Hip kinetics*

241 Peak hip force was significantly larger (P=0.037, $p\eta^2 = 0.34$) in the barefoot condition (Table

242 3; Figure 3e). In addition, hip instantaneous load rate was significantly larger (P=0.002, $p\eta^2 =$

243 0.59) in the barefoot condition (Table 3).

244

245 *Patellofemoral kinetics*

246 No differences (P>0.05) in patellofemoral loading were observed (Table 3-4; Figure 2ab).

247

248 *Achilles tendon kinetics*

249 Peak Achilles tendon force was significantly larger (P=0.039, $p\eta^2 = 0.33$) in the barefoot

250 condition (Table 3; Figure 2c). In addition, Achilles tendon force per mile was significantly

251 larger (P=0.028, $p\eta^2 = 0.37$) in the barefoot condition (Table 4).

252

253

254 **@@@ TABLE 3 NEAR HERE @@@**

255 **@@@ TABLE 4 NEAR HERE @@@**

256 **@@@ FIGURE 2 NEAR HERE @@@**

257 **@@@ FIGURE 3 NEAR HERE @@@**

258

259 **Discussion**

260 The aim of the current examination, was to examine the effects of barefoot and shod running

261 on lower extremity joint loading using a musculoskeletal simulation approach. To the authors

262 knowledge, this represents the first investigation to explore the biomechanical differences

263 between barefoot and shod running using this methodology. This investigation provides

264 further insight into the biomechanical differences between barefoot and shod running.

265

266 A key observation from the current analysis, is that patellofemoral loading parameters were

267 not statistically different between barefoot and shod running. This finding opposes those of

268 Bonacci et al., (18) and Sinclair, (19) who showed significant reductions in patellofemoral

269 loading when running barefoot. It is proposed that this observation may relate to the specific

270 kinematic adjustments that runners made in the current investigation. Typically, when

271 running barefoot the ankle is in a plantarflexed position at footstrike (15-17), and the knee

272 ROM is significantly reduced (19), which effectively attenuates the role of the knee as a

273 shock absorber (19). However, the current investigation showed no differences in knee

274 kinematics when running barefoot, and whilst the ankle angle at footstrike was significantly

275 altered in the barefoot condition, it was still in a dorsiflexed position. As such, it appears that

276 the kinematic adaptations that runners typically make in the absence of footwear were less

277 pronounced in this investigation, which may consequently explain the lack of differences in

278 patellofemoral loading. Additionally, this may relate to the manner in which patellofemoral

279 loading was calculated in the current study, as previous analyses have used mathematical

280 models which do not account for co-contraction of the knee flexors (18, 19). Nonetheless, the

281 current investigation indicates that running barefoot may not always attenuate the

282 patellofemoral loading parameters linked to the aetiology of patellofemoral pain in runners.

283

284 The current investigation also revealed that the rate at which both the medial and lateral

285 aspects of the tibiofemoral joint were loaded, was significantly larger in the barefoot

286 condition. This finding is supported by those of Sinclair et al., (36) who found that the

287 tibiofemoral rate of loading measured using an inverse dynamics based approach was

288 significantly larger when running barefoot, in relation to traditional running trainers. This

289 finding may be important, as increased compressive loading at the tibiofemoral joint, is a risk

290 factor for the onset and progression of osteoarthritis (37). Therefore, the current analysis

291 indicates that running barefoot may increase susceptibility to the risk factors associated with

292 tibiofemoral osteoarthritis.

293

294   A further important observation from the current investigation was that Achilles tendon

295   loading parameters were shown to be significantly larger in the barefoot condition. This

296   observation concurs with those of Sinclair, (19), who similarly showed that Achilles tendon

297   loading was greater when running barefoot. This observation may provide important clinical

298   information in regards to the initiation and progression of Achilles tendinopathy (38). The

299   aetiology of Achilles tendinopathy is mediated through repeated and excessive mechanical

300   loading of the tendon during activities such as running. Repetitive tendon loads such as those

301   initiate collagen and extracellular matrix synthesis and tissue degradation (39). Therefore, the

302   current investigation shows that running barefoot may place runners at increased risk from

303   the biomechanical parameters linked to Achilles tendinopathy.

304

305   In addition, this investigation also showed that peak compressive hip joint loading was

306   significantly larger when running barefoot, in comparison to the shod condition. This study

307   represents the first investigation to contrast hip joint loading during barefoot and shod

308   running using musculoskeletal simulation, therefore comparisons against previous analyses

309   are difficult. However, our findings are partially supported by those of Rooney & Derrick,

310   (40) who showed that non-rearfoot strike runners experienced significantly greater

311   compressive hip joint loading during running. However, in their prospective investigation of

312   running injuries in barefoot and shod runners Altman & Davis, (41) found that hip injuries

313   were statistically more frequent in shod runners. This appears to be contradictory as hip joint

314   pathologies are strongly influenced by compressive hip joint loading (42). It is clear from this

315   observation that further epidemiological research is required concerning the potential clinical

316   influence of running barefoot.

317

318   A potential drawback to the current study is that it examined only habitual shod runners, who

319   do not customarily run barefoot. Previous work examining the biomechanics of running

320   barefoot has drawn conflicting observations, often on the basis of the barefoot running

321   experience of their participants (15-17, 43). It can therefore, be speculated that the results

322   from the current analysis may have been different had a sample of habitual barefoot runners

323   been examined. Therefore, repeating the current investigation using habitual barefoot runners

324   is advisable for future research, which may allow more definitive assertions with regards to

325   injury predisposition to be made. That this study utilized a simulation based procedure to

326   quantify muscles forces and joint loading may also serve as a limitation. Whist this procedure

327   is considered an improvement over previous approaches, in that joint reaction analyses are

328   representative of localized joint loading and muscular co-contraction is accounted for.

329   Musculoskeletal simulations depend on the underlying mathematical model and numerous

330   mechanical assumptions are made in the construction of musculoskeletal simulation models

331   (22). These predominately relate to the constrained rotational degrees of freedom at the knee

332   and ankle joints and the lack of key muscles such as recuts abdominis, which may lead to

333   incorrectly predicted muscle forces. However, as direct quantification of muscle forces are

334   not possible at this time, the current procedure is the most practicable method in dynamic

335   movements.

336

337   In conclusion, although the biomechanics of barefoot running have received extensive

338   research attention; there has yet to be a quantitative comparison of lower extremity joint

339   loading during barefoot and shod running using a musculoskeletal simulation based approach.

340   The present investigation therefore adds to the current knowledge, by providing a

341   comprehensive evaluation of lower extremity joint loading during barefoot and shod running

342   conditions. On the basis that hip, tibiofemoral and Achilles tendon loading parameters were

343 significantly greater when running barefoot, the findings from the current investigation

344 indicate that barefoot running may place runners at increased risk from the biomechanical

345 risk factors linked to the aetiology of chronic lower extremity pathologies. However, future

346 analyses using habitual barefoot runners, are required before more definitive affirmations

347 regarding injury predisposition can be made.

348

349 **Acknowledgements**

350 We thank Gareth Shadwell for his technical assistance.

351

352 **Compliance with ethical standards**

353 *Conflict of interest*

354 We declare that we have no conflict of interest.

355 *Ethical approval*

356 The current research project was approved by an institutional ethical panel. All procedures

357 performed in studies involving human participants were in accordance with the ethical

358 standards of the institutional and the declaration of Helsinki.

359 *Informed consent*

360 All of the subjects provided written consent.

361

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Figures

Figure 1: Joint kinematics as a function of footwear a. = hip, b. = knee and c. = ankle (black = barefoot and grey = shod).

Figure 2: Patellofemoral and Achilles tendon kinetics as a function of footwear a. = patellofemoral force, b. = patellofemoral stress and c. Achilles tendon force (black = barefoot and grey = shod).

Figure 3: Tibiofemoral and hip kinetics as a function of footwear a. = medial tibiofemoral force, b. = medial tibiofemoral stress, c. = lateral tibiofemoral force, d. = lateral tibiofemoral stress and e. = hip force (black = barefoot and grey = shod).

Table 1: Hip, knee and ankle kinematics (Mean, SD and 95% CI's) as a function of footwear.

	Barefoot				Shod				
	Mean	*SD*	95% CI Lower	95% CI Upper	**Mean**	*SD*	95% CI Lower	95% CI Upper	
Hip angle at footstrike (˚)	34.29	12.38	26.42	42.15	42.27	7.77	37.34	47.21	*
Peak hip flexion (˚)	34.84	12.03	27.20	42.49	42.76	7.24	38.16	47.35	*
Hip ROM (˚)	0.56	1.26	0.24	1.36	0.48	1.13	0.22	1.20	
Knee angle at footstrike (˚)	25.05	5.45	21.59	28.52	24.67	9.12	18.88	30.47	
Peak knee flexion (˚)	45.90	4.48	43.05	48.75	47.90	6.41	43.82	51.97	
Knee ROM (˚)	20.85	7.38	16.16	25.54	23.22	8.54	17.80	28.65	
Ankle angle at footstrike (˚)	4.56	6.93	0.15	8.96	12.74	2.62	11.07	14.40	*
Peak dorsiflexion (˚)	18.35	4.17	15.70	21.00	22.82	3.85	20.37	25.26	*
Ankle ROM (˚)	13.80	7.70	8.90	18.69	10.08	4.08	7.49	12.67	*

Key: * = significant difference

Table 2: Peak hip, knee and ankle loading parameters (Mean, SD and 95% CI's) as a function of footwear.

	Barefoot				Shod				
	Mean	*SD*	95% CI Lower	95% CI Upper	**Mean**	*SD*	95% CI Lower	95% CI Upper	
Peak patellofemoral force (BW)	4.32	0.93	3.73	4.91	4.51	1.07	3.83	5.19	
Peak patellofemoral stress (MPa)	5.05	0.93	4.46	5.64	5.14	0.78	4.65	5.63	
Patellofemoral instantaneous load rate (BW/s)	159.55	56.26	123.81	195.29	149.80	56.60	113.84	185.76	
Peak Achilles tendon force (BW)	6.85	1.95	5.61	8.09	6.07	1.22	5.29	6.84	*
Achilles tendon instantaneous load rate (BW/s)	174.17	85.71	119.71	228.63	142.16	32.01	121.83	162.50	
Peak medial tibiofemoral force (BW)	6.53	1.64	5.49	7.57	6.23	1.25	5.44	7.03	
Peak medial tibiofemoral stress (MPa)	12.51	2.75	10.76	14.26	11.77	2.04	10.47	13.07	
Medial tibiofemoral instantaneous load rate (BW/s)	289.17	142.69	198.50	379.83	167.57	77.16	118.54	216.59	*
Peak lateral tibiofemoral force (BW)	4.17	1.09	3.48	4.87	3.94	0.75	3.47	4.42	
Peak lateral tibiofemoral stress (MPa)	13.15	3.56	10.89	15.41	12.32	2.17	10.94	13.70	
Lateral tibiofemoral instantaneous load rate (BW/s)	179.59	60.90	140.89	218.28	116.40	30.13	97.25	135.54	*
Peak hip force (BW)	9.70	1.32	8.86	10.53	8.51	0.94	7.92	9.11	*
Hip instantaneous load rate (BW/s)	377.38	140.49	288.12	466.64	167.25	78.35	117.47	217.03	*

Key: * = significant difference

Table 3: Step characteristics (Mean, SD and 95% CI's) as a function of footwear.

	Barefoot				Shod				
	Mean	*SD*	95% CI Lower	95% CI Upper	**Mean**	*SD*	95% CI Lower	95% CI Upper	
Step length (m)	1.27	0.05	1.24	1.31	1.38	0.06	1.34	1.42	*
Steps per mile	632.42	26.41	615.64	649.19	583.20	24.32	567.75	598.65	*

Key: * = significant difference

	Barefoot				Shod				
	Mean	SD	95% CI Lower	95% CI Upper	Mean	SD	95% CI Lower	95% CI Upper	
Patellofemoral force per mile (BW)	321.49	52.39	288.20	354.77	322.16	84.85	268.25	376.07	
Achilles tendon force per mile (BW)	402.47	93.60	343.00	461.94	356.31	79.19	306.00	406.62	*
Medial tibiofemoral force per mile (BW)	464.62	110.98	394.11	535.14	441.14	81.48	389.38	492.91	
Lateral tibiofemoral force per mile (BW)	283.32	56.09	247.68	318.96	290.12	58.62	252.87	327.37	
Hip force per mile (BW)	854.05	187.03	735.22	972.88	781.19	109.56	711.58	850.80	