1   ***Abstract***

2   *Barefoot running has experienced a resurgence in footwear biomechanics literature, based on*

3   *the supposition that it serves to reduce the occurrence of overuse injuries in comparison to*

4   *conventional shoe models. This consensus has lead footwear manufacturers to develop shoes*

5   *which aim to mimic the mechanics of barefoot locomotion.*

6   *This study compared the impact kinetics and 3-D joint angular kinematics observed whilst*

7   *running: barefoot, in conventional cushioned running shoes and in shoes designed to*

8   *integrate the perceived benefits of barefoot locomotion. The aim of the current investigation*

9   *was therefore to determine whether differences in impact kinetics exist between the footwear*

10   *conditions and whether shoes which aim to simulate barefoot movement patterns can closely*

11   *mimic the 3-D kinematics of barefoot running.*

12   *Twelve participants ran at 4.0 m.s^{-1}±5% in each footwear condition. Angular joint kinematics*

13   *from the hip, knee and ankle in the sagittal, coronal and transverse planes were measured*

14   *using an eight camera motion analysis system. In addition simultaneous tibial acceleration*

15   *and ground reaction forces were obtained. Impact parameters and joint kinematics were*

16   *subsequently compared using repeated measures ANOVAs.*

17   *The kinematic analysis indicates that in comparison to the conventional and barefoot inspired*

18   *shoes that running barefoot was associated significantly greater plantar-flexion at footstrike*

19   *and range of motion to peak dorsiflexion. Furthermore, the kinetic analysis revealed that*

20   *compared to the conventional footwear impact parameters were significantly greater in the*

21   *barefoot condition.*

22   *Therefore this study suggests that barefoot running is associated with impact kinetics linked*

23   *to an increased risk of overuse injury, when compared to conventional shod running.*

24   *Furthermore, the mechanics of the shoes which aim to simulate barefoot movement patterns*

25   *do not appear to closely mimic the kinematics of barefoot locomotion.*

Introduction

In recent years the concept of barefoot running has been the subject of much attention in footwear biomechanics literature. Furthermore, a number of well known athletes have competed barefoot, most notably Zola Budd-Pieterse and the Abebe Bikila who both held world records for the 5000m and marathon events respectively. This demonstrates that barefoot running does not appear to prevent athletes from competing at the highest levels (Warburton 2001). Barefoot locomotion presents a paradox in footwear literature (Robbins and Hanna 1987); and has been used for many years both by coaches and athletes (Nigg 2009) based around the supposition that running shoes are associated with an increased incidence of running injuries (Lieberman et al., 2010, Robbins and Hanna 1987; Warburton 2001).

Based on such research and taking into account the barefoot movement's recent rise in popularity, shoes have been designed in an attempt to transfer the perceived advantages of barefoot movement into a shod condition (Nigg 2009). Yet, given the popularity of barefoot running, surprisingly few investigations have specifically examined the both the impact kinetics and 3-D kinematics of the lower extremities of running barefoot and in barefoot inspired footwear in comparison to shod. Furthermore, there is a paucity of research reporting the prospective epidemiological investigations into the aetiology of injury in runners and how footwear may affect the frequency of injury. This study provides a comparison of the kinetics and 3-D kinematics of running: barefoot, in conventional running shoes and in barefoot inspired footwear, in order to highlight the differences among conditions.

The aim of the current investigation was therefore to determine 1: whether differences in impact kinetics during running exist between the footwear conditions and 2: whether shoes

50 which aim to simulate barefoot movement patterns can closely mimic the 3-D kinematics of

51 barefoot running.

52

53 *Methods*

54 *Participants*

55 The procedure utilized for this investigation was approved by the University of Central

56 Lancashire, School of Psychology, ethical committee. Twelve experienced male runners

57 completing at least 30 km per week, volunteered to take part in this study. All were injury free

58 at the time of data collection and provided written informed consent. The mean characteristics

59 of the participants were; age 24.34 ± 1.10 years, height 178.10 ± 5.20 cm and body mass

60 76.79 ± 8.96 kg. A statistical power analysis was conducted using G* Power Software using a

61 moderate effect size (Erdfelder et al., 1996), to reduce the likelihood of a type II error and

62 determine the minimum number participants needed for this investigation. It was found that

63 the sample size was sufficient to provide more than 80% statistical power.

64

65 *Procedure*

66 Participants ran at 4.0 m.s^{-1} over a force plate (Kistler, Kistler Instruments Ltd., Alton,

67 Hampshire) embedded in the floor (Altrosports 6mm, Altro Ltd,) of a 22 m biomechanics

68 laboratory. Running velocity was quantified using Newtest 300 infrared timing gates

69 (Newtest, Oy Koulukatu, Finland), a maximum deviation of $\pm5\%$ from the set velocity was

70 allowed. Stance time was defined as the time over which 20 N or greater of vertical force was

71 applied to the force platform (Sinclair et al., 2011). A successful trial was defined as one

72 within the specified velocity range, where all tracking clusters were in view of the cameras,

73 the foot made full contact with the force plate and no evidence of gait modifications due to

74 the experimental conditions. Runners completed a minimum of six successful trials in each

75 footwear condition. Participants were non-habitual barefoot runners and were thus given time

76 to accommodate to the barefoot and barefoot inspired footwear prior to the commencement of

77 data collection. This involved 5 minutes of running through the testing area without concern

78 for striking the force platform.

79

80 Kinematics and tibial acceleration data were also synchronously collected. Kinematic data

81 was captured at 250 Hz via an eight camera motion analysis system (Qualisys Medical AB,

82 Goteburg, Sweden). Calibration of the system was performed before each data collection

83 session. Only calibrations which produced average residuals of less than 0.85 mm for each

84 camera for a 750.5 mm wand length and points above 3000 in all cameras were accepted prior

85 to data collection.

86

87 The marker set used for the study was based on the calibrated anatomical systems technique

88 (CAST) (Cappozo et al., (1995). In order to define the right foot, shank and thigh retro-

89 reflective markers were attached unilaterally to the 1st and 5th metatarsal heads, medial and

90 lateral maleoli, medial and lateral epicondyle of the femur and greater trochanter. To define

91 the pelvis additional retro-reflective markers were placed on the anterior (ASIS) and posterior

92 (PSIS) superior iliac spines. Rigid tracking clusters were positioned on the shank and thigh.

93 Each rigid cluster comprised four 19mm diameter spherical reflective markers mounted to a

94 thin sheath of lightweight carbon fibre with length to width ratios in accordance with

95 Cappozzo et al., (1997). A static trial was conducted with the participant in the anatomical

96 position in order for the positions of the anatomical markers to be referenced in relation to the

97 tracking clusters, following which they were removed.

98 A tri-axial (Biometrics ACL 300, Gwent United Kingdom) accelerometer sampling at 1000Hz

99 was utilized to measure axial accelerations at the tibia. The device was mounted on a piece of

100 lightweight carbon-fibre material using the protocol outlined by Sinclair et al., (2010). The

101 combined weight of the accelerometer and mounting instrument was 9g. The voltage

102 sensitivity of the signal was set to 100mV/g, allowing adequate sensitivity with a

103 measurement range of $\pm$ 100 g. The device was attached securely to the distal anterio-medial

104 aspect of the tibia in alignment with its longitudinal axis 8 cm above the medial maleolus.

105 This location was selected to attenuate the influence ankle rotation can have on the

106 acceleration magnitude (Lafortune & Hennig, 1991). Strong non-stretch adhesive tape was

107 placed over the device and leg to avoid overestimating the acceleration due to tissue artefact.

108

109 *Data Processing*

110 Trials were processed in Qualisys Track Manager in order to identify anatomical and tracking

111 markers then exported as C3D files. Kinematic parameters were quantified using Visual 3-D

112 (C-Motion Inc, Gaithersburg, USA) after marker data were smoothed using a low-pass

113 Butterworth 4th order zero-lag filter at a cut off frequency of 10Hz. This frequency was

114 selected as being the frequency at which 95% of the signal power was below. 3-D kinematics

115 of the hip knee and ankle joints were calculated using an XYZ cardan sequence of rotations

116 (where X is flexion-extension; Y is ab-adduction and is Z is internal-external rotation). All data

117 were normalized to 100% of the stance phase then processed gait trials were averaged. 3-D

118 kinematic measures from the hip, knee and ankle which were extracted for statistical analysis

119 were 1) angle at footstrike, 2) angle at toe-off, 3) range of motion during stance, 4) peak angle

120 during stance and 5) relative range of motion from footstrike to peak angle.

121 The acceleration signal was filtered using a 60 Hz Butterworth zero-lag 4th order low pass

122 filter in accordance with the Lafortune and Hennig, (1992) recommendations to prevent any

123 resonance effects on the acceleration signal. Peak positive axial tibial acceleration was

124   defined as the highest positive acceleration peak measured during the stance phase. To

125   analyze data in the frequency domain, a fast fourier transformation function was performed

126   and median power frequency content of the acceleration signals were calculated.

127   Forces were reported in bodyweights (BWs) to allow normalisation of the data among

128   participants. From the force plate data, peak braking and propulsive forces, stance time,

129   average loading rate, instantaneous loading rate, peak impact force and time to peak impact

130   were calculated. Average loading rate was calculated by dividing the impact peak magnitude

131   by the time to the impact peak. Instantaneous loading rate was quantified as the maximum

132   increase in vertical force between frequency intervals.

133

134   *Shoes*

135   The shoes utilized during this study consisted of a Saucony Pro Grid Guide 2 and a Nike Free

136   3.0. The shoes were the same for all runners; they differed in size only (sizes 6, 7 and 9 in

137   men's shoe UK sizes).

138

139   *Statistical Analysis*

140   Descriptive statistics including means and standard deviations of 3-D kinematic, impact shock

141   and impact force parameters were calculated for each footwear condition. Differences

142   between the parameters were examined using repeated measures ANOVA's with significance

143   accepted at the $p \leq 0.05$ level. Appropriate post-hoc analyses were conducted using a

144   Bonferroni correction to control for type I error. Effect sizes were calculated using a μ^2. If the

145   sphericity assumption was violated then the degrees of freedom were adjusted using the

146   Greenhouse Geisser correction. The Shapiro-Wilk statistic for each footwear condition

147 confirmed that all data were normally distributed. All statistical procedures were conducted

148 using SPSS 19.0 (SPSS Inc, Chicago, USA).

149

150 Results

151 Figure 1 presents the mean 3-D angular kinematics of the hip, knee and ankle joints during

152 the stance phase. Tables 1-4 present the kinetic and 3-D kinematic parameters observed as a

153 function of footwear.

154

155 Kinetic Results

156

157 @@@TABLE 1 NEAR HERE@@@

158 The results indicate that a significant main effect was observed for the instantaneous loading

159 rate $F_{(1.08, 11.88)}$, $= 20.05$, $p \leq 0.01$, $\mu^2 = 0.65$. Post-hoc analyses revealed that the instantaneous

160 loading rate was significantly higher in the barefoot condition in comparison to the footwear

161 designed to simulate barefoot locomotion (p=0.011) and conventional shoe (p=0.001)

162 conditions). Furthermore the post-hoc analysis also showed that the footwear designed to

163 simulate barefoot locomotion was associated with a significantly (p=0.001) higher instantaneous

164 loading rate than the conventional shoe condition. In addition a significant main effect was also

165 observed for the average loading rate $F_{(1.08, 11.84)} = 9.19$, $p \leq 0.01$, $\mu^2 = 0.46$. Post-hoc analyses

166 revealed that the average loading rate was significantly lower in the conventional shoe condition

167 in comparison to the shoes designed to simulate barefoot running (p=0.004) and barefoot

168 conditions (p=0.02) which did not differ significantly (p=0.084) from one another. A significant

169 main effect was observed for the time to impact peak $F_{(1.23, 13.58)} = 7.94$, $p \leq 0.01$, $\mu^2 = 0.41$. Post-

170   hoc analyses revealed that the time to impact peak was significantly greater in the conventional

171   shoe condition in comparison to the shoes designed to simulate barefoot running (p=0.006) and

172   barefoot (p=0.042) conditions which did not differ significantly (p=0.504) from one another.

173   Finally, a significant main effect $F_{(1.21, 13.35)} = 15.81$, $p \leq 0.01$, $\mu^2 = 0.59$ was found for the

174   magnitude of peak axial impact shock. Post-hoc analysis revealed that peak impact shock was

175   significantly greater in the barefoot p=0.021 and shoes designed to simulate barefoot running

176   p=0.01 conditions in comparison to the conventional shoe condition. The spectral analysis of the

177   acceleration signal revealed that a significant main effect $F_{(1.29, 14.14)}$ 14.09, $p \leq 0.01$, $\mu^2 = 0.56$

178   existed for the median frequency content. Post-hoc analysis revealed that the conventional shoe

179   condition was associated with a significantly lower frequency content than the barefoot p=0.001

180   and shoes designed to simulate barefoot conditions p=0.0001. No significant differences were

181   observed between the barefoot and shoes designed to simulate barefoot conditions p=0.35.

182   Finally, a significant main effect $F_{(2, 22)} = 8.10$, $p \leq 0.01$, $\mu^2 = 0.42$ was found for the stance time

183   duration. Post-hoc analysis revealed that stance times were significantly shorter in the barefoot

184   p=0.003 and the shoes designed to simulate barefoot p=0.008 conditions in comparison to the

185   conventional shoe condition. No significant differences p=0.512 were found between the

186   barefoot and shoes designed to simulate barefoot running.

187

188

189   Kinematic results

190   @@@FIGURE 1 NEAR HERE@@@

191

192   Hip

193   @@@TABLE 2 NEAR HERE@@@

194   A significant main effect $F_{(1.25, 13.73)} = 5.24$, $p \leq 0.05$, $\mu^2 = 0.32$ was found for peak flexion.

195   Post-hoc analysis revealed that peak flexion was significantly $p=0.039$ greater in the

196   conventional shoe condition, in comparison to the barefoot condition.

197

198   Knee

199   @@@TABLE 3 NEAR HERE@@@

200   No significant ($p \leq 0.05$) differences were in knee joint kinematics were found among footwear

201   conditions.

202

203   Ankle

204   @@@TABLE 4 NEAR HERE@@@

205   A significant main effect $F_{(2, 22)} = 7.91$, $p \leq 0.01$, $\mu^2 = 0.42$ was observed for the magnitude of

206   plantarflexion at foot strike. Post-hoc analysis revealed that in the barefoot condition the ankle

207   was significantly more plantar flexed than in both the conventional $p=0.01$ and the shoes

208   designed to simulate barefoot running $p=0.015$. A significant main effect $F_{(1.06, 11.66)} = 8.23$,

209    $p \leq 0.01$, $\mu^2 = 0.43$ existed for the range of movement from footstrike to peak dorsiflexion. Post-

210   hoc analyses revealed that this motion was significantly greater in the barefoot condition in

211   comparison to the barefoot inspired footwear $p=0.011$ and conventional shoe $p=0.013$

212   conditions.

213

214   The results indicate that a significant main effect $F_{(2, 22)} = 7.23$, $p \leq 0.01$, $Eta^2 = 0.40$ exists for

215   the magnitude of peak axial rotation. Post-hoc analysis revealed that the barefoot condition

216 was significantly p=0.001 more externally rotated in comparison to the shoes designed to

217 simulate barefoot running. The results indicate that a significant main effect $F_{(2, 22)} = 6.09$,

218 $p \leq 0.01$, $\mu^2 = 0.36$ exists for the magnitude of axial rotation at toe-off. Post-hoc analysis

219 revealed that external rotation was significantly p=0.001 greater in the barefoot condition in

220 comparison to the shoes designed to simulate barefoot running.

221

222 *Discussion*

223 This study represents is the first to examine synchronously examine alterations in 3-D

224 kinematics, force and axial impact shock associated with running barefoot, in conventional

225 footwear and in footwear designed to simulate barefoot running.

226

227 The results from the kinetic analysis indicate that the conventional shoes were associated with

228 lower impact parameters than running barefoot. This finding corresponds with the results of

229 previous investigations (Dickinson et al., 1985, De Koning and Nigg 1993, De Clercq et al.,

230 1994 and De Wit et al., 2000) who reported significantly greater impact parameters when

231 running barefoot. This however opposes the findings of Squadrone and Gallozzi (2009) and

232 Lieberman et al., (2010) who observed that those running barefoot were associated with

233 smaller collision forces than shod. Moreover, that instantaneous loading rate was found to be

234 significantly greater in the barefoot condition in comparison to the barefoot inspired shoes

235 opposes the findings of Squadrone and Gallozzi (2009) who reported that impact forces did

236 not differ significantly between barefoot and barefoot inspired footwear. These observations

237 may relate to the differences in barefoot running experience between studies. Squadrone and

238 Gallozzi (2009) and Lieberman et al., (2010) utilized habitual barefoot runner which is in

239 contrast to the non-habitual barefoot runners examined in the current investigation. Therefore

240 the kinetic observations in barefoot analyses may relate to the experience of the participants in

241   barefoot locomotion, this is an interesting notion and future research may wish to replicate the

242   current investigation using habitually barefoot runners.

243

244   The results also indicate that stance times were significantly shorter whilst running barefoot

245   and in barefoot inspired footwear in comparison to the conventional running shoe condition.

246   This also corresponds with previous investigations with respect to shorter stance times being

247   associated with barefoot running (De Wit et al., 2000, Warburton 2001). Furthermore it would

248   also appear to confirm that the barefoot condition was associated with a greater step

249   frequency/reduced step lengths, as De Wit et al., (2000) found stance times to be strongly

250   correlated with step length. With respect to the hip joint complex, in the sagittal plane a

251   significant increase in peak flexion during the early stance phase was found in the

252   conventional shoe condition in comparison to the barefoot condition. It is surmised that this

253   finding is attributable to the mechanical alterations that runners make when running barefoot

254   (as described above). Runners traditionally take longer steps when running in traditional

255   footwear, so their centre of mass moves through a greater horizontal displacement during each

256   step. As such, during early stance the hip must flex to a greater extent in order to reduce the

257   horizontal distance from the stance leg to the centre of mass to maintain balance during the

258   early stance phase.

259

260   The results indicate that the ankle was significantly more plantar flexed at initial contact in

261   the barefoot condition in comparison to the conventional shoe and barefoot inspired footwear,

262   suggesting a mid or forefoot strike pattern. This concurs with the findings of (De Wit et al.,

263   2000, Hartveld and Chockalingam 2001 and Griffin et al., 2007) findings. Barefoot running or

264   running in shoes with less midsole cushioning is proposed to facilitate increases in plantar

265   discomfort which are sensed and moderated (Robbins and Gouw, 1991). Footwear with

266   greater cushioning i.e. the conventional and barefoot inspired footwear conditions provoke a

267   reduction in shock-moderating behaviour as evidenced by the increased dorsiflexion angle at

268   footstrike (Robbins and Hanna, 1987; Robbins et al., 1989; Robbins and Gouw, 1991). This

269   may lend support to the supposition that the body adapts to a lack of cushioning via kinematic

270   measures. However, it appears that these measures do not offer the same shock attenuating

271   properties as do cushioned midsoles found in conventional footwear.

272

273   The increase in plantarflexion at footstrike associated with barefoot running is considered to

274   be the primary mechanism by which runners adjust to this condition (De Wit et al., 2000,

275   Warburton 2001 and Griffin et al., 2007). Thus, it appears that the barefoot inspired footwear

276   do not closely mimic the kinematics of barefoot running with respect to the ankle joint

277   complex. It is proposed that this finding is attributable to the perceptual effects of increased

278   cushioning in the barefoot inspired footwear which were found to have increased shock

279   attenuating properties. This finding opposes the observations of Squadrone and Gallozzi

280   (2009) who found that barefoot inspired footwear where effective in imitating barefoot

281   conditions. However, Squadrone and Gallozzi (2009) utilized the vibram five-fingers which

282   are characterized by their minimalist features in contrast to the Nike Free footwear utilized in

283   the current investigation which aims to simulate barefoot locomotion through a flexible

284   outsole construction. BAREFOOT SHOES ARE NOT ALL THE SAME THEREFORE

285   Future research is necessary to examine the efficacy of the various conceptual shoe models

286   which aim to replicate barefoot locomotion.

287

288   Interestingly, no significant differences were found between the three footwear conditions, in

289   terms of the peak eversion magnitude during stance. This is appears to oppose the findings of

290   Warburton (2001), Shorten (2000), Edington et al,. (1990), Stacoff et al., (1991) and Smith et

291   al., (1986) who reported that ankle eversion is greater during shod running. Greater ankle

292   eversion is reputed to be due to a reduction in stability caused by the cushioned midsole

293   (Shorten 2000). However like most modern footwear, both the conventional and barefoot

294   inspired footwear encompass features stiffer cushioning, stiff heel counters, insole boards,

295   medially posted midsoles, varus wedges designed to control excessive ankle eversion.

296   Therefore, whilst it appears logical that cushioning will lead to increased ankle eversion the

297   results of this investigation suggest that a combination of cushioning and features designed to

298   control pronation can be effective.

299

300   There is a paucity of research directly comparing injury rates in shod and barefoot running.

301   However, the findings of this study in conjunction with epidemiological analyses suggest that

302   running in conventional footwear may lower the incidence of impact related overuse injuries

303   as increases in impact parameters have been linked to the aetiology of a number overuse

304   pathologies (Hardin et al., 2003; Misevich and Cavanagh 1984). Furthermore, the results of

305   the kinetic analysis suggest that the barefoot inspired footwear offer shock attenuating

306   properties that are superior to barefoot conditions, but inferior to the conventiofnal running

307   shoe. Thus it appears based on the findings from the impact kinetic analysis that the footwear

308   designed to mimic barefoot running places runners at greater risk of musculoskeletal injuries

309   compared to the conventional footwear but lesser risk in comparison to barefoot running at

310   comparable velocities.

311

312　That this investigation quantified barefoot locomotion with skin mounted markers and shod

313　motion using shoe mounted markers may serve as a limitation of the current investigation.

314　There is almost certain be movement of the foot within the shoe, thus it is questionable as to

315　whether anatomical markers located on the shoe provide comparable results to those placed

316　on the foot itself Stacoff et al., (1992). However, given that cutting holes in the shoes in order

317　to attach markers to skin would likely cause further problems by compromising the structural

318　integrity of the upper, it was determined that the current technique was the most appropriate.

319

320　In conclusion although previous studies have compared barefoot and shod running, the current

321　knowledge with respect to the degree in which these modalities differ is limited. The present

322　study adds to the current knowledge of barefoot running by providing a comprehensive kinetic

323　and 3-D kinematic evaluation. Furthermore, this study is the first to contrast synchronous 3-D

324　kinematic and kinetic variables against barefoot inspired footwear. Given that significant

325　differences were observed between running barefoot and in barefoot inspired footwear, it was

326　determined that they do not closely mimic the mechanics of barefoot running. Future research

327　will serve to determine the efficacy of footwear designed to mimic barefoot running. Finally,

328　although further investigation is necessary it appears in this case that conventional shod running

329　is superior to both barefoot running and shoes designed to mimic barefoot running, in terms of

330　protection from running injuries. Future research should focus on prospective epidemiological

331　analyses and the influence of different conditions footwear on the aetiology of running injuries.

332

333

334

335

336

337

338

339

340

341

342

343

344

345

346

347

348 **<u>References</u>**

349 1. Cappozzo A, Catani F, Leardini A, Benedeti MG and Della CU (1995). Position and
350   orientation in space of bones during movement: Anatomical frame definition and
351   determination. Clinical Biomechanics, **10**, p 171-178.

352 2. Cappozzo, A. Cappello, A Della-Croce U and Pensalfini F (1997). Surface-marker
353   cluster design criteria for 3-D bone movement reconstruction, IEEE Transactions on
354   Biomedical Engineering, **44**, p 1165-1174.

355 3. De Koning J and Nigg B (1993). Kinematic factors affecting initial peak vertical ground reaction forces in running. In XIVth Congress of the International Symposium of Biomechanics France.

358 4. De Clerq D, Aerts P and Kunnon M (1994). The mechanical characteristics of the heel pad during foot strike in running: An in vivo cineradiographic study. Journal of Biomechanics, **27**, p 1213-1222.

361 5. De wit B, De Clerq D and Aerts P (2000). Biomechanical analysis of the stance phase during barefoot and shod running. Journal of Biomechanics, **33**, p 269-279.

363 6. Dickinson, J.A., Cook, S.D., Leinhardt, T.M. (1985). The measurement of shock waves following heel strike while running. Journal of Biomechanics, **18**, p 415-22.

365 7. Edington CJ, Frederick EC and Cavanagh PR (1990). Rearfoot motion in distance running. In: Cavanagh P.R ed Bimechanics of distance running. Human Kinetics, Champaign, IL.

368 8. Erdfelder, E., Faul, F., Buchner, A., (1996). G*Power: A general power analysis program. Behaviour Research Methods Instruments and Computers, **28**, p 1–11.

370 9. Griffin JR, Mercer JA and Dufek JS (2007). Kinematic comparison of running barefoot and in the barefoot shoe Free 5.0. Medicine and Science in Sports and Exercise, **39**, S73.

373 10. Hardin EC, Van Den Bogert AJ and Hamill J (2004). Kinematic adaptations during running: Effects of footwear, surface and duration. Medicine and Science in Sports and Exercise, **36**, p 838-844.

376 11. Hartveld A and Chockalingam N (2003) Shock absorption during jumping barefoot and in shoes. International Journal of Podiatric Biomechanics, **1**, p16-20.

378 12. Lafortune, M. A., Hennig, E. M. 1991. Contribution of angular motion and gravity to tibial acceleration. Medicine and Science in Sports and Exercise, **23**, p360-363.

380

381 13. Lafortune, M. A., Hennig, E. M. 1992. Cushioning properties of footwear during

382   walking: accelerometer and force platform measurements, Clinical Biomechanics, **7**,

383   p181-184.

384 14. Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, D'Andrea S, Davis IS,

385   Mang'eni RO, Pitsiladis Y. (2010) Foot strike patterns and collision forces in

386   habitually barefoot versus shod runners. Nature, **463**, p531-535.

387 15. Misevich KW and Cavanagh R (1984). Material aspects of modelling shoe/foot

388   interaction. In: Frederick, E.C. Editor. Sport Shoes and Playing Surfaces. Human

389   Kinetics Publishers, Champaign, IL, p 1–23.

390 16. Nigg B (2009). Biomechanical considerations on barefoot movement and barefoot

391   shoe concepts. Footwear Science, 1, 73-79.

392 17. Robbins SE and Gouw GJ (1991). Athletic footwear: Unsafe due to perceptual illusions.

393   Medicine and Science in Sports and Exercise, **22**, p 217-224.

394 18. Robbins SE, Gouw GJ and Hanna AM (1989). Running related injury prevention

395   through innate impact moderating behaviour, Medicine and Science in Sports and

396   Exercise, **21**, 130-139.

397 19. Robbins and Hanna (1987). Running Related Injury Prevention Through barefoot

398   Adaptations, Medicine and Science in Sports and Exercise, **19**, p148-156.

399 20. Shorten MA (2000). Running shoe design: protection and performance pp 159-169 in

400   Marathon Medicine (Ed. D. Tunstall Pedoe) London, Royal Society of Medicine.

401 21. Sinclair, J., Bottoms, L., Taylor, K. & Greenhalgh, A (2010). Tibial shock measured

402   during the fencing lunge: the influence of footwear. Sports Biomechanics, **9**, 65-71.

403 22. Smith L, Clarke T, Hamill C and Santopierto F (1986). The effect of soft and semi-rigid

404   orthoses upon rearfoot movement in running. Podiatric sports medicine, **76**, p 227-233.

405   23. Squadrone., R, Gallozzi., C (2009). Biomechanical and physiological comparison of

406   barefoot and two shod conditions in experienced barefoot runners. Journal of Sports

407   Medicine and Physical Fitness, **49**, p 6-13.

408   24. Stacoff, A., Kaelin, X., Stussi, E (1991). The effects of shoes on the torsion and rearfoot

409   motion in running. Medicine and Science in Sports and Exercise**, 23,** p 482-490.

410   25. Warburton M (2001). Training and performance - barefoot running. Sport science, 5.

411   26. Willy RW and Davis IMS (2009). Kinematic and Kinetic Comparison of Running in a

412   Neutral Cushioned Shoe and a Minimal Shoe, Medicine and Science in Sports and

413   Exercise, **41**, p 390-391.