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Title: Understanding the effect of touchdown distance and ankle joint kinematics on sprint acceleration performance through computer simulation

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1　**Abstract**

2　This study determined the effects of simulated technique manipulations on early acceleration

3　performance. A planar seven-segment angle-driven model was developed and quantitatively

4　evaluated based on the agreement of its output to empirical data from an international-level

5　male sprinter (100 m personal best = 10.28 s). The model was then applied to independently

6　assess the effects of manipulating touchdown distance (horizontal distance between the foot

7　and centre of mass) and range of ankle joint dorsiflexion during early stance on horizontal

8　external power production during stance. The model matched the empirical data with a mean

9　difference of 5.2%. When the foot was placed progressively further forward at touchdown,

10　horizontal power production continually reduced. When the foot was placed further back,

11　power production initially increased (a peak increase of 0.7% occurred at 0.02 m further

12　back) but decreased as the foot continued to touchdown further back. When the range of

13　dorsiflexion during early stance was reduced, exponential increases in performance were

14　observed. Increasing negative touchdown distance directs the ground reaction force more

15　horizontally; however, a limit to the associated performance benefit exists. Reducing

16　dorsiflexion, which required achievable increases in the peak ankle plantar flexor moment,

17　appears potentially beneficial for improving early acceleration performance.

18

19　200 words.

20

21　*Keywords***:** kinematics, kinetics, modelling, sprinting, technique

22

Introduction

Sprinting is a pure athletic endeavour where overall performance is determined by the ability to cover a short distance in the least possible time. The margins of success in international sprinting are often small and technique adjustments which could result in slight performance improvements are therefore of great interest to coaches and athletes. It has been demonstrated that the production of maximum external power from the very first step of a sprint is the most favourable strategy for optimum overall sprint performance (de Koning, de Groot, & van Ingen Schenau, 1992; van Ingen Schenau, de Koning, & de Groot, 1994; van Ingen Schenau, Jacobs, & de Koning, 1991). The techniques associated with a powerful early acceleration phase are therefore of clear relevance to overall sprint performance.

Empirical research has recently supported the importance of technical ability for early acceleration performance (Kugler & Janshen, 2010; Morin, Edouard, & Samozino, 2011; Rabita et al., 2015). These studies identified that the ability to direct the resultant ground reaction force (GRF) vector in a more horizontal direction was associated with higher levels of sprint acceleration performance, whereas the magnitude of the GRF vector was not. Furthermore, Kugler and Janshen (2010) suggested that a greater negative touchdown distance, i.e. planting the stance foot more posterior relative to the centre of mass (CM) at touchdown, facilitated a forward leaning position and the generation of greater horizontal propulsive forces. The knee joint has been linked to forward lean during the first stance phase (Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2013) and knee extensor moments and powers have recently been identified as an important feature of the first stance phase in well-trained and international-level sprinters (Bezodis, Salo, & Trewartha, 2014; Charalambous, Irwin, Bezodis, & Kerwin, 2012; Debaere et al., 2013). It is therefore possible that any effects of touchdown distance on early acceleration performance are related to knee joint mechanics

48   at touchdown. Whilst it has been proposed that a large negative touchdown distance is

49   favourable for early acceleration performance (Bezodis, Salo, & Trewartha, 2008; Kugler &

50   Janshen, 2010), this has only been based on descriptive differences between sprinters.

51   Furthermore, if such a strategy is beneficial for performance, it is conceivable that a limit

52   may exist and that sprinters should not continually strive to increase the negative touchdown

53   distance.

54

55   Whilst there are likely to be numerous aspects of technique which are important for early

56   acceleration performance, one other important aspect proposed in the literature relates to the

57   energy generating role of the ankle joint (Bezodis et al., 2014; Charalambous et al., 2012).

58   The ankle goes through dorsiflexion followed by plantar flexion whilst a net plantar flexor

59   moment is typically dominant throughout stance in every stance phase of a sprint. Bezodis et

60   al. (2014) identified that the ankle generates up to four times more energy than it absorbs

61   during the first stance phase compared to zero net energy generation during the mid-

62   acceleration phase (Johnson & Buckley, 2001) and net energy absorption during the

63   maximum velocity phase (Bezodis, Kerwin, & Salo, 2008). Charalambous et al. (2012) also

64   determined that a 'stiffer' ankle whilst dorsiflexing during the early part of the first stance

65   phase was positively related to higher horizontal CM velocities in a single sprinter. It is

66   therefore conceivable that a reduction in ankle joint dorsiflexion during early stance could be

67   another technical feature which is of benefit to early acceleration performance.

68

69   Whilst empirical evidence suggests that a large negative touchdown distance and reduced

70   ankle joint dorsiflexion during early stance may be beneficial for early acceleration sprint

71   performance, the effect of manipulating these aspects of technique on performance have not

72   been determined. This is likely due to an understandable resistance to exploratory

73 experimental manipulation of technique from coaches and athletes, particularly in elite sport

74 (Kearney, 1999). Simulation modelling offers an alternative approach which allows the

75 consideration of hypothetical situations to yield a more complete understanding than that

76 possible experimentally (Yeadon & Challis, 1994) and which provides valuable preliminary

77 evidence to determine the theoretical feasibility of potential applied interventions (Knudson,

78 Elliott, & Hamill, 2014). Such models are typically customised based on empirical data from

79 a single, highly-trained athlete. Model parameters and inputs are obtained from data on real

80 performances and quantitative evaluation of the model output is performed against relevant

81 aspects of the athlete's technique and performance. Angle-driven simulation models have

82 been previously used in other sports to systematically manipulate kinematic aspects of

83 technique and determine the consequent effects on performance (e.g. Gittoes, Brewin, &

84 Kerwin, 2006; Hiley & Yeadon, 2003a; 2003b; 2007). However, no such model exists which

85 has been specifically designed and evaluated to investigate sprinting. The primary aim of this

86 study was to determine the effects of manipulating touchdown distance and ankle joint

87 dorsiflexion during the first stance phase of a maximal effort acceleration out of blocks. It

88 was hypothesised that: 1) an increasingly large negative touchdown distance and 2) reduced

89 ankle joint dorsiflexion during early stance would each independently lead to increases in

90 first stance phase performance. In order to address this primary aim and these hypotheses, a

91 prerequisite aim was to develop a computer simulation model and evaluate its representation

92 of technique and performance during the first stance phase of a sprint.

93

94 **Methods**

95 Empirical data were collected from an international-level male sprinter (age, 20 years; mass,

96 86.9 kg; height, 1.78 m; 100 m personal best, 10.28 s) to obtain appropriate simulation model

97 parameters and allow a quantitative evaluation. The sprinter's ability to accelerate was

98 highlighted by the fact that he had reached the 60 m final of the European Indoor

99 Championships in the previous season. Three maximal effort 30 m sprints from blocks were

100 completed at an indoor track just prior to the competition phase of the indoor season. The

101 sprinter provided written informed consent to participate and the study was approved by the

102 University research ethics committee. Synchronised GRF and two-dimensional video data

103 were collected. A simulation model was developed using input data and parameters obtained

104 from the empirical collection and matching optimisations. Specific model outputs were

105 evaluated against empirical data to ensure that the model appropriately reflected reality.

106 Model-based simulations were then run by separately manipulating touchdown distance and

107 ankle joint dorsiflexion during early stance to determine their effects on first stance phase

108 performance and address the primary aim of this study.

109

110 *Empirical data collection*

111 Two digital video cameras (MotionPro® HS-1, Redlake, San Diego, CA, USA) were

112 positioned in series with overlapping 2.5 m wide fields of view to obtain sagittal plane

113 images (1280×1024 pixels) from the 'set' position until the end of the first stance phase at

114 200 Hz. Ground reaction forces from the first stance phase were obtained at 1000 Hz using a

115 force platform (Kistler, 9287BA, 1000 Hz, Winterthur, Switzerland) covered with artificial

116 track surface. A third camera (MotionPro® HS-1, Redlake, San Diego, CA, USA) was

117 positioned perpendicular to the centre of the force platform to obtain images (800×600

118 pixels) of the lower leg and foot during ground contact inside a 0.9 m field of view. The three

119 video cameras and the force platform were synchronised to within 1 ms using a custom

120 designed trigger system. An experienced starter administered standard '*on your marks*' and

121 '*set*' commands before pressing a trigger button which sent a signal to initiate and

122 synchronise all devices and an audio signal to the athlete.

123

124   The raw video files were imported into digitising software (Peak Motus®, v. 8.5, Vicon,

125   Oxford, UK), and were manually digitised at full resolution with a zoom factor of 2.0. For the

126   200 Hz cameras, twenty anatomical points were digitised (vertex, C7, shoulder, elbow, wrist,

127   hip, knee, ankle and metatarsal-phalangeal (MTP) joint centres, fingertips and toes) from 10

128   frames prior to movement onset until 10 frames after first stance toe-off. For the 1000 Hz

129   camera, the 5th MTP joint centre and toe were digitised from 10 frames prior to touchdown

130   until 10 frames after toe-off. The raw digitised co-ordinates were projectively scaled and the

131   resulting raw displacement time-histories were exported from Peak Motus® for subsequent

132   analysis in Matlab™ (v. 7.4.0, The MathWorks™, Natick, MA, USA).

133

134   The raw horizontal and vertical displacement time-histories from the 200 Hz cameras were

135   digitally filtered using a fourth-order Butterworth filter at 24 Hz. The filtered displacement

136   data were combined with individual-specific segmental inertia data obtained from 95 direct

137   measurements on the sprinter (Yeadon, 1990). The mass of each foot was increased by 0.2 kg

138   to account for the spiked shoes and the division of spike mass was determined directly from

139   the ratio of forefoot:rearfoot length. Whole body CM displacement time-histories were then

140   calculated using the summation of segmental moments approach (Winter, 2005). Joint angles

141   were determined and were resampled at 1000 Hz using an interpolating cubic spline before

142   their derivatives were numerically determined. Touchdown distance was determined as the

143   horizontal distance between the whole body CM and stance MTP at touchdown (recognised

144   by vertical force increasing and remaining more than two standard deviations above the zero

145   load level), with negative values indicating the MTP was behind the CM.

146

147   *Model structure*

148   A planar seven-segment angle-driven simulation model (Figure 1) was developed using

149   Simulink® (v. 7.1, The Mathworks™, Natick, MA, USA). The model incorporated a two

150   segment representation of the stance foot (Figure 1b) due to the importance of rotation around

151   the MTP joint in sprinting (Bezodis, Salo, & Trewartha, 2012), along with stance shank,

152   stance thigh and swing thigh segments. The swing foot was incorporated into the swing shank

153   segment, and the head, arms and trunk were combined into a single segment (Figure 1a). The

154   properties of each segment were defined based on the individual-specific segmental inertia

155   data. Segments were connected at revolute joints which permitted motion in the sagittal

156   plane. Ground contact was modelled at each end of the forefoot segment (i.e. beneath the

157   distal end of the toe and the MTP joint) using spring-damper systems which represented the

158   combined visco-elasticity of the soft tissue, spiked shoe and track surface (Figure 1b). The

159   damping terms were additionally dependent on spring length because damping increases as a

160   spring compresses (i.e. as an increased area of the spiked shoe and track come into contact)

161   and to avoid discontinuity in the forces at touchdown (Marhefka & Orin, 1996). Furthermore,

162   the horizontal spring-damper systems included a term related to the vertical spring

163   displacement because larger horizontal forces are required to achieve a given horizontal

164   displacement when vertical spring compression is greater due to greater frictional forces

165   (Wilson, King, & Yeadon, 2006):

$$F_{x_i} = (-k_{x_i} x_i - c_{x_i} |x_i| \dot{x}_i) y_i \text{ (for } i = 1,2)$$

$$F_{y_i} = -k_{y_i} y_i - c_{y_i} |y_i| \dot{y}_i \text{ (for } i = 1,2)$$

168   where F_x and F_y are the horizontal and vertical forces, x and y are the horizontal and vertical

169   displacements relative to the original contact point, $\dot{x}$ and $\dot{y}$ are the derivatives of x and y, k_x

170   and k_y, c_x and c_y are the horizontal and vertical stiffness and damping coefficients,

171   respectively, and i represents the contact point (i.e. the toe or MTP). The model initiated at

172   toe touchdown and forces in the MTP spring-dampers were generated when the vertical MTP

173 co-ordinate fell below a threshold level which was initially visually estimated (0.03 m) from

174 empirical data. The model terminated when the vertical toe spring returned to its initial

175 length.

176

177 ****Figure 1 near here****

178

179 *Model parameters*

180 Initial conditions for the model included horizontal and vertical velocities of the stance toe at

181 touchdown and forefoot angle and angular velocity. Each joint was angle-driven using initial

182 joint angular positions, initial angular velocities and the angular-acceleration time-histories

183 throughout stance. Similar to Wilson et al. (2006), these joint angular acceleration time-

184 histories were allowed to vary from empirical data from the instant of touchdown using a

185 combination of five sine and cosine terms (ε):

186 $\quad\quad \varepsilon_j(t) = j_1 \sin(t) + j_2 \cos(2t) + j_3 \sin(3t) + j_4 \cos(4t) + j_5 \sin(5t) \quad\quad$ (for j = 1,6)

187 where j_n is the coefficient for the term of frequency n Hz at joint j. The coefficients applied

188 to the angular acceleration input parameters were allowed to vary between $\pm$ 1250º/s^2

189 (approximately 1% of the highest empirically recorded peak angular accelerations). Input

190 data from each empirical trial (hereafter Trial 1, 2 and 3) were separately used in matching

191 optimisations to determine the required coefficients for the toe and MTP horizontal and

192 vertical spring-damper systems and the angular acceleration functions at each joint which

193 provided the closest match between the model and each empirical trial. All horizontal foot-

194 ground interface stiffness and damping coefficients were allowed to vary between 0 and 1.0 $\times$

195 10^6 N/m^2 and Ns/m^3, respectively, and all vertical stiffness and damping coefficients between

196 0 and 1.0 $\times$ 10^5 N/m and Ns/m^2, respectively. Similar to previous procedures (Wilson et al.,

197 2006; Yeadon & King, 2002), variation was also permitted in the touchdown estimates of

198 linear toe velocity (± 0.25 m/s), forefoot angle (± 1°) and forefoot angular velocity (± 25°/s),

199 as well as the threshold level at which the MTP was deemed to have made contact with the

200 track (± 0.01 m).

201

202 *Model evaluation*

203 A variable-step Runge-Kutte integration algorithm was used to advance the model and a

204 Latin Hypercube optimisation algorithm (McKay, Beckman, & Conover, 1979) was used to

205 find an optimum match with reality within the specified limits. The closeness of the match

206 between the model and empirical data from Trial 1 was evaluated using five kinetic and

207 kinematic criteria (Table 1) based on previous model evaluations (Yeadon & King, 2002;

208 Wilson et al., 2006; Hiley & Yeadon, 2007) as well as the specific application of this model.

209 The orientation criterion provided an additional kinematic indication of any systematic effect

210 of the cumulative configuration differences whilst the GRF accuracy criterion verified that

211 accurate impulses were not achieved as a result of large fluctuations above and below the

212 empirical GRF. The power criterion was used as an objective and appropriate measure of first

213 stance phase performance (Bezodis, Salo, & Trewartha, 2010; de Koning et al., 1992; van

214 Ingen Schenau et al., 1991; 1994). Errors in degrees were equated to those in percent (e.g.

215 Wilson et al., 2006; Yeadon & King, 2002) and the mean value of the five criteria yielded an

216 overall score reflective of the closeness of the match between the model and empirical data.

217 To quantify the robustness of the optimised foot-ground interface parameters, an independent

218 re-optimisation analysis was undertaken using the optimised spring-damper coefficients

219 obtained from the two empirical trials which were not used in the initial evaluation (i.e. Trials

220 2 and 3). These coefficients were independently determined using the same methods as

221 previously outlined, and were then used in the foot-ground interface alongside the remaining

222 input data from Trial 1, which was again allowed to vary within the previously described pre-

223   determined limits. The accuracy of this match was evaluated using the five criteria described

224   in Table 1.

225

226   ****Table 1 near here****

227

228   ***Simulations using the model***

229   To determine the effects of touchdown distance on average horizontal external power

230   production during the first stance phase, the initial knee joint angle was systematically varied

231   at touchdown by ±10° in 1° increments. This varied touchdown distance from -0.9 to

232   -14.1 cm (an increasingly negative number represents the foot further behind the CM at

233   touchdown; touchdown distance was -7.3 cm in the matched optimisation). Manipulations

234   were made to the knee joint due to its aforementioned importance in the first stance phase

235   (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013), particularly in relation

236   to the lean of the body relative to the stance foot (Debaere et al., 2013). To determine the

237   effects of ankle joint dorsiflexion during early stance on average horizontal external power

238   production during the first stance phase, the ankle joint angular acceleration time-history

239   from the matched optimisation was combined with the following function:

$$\varepsilon(t) = a \cdot \cos\frac{t}{2} - b \cdot sin\frac{t}{4}$$

240   Coefficients *a* and *b* were adjusted to yield ankle angular acceleration input data for five

241   simulations which reduced the amount of dorsiflexion during early stance without altering the

242   overall net change in ankle angle throughout stance. All simulations started from the matched

243   optimisation ankle angle of 98º and ended at the matched optimisation angle of 149º, but the

244   minimum ankle angle during stance ranged from 84º to 90º (compared to 82º in the matched

245   optimisation; see Figure 2). For all simulations, the remaining input data used the values from

246   the matched optimisation. Each simulation was advanced until the stance toe left the ground

247 and ground contact was terminated. The effect of the simulated changes on selected output

248 variables were identified to allow the primary aim of this paper to be addressed.

249

250   ****Figure 2 near here****

251

252 **Results**

253 A mean evaluation score of 5.2% was obtained between the empirical data from Trial 1 and

254 the matched optimisation. This evaluation comprised a mean difference of 5.7° in

255 configuration throughout stance (Figure 3), 8.6° in orientation throughout stance, 8.3% in the

256 overall GRF accuracy (Figure 4), 1.4% in the mean stance phase horizontal and vertical

257 impulses, and 2.0% in average horizontal external power during stance. The optimised

258 spring-damper coefficients used for modelling the foot-ground interface in each of the three

259 trials are presented in Table 2. When assessing the foot-ground interface parameters, the

260 overall evaluation scores for the two independent evaluations using the spring-damper

261 coefficients from the matching optimisations of Trials 2 and 3 with the remaining input data

262 from Trial 1 were 7.4% and 7.0%. Values for the five individual criteria from each of these

263 independent evaluations are presented in Table 3.

264

265   ****Figure 3 near here****

266   ****Figure 4 near here****

267   ****Table 2 near here****

268   ****Table 3 near here****

269

270 In the first set of simulations, a curvilinear relationship was identified between touchdown

271 distance and horizontal external power (Figure 5a). When the foot was positioned less far

272   behind the CM at touchdown than in the matched optimisation, horizontal external power

273   production progressively decreased. When the foot was positioned further behind the CM at

274   touchdown than in the matched optimisation, horizontal external power production initially

275   increased before reaching a peak value (a 0.7% increase relative to the matched optimisation

276   at 0.02 m further back). Beyond this, horizontal external power production began to decrease

277   again. The change in the ratio of force (the horizontal component of the GRF expressed as a

278   percentage of the total GRF magnitude and averaged over the entire stance phase; Morin et

279   al., 2011) associated with each of these simulations is presented in Figure 5b. In the second

280   set of simulations, as ankle joint dorsiflexion during early stance was reduced, horizontal

281   external power exponentially increased (Figure 6a). The peak resultant plantar flexor

282   moments associated with each of these simulations were extracted from the model and also

283   displayed an exponential increase (Figure 6b).

284

285   ****Figures 5a and 5b near here****

286   ****Figures 6a and 6b near here****

287

288

289   **Discussion and Implications**

290   This study developed and evaluated a simulation model in order to systematically determine

291   the effects of manipulations to touchdown distance and ankle joint dorsiflexion during early

292   stance on average horizontal external power production during the first stance phase. Using

293   empirical input data from an international-level sprinter, the model was quantitatively

294   demonstrated to match reality closely based on five criteria that were specific to early

295   acceleration technique and performance. The movement pattern of this sprinter during the

296   first stance phase (see sprinter B, Bezodis et al., 2014 for detailed stance leg joint mechanics

297   from the same empirical data collection) is clearly representative of that exhibited by other

298   international-level and highly-trained sprinters (e.g. Bezodis et al., 2014; Charalambous et al.,

299   2012; Debaere et al., 2013). These simulation results therefore provide preliminary evidence

300   to support and inform the design of future experimental research and applied interventions

301   (Knudson et al., 2014) with other participants from this population. However, a further

302   benefit of this novel, exploratory research is that it demonstrates that this simulation model

303   provides a means for assessing the efficacy of individual technique manipulations when

304   appropriate input parameters have been obtained. Hypothesis 1 was partly accepted as it was

305   found that positioning the stance foot increasingly further behind the CM at touchdown led to

306   small improvements in horizontal external power generation, but that this was only true up a

307   point. Beyond this, horizontal external power began to decrease again. Hypothesis 2 was

308   accepted as reductions in the range of dorsiflexion during early stance were shown to increase

309   the horizontal external power generated. This required greater peak resultant plantar flexor

310   moments which increased considerably as the reductions in dorsiflexion were systematically

311   increased.

312

313   The touchdown distance simulations revealed a curvilinear relationship with horizontal

314   external power (Figure 5a). This provided some support for the previous suggestions

315   (Bezodis et al., 2008; Kugler & Janshen, 2010) upon which hypothesis 1 was devised that

316   placing the foot further behind the CM at touchdown leads to increases in horizontal external

317   power production. However, an optimum touchdown distance was found to exist, beyond

318   which increasingly negative touchdown distances were associated with reductions in

319   horizontal external power production. A clear relationship existed between touchdown

320   distance and the ratio of force (Figure 5b): as the foot was positioned further behind the CM

321   at touchdown, the ratio of the horizontal component of the GRF to the total GRF magnitude

322   increased. The range in ratio of force values across all simulations is comparable to the range

323   exhibited during the first stance phase (approximately 35 to 55%) by the nine international-

324   and national-level sprinters analysed by Rabita et al. (2015), providing further confidence in

325   the structure and outputs of the model. It has previously been identified that a high ratio of

326   force is associated with superior sprint acceleration performance (Kugler & Janshen, 2010;

327   Morin et al., 2011; Rabita et al., 2015) and the current simulation results identify touchdown

328   distance as a specific technical factor which affects the ratio of force produced. Given that

329   horizontal external power exhibited a curvilinear relationship with touchdown distance,

330   continuing to increase the ratio of force through greater negative touchdown distances did not

331   lead to continued performance improvements. Further analysis of the model outputs revealed

332   that the magnitude of the stance-averaged resultant GRF production was less at the greater

333   negative touchdown distances where the ratio of force was highest. During sprint

334   acceleration, it has been suggested that provided sufficient vertical impulse is produced, all

335   remaining strength should be directed towards the production of propulsive horizontal

336   impulse (Hunter, Marshall, & McNair, 2005). The reduction in horizontal external power

337   production as touchdown distance became increasingly negative could therefore be reflective

338   of an inability of the sprinter to generate sufficient vertical impulse from this touchdown

339   position. It is conceivable that the body configurations at the larger negative touchdown

340   distances are associated with poor force producing capabilities *per se* but further investigation

341   is needed as factors such as specific muscle length and velocity changes cannot be accounted

342   for with the current modelling approach. Coaches and researchers should be encouraged to

343   explore strategies for manipulating foot placement with a view to finding the optimum

344   touchdown distance for a given sprinter. Although the trajectory of the CM is not visible to

345   coaches, its path during the first flight phase is fully determined at block exit. This first flight

346   phase provides sufficient duration (Bezodis, Salo, & Trewartha, 2015) for technical

347   adjustments at the leading swing knee to alter the location of the foot relative to the CM at

348   touchdown. However, caution is advised not to over-increase the negative touchdown

349   distance as placing the foot too posteriorly may be detrimental to performance.

350

351   The simulations which manipulated ankle joint dorsiflexion during early stance provided

352   support for the empirically-based assertions of Charalambous et al. (2012) and Bezodis et al.

353   (2014) upon which hypothesis 2 was devised. As the amount of dorsiflexion exhibited at the

354   ankle joint during early stance was progressively reduced, average horizontal external power

355   was found to increase exponentially (Figure 6a). Further investigation of the model outputs

356   revealed that this initially occurred due to a reduction in ground contact time without a

357   corresponding decrease in the net horizontal impulse generated. At greater reductions in

358   dorsiflexion, performance was enhanced due to both a shorter ground contact time and

359   greater net horizontal impulse generation. Reducing dorsiflexion during early stance likely

360   requires a 'stiffer' ankle joint (Charalambous et al., 2012). The peak resultant ankle plantar

361   flexor moments associated with each simulation were 7, 16, 30, 56 and 80 Nm greater than

362   the matched optimisation (299 Nm), respectively (Figure 6b). Resultant plantar flexor

363   moments have been shown to be higher in other exercises (e.g. maximal hopping, group

364   mean = 345 Nm; Farley & Morgenroth, 1999) than they are in the first stance phase.

365   Although the higher end of the current simulated increases in peak resultant plantar flexor

366   moment may therefore be an unrealistic expectation, even the smallest simulated reduction in

367   dorsiflexion was beneficial for performance and was associated with only a 7 Nm increase in

368   the peak resultant plantar flexor moment. This suggests that any reduction in ankle

369   dorsiflexion during early stance could be beneficial for horizontal external power production

370   and sprinters could therefore seek to increase their reactive plantar flexor strength through

371   plyometric training if endeavouring to improve early acceleration performance. Although

372   small reductions in ankle dorsiflexion may be difficult to accurately quantify, coaches could

373   seek to monitor this through changes to contact time or ground reaction forces given the

374   appropriate equipment.

375

376   The current overall difference between the model and empirical data (5.2%) can be

377   considered a close match compared with previously published kinetic and kinematic

378   evaluations of angle-driven models containing ground contact (e.g. 5.6 – 9.4%; Wilson et al.,

379   2006). The five individual criteria indicated that no single kinematic or kinetic aspect of the

380   model was matched considerably better than the others. The optimised foot-ground interface

381   spring-damper coefficients (Table 2) cannot be directly compared to previously published

382   angle-driven models containing ground contact due to the model-specific nature of the foot-

383   ground interface (i.e. two-segment structure of the foot, dependence of damping terms on

384   spring lengths, dependence of horizontal springs on vertical spring displacements in the

385   current model). The values obtained offer a sensible and relatively consistent representation

386   of ground contact with large horizontal forces consistently generated in the toe springs and

387   large vertical forces consistently due to the stiffness of the MTP springs once the MTP had

388   made contact with the ground (Table 2). Ultimately, the appropriateness of the foot-ground

389   interface should be considered in the context of modelled GRF profiles. The current

390   evaluation score for GRF accuracy (8.3%) compares favourably against previous angle-

391   driven models which have used a single-segment foot to model ground contact and returned

392   values of 9 to 22% using an identical GRF accuracy criterion (Gittoes et al., 2006; Wilson et

393   al., 2006). The impulse criterion scores (1.4%) further confirm the systematic closeness of the

394   current match. This good representation of the external kinetics may in part be due to the

395   novel inclusion of a two-segment foot in the current model. Such an approach could therefore

396   improve the modelling of ground contact in other activities where considerable MTP motion

397   exists but has previously been overlooked.

398

399   The variation in the optimised spring-damper coefficients between trials (Table 2) is

400   consistent with previous detailed evaluations of multiple trials. In a landing model, optimised

401   stiffness coefficients ranging from 3.9×10^5 to 1.9×10^9 N/m, and 9.5×10^4 to 2.0×10^9 N/m

402   at the toe and heel, respectively and damping coefficients ranging from 1.6×10^5 to $1.9 \times$

403   10^8 Ns/m, and 1.0×10^4 to 2.0×10^7 Ns/m at the toe and heel, respectively, were determined

404   between different trials (Gittoes, 2004). These results confirm that foot-ground interface

405   spring-damper coefficients are typically trial-specific, even when trials have been collected

406   from a single participant (Yeadon, Kong, & King, 2006). Although this highlights the need

407   for simulation models to initially be customised to an individual using empirical data from

408   specific trials, the results of the current independent re-optimisation analysis confirmed that

409   this model was relatively insensitive to these parameters (the global error of 5.2% increased

410   to a maximum of 7.4%). These independent re-optimisation results (Table 3) indicated that

411   the use of independent foot-ground interface spring-damper coefficients from different trials

412   still yielded accurate model output data. The model is clearly not overly sensitive to changes

413   in these input parameters, and the fact that none of the individual evaluation criteria increased

414   markedly more than any of the others (Table 3) as a result of these independent alterations

415   again supports the robustness of this model.

416

417   As with any theoretical investigations, by simplifying the human body into a computer-based

418   representation, several assumptions were made. The two-dimensional nature of the model is

419   consistent with the majority of empirical sprint acceleration research where sagittal plane

420   motion is of primary concern and non-sagittal forces are negligible (Debaere et al., 2013;

421   Rabita et al., 2015). The head, arms and trunk were combined in to a single segment, but

422   dividing the foot into two segments about the MTP joint helped to provide realistic

423   representations of the ground reaction forces. An angle-driven approach to actuate the model

424   was adopted due to the applied aims of this study as kinematic aspects of technique cannot be

425   directly manipulated with a torque- or muscle-driven model (Yeadon & King, 2002). This

426   approach therefore provided the most appropriate means with which to address our

427   technique-related hypotheses and is most appropriate to practical training situations in which

428   the coaching cues are generally kinematic in nature. For questions with a strength-related

429   focus, this model can now be adapted so it can be driven by joint torques and there is

430   potential to seek to develop a version driven by muscle actuators. This angle-driven model

431   provides a useful framework which can now be used to investigate the importance of other

432   aspects of technique for early acceleration performance.

433

434   **Conclusion**

435   The current study has developed, evaluated and applied a simulation model to investigate and

436   further the understanding of early acceleration technique and performance. The first set of

437   simulations extended previous empirical research which had advocated the production of a

438   more horizontally-directed GRF vector by identifying alterations to touchdown distance as a

439   means of achieving this. However, the simulation results provided preliminary evidence

440   suggesting the existence of potential limits to the benefits of positioning the foot further

441   behind the CM at touchdown and coaches should be wary of encouraging foot placement too

442   far behind the CM where performance benefits may be reduced. The second set of

443   simulations provided preliminary evidence for the beneficial effects of reducing ankle joint

444   dorsiflexion during early stance on early acceleration performance and identified the need for

445   coaches to increase ankle plantar flexor strength to facilitate this. Intervention studies are

446 required to extend these findings and to determine how coaches could affect early

447 acceleration performance through specific technical or physical training interventions related

448 to the above features.

449

450 **Acknowledgements**

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567   176.

568 **Tables**

569 Table 1. Definition of the five criteria used to evaluate the agreement of the optimised kinetic

570 and kinematic match between the model and empirical data.

Criterion	Definition
Configuration	The mean RMS difference between the model and empirical joint angle time-histories at each 1% of stance from the six joints.
Orientation	The RMS difference between the model and empirical HAT segment angle at each 1% of stance.
Impulse	The average percentage difference between the model and empirical vertical and net horizontal impulses from the entire stance phase
Ground reaction force accuracy	The RMS difference between the model and empirical horizontal and vertical ground reaction forces at each 1% of stance, expressed as a percentage of the total force excursion.
Power	The percentage difference between the model and empirical average horizontal external power generated during stance.

571 RMS: Root mean square; HAT: head, arms and trunk.

572   Table 2. Optimised stiffness and damping coefficients for the representation of the foot-

573   ground interface from the matching optimisations for all three trials.

Parameter	Trial 1	Trial 2	Trial 3
Horizontal toe stiffness (N/m^2)	235,850	914,274	196,843
Horizontal MTP stiffness (N/m^2)	239,990	1,327	7,031
Horizontal toe damping (Ns/m^3)	110,310	544,526	55,458
Horizontal MTP damping (Ns/m^3)	0	4,008	0
Vertical toe stiffness (N/m)	60	3,565	11,594
Vertical MTP stiffness (N/m)	48,661	35,024	28,902
Vertical toe damping (Ns/m^2)	42	46	51
Vertical MTP damping (Ns/m^2)	15,590	894	245

574

575

576 Table 3. Evaluation scores from the independent re-optimisation of Trial 1 using of spring-

577 damper coefficients from Trials 2 and 3.

	With Trial 2 coefficients	With Trial 3 coefficients
Configuration	8.1°	7.1°
Orientation	11.5°	10.6°
Impulse	2.3%	4.6%
Ground reaction force accuracy	14.3%	9.4%
Horizontal external power	1.0%	3.3%
Mean	7.4%	7.0%

578

579

580　**Figures**

581
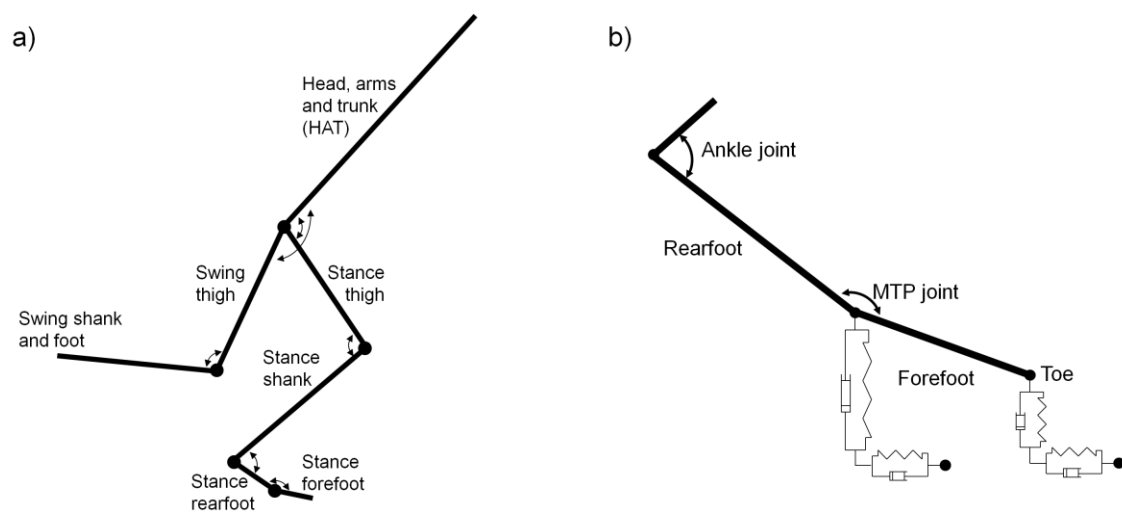
582

583　Figure 1. a) Basic structure of the seven-segment simulation model. b) Structure used to

584　represent ground contact which comprised horizontal and vertical spring-damper systems

585　between the foot and the ground at the toe (distal hallux) and MTP joint.

586
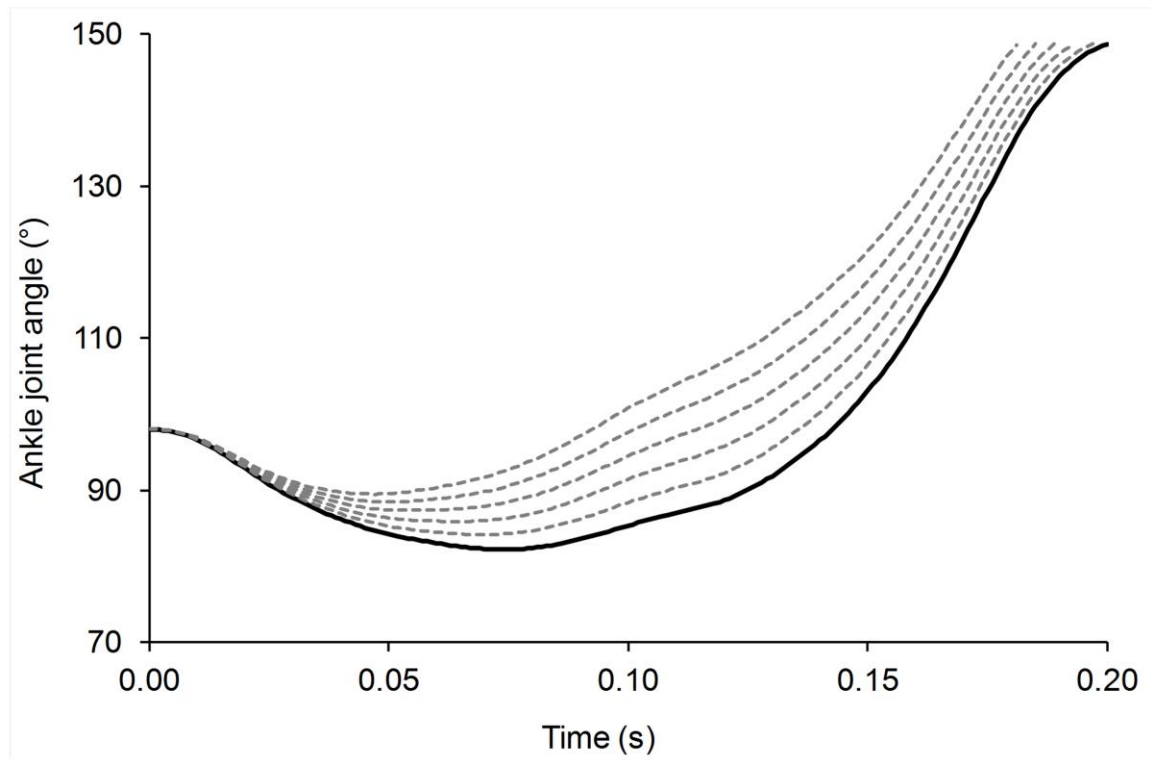
587

588   Figure 2. The ankle joint angle time histories from the matched optimisation (solid black line)
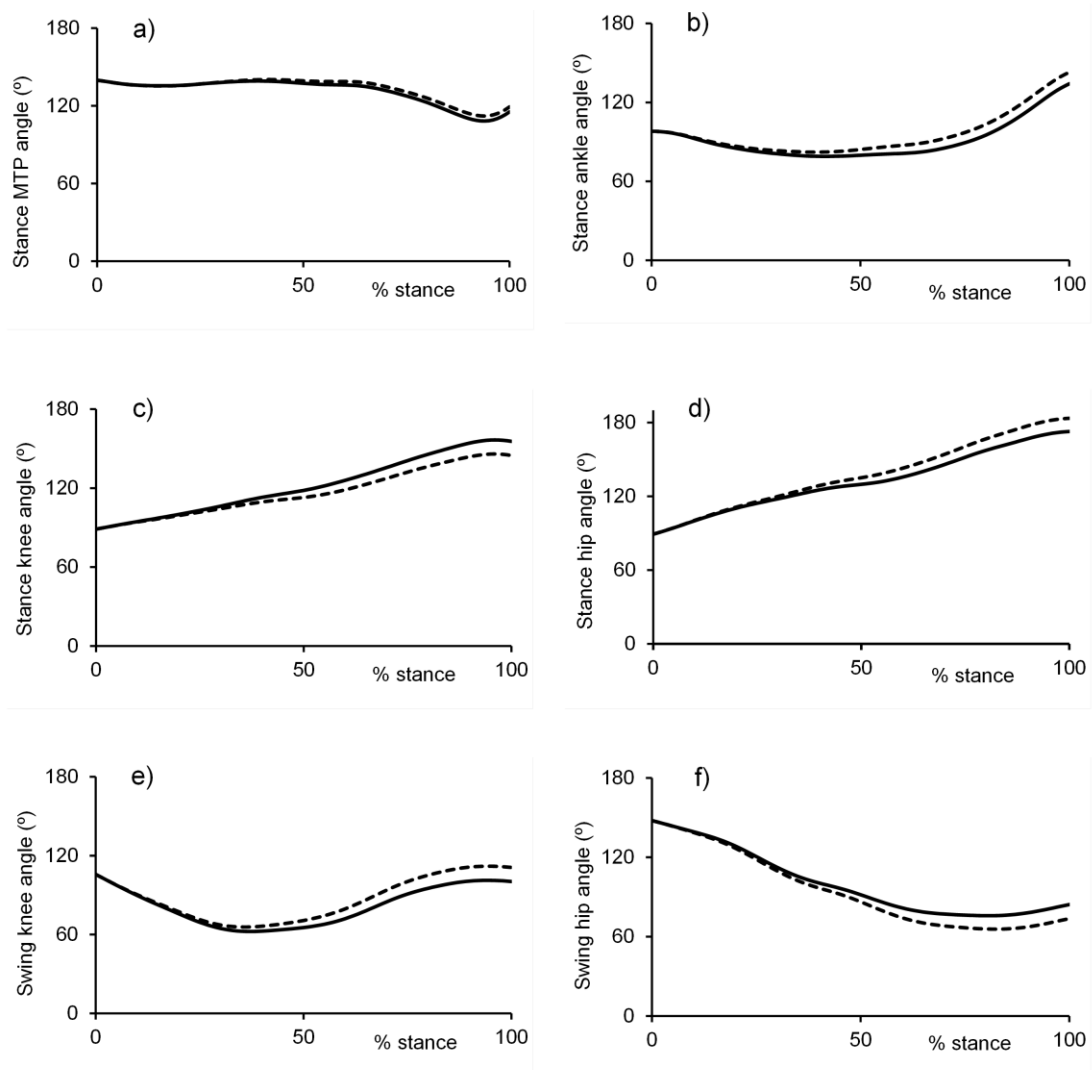
589   and each of the five simulations (dotted grey lines) after addition of the respective sine and
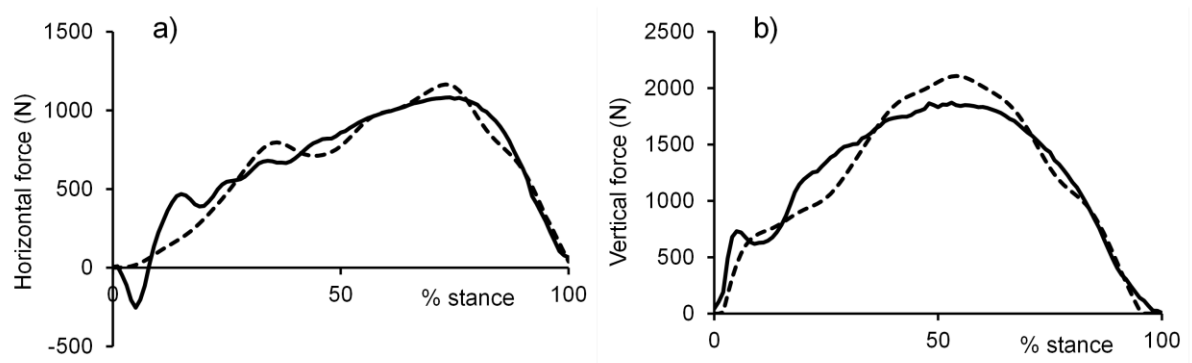
590   cosine terms.

591

592

593 Figure 3a-f. Joint angle time histories for the six angle-driven joints from the matching

594 optimisation (empirical data = solid line, model data = dotted line).
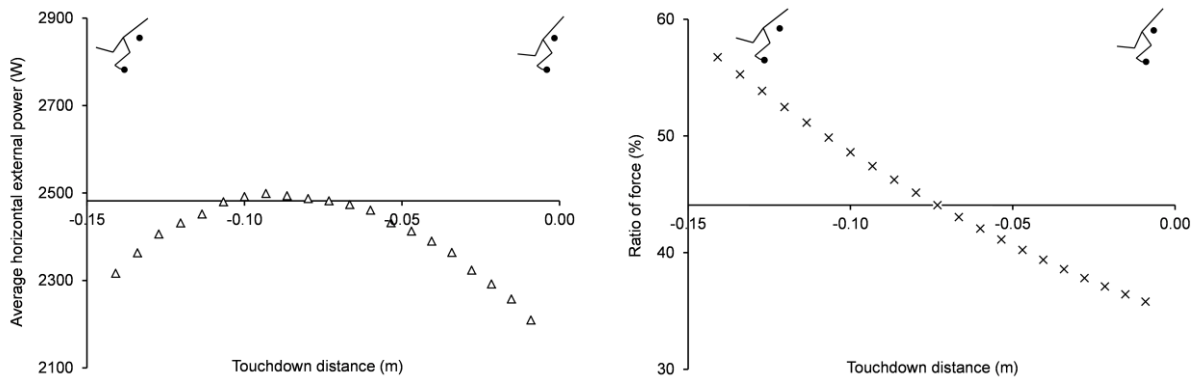
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597   Figure 4a-b. Horizontal (a) and vertical (b) ground reaction force time-histories from the

598   matching optimisation (empirical data = solid line, model data = dotted line).

599

600

601 Figure 5. The effect of simulated changes in touchdown distance on (a) average horizontal

602 external power. and (b) ratio of force. The stick figures provide illustrations (not to scale) of

603 the positions of the centre of mass and MTP joint, the horizontal distance between which is

604 the touchdown distance (i.e. a greater negative value represents the stance toe further behind

605 the CM at touchdown).

606
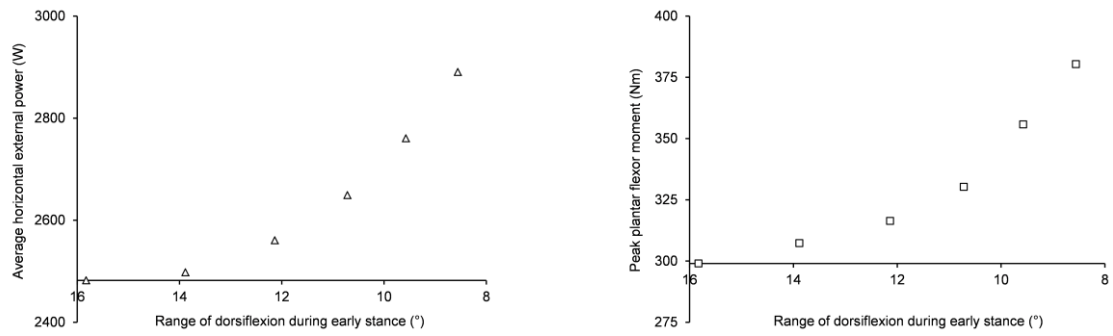
607

608   Figure 6. The effect of simulated changes in ankle joint dorsiflexion during early stance on

609   (a) average horizontal external power and (b) and peak resultant plantar flexor moment.