1   Technical Note

2

3   Title:

4   Modelling the stance leg in 2D analyses of sprinting: inclusion of the MTP joint affects joint

5   kinetics (corrected version)

6

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19

20   Abstract

21   Two-dimensional analyses of sprint kinetics are commonly undertaken but often ignore the

22   metatarsal-phalangeal (MTP) joint and model the foot as a single segment. The aim of this

23   study was to quantify the role of the MTP joint in the early acceleration phase of a sprint and to

24   investigate the effect of ignoring the MTP joint on the calculated joint kinetics at the other stance

25   leg joints. High-speed video and force platform data were collected from four to five trials for

26   each of three international athletes. Resultant joint moments, powers and net work at the stance

27   leg joints during the first stance phase after block clearance were calculated using three

28   different foot models. Considerable MTP joint range of motion (>30°) and a peak net MTP

29   plantar flexor moment of magnitude similar to the knee joint were observed, thus highlighting the

30   need to include this joint for a more complete picture of the lower limb energetics during early

31   acceleration. Inclusion of the MTP joint had minimal effect on the calculated joint moments, but

32   some of the calculated joint power and work values were significantly ($P < 0.05$) and

33   meaningfully affected, particularly at the ankle. The choice of foot model is therefore an

34   important consideration when investigating specific aspects of sprinting technique.

35

36 Introduction

37 Biomechanists often develop linked-segment rigid body models comprising the segments and

38 joints deemed to be of sufficient importance to an activity of interest. When joint kinetics are also

39 required, these models are typically incorporated within inverse dynamics analyses (IDA). The

40 lower limb joint moments in sprinting have been widely investigated using IDA to understand the

41 two-dimensional (2D) sagittal plane movements occurring in the primary plane (e.g. Mann,

42 1981; Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Kuitunen et al., 2002;

43 Hunter et al., 2004; Mero et al., 2006; Bezodis et al., 2008). These studies all used a three

44 segment representation of the leg which included thigh, shank and foot segments. Whilst the

45 thigh and shank segments were consistently modelled from hip to knee, and knee to ankle joint

46 centres, respectively, some of these studies modelled the foot from the ankle to the distal hallux,

47 and others to the metatarsal-phalangeal (MTP) joint. Kinematic 2D analyses of sprinting have

48 revealed that rotation in excess of 20° occurs about the MTP joint (Stefanyshyn & Nigg, 1997;

49 Krell & Stefanyshyn, 2006; Toon et al., 2009); by ignoring this motion any resultant joint

50 moments generated about the MTP joint, and their consequent effects, are also ignored.

51

52 Since Elftman (1940) proposed that the resultant moments about the MTP joint are large

53 enough to warrant consideration in sprint analyses, it appears that only Stefanyshyn & Nigg

54 (1997) have included an MTP joint when calculating 2D joint kinetics during sprinting.

55 Stefanyshyn & Nigg (1997) observed peak resultant MTP plantarflexor moments of up to

56 120 N·m (at the 15 m mark), and up to 70 J of energy was found to be absorbed at the MTP

57 joint, accounting for around 32% of the total energy absorbed in the four leg joints (MTP, ankle,

58 knee, hip) during ground contact. These results suggest that it could be important to include the

59 MTP joint when conducting a sprint-related IDA, but the extent to which this would affect the

60 calculated kinetics at the other joints in the leg model is not clear. Whilst using different distal

61 endpoints for a single foot segment could slightly affect the magnitude of the calculated

62  resultant joint moments in the stance leg, it is proposed that ignoring the MTP joint will have a

63  more pronounced effect. The aim of this study was thus to investigate the effect of three

64  different foot models on leg joint kinetics during a stance phase in sprinting.

65

66  Methods

67  A single-subject approach was adopted since the foot models may affect the joint kinetics on an

68  individual basis. However, to widen the potential application of the findings, this within-subject

69  analysis was repeated across three relatively heterogeneous trained athletes (Table 1).

70  Following ethical approval and written informed consent, a high-speed digital video camera

71  (Motion Pro®, HS-1, Redlake, USA; 200 Hz) was used to capture full body sagittal plane

72  kinematic data during the first stance phase of maximal effort sprints to 30 m on an indoor track

73  as a part of larger research study. The camera was positioned 25.00 m away from the centre of

74  the running lane, perpendicular to the direction of the sprint, 0.95 m in front of the start line and

75  with the lens centre 1.00 m above the ground. An area of 2.000 m horizontally × 1.600 m

76  vertically was calibrated, and the camera collected images at a resolution of 1280 × 1024 pixels

77  with a 1/1000 s shutter speed. A start line was positioned on the track such that the first foot

78  contact would occur near the centre of a 0.900 × 0.600 m covered force platform (Kistler,

79  9287BA, Kistler Instruments Ltd., Switzerland; 1000 Hz) embedded in the track. Each trial was

80  initiated by a trigger button which activated a sounder (to which the athletes reacted), the force

81  platform, and a series of 20 LEDs (Wee Beasty Electronics, UK) to allow synchronisation of the

82  video and ground reaction force (GRF) data to the nearest 1 ms.

83

84  ****Table 1 near here****

85

86  From the video files, six points (shoulder, stance hip, knee, ankle and mid MTP joint centres,

87  and distal hallux) were manually digitised and affine scaled from 10 frames prior to touchdown

88   until 10 frames after toe-off (Peak Motus®, v. 8.5, Vicon, USA). It has previously been proposed

89   that displacement and force data used for IDA should be subjected to the same level of

90   smoothing to prevent artificial impact joint moments being introduced (van den Bogert & de

91   Koning, 1996; Bisseling & Hof, 2006). The displacement and GRF data were therefore passed

92   through a fourth-order Butterworth filter using the mean optimal cut-off frequency (24 Hz)

93   determined from a residual analysis of all displacement data (Winter, 1990).

94

95   To create the experimental conditions, the stance leg was represented using three different

96   models (Figure 1). The thigh and shank segments were consistently modelled from hip to knee,

97   and knee to ankle joint centres, respectively. For two of the models, the foot was modelled as a

98   single segment, firstly from ankle to distal hallux (model 3segH) and secondly from ankle to

99   MTP (3segM). The final model (4seg) included a two segment foot, comprising a rearfoot

100  segment from ankle to MTP and a forefoot segment from MTP to distal hallux. Individual-

101  specific segmental inertia data were obtained using the model of Yeadon (1990), which

102  provided appropriate data for the foot in all three models. To account for the spiked shoes,

103  0.20 kg was added to the mass of the foot (e.g. Hunter et al., 2004). For model 4seg, this was

104  divided between the segments based on the ratio of forefoot:rearfoot length. Joint angles were

105  determined, and were subjected to second central difference calculations (Miller & Nelson,

106  1973) to derive corresponding velocity and acceleration time-histories.

107

108  ****Figure 1 near here****

109

110  Prior to filtering, the raw GRF data were downsampled to 200 Hz, and centre of pressure data

111  were calculated accounting for the thickness of the track surface. These downsampled GRF

112  data were combined with the kinematic and inertia data in an IDA (Elftman, 1939; Winter, 1990).

113  Since contact only occurred with the forefoot segment during this early part of a sprint for these

114    three sprinters, all calculations started with the GRF being applied at the centre of pressure to

115    the most distal segment and proceeded in a distal-to-proximal fashion (i.e. there was no need to

116    share the GRF between the forefoot and rearfoot in model 4seg). Contact with only the forefoot

117    was confirmed as a normal occurrence during the first stance phase of a sprint through an

118    additional qualitative analysis of the 13 University-level sprinters studied by Bezodis et al.

119    (2010). Joint power was calculated as the product of resultant moment and angular velocity, and

120    net joint work was calculated as the time-integral of power. For all calculated variables,

121    extension/plantarflexion was defined as positive. Mean and standard deviations were calculated

122    for all variables for each athlete. Repeated measures ANOVA comparisons (SPSS 15.0 for

123    Windows, SPSS Inc., USA) were run for dependent variables (peak resultant extensor joint

124    moments and powers, and net joint work) for all three athletes separately. When a significant ($P$

125    $< 0.05$) main effect was observed, Bonferroni *post hoc* tests were calculated to investigate the

126    pairwise differences.

127

128    Results

129    The mean horizontal velocity of the athletes at touchdown was $3.29 \pm 0.22$ m/s, and during the

130    first stance phase (mean duration = $0.188 \pm 0.009$ s), velocity increased by $1.27 \pm 0.11$ m/s. The

131    MTP angle ranges of motion during stance for athletes A, B, and C were $34 \pm 7°$, $30 \pm 7°$, and

132    $31 \pm 1°$, respectively. Time histories for MTP joint angle, angular velocity, resultant moment, and

133    power from model 4seg are presented in Figure 2. To illustrate the general temporal patterns of

134    the joint kinetic data during stance when using each of the three leg models, Figure 3 presents

135    the mean resultant moment and power time histories for the ankle, knee, and hip joints for

136    athlete C. Differences between leg models were essentially non-existent when considering joint

137    moment patterns at the ankle, knee and hip joints (some significant differences were observed

138    due purely to the systematic nature of these small effects; Table 2). However, some significant

139    and more meaningful differences were observed in joint power and work values due to

140    variations in the calculated angular velocity data between leg models, particularly at the ankle

141    joint.

142

143    ****Figures 2a-d near here****

144    ****Table 2 near here****

145    ****Figures 3a-f near here****

146

147    Discussion

148    The MTP joint rotated through mean ranges of motion in excess of 30° for each of the three

149    athletes (Figure 2a), similar to previous results (Krell & Stefanyshyn, 2006; Toon et al., 2009).

150    The mean peak MTP resultant joint moments ranged from 67 to 143 N·m (1.1–1.7 N·m/kg;

151    Figure 2c), and are due to both the biological structures crossing the MTP joint and to the

152    spiked shoe (Oleson et al., 2005). Due to these moments and the observed angular velocities

153    (Figure 2b), the MTP joint is clearly important in absorbing energy during the stance phase

154    (Figure 2d), reaching magnitudes of up to 50 J for some trials of athlete C (Table 2). For

155    athletes A and B in particular, the magnitudes of the resultant joint moments, power and net

156    work at the MTP joint were comparable to those of the knee joint, and it therefore appears

157    important to include this joint in analyses of the energetics of sprinting to obtain a more

158    complete understanding of the internal kinetics. Although there were systematic and statistically

159    significant differences in ankle and hip joint moment (Table 2), these were very small in

160    magnitude (typically less than 1 Nm at the ankle joint). When placed in the context of the typical

161    within-athlete variation based on the standard deviation data presented in Table 2, the practical

162    significance of these differences due to the choice of leg model is clearly minimal, opposing the

163    suggestion in our original paper (Bezodis et al., 2012). The observed significant differences in

164    ankle joint work and power (Table 2 and Figure 3b) between the models which linked the ankle

165    to the MTP joint (3segM and 4seg) and the model which linked the ankle to the distal hallux

166    (3segH) are more practically meaningful. These differences can be attributed to contrasting

167    ankle joint angular velocities between these two three-segment leg models, and they highlight

168    that the choice of distal endpoint for a single segment foot could influence the results if absolute

169    values of ankle joint power or work are of interest.

170

171    The foot is clearly multisegmental and three dimensional, and while inclusion of the MTP joint

172    reveals 'within-foot' energetics that would be overlooked if using a single-segment

173    representation, it is acknowledged that it remains a simplification. However, coaches and

174    biomechanists are often interested in the 2D mechanics of sprinting (e.g., Mann, 1981; Jacobs

175    & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Kuitunen et al., 2002; Hunter et al.,

176    2004; Mero et al., 2006; Bezodis et al., 2008) due to the largely planar nature of the skill in

177    addition to time and equipment/instrumentation constraints.

178

179    The results of the current study revealed that the resultant joint moments, power and net work at

180    the MTP joint are large enough to warrant consideration in future kinetic analyses of early

181    acceleration. Due to the increased requirement for energy absorption combined with the

182    considerable motion previously observed at the MTP joint during maximum velocity sprinting

183    (Krell and Stefanyshyn, 2006), it is likely that the MTP joint should be considered in kinetic

184    analyses throughout all phases of a sprint. However, if the specific kinetics of just the ankle,

185    knee and/or hip joint are the sole focus of a study, a three segment leg model will yield

186    appropriate data providing that the MTP joint is used as the distal endpoint for the foot segment

187    if ankle joint power or work data are of interest.

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189    Acknowledgements

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261    Table 1. Descriptive characteristics for the three athletes.

|  | A | B | C |
|---|---|---|---|
| Age [years] | 26 | 21 | 20 |
| Gender | Female | Male | Male |
| Mass [kg] | 60.5 | 82.6 | 86.9 |
| Height [m] | 1.76 | 1.81 | 1.78 |
| PB [s] | 12.72[#] | 10.14* | 10.28* |
| No. of trials | 4 | 5 | 5 |

262    [#] indicates personal best (PB) for 100 m hurdles; * indicates PB for 100 m; A: World Indoor
263    Championships medalist; B: European Indoor Championships medalist; C: European Indoor
264    Championships finalist

265 Table 2. Peak resultant joint moments and powers, and net work, for each of the three athletes
266 using each of the three leg models (mean ± *s*).

| | Athlete | 3segH | 3segM | 4seg |
|---|---|---|---|---|
| Peak resultant MTP joint extensor moment [N·m] | A | | | 67 ± 6 |
| | B | | | 107 ± 5 |
| | C | | | 143 ± 8 |
| Peak resultant ankle joint extensor moment [N·m] | A* | 210 ± 9[b,c] | 210 ± 9[a,c] | 210 ± 9[a,b] |
| | B* | 351 ± 19[b,c] | 351 ± 19[a,c] | 351 ± 19[a,b] |
| | C* | 363 ± 6[b,c] | 364 ± 6[a,c] | 364 ± 6[a,b] |
| Peak resultant knee joint extensor moment [N·m] | A | 75 ± 14 | 75 ± 14 | 75 ± 14 |
| | B | 67 ± 21 | 66 ± 22 | 66 ± 22 |
| | C | 172 ± 18 | 172 ± 18 | 172 ± 19 |
| Peak resultant hip joint extensor moment [N·m] | A | 137 ± 14 | 136 ± 14 | 136 ± 14 |
| | B* | 237 ± 56[c] | 245 ± 53 | 247 ± 53[a] |
| | C* | 264 ± 33 | 266 ± 32 | 262 ± 31 |
| Peak positive MTP joint power [W] | A | | | 253 ± 106 |
| | B | | | 612 ± 418 |
| | C | | | 219 ± 109 |
| Peak positive ankle joint power [W] | A | 2177 ± 326 | 2228 ± 260 | 2221 ± 259 |
| | B* | 2629 ± 236[b,c] | 2970 ± 189[a,c] | 2963 ± 188[a,b] |
| | C* | 3378 ± 83[b,c] | 3891 ± 79[a,c] | 3881 ± 79[a,b] |
| Peak positive knee joint power [W] | A | 423 ± 28 | 420 ± 33 | 425 ± 37 |
| | B | 383 ± 200 | 350 ± 191 | 351 ± 191 |
| | C* | 1053 ± 95[c] | 1051 ± 96[c] | 1062 ± 97[a,b] |
| Peak positive hip joint power [W] | A | 1292 ± 208 | 1295 ± 213 | 1268 ± 211 |
| | B* | 2980 ± 696[c] | 3088 ± 651 | 3107 ± 647[a] |
| | C* | 2853 ± 479 | 2868 ± 472[c] | 2815 ± 469[b] |
| Net MTP joint work [J] | A | | | -22 ± 5 |
| | B | | | -26 ± 10 |
| | C | | | -46 ± 4 |
| Net ankle joint work [J] | A* | 49 ± 9[b,c] | 68 ± 6[a,c] | 68 ± 6[a,b] |
| | B* | 81 ± 13[c] | 97 ± 16[c] | 96 ± 16[a,b] |
| | C* | 91 ± 7[b,c] | 127 ± 9[a,c] | 126 ± 9[a,b] |
| Net knee joint work [J] | A* | 20 ± 13[b,c] | 19 ± 12[a] | 18 ± 12[a] |
| | B* | -5 ± 18[b,c] | -9 ± 17[a] | -9 ± 17[a] |
| | C* | 82 ± 17[b,c] | 80 ± 17[a] | 80 ± 17[a] |
| Net hip joint work [J] | A* | 76 ± 15[b,c] | 78 ± 15[a,c] | 80 ± 15[a,b] |
| | B* | 108 ± 20[b,c] | 111 ± 19[a,c] | 114 ± 19[a,b] |
| | C* | 111 ± 22[b,c] | 113 ± 22[a,c] | 115 ± 21[a,b] |

267 * significant effect of leg model (*P* < 0.05); [a] significantly different from 3segH; [b] significantly
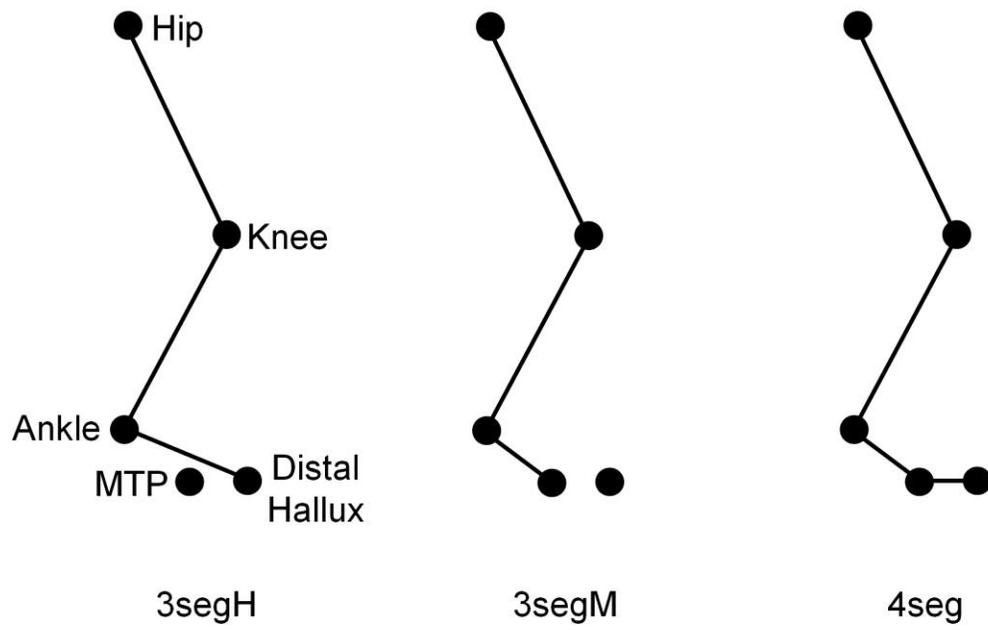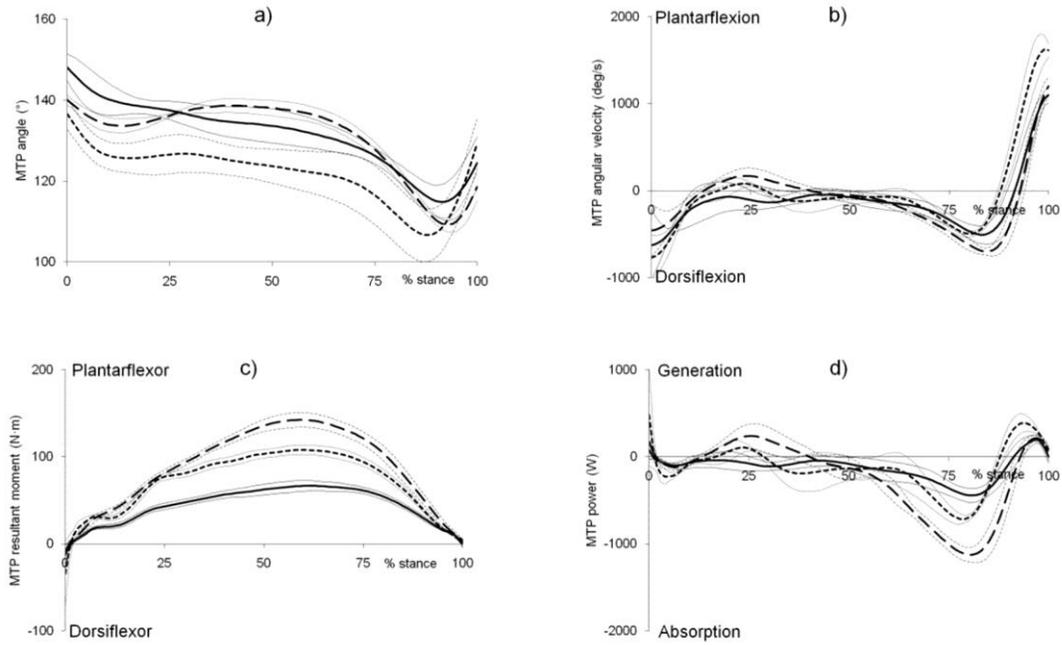268 different from 3segM; [c] significantly different from 4seg.

Figure 1. The three models used to represent the stance leg.

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Figures 2a-d. Time-histories (mean ± *s*) for joint angle (a), angular velocity (b), resultant moment (c) and power (d) at the MTP joint during stance for each of the three athletes calculated using the 4seg model (athlete A = solid line, athlete B = dotted line, athlete C = dashed line). MTP joint angle was calculated as the angle between the rearfoot and forefoot segments on the proximal side of the foot.
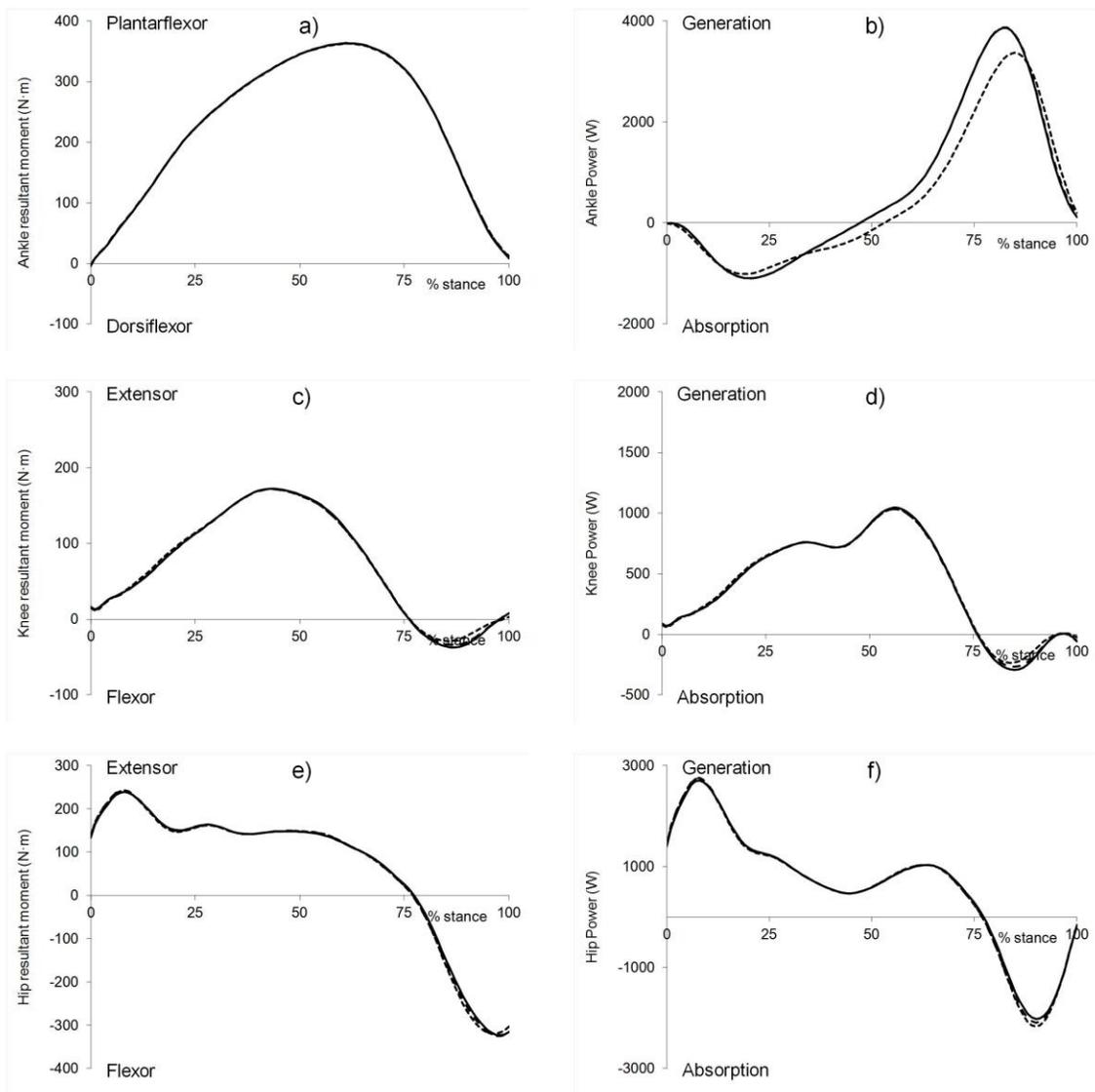
Figure 3. Mean time histories for ankle resultant joint moment (a) and power (b), knee resultant joint moment (c) and power (d), hip resultant joint moment (e) and power (f) for athlete C (model 4seg = solid line, 3segH = dotted line, 3 segM = dashed line).

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