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1 Mechanical and neural function of triceps surae in elite racewalking

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17 Running title: Neuromechanics of racewalking

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22 Abstract

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24 Racewalking is a unique event combining mechanical elements of walking with speeds
25 associated with running. It is currently unclear how racewalking technique impacts upon
26 lower limb muscle-tendon function, despite the relevance of this to muscle economy and
27 overall performance. The present study examined triceps surae neuromechanics in 11
28 internationally competitive racewalkers (age 25 ± 11 years) walking and running on a
29 treadmill at speeds between 4.5 - 13.8 km/h whilst triceps surae fascicle lengths,
30 electromyography and kinematic data were recorded. Cumulative muscle activity required to
31 traverse a unit distance (CMAPD) was calculated for each muscle. Medial gastrocnemius
32 (MG) and soleus fascicle lengths/velocities were determined using an automated tracking
33 algorithm, and muscle-tendon unit lengths were determined. Running was associated with net
34 shortening of muscle fascicles during stance, combined with substantial lengthening of the
35 muscle-tendon unit, implying energy storage in the Achilles tendon. When the same
36 participants racewalked at the same speed, the fascicles shortened (soleus) or lengthened
37 (MG), coinciding with rapid shortening followed by a relatively small increase in muscle-
38 tendon length during stance. Consequently, compared with running at the same speed,
39 racewalking decreased the energy-saving role of the Achilles tendon. Moreover, CMAPD
40 was generally highest in racewalking, implying that in individual muscles, the energy cost of
41 racewalking was higher than running. Together these results suggest that racewalking is
42 neurally and mechanically costly relative to running at a given speed. As racewalking events
43 are typically between 10 and 50 km, neuromechanical inefficiencies that occur with each
44 stride likely result in substantial energetic penalties.

45

46

47 New and noteworthy

48

49 In internationally competitive racewalkers, muscle-tendon unit length changes indicate a
50 decrease in the spring-like function of the Achilles tendon compared to running at a given
51 speed. For individual triceps surae muscles, cumulative muscle activity required to move a
52 unit distance was also higher in racewalking than running. Thus, racewalking is neurally and
53 mechanically costly relative to running, which may lead to major energetic penalties in
54 racewalking events, which are typically between 10 and 50 km.

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56 Keywords

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58 Racewalking, muscle-tendon, athletics, ultrasound, gait

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72 Introduction

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74 Humans are well adapted to walk and run economically. This is evident in parameters such as
75 relative oxygen cost (18), as well as muscle mechanical behavior. For example, during
76 walking at preferred speed, extensor muscles such as gastrocnemius and soleus function at or
77 near the optimal region of the force-length curve (3), and are never required to shorten at high
78 velocities (e.g. (9)). Similarly, during running, Farris & Sawicki (10) have shown that the
79 medial gastrocnemius shortens slowly, whilst the elastic Achilles tendon acts as an efficient
80 spring.

81

82 However, walking and running are two clearly distinct gaits, and represent efficient ways of
83 moving at slow and fast speeds respectively. Racewalking is a unique event within the
84 Olympic track and field program that essentially combines some of the mechanical elements
85 of a walking gait with speeds usually associated with running, and it is currently unclear how
86 the technique used impacts upon the muscle-tendon function of lower leg structures. It has
87 previously been shown that increasing walking speed from 2.7 to 7.2 km/h is associated with
88 faster muscle shortening velocity in the gastrocnemius muscle, resulting in decreased force
89 production per unit of active muscle according to the well-known force-velocity relation (10).
90 When shifting to a running gait, the muscle is again able to shorten slowly because of tendon
91 elasticity, thus reducing muscle-tendon energy cost. During racewalking, which typically
92 occurs at speeds much greater than 7.2 km/h (12), it remains to be determined whether
93 muscles function as in fast walking, running, or indeed a different pattern unique to
94 racewalking.

95

96 Racewalking is an unusual form of gait because the rule defining it states that the knee must
97 be straightened from initial contact to midstance (16), and in fact in world-class competitors
98 the knee was typically found to be hyperextended during this phase (12), unlike in normal
99 walking and running. The knee's restricted motion during racewalking means that the
100 muscles crossing the joint generate little energy during stance (11), which could have a
101 profound effect on the muscle-tendon function of biological structures located below the knee
102 joint (e.g. triceps surae). Whether this function differs from walking and running gait is
103 important from the perspective of muscle economy, and thus overall racewalking economy,
104 an especially important factor in competitive success given the distances covered during
105 official events (10 – 50 km).

106

107 There is currently no information about muscle-tendon mechanics in competitive
108 racewalkers, despite the value of such information for training and performance
109 enhancement. Furthermore, since humans have not evolved to racewalk and it is a relatively
110 new discipline, knowledge of muscle-tendon mechanics in elite-standard racewalkers may
111 give insight to the adaptability of muscles and tendons to drive the body through nonstandard
112 movement patterns. The present study examined this issue in a group of internationally
113 competitive racewalkers at a range of walking and running speeds.

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121 Methods

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123 **Participants**

124

125 Eleven healthy volunteers (5 males, 6 females; age 25 ± 11 years [mean \pm SD]; height
126 1.74 ± 0.11 m; body mass 62 ± 10 kg) with no history of neurological disorder took part in the
127 study. All participants were nationally or internationally competitive racewalkers, and
128 racewalked a mean of 56 ± 24 km per week at the time of testing. The experimental protocol
129 was approved by the Faculty Research Ethics Committee of Leeds Beckett University, and
130 testing was conducted in accordance with the Declaration of Helsinki. All volunteers
131 provided written informed consent.

132

133 **Methodology**

134

135 Anthropometric measures such as shank length (lateral malleolus to lateral femoral
136 epicondyle) and whole leg length (lateral malleolus to greater trochanter) were determined
137 with a tape measure. To calculate knee and ankle joint angles, reflective markers were placed
138 over the greater trochanter, lateral femoral condyle, lateral malleolus, with two additional
139 markers placed between the trochanter and the femoral condyle, as the trochanter marker was
140 occasionally blocked by a sidebar on the treadmill. Two-dimensional marker trajectories were
141 recorded using a Fastec camera (TS3; Fastec Imaging, California, USA) positioned to the
142 participants' right side perpendicular to the direction of movement and sampling at 100 Hz.
143 The resolution of the camera was 1280 x 1024 pixels, and extra illumination was provided by
144 two spotlights of 1250 W each (ARRI; Munich, Germany). Bipolar electromyography (EMG)
145 electrodes (Trigno wireless; Delsys, Massachusetts, USA) were positioned over the medial

146 gastrocnemius (MG), soleus and tibialis anterior (TA) muscles with an inter-electrode
147 distance of 10 mm. Data were sampled wirelessly at 2 kHz via EMGworks software (Delsys)
148 and stored in a computer for subsequent processing. Before electrode placement, the skin was
149 shaved and cleaned with alcohol to reduce the skin-electrode impedance. An ultrasound
150 device (Acuson P300; Siemens, Pennsylvania, USA) was used to examine muscle fascicle
151 lengths. The probe (7.5 MHz, 5 cm) was positioned over MG so that soleus muscle fascicles
152 were also visible, and attached firmly with an elastic bandage. Data were sampled at 42 Hz.
153 All data were synchronized using a common 5 V trigger pulse. The timing of heel-ground
154 contact and stance-swing transition were determined visually based on video data.

155

156 **Protocol**

157

158 Participants initially walked normally on a motorized treadmill (h/p/cosmos Gaitway;
159 Nussdorf, Germany) at a speed of 4.5 km/h for at least 4 min to become familiar with the test
160 environment. The treadmill's inclination was set at 0% during data collection (1) as racewalk
161 events are held on flat, even surfaces. Participants were all habitual treadmill users and wore
162 their normal training clothing and footwear. Subsequently, participants racewalked and ran at
163 both 10 km/h and their individually determined racewalking pace (based on 10 or 20 km
164 personal best; 10.9 - 13.8 km/h), resulting in a total of five test conditions. Walking at 4.5
165 km/h was always performed first, but the order of subsequent conditions was randomized.
166 During all trials, ultrasound, EMG and kinematic data were recorded synchronously. Each
167 speed was maintained for at least 2 min before data collection to allow for adaptation.

168

169 **Analysis**

170

171 Reflective marker trajectories were tracked semi-automatically using Simi software (Simi
172 Reality Motion Systems GmbH, Unterschleissheim, Germany). EMG data were band-pass
173 filtered online at 20-450 Hz and DC offset corrected. The cumulative muscle activity required
174 to traverse a unit distance (CMAPD) was calculated for each muscle based on a modified
175 version of the method of Carrier et al. (5). Individual strides were first identified, and those at
176 least 20% above or below mean stride duration were excluded. A single root mean square
177 (rms) EMG value was then calculated for each stride. Finally, to calculate CMAPD, rms
178 values were normalized to a travel distance of 1 km by dividing the rms value for a given
179 stride by walking/running speed. MG and soleus fascicle lengths were determined using an
180 automated tracking algorithm validated previously in walking and running (8), and fascicle
181 velocities were obtained by differentiating length with respect to time. MG and soleus
182 muscle-tendon unit lengths were determined by combining knee/ankle joint kinematic data
183 with the equations of Hawkins and Hull (14). Kinematic, EMG and fascicle data were
184 averaged from 6-12 steps per condition and participant (see Figure 1).

185

186 **Statistics**

187

188 EMG and fascicle length/velocity values were compared between conditions using repeated
189 measures ANOVA, and Bonferroni post hoc tests were used where appropriate. For all
190 ANOVAs, Mauchly's sphericity test was performed, and where this assumption was violated,
191 Greenhouse-Geisser adjustments were used. In all cases, statistical significance was
192 determined as $p < 0.05$. All statistical tests were carried out using IBM SPSS statistics
193 (version 22; Chicago, USA).

194

195

196 Results

197

198 For all three examined muscles, RM ANOVA for absolute RMS EMG revealed a significant
199 effect of test condition (MG: $F[GG] = 35.922$, $p < 0.001$; soleus: $F = 23.023$, $p < 0.001$; TA:
200 $F = 16.058$, $p < 0.001$). As absolute EMG values are often highly variable between
201 individuals, only EMG values normalized to distance (CMAPD) for each condition are
202 presented hereafter. Figure 2 shows group mean normalized EMG values for all conditions.
203 RM ANOVA again revealed a significant effect of condition for all muscles (MG: $F =$
204 33.049 , $p < 0.001$; soleus: $F = 21.053$, $p < 0.001$; TA: $F[GG] = 43.046$, $p < 0.001$). The
205 results of post hoc tests are shown in Figure 2.

206

207 Mean instantaneous fascicle velocity was calculated for MG and soleus across the stance
208 phase. RM ANOVA revealed a significant effect of condition for MG ($F = 13.290$, $p < 0.001$)
209 but not soleus ($F = 1.175$, $p = 0.253$; Figure 3). The absolute range of fascicle length change
210 was also calculated during the stance phase, but there was no effect of test condition in either
211 muscle (MG: $F = 1.439$, $p = 0.241$; soleus: $F = 1.596$, $p = 0.122$). Similarly, absolute fascicle
212 length at the time of ground contact did not differ between conditions for MG ($F = 2.437$, $p =$
213 0.106) or soleus ($F = 1.845$, $p = 0.232$).

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221 Discussion

222

223 In walking and running, triceps surae muscle fascicles generally behave almost isometrically,
224 allowing muscle-tendon length changes to be primarily taken up by elastic, energy-storing
225 tendinous tissues (e.g. (9)). This enables these muscles to operate in favorable regions of their
226 force-length and force-velocity relations, which in turn contributes to minimizing muscle-
227 tendon energy cost. Indeed, in this study, running was associated with a net shortening of MG
228 and soleus fascicles in the stance phase, combined with substantial lengthening of their
229 respective muscle-tendon units in the early and mid-stance phase, implying energy storage in
230 the Achilles tendon (Figure 4). However, when the same participants racewalked at the same
231 speed, soleus fascicles exhibited similar behaviour but the MG fascicles underwent net
232 lengthening during the stance phase. This coincided with rapid shortening followed by a
233 relatively small increase in muscle-tendon length during the early and mid-stance phase.
234 Therefore, both the amplitude of muscle-tendon lengthening and the proportion of muscle-
235 tendon unit lengthening taken up by the Achilles tendon were smaller in racewalking than
236 running at the same speed. The Achilles tendon is known to act as an important energy saver
237 in walking and particularly running (2) because of its ability to store and return elastic
238 energy. Compared with running at the same speed, racewalking appears to decrease the
239 energy-saving role of the Achilles tendon. Given that this occurs on a per stride basis, it is
240 likely that this pattern of muscle-tendon behavior is associated with significant energy costs
241 in racewalking events, which are typically between 10 and 50 km and induce substantial
242 muscle fatigue that may accentuate the already inefficient pattern of muscle-tendon
243 mechanics. Moreover, these results further demonstrate the performance-limiting effects of
244 maintaining a straightened knee from initial contact to midstance.

245

246 Contrary to MG, the fascicle behavior of the uniarticular soleus muscle was largely
247 unaffected by the different test conditions. This finding is consistent with several previous
248 studies that suggest that soleus fascicle behavior is not noticeably affected by changes in
249 speed (7) or gait (21). Conversely, Lai et al. (17) found a general increase in soleus
250 shortening velocity and absolute length change with increasing walking and running speeds.
251 This discrepancy could be due to the large differences in training backgrounds of the
252 participants, as Lai et al. tested recreational runners compared to elite racewalkers in this
253 study. Moreover, the lower ultrasound sampling frequency used here may have somewhat
254 smoothed the real length changes and thus reduced the ability to detect the small differences
255 between speeds that Lai et al. observed. Finally, soleus length changes are generally more
256 difficult to quantify than MG, due partly to the greater depth and lower quality of the
257 resulting ultrasound images (see (6)). Therefore, tracking errors likely contribute to all
258 reported soleus fascicle length and velocity values in the literature, as do differences in the
259 specific measures reported. In any case, in racewalking, at the level of the muscle-tendon
260 unit, both MG and soleus showed rapid and substantial shortening in the early contact phase,
261 followed by minimal lengthening. This is in sharp contrast to the case in running at identical
262 speeds, where muscle-tendon length continuously increased in the early stance phase,
263 implying greater tendon strain in running. Thus, although fascicle behaviour differed
264 somewhat between MG and soleus in this study, it can be concluded that racewalking
265 decreases the spring-like role of the Achilles tendon, and this is likely associated with large
266 energy costs over the course of a racewalking event.

267

268 Differences in fascicle behavior between MG and soleus, which were most pronounced in the
269 racewalking conditions, are noteworthy in light of the fact that both of these muscles share a
270 common distal tendon, and are thus often considered to be functionally similar. It has been

271 known for some time that relative sliding (or shear) can occur between the aponeuroses of
272 these muscles (e.g. (4)), although the functional significance of this finding is not clear. It
273 seems that one outcome of the relative independence between MG and soleus is that they can
274 exhibit different mechanical behavior in certain conditions, as shown here and in previous
275 gait studies (e.g. (7)). However, further work is required to identify the specific conditions in
276 which shear between the MG and soleus aponeuroses may be functionally beneficial.

277

278 In MG and soleus, normalized EMG was generally highest in the two racewalking conditions,
279 reinforcing earlier findings that the ankle plantarflexors are a key generator of positive
280 mechanical energy during late stance in racewalking (11, 15). As calculated in this study, the
281 CMAPD measure gives an estimate of the EMG or energy cost of an individual muscle
282 associated with moving a distance of 1 km at that speed and with that gait (5). This implies
283 that at the level of the individual muscles that we studied, the energy cost of racewalking was
284 higher than running at the same speed. When combined with the observed inefficiencies in
285 muscle-tendon behavior, these results suggest that racewalking is both neurally and
286 mechanically costly relative to running at a given speed.

287

288 A strength of this study was that elite-standard racewalkers were used, including one multiple
289 Olympian. The findings suggest that either the technical demands of racewalking dictate that
290 an efficient pattern of muscle-tendon interaction cannot be achieved, or that current training
291 methods do not encourage such an efficient pattern. Future studies should examine the effects
292 of modifying training programs to see if muscle-tendon interaction (and the associated cost of
293 muscle action) in racewalking can be tuned toward the more economical patterns observed in
294 running, whilst also staying within the biomechanical constraints of the rules. In addition, it
295 would be valuable to conduct research on the muscle-tendon function of other muscle groups

296 in racewalking whose role might also be altered by the technical restraints of the event,
297 including those most frequently injured (e.g. the hamstring muscles (13)). Moreover, the
298 absence of movement economy data (e.g. O₂ uptake) is a limitation of this study that should
299 be incorporated in future studies.

300

301 In conclusion, previous research on racewalking showed a higher energy cost than running at
302 an identical speed (e.g. (19)), although the sources of this additional cost had not been
303 explored in detail, and not under the modern definition of racewalking. Some of the cost
304 likely comes from the activation of a large number of upper and lower body muscles to
305 achieve the characteristic, defined gait pattern of racewalking (e.g. (11, 20)). Our data suggest
306 that, in the triceps surae at least, one source of increased energy cost in racewalking is a
307 decreased reliance on tendon energy-saving mechanisms. Moreover, our EMG data suggest
308 that individual lower limb muscle energy costs are higher in racewalking than running at the
309 same speed. Given the importance of the ankle plantarflexors to energy generation in elite-
310 standard racewalking, these two mechanisms could have a considerable cumulative effect on
311 performance over the course of a race that involves thousands of steps. In addition, from an
312 anthropological perspective, it is noteworthy that elite-standard racewalkers still exhibit
313 neuromechanical inefficiencies. Racewalking is an artificial gait form that, even when trained
314 for many years, is less economical than walking and running, which humans have evolved to
315 do over a much longer timeframe.

316

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318

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320 with athlete recruitment.

321

322 Figure legends

323

324 Figure 1: Typical example of EMG, kinematic and ultrasound data from one participant
325 racewalking and running at 10 km/h (left column) and 12.5 km/h (right column). Data are the
326 mean of nine strides and are time normalized to a single stride (i.e. heel contact to heel
327 contact). For the sake of visual clarity, raw EMG data in this figure were low pass filtered.
328 Vertical dashed lines denote approximate stance to swing phase transition.

329

330 Figure 2: Group mean EMG data normalized to a distance of 1 km to give the relative EMG
331 cost for each condition. Horizontal lines denote significant differences between conditions.
332 Note that the CMAPD calculation includes data from the entire stride, and thus includes the
333 cost of these muscles during the swing phase. The mean speed for the ‘fast’ conditions was
334 12.4 ± 1.1 km/h.

335

336 Figure 3: Group mean fascicle data showing mean instantaneous velocity throughout the
337 stance phase for MG and soleus for all conditions. Horizontal lines denote significant
338 differences between conditions. Note that no post hoc tests were performed for soleus data
339 because the RM ANOVA result for main effects was not significant.

340

341 Figure 4. Mean muscle-tendon unit length changes (upper panels) and fascicle length changes
342 (lower panels) for MG and soleus from all five test conditions. Absolute values are shown
343 relative to the respective length at the time of ground contact. Data are time normalized to
344 one stride. Hollow circles indicate the approximate stance to swing phase transition.

345

346

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348

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400

Figure 1

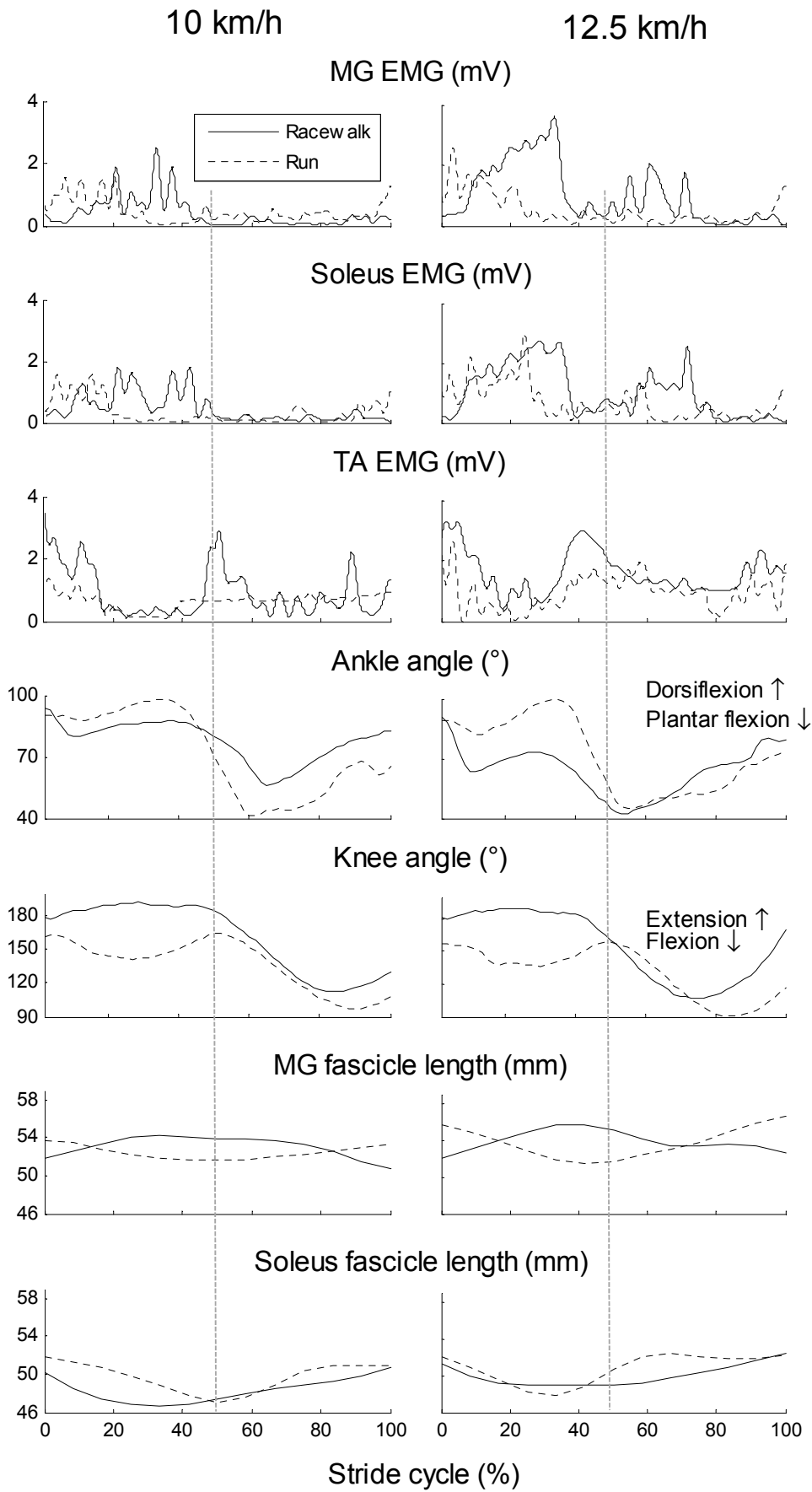


Figure 2

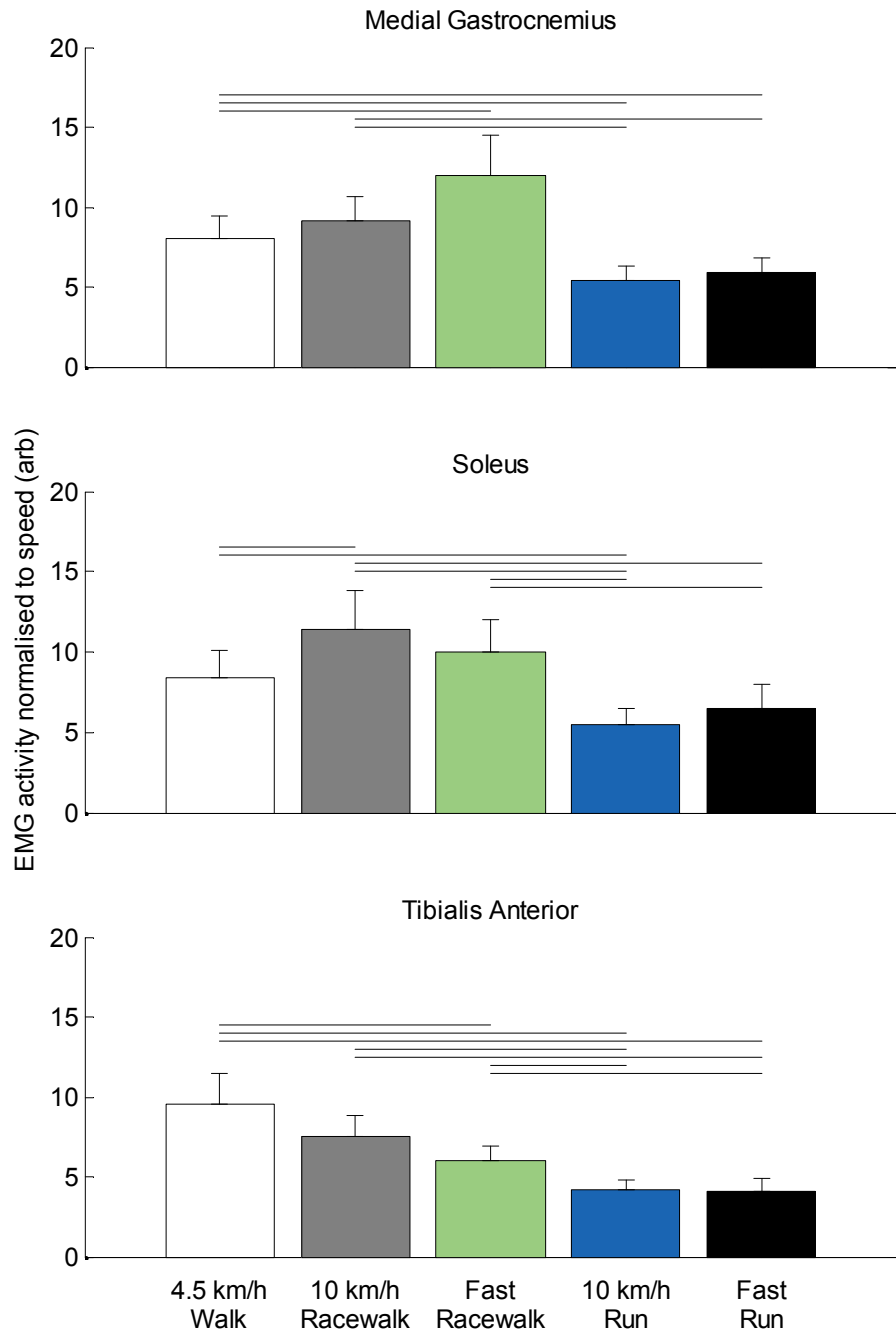


Figure 3

