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Mechanical and neural function of triceps surae in elite racewalking

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Running title: Neuromechanics of racewalking

Abstract

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

New and noteworthy

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

Keywords

Racewalking, muscle-tendon, athletics, ultrasound, gait

Introduction

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

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

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

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

Methods

Participants

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

Methodology

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

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

Protocol

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

Analysis

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

Statistics

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

Results

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

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

Discussion

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

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

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

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

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

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

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

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

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Figure legends

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

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

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

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

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Figure 1

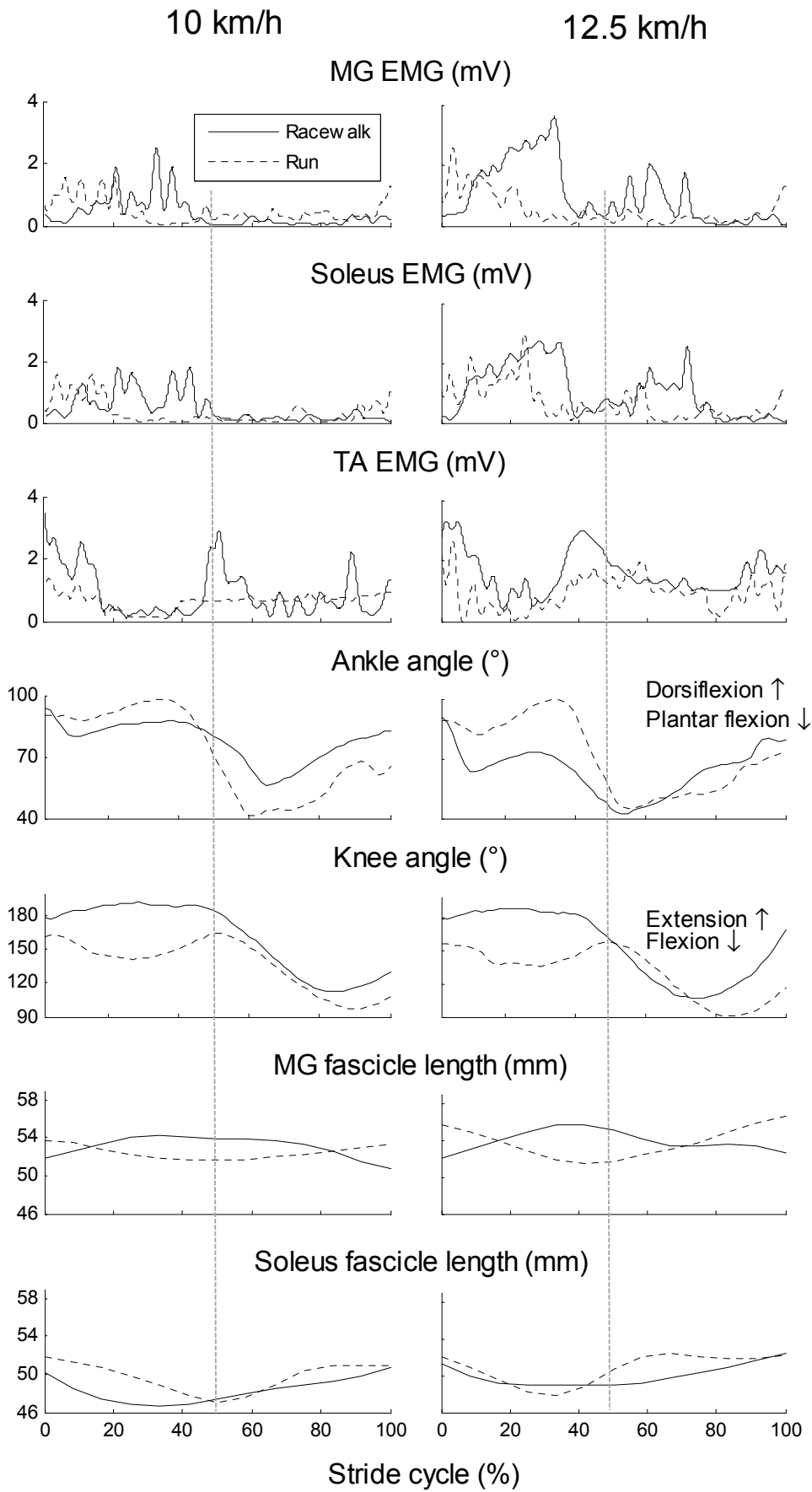


Figure 2

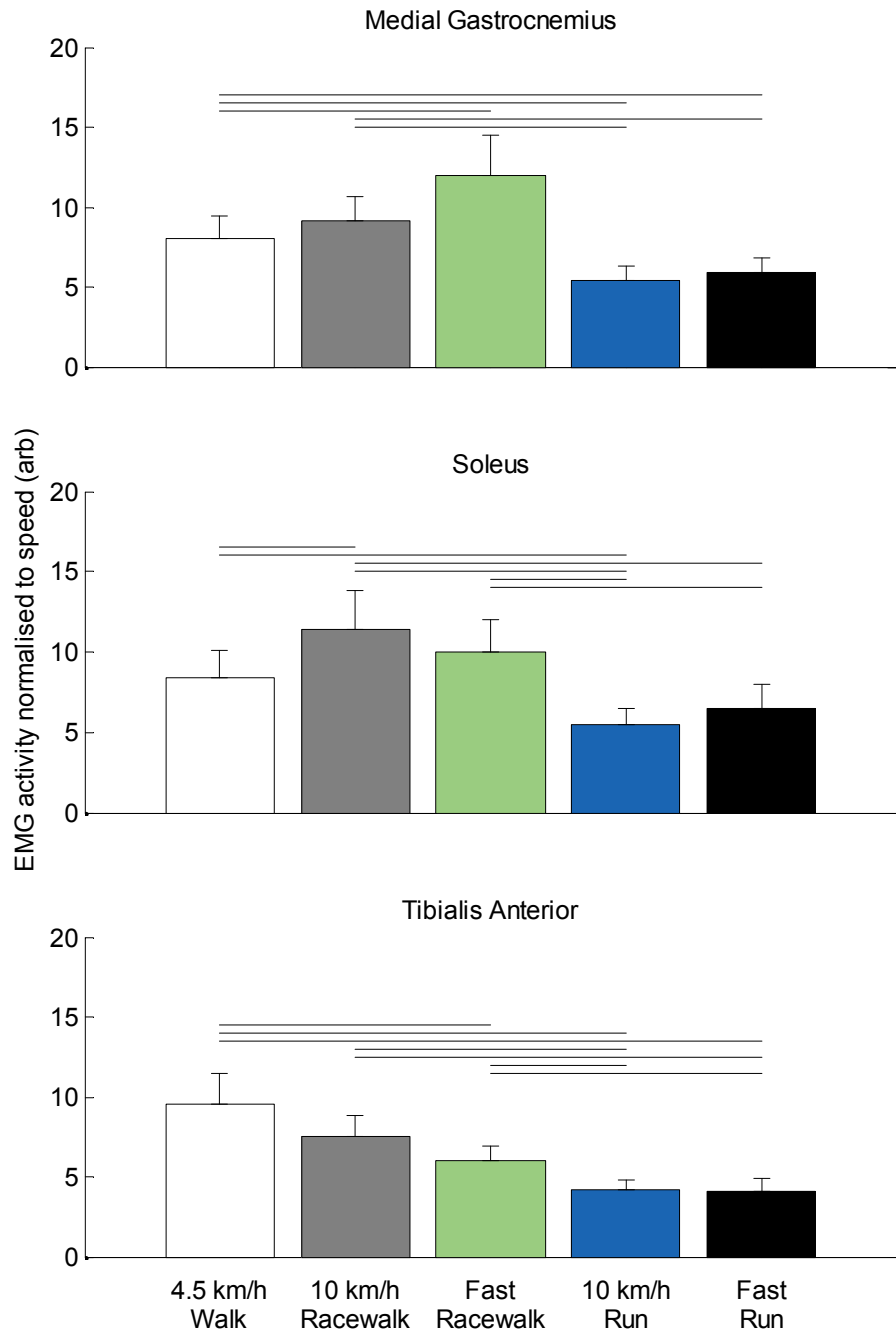


Figure 3

