MORPHOLOGICAL AND MECHANICAL PROPERTIES OF LOWER LIMBS IN COMPETITIVE RACEWALKERS: ASSOCIATIONS WITH PERFORMANCE

Original article

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ABSTRACT

Racewalking is an unconventional form of competitive gait that elicits a unique loading profile on lower limb muscles and tendons. This study mapped the structural and mechanical properties of lower limbs in competitive racewalkers and made associations with World Athletics competition performance points. Fourteen international racewalkers (seven men, seven women) were recruited for this study. Static ultrasonography was used to quantify muscle and tendon morphological characteristics. An isokinetic dynamometer was used to measure passive musculotendinous stiffness of the triceps surae, isometric (seven knee/ankle angle combinations) and isokinetic (four angular velocities) strength parameters in the plantarflexors and dorsiflexors, and isokinetic knee flexion and extension strength at five angular velocities. Correlations were found between performance and fascicle length of gastrocnemius medialis (r = –0.569, p = 0.034), dorsiflexor strength at 120°/s (r = 0.649, p = 0.016) and knee flexor strength at 30°/s (r = 0.632, p = 0.020). No associations were found for isometric plantarflexion or passive stiffness properties. Overall, the study showed various morphological and mechanical properties are associated with performance in competitive racewalkers. These associations seem to be related to the specific and unique biomechanical characteristics of racewalking.

KEYWORDS

Endurance, muscle, strength, tendon, track and field.

1. INTRODUCTION

Racewalking is an endurance event with rules stating there can be no visible loss of ground contact and the knee must be straightened from initial ground contact until the vertical upright position (Pavei et al., 2014; World Athletics, 2019). This creates a problem as the knee extensors do not absorb energy after ground contact or generate energy during push-off, making racewalking a unique and unconventional gait. This problem is overcome at the hip and ankle joints (Hanley and Bissas, 2017; White and Winter, 1985), although the extent of this depends on the models used to calculate joint moments (Pavei et al., 2017). During racewalking at a competitive pace, Hanley and Bissas (2017) showed that elite-standard athletes generate most work using the hip flexors and extensors and ankle plantarflexors, contributing >80% to total work during stance. For the plantarflexors, this increased mechanical demand is reflected by increased activity in gastrocnemius medialis (GM) and soleus (SOL) compared with normal walking and running (Cronin et al., 2016). Furthermore, racewalking leads to different fascicle mechanical behavior, especially in GM. This is characterized by net lengthening during stance, instead of near isometric or net shortening in walking and running, respectively (Cronin et al., 2016). This has subsequent effects on muscle-tendon interaction in the triceps surae (TS) muscle-tendon complex (MTC), which could lead to chronic changes to MTC structure and function of in trained racewalkers.

MTC properties have been investigated for various populations, involving measures such as muscle-tendon morphology (e.g., Hansen et al., 2003; Kovács et al., 2020; Magnusson and Kjaer, 2003; Stenroth et al., 2016), passive stiffness-type metrics (e.g., Moltubakk et al., 2018), and isometric or isokinetic strength parameters (e.g., Epro et al., 2019; Herzog et al., 1991; Moltubakk et al., 2018; So et al., 1994; Theoharopoulos and Tsitskaris, 2000). It is possible that some of these properties adapt over time, leading to an improved metabolic efficiency of a given task (Peyré-Tartaruga and Coertjens, 2018). For instance, Magnusson and Kjaer (2003) showed runners have a greater cross-sectional area (CSA) across several portions of the Achilles tendon (AT) compared with non-runners, which has implications for the stress-strain properties of AT during locomotion. Further, morphological characteristics have been associated with marathon performance in competitive runners, showing factors such as SOL physiological CSA and AT CSA to display strong positive associations with marathon performance (Kovács et al., 2020). In addition to morphological structure, Moltubakk et al. (2018) showed differences in passive musculotendinous stiffness in the TS in well-trained ballerinas. These athletes regularly practice stretching exercises, which potentially led to the greater maximum dorsiflexion angle and reduced passive stiffness at common joint angles compared with controls. The ballerinas were also stronger in plantarflexion strength assessments compared with controls (Moltubakk et al., 2018). Similar properties could also be evident in endurance athletes, with a recent review article by Boullosa et al. (2020) showing that faster recreational long-distance runners show greater maximal muscle strength and improved elastic energy storage, leading to a better running economy. However, it remains unclear whether these group-based differences are specific chronic adaptations to repetitive loading due to the retrospective nature of the study design, or whether they were characteristics established before the commencement of training.

Despite the uncertainty around the causality of these differences between trained and untrained populations, it appears that certain characteristics might possess some association with performance within a trained population, which would have implications for the optimization of strength training programs. For example, as racewalkers must increase the relative contribution of the plantarflexors to overall mechanical work, it could be hypothesized that better athletes possess morphological and mechanical characteristics favorable for joint work contribution, whilst minimizing any increase in metabolic cost. However, no data of this type exist for racewalkers, despite the unique movement patterns they must adhere to in competition. Therefore, the aim of this study was to map mechanical properties of several lower-limb MTCs in elite-standard racewalkers. The relevance of these parameters to performance was investigated by associating them with athletes' World Athletics competition performance points (World Athletics, 2020).

2. METHODS

2.1. Participants

Participants were 14 racewalkers of five nationalities (seven men and women; age: 21 ± 3 years; stature: 1.73 ± 0.06 m; mass: 60.4 ± 7.3 kg). All participants competed internationally over either 10 km or 20 km and were allocated competition performance points by World Athletics, available via the World Athletics website (World Athletics, 2020). Competition performance points are calculated independently for men and women so for the purposes of this study, points were adjusted so men's and women's values were calculated equally. This was done using linear regression, where the midpoints of the gradient and y-intercept for each sex's points-time relationships were used. Adjusted performance points ($PP_{adjusted}$) for the participants in the current study were 928 ± 193. Participants gave written informed consent and confirmed they were free of any known neurological disorder or musculoskeletal injury at the time of testing. They were also asked to refrain from exercise for at least 24 hours before testing. This study gained ethical approval from the local university ethics committee (project number 61804) and testing was carried out in accordance with the Declaration of Helsinki.

2.2. Muscle and tendon morphological assessment

Muscle and tendon morphology was measured at various sites of the right leg using two-dimensional B-mode ultrasound (Acuson P300, Siemens Healthineers AG, Germany). A 50-mm linear array probe (5-12 MHz) was used to obtain *in vivo* longitudinal-plane scans of GM, SOL, gastrocnemius lateralis (GL), tibialis anterior (TA) and vastus lateralis (VL) muscle bellies, with the probe aligned with the mid-sagittal axis of the muscle and in the direction of muscle fibers (Maganaris et al., 1998). A 40-mm linear array probe (12-18 MHz) was used to collect longitudinal- and transverse-plane images of AT. The probe was placed 40 mm proximal to the calcaneal notch (approximated using ultrasound) to obtain thickness and CSA measurements (Bissas et al., 2020). For each site, a minimum of three scans were analyzed. AT resting length was estimated by measuring the distance from the calcaneal notch to the most distal point of the GM myotendinous junction with the AT with a tape measure. This procedure was guided by ultrasound, using a comparable technique to that described by Barfod et al. (2015).

Images were analyzed manually using open-source software Fiji (ImageJ 1.52i, 64-bit, National Institutes of Health, USA), and all scans were collected and analyzed by a single experienced operator. From the muscular images, architectural features were measured:

muscle thickness (distance between deep and the superficial aponeuroses); pennation angle (angle that a given fascicle inserts into the deep aponeurosis); and fascicle length (distance between a fascicle's insertions into the deep and superficial aponeuroses). If a full fascicle was not captured within the field of view, manual interpolation was carried out by projecting the aponeuroses beyond the field of view, which was corroborated with trigonometric estimations (Ando et al., 2014; Kawakami et al., 1995). AT thickness was defined as the distance between deep and superficial edges of the tendon (including peritenon), and AT CSA was measured by outlining the echogenic area of the tendon using the freehand drawing tool in Fiji. This method for obtaining AT CSA has previously been shown to lack accuracy when compared to magnetic resonance imaging (Bohm et al., 2016). However, intra-rater reliability was determined by the operator analyzing a subset of 10 randomly selected images on two occasions (separated by 48 h). The intraclass correlation coefficient for AT CSA was 0.975, and reliability values across measurements ranged from 0.898 (VL fascicle length) to 0.999 (VL and GM muscle thickness).

2.3. Passive MTC properties

Passive measurements of the right TS MTC were undertaken using an isokinetic dynamometer (System 4 Pro, Biodex Medical Systems, USA) with an attachment used for rotating the ankle joint in the sagittal plane. Participants were seated with their hip joint fixed at ~65° flexion, with their knee joint extended and aligned parallel to the ground. Straps were placed across the pelvis and involved knee to limit movement at the hip and knee joints. The foot was fixed to the dynamometer attachment using ratchet straps and additional Velcro fixings to minimize heel lift from the footplate. The center of the ankle joint (approximated using the lateral malleolus) was aligned with the dynamometer's axis of rotation. A gravity correction was applied to the dynamometer (Baltzopoulos, 2018) after measuring the resting moment at 10° plantarflexion.

The test was carried out by the dynamometer passively rotating the ankle through its full range of motion (based on the participant's perceived limits) from maximal dorsiflexion to maximal plantarflexion and back to maximal dorsiflexion, at a constant angular velocity of 10°/s. Ankle angle was defined as the angle between the foot (first metatarsal to the calcaneus) and shank segments. Six repetitions were repeated in sequence, with the final full repetition analyzed. Participants were instructed to remain passive throughout the test. To ensure this, surface electromyography of the GM, GL, SOL and TA was recorded throughout the test (2,000 Hz; Trigno wireless, Delsys Inc., USA). Although this was not processed after data collection for the current study, the raw muscle activity data permitted the researchers to detect any activity above what would be expected during slow, passive joint rotation (Moltubakk et al., 2018). No trials were omitted because of visually detected muscle activity.

Passive joint moment and ankle joint angle were obtained from the dynamometer at a sampling rate of 100 Hz. The joint moment-angle curve was fitted with a fourth-order polynomial from maximal plantarflexion to maximal dorsiflexion, from which passive joint moment and passive stiffness were obtained (Nordez et al., 2006). Passive joint moment was analyzed at a common ankle joint angle (5° dorsiflexion) and at each participant's individual maximal dorsiflexion angle (Moltubakk et al., 2018). Passive stiffness was calculated at the same joint angles from the slope of the moment-angle polynomial curve.

2.4. Strength assessments

Following the passive stiffness assessments, isometric and isokinetic strength testing was undertaken using the same dynamometer described above. Firstly, isometric strength of the TS MTC was tested at a standardized hip angle of approximately 65° with the center of the ankle joint aligned with the dynamometer axis. Five ankle angles were tested in a randomized order (5° dorsiflexion, neutral (0°), and 5, 10 and 20° plantarflexion) at a knee angle of 35° flexion. Additionally, the neutral ankle condition was repeated at full knee extension and 70° flexion to produce multi-faceted joint moment-angle curves by altering the relative contributions of biarticular GM and GL across a range of muscle-tendon unit (MTU) lengths. After a familiarization repetition, participants were urged to plantarflex “as hard and fast as possible” for 2-3 s for two repetitions (5-s repetition interval), with 120-s rest between joint positions. The highest instantaneous joint moment recorded across the two repetitions was analyzed from the raw joint moment data (100 Hz) in MATLAB (version R2020b, MathWorks Inc., USA). A well-known limitation of isometric plantarflexion strength assessments with a conventional dynamometer is axis misalignment, caused by compliance in the system and the heel lifting away from the footplate (Arampatzis et al., 2005). An additional Velcro strap was placed around the foot to reduce this, although it cannot be completed eliminated.

Isokinetic strength of the plantarflexors and dorsiflexors was then tested with a fully extended knee joint and at four randomized-order angular velocities: 30, 60, 90, and 120°/s. After three familiarization repetitions, three maximal efforts were carried out through the participants’ full range of motion. Dorsiflexion and plantarflexion measurements were taken within the same trials for each angular velocity, each of which were separated by 120-s rest. Only the best trial for each direction was analyzed. Joint moment data were analyzed only when angular velocity was within 5% of the target velocity, termed the isokinetic range (Baltzopoulos, 2018). The highest instantaneous joint moment within the defined isokinetic range recorded for plantarflexors and dorsiflexors were analyzed. Finally, isokinetic testing was also carried out for the knee flexors and extensors at five angular velocities: 30, 90, 150, 210, and 270°/s using the same protocol as the ankle. For the knee strength assessment, the hip joint was placed at approximately 90°, and the center of the knee joint (approximated using the lateral femoral epicondyle) was aligned with the dynamometer’s axis of rotation.

2.5. Statistical analysis

Statistical analyses were carried out in MATLAB. Pearson’s correlations (two-tailed) were used to establish associations between $PP_{adjusted}$ and muscle-tendon properties. Magnitudes of correlations were interpreted according to the guidelines of Hopkins et al. (2009).

Significance was set at $p < 0.05$. Variables were computed as absolute and relative values. However, as no differences in trends were found, data were presented as relative values only.

3. RESULTS

AT morphology, muscle thickness and pennation angles are presented in Table 1. There was no correlation between AT length or thickness and $PP_{adjusted}$ ($p \geq 0.79$). A moderate positive correlation was found for AT CSA, but was not significant ($r = 0.451$, $p = 0.105$). Muscle thickness correlations were not significant, and pennation angles for SOL, TA and VL also showed no significant associations with $PP_{adjusted}$. Pennation angles for GM and GL showed moderate positive correlations, but also were not statistically significant (Table 1).

[INSERT TABLE 1 HERE]

Figure 1 shows associations between fascicle length data and $PP_{adjusted}$. Fascicle length for GM showed a large, negative correlation with $PP_{adjusted}$ (Figure 1A; $r = -0.57$, $p = 0.034$, 95% confidence intervals = −0.845 to −0.055). Other fascicle length measurements showed no significant correlations with $PP_{adjusted}$.

[INSERT FIGURE 1 HERE]

Racewalkers displayed a passive ankle range of motion of 65 ± 8° with a maximum dorsiflexion angle of 17 ± 5° (Table 2). Neither ankle range of motion nor maximum dorsiflexion angle was associated with $PP_{adjusted}$ (Table 2). Additionally, mechanical properties of the ankle joint during passive dorsiflexion had no associations with $PP_{adjusted}$ (Table 2).

[INSERT TABLE 2 HERE]

[INSERT TABLE 3 HERE]

During the isometric plantarflexion assessment, no correlations were found between maximum joint moment and $PP_{adjusted}$ at any joint angle (Table 3). During isokinetic plantarflexion, no correlations were found between maximum joint moment and $PP_{adjusted}$ (Table 4). However, during isokinetic dorsiflexion, a large, positive correlation was found for maximum joint moment at 120°/s (Table 4). Dorsiflexor strength at other angular velocities showed small or moderate positive correlations.

[INSERT TABLE 4 HERE]

A large, positive correlation was found between maximum isokinetic knee flexion moment at 30°/s and $PP_{adjusted}$ (Table 5). Large, positive correlations were also found for both the maximum knee flexion and extension moments at 210°/s, although these were not statistically significant. Maximum joint moments at other angular velocities showed small or moderate correlations (Table 5).

[INSERT TABLE 5 HERE]

4. DISCUSSION

The aim of this study was to analyze morphological and mechanical characteristics in lower limbs of competitive racewalkers by mapping passive and active lower-limb MTC properties. To the authors' knowledge, this is the first study to present these characteristics in this population and provides added context to previous description of muscle-tendon function during the racewalking action (Cronin et al., 2016). To provide an indication of relevance to performance, data were correlated with $PP_{adjusted}$, World Athletics' competition performance points adjusted to negate the weightings for men and women. Significant correlations were found for some morphological and mechanical properties, namely GM fascicle length, isokinetic dorsiflexion moment at 120°/s and knee flexion moment at 30°/s.

AT CSA has been shown to positively correlate with competition performance points (Kovács et al., 2020) and other research has shown differences between runners and non-runners (Magnusson and Kjaer, 2003). The same association in the current study was moderate but as it was not statistically significant, this implies that associations between AT CSA and performance are less important in racewalking than running, which is reasonable given the higher dependence of elastic energy storage and return during stance in running. Racewalking has no distinguishable flight phase, so stress-strain properties of AT might be less adapted in these populations, meaning it is not a key determinant of success. The accuracy of obtaining AT CSA using ultrasound has previously been criticized (Bohm et al., 2016), which might have influenced the current findings. However, excellent test-retest reliability was shown for manual analysis here, so any inaccuracies in the measurement were possibly systematic and would not affect relationships with $PP_{adjusted}$. Nonetheless, direct comparisons with populations from previous literature should be interpreted with some caution.

Athletes with higher $PP_{adjusted}$ tended to have shorter GM fascicles (Figure 1). This was interesting as previous literature in runners showed no association between GM fascicle length and competition performance points (Kovács et al., 2020) and has also been shown not to differ between sprinters and endurance runners (Stenroth et al., 2016), although this is not consistent throughout the literature (Abe et al., 2000). The relationship observed here is possibly unique to racewalkers, and could be an effect of the additional mechanical demand placed on the biarticular gastrocnemius muscles during the stance phase in racewalking (Hanley and Bissas, 2017). A similar trend was observed in GL, although this was not statistically significant. Other research into the role of GM during racewalking showed fascicles undergo net lengthening during the stance phase (Cronin et al., 2016) which is different to the near-isometric or slow shortening during conventional walking or running (Lichtwark et al., 2007). The negative correlation for fascicle length in the current study therefore appears to be counterintuitive. However, longer fascicles could mean less AT elongation for a given amount of MTU elongation, leading to less energy storage in the AT meaning more active work must be done by the contractile element, which can lead to a higher energetic cost (Bohm et al., 2019; Doke and Kuo, 2007). Correlations between $PP_{adjusted}$ and other morphological characteristics were generally small-moderate, with VL showing the weakest correlations overall (Table 1; Figure 1). VL thickness and pennation angle were also lower than previously reported for trained and untrained populations (Abe et al., 2000). This was expected given the limited active role the knee extensors have in energy generation during the stance phase of racewalking (Hanley and Bissas, 2017; White and Winter, 1985). It should be acknowledged that extending fascicles beyond the ultrasound probe's field-of-view can cause erroneous measurements in fascicle length (Ando et al., 2014), especially in muscles with longer fascicles such as VL. This should be considered when comparing data from this study with future measurements, although it was unlikely to have affected the correlations presented here (Figure 1).

There were no significant associations between knee extensor strength and $PP_{adjusted}$ (Table 5). However, there is evidence of a positive association between knee flexor strength and $PP_{adjusted}$, with a large correlation being observed at the slowest angular velocity tested (Table 5). Correlations for knee flexor strength at other angular velocities were not significant (Table 5). The association found at 30°/s supports previous literature suggesting the inclusion of strength training for endurance athletes is beneficial for overall performance (Beattie et al., 2014). Emphasis should be placed on the hamstring muscles in strength training because of their increased contribution to overall work (as knee flexors and hip extensors) in contrast to the knee extensor muscles during racewalking, although future research implementing strength training interventions in these athletes would expand on the efficacy of this for performance. The finding that only the 30°/s condition showed a correlation was interesting and could be because during the early- and mid-stance phases of racewalking, the knee flexors elicit large forces at very low angular velocities (Hanley and Bissas, 2017), meaning the slower isokinetic condition bears more relevance to performance. However, it should be noted that the knee joint isokinetic strength in the current study was collected with the hip joint fixed in a flexed position and which does not occur during racewalking. Furthermore, it remains undetermined from these findings how knee flexor strength impacts racewalking kinematics. We have simply shown that there is an association with overall performance. Future research could consider the implementation of strength characteristics in musculoskeletal models when aiming to investigate optimal performance in racewalkers. It should be acknowledged that maximal strength and passive MTU characteristics are considered in endurance performance models, which also include physiological factors such as movement economy (Bohm et al., 2021; Boullosa et al., 2020). Although these factors were not considered in the current study, the correlations established develop an understanding of which mechanical factors should be implemented in future racewalking models.

Ankle isokinetic strength showed varied associations with $PP_{adjusted}$, with maximum dorsiflexor moment at 120°/s showing a large, positive correlation (Table 4). This finding could imply some adaptation to the constrained movement of racewalking because of how the ankle is dorsiflexed to its physical limit during swing, ensuring ground clearance and a heel strike at initial contact (Hanley and Bissas, 2017). The fact that only the highest angular velocity condition showed a correlation is likely due to the high angular velocity seen at the ankle during early swing, meaning athletes are required to shift into a dorsiflexed position quickly when walking at race pace (Hanley and Bissas, 2017). Few isokinetic strength data exist for the ankle joint in athletic and healthy populations (Moltubakk et al., 2018; So et al., 1994; Theoharopoulos and Tsitskaris, 2000), so these data could be used in future research to compare other endurance-trained athletes. Like isokinetic plantarflexor strength, there were no significant correlations between isometric plantarflexor strength and $PP_{adjusted}$ in any joint configuration (Table 3). This suggests that despite ankle plantarflexors contributing considerably to overall energy generation during the stance phase, maximal strength is not a distinguishing feature in higher-standard performers. One notable limitation with isokinetic dynamometry is joint misalignment with the dynamometer's axis of rotation (Arampatzis et al., 2005). Although this was partially mitigated for the ankle dynamometry, it cannot be fully eliminated.

The findings of this study might be affected by several other limitations. Errors within the dynamometry joint moment data could affect the passive stiffness and strength-based measurements in the current study. Preparation, collection, and analysis protocols were consistent between participants, meaning relationships with $PP_{adjusted}$ were likely unaffected. However, errors in the absolute signal can be caused by analogue-to-digital conversion (Baltzopoulos, 2018), and noise reduction methods (e.g., low-pass filtering) were not considered for the purposes of this study given there is no consensus on optimal methods for dynamometry data. Further, as the muscle activity was visually inspected in the current study, low-level voluntary activity cannot be discounted. However, a limitation of this measurement is that some activity is expected during passive elongation of a MTU, meaning distinguishing between voluntary and "involuntary" activity is difficult. Additionally, a reasonably small sample size (due to the specialized participant group) might have affected the statistical power of established relationships. However, racewalkers were of varying competitive standards (although all were international competitors; unadjusted competition performance points ranged from 841 to 1199), meaning the dataset should be heterogenous enough to provide scope across competitive athletes. Future research should investigate these parameters in athletes from various competitive backgrounds, and even compare with other populations such as endurance runners or controls, to build on the generalizability of these findings. The performance criterion used in the current study ($PP_{adjusted}$) is derived from completion time for a given distance, so is a measure of overall performance for an athlete. Given the strong influence of aerobic capacity and movement economy has on endurance performance, it is possible that few strong associations were found here because there are myriad factors affecting $PP_{adjusted}$. Future research might wish to break down factors affecting racewalking performance further to establish relationships between muscle-tendon mechanical characteristics and other performance factors such as step length or cadence.

5. CONCLUSIONS

This study was the first to create a muscle-tendon morphological and mechanical profile for racewalkers. GM fascicle length and knee flexor and ankle dorsiflexor strength showed some large correlations with $PP_{adjusted}$, highlighting important morphological and mechanical characteristics required for better performance. These data provide a point of reference for scientists and coaches when working with competitive racewalkers. Future research should aim to compare these measurements between populations, whether that be between sports or within racewalking to appreciate the chronic adaptations observed in MTUs in response to the unique, constrained movement of racewalking.

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CONFLICT OF INTEREST STATEMENT

The named authors have no conflict of interest to disclose, financial or otherwise.

REFERENCES

Abe, T., Kumagai, K., Brechue, W.F., 2000. Fascicle length of leg muscles is greater in sprinters than distance runners. Medicine and Science in Sports and Exercise 32, 1125-1129.

Ando, R., Taniguchi, K., Saito, A., Fujimiya, M., Katayose, M., Akima, H., 2014. Validity of fascicle length estimation in the vastus lateralis and vastus intermedius using ultrasonography. Journal of Electromyography and Kinesiology 24, 214-220.

Arampatzis, A., Morey-Klapsing, G., Karamanidis, K., DeMonte, G., Stafilidis, S., Brüggemann, G.-P., 2005. Differences between measured and resultant joint moments during isometric contractions at the ankle joint. Journal of Biomechanics 38, 885-892.

Baltzopoulos, V., 2018. Isokinetic dynamometry, in: Payton, C., Burden, A. (Eds.), Biomechanical evaluation of movement in sport and exercise, 2nd ed. Routledge, Oxon, United Kingdom, pp. 140-167.

Barfod, K.W., Riecke, A.F., Boesen, A., Hansen, P., Maier, J.F., Døssing, S., Troelsen, A., 2015. Validation of a novel ultrasound measurement of Achilles tendon length. Knee Surgery, Sports Traumatology, Arthroscopy 23, 3398-3406.

Beattie, K., Kenny, I.C., Lyons, M., Carson, B.P., 2014. The effect of strength training on performance in endurance athletes. Sports Medicine 44, 845-865.

Bissas, A., Havenetidis, K., Walker, J., Hanley, B., Nicholson, G., Metaxas, T., Christoulas, K., Cronin, N.J., 2020. Muscle-tendon morphology and function following long-term exposure to repeated and strenuous mechanical loading. Scandinavian Journal of Medicine and Science in Sports 30, 1151-1162.

Bohm, S., Mersmann, F., Santuz, A., Arampatzis, A., 2019. The force-length-velocity potential of the human soleus muscle is related to the energetic cost of running. Proceedings of the Royal Society of London B: Biological Sciences 286.

Bohm, S., Mersmann, F., Santuz, A., Arampatzis, A., 2021. Enthalpy efficiency of the soleus muscle contributes to improvements in running economy. Proceedings of the Royal Society B 288.

Bohm, S., Mersmann, F., Schroll, A., Mäkitalo, N., Arampatzis, A., 2016. Insufficient accuracy of the ultrasound-based determination of Achilles tendon cross-sectional area. Journal of Biomechanics 49, 2932-2937.

Boullosa, D., Esteve-Lanao, J., Casado, A., Peyré-Tartaruga, L.A., Gomes da Rosa, R., Del Coso, J., 2020. Factors affecting training and physical performance in recreational endurance runners. Sports 8.

Cronin, N.J., Hanley, B., Bissas, A., 2016. Mechanical and neural function of triceps surae in elite racewalking. Journal of Applied Physiology 121, 101-105.

Doke, J., Kuo, A.D., 2007. Energetic cost of producing cyclic muscle force, rather than work, to swing the human leg. Journal of Experimental Biology 210, 2390-2398.

Epro, G., Hunter, S., König, M., Schade, F., Karamanidis, K., 2019. Evidence of a uniform muscle-tendon unit adaptation in healthy elite track and field jumpers: a cross sectional investigation. Frontiers in Physiology 10.

Hanley, B., Bissas, A., 2017. Analysis of lower limb work-energy patterns in world-class race walkers. Journal of Sports Sciences 35, 960-966.

Hansen, P., Aagaard, P., Kjaer, M., Larsson, B., Magnusson, S.P., 2003. Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. Journal of Applied Physiology 95, 2375-2380.

Herzog, W., Guimaraes, A., Anton, M., Carter-Erdman, K., 1991. Moment-length relations of rectus femoris muscles of speed skaters/cyclists and runners. Medicine and Science in Sports and Exercise 23, 1289-1296.

Hopkins, W.G., Marshall, S.W., Batterham, A.M., Hanin, J., 2009. Progressive statistics for studies in sports medicine and exercise science. Medicine and Science in Sports and Exercise 41, 3-12.

Kawakami, Y., Abe, T., Kuno, S.-Y., Fukunaga, T., 1995. Training-induced changes in muscle architecture and specific tension. European Journal of Applied Physiology and Occupational Physiology 72, 37-43.

Kovács, B., Kóbor, I., Gyimes, Z., Sebestyén, Ö., Tihanyi, J., 2020. Lower leg muscle–tendon unit characteristics are related to marathon running performance. Scientific Reports 10.

Lichtwark, G., Bougoulias, K., Wilson, A., 2007. Muscle fascicle and series elastic element length changes along the length of the human gastrocnemius during walking and running. Journal of Biomechanics 40, 157-164.

Maganaris, C.N., Baltzopoulos, V., Sargeant, A.J., 1998. In vivo measurements of the triceps surae complex architecture in man: implications for muscle function. Journal of Physiology 512, 603-614.

Magnusson, S.P., Kjaer, M., 2003. Region-specific differences in Achilles tendon cross-sectional area in runners and non-runners. European Journal of Applied Physiology 90, 549-553.

Moltubakk, M., Magulas, M., Villars, F., Seynnes, O., Bojsen-Møller, J., 2018. Specialized properties of the triceps surae muscle-tendon unit in professional ballet dancers. Scandinavian Journal of Medicine and Science in Sports 28, 2023-2034.

Nordez, A., Cornu, C., McNair, P., 2006. Acute effects of static stretching on passive stiffness of the hamstring muscles calculated using different mathematical models. Clinical Biomechanics 21, 755-760.

Pavei, G., Cazzola, D., La Torre, A., Minetti, A.E., 2014. The biomechanics of race walking: literature overview and new insights. European Journal of Sport Science 14, 661-670.

Pavei, G., Seminati, E., Cazzola, D., Minetti, A.E., 2017. On the estimation accuracy of the 3D body center of mass trajectory during human locomotion: inverse vs. forward dynamics. Frontiers in Physiology 8.

Peyré-Tartaruga, L.A., Coertjens, M., 2018. Locomotion as a powerful model to study integrative physiology: efficiency, economy, and power relationship. Frontiers in Physiology 9.

So, C.-H., Siu, T., Chan, K., Chin, M., Li, C., 1994. Isokinetic profile of dorsiflexors and plantar flexors of the ankle - a comparative study of élite versus untrained subjects. British Journal of Sports Medicine 28, 25-30.

Stenroth, L., Cronin, N.J., Peltonen, J., Korhonen, M.T., Sipilä, S., Finni, T., 2016. Triceps surae muscle-tendon properties in older endurance-and sprint-trained athletes. Journal of Applied Physiology 120, 63-69.

Theoharopoulos, A., Tsitskaris, G., 2000. Isokinetic evaluation of the ankle plantar and dorsiflexion strength to determine the dominant limb in basketball players. Isokinetics and Exercise Science 8, 181-186.

White, S.C., Winter, D., 1985. Mechanical power analysis of the lower limb musculature in race walking. Journal of Applied Biomechanics 1, 15-24.

WorldAthletics, 2019. C2.1 - Technical Rules. World Athletics, Monte Carlo.

WorldAthletics. 2020. Overall rankings [Internet]. Available from: <https://www.worldathletics.org/world-ranking-rules/overall-rankings> [Accessed 15 August, 2020].

TABLE AND FIGURE CAPTIONS

Table 1. Mean ± S.D. for AT length, thickness and CSA, as well as muscle thickness and pennation angle for the five imaged muscles (GM, GL, SOL, TA, VL). All length and thickness measures are presented as a percentage of stature. Pearson's correlations between morphological characteristics and $PP_{adjusted}$ are displayed with 95% confidence intervals.

Table 2. Mean ± S.D. for mechanical properties of the ankle joint during slow, passive dorsiflexion. Pearson's correlations between mechanical properties and $PP_{adjusted}$ are displayed with 95% confidence intervals.

Table 3. Mean ± S.D. for isometric plantarflexion moments at the seven different knee and ankle configurations. Pearson's correlations between maximum plantarflexion moment and $PP_{adjusted}$ are displayed with 95% confidence intervals.

Table 4. Mean ± S.D. for isokinetic plantarflexion and dorsiflexion moments at the four tested angular velocities. Data are presented relative to body mass. Pearson's correlations between maximum plantarflexion moment and $PP_{adjusted}$ are displayed with 95% confidence intervals.

Table 5. Mean ± S.D. for isokinetic knee extension and flexion moments at the four tested angular velocities. Data are presented relative to body mass. Pearson's correlations between maximum plantarflexion moment and $PP_{adjusted}$ are displayed with 95% confidence intervals.

Figure 1. Scatterplots showing correlations between fascicle length and $PP_{adjusted}$ for: (A) GM, (B) GL, (C) SOL, (D) TA, and (E) VL. Fascicle length data are presented as a percentage of stature.

	Mean ± S.D.	Correlation with $PP_{adjusted}$ *r*-value (*p*-value)	95% CI±
AT length (% stature)	11.9 ± 1.3	0.078 (0.790)	−0.472 to 0.585
AT thickness (% stature)	0.3 ± < 0.1	0.038 (0.899)	−0.503 to 0.558
AT CSA (mm^2)	57.2 ± 14.0	0.451 (0.105)	−0.104 to 0.792
GM thickness (% stature)	1.3 ± 0.2	−0.281 (0.331)	−0.706 to 0.293
GM pennation angle (°)	21.6 ± 3.8	0.465 (0.094)	−0.087 to 0.799
GL thickness (% stature)	0.9 ± 0.2	−0.317 (0.269)	−0.726 to 0.256
GL pennation angle (°)	13.4 ± 2.1	0.496 (0.072)	−0.048 to 0.813
SOL thickness (% stature)	0.8 ± 0.2	−0.175 (0.550)	−0.646 to 0.392
SOL pennation angle (°)	21.7 ± 3.6	0.077 (0.795)	−0.473 to 0.583
TA thickness (% stature)	0.7 ± 0.1	−0.162 (0.579)	−0.753 to 0.200
TA pennation angle (°)	12.0 ± 1.6	−0.255 (0.378)	−0.692 to 0.318
VL thickness (% stature)	1.3 ± 0.2	−0.281 (0.331)	−0.706 to 0.293
VL pennation angle (°)	15.5 ± 3.1	0.075 (0.800)	−0.475 to 0.582

$PP_{adjusted}$ = adjusted World Athletics competition performance points.

		Mean ± S.D.	Correlation with $PP_{adjusted}$ *r*-value (*p*-value)	95% CI±
Passive ankle range of motion (°)		65.1 ± 7.5	−0.119 (0.686)	−0.611 to 0.440
Individual maximum dorsiflexion (°)		17.0 ± 5.1	0.343 (0.230)	−0.229 to 0.739
Passive joint moment (N·m)	*at 5° dorsiflexion*	5.11 ± 1.76	0.132 (0.653)	−0.429 to 0.619
	at maximal dorsiflexion	11.33 ± 4.57	0.353 (0.216)	−0.219 to 0.744
Passive stiffness (N·m/°)	*at 5° dorsiflexion*	0.37 ± 0.14	−0.033 (0.911)	−0.554 to 0.507
	at maximal dorsiflexion	0.65 ± 0.27	0.283 (0.328)	−0.292 to 0.707

$PP_{adjusted}$ = adjusted World Athletics competition performance points.

Maximum isometric plantarflexion moment (N·m/kg)	Mean ± S.D.	Correlation with $PP_{adjusted}$ *r*-value (*p*-value)	95% CI±
K35,A−5	2.09 ± 0.60	0.138 (0.639)	−0.424 to 0.623
K35,A0	1.90 ± 0.51	0.064 (0.828)	−0.483 to 0.575
K35,A5	1.67 ± 0.48	0.036 (0.902)	−0.504 to 0.528
K35,A10	1.36 ± 0.38	−0.004 (0.990)	−0.533 to 0.528
K35,A20	0.96 ± 0.34	−0.076 (0.796)	−0.583 to 0.474
K0,A0	1.91 ± 0.38	0.313 (0.277)	−0.261 to 0.723
K70,A0	1.41 ± 0.38	0.311 (0.278)	−0.262 to 0.723

$PP_{adjusted}$ = adjusted World Athletics competition performance points.

		Mean ± S.D.	Correlation with $PP_{adjusted}$ *r*-value (*p*-value)	95% CI±
Maximum isokinetic plantarflexion moment (N·m/kg)	*30°/s*	1.05 ± 0.31	0.413 (0.161)	−0.178 to 0.785
	60°/s	0.77 ± 0.19	0.040 (0.896)	−0.522 to 0.578
	90°/s	0.60 ± 0.19	0.291 (0.336)	−0.310 to 0.725
	120°/s	0.50 ± 0.16	0.198 (0.516)	−0.396 to 0.675
Maximum	*30°/s*	0.36 ± 0.05	0.448 (0.125)	−0.136 to 0.801

isokinetic dorsiflexion moment (N·m/kg)	*60°/s*	0.32 ± 0.05	0.308 (0.307)	−0.293 to 0.734
	90°/s	0.26 ± 0.03	0.148 (0.629)	−0.439 to 0.646
	120°/s	0.25 ± 0.03	0.649 (0.016)*	0.153 to 0.884

$PP_{adjusted}$ = adjusted World Athletics competition performance points. * = statistically significant correlation ($p < 0.05$).

		Mean ± S.D.	Correlation with $PP_{adjusted}$ *r*-value (*p*-value)	95% CI±
Maximum isokinetic knee extension moment (N·m/kg)	*30°/s*	2.30 ± 0.43	0.338 (0.259)	−0.262 to 0.749
	90°/s	1.93 ± 0.36	0.296 (0.327)	−0.305 to 0.728
	150°/s	1.50 ± 0.47	0.319 (0.288)	−0.281 to 0.740
	210°/s	1.37 ± 0.33	0.552 (0.051)	0.001 to 0.846
	270°/s	1.21 ± 0.34	0.450 (0.142)	−0.167 to 0.814
Maximum isokinetic knee flexion moment (N·m/kg)	*30°/s*	1.28 ± 0.25	0.632 (0.020)*	0.125 to 0.878
	90°/s	1.12 ± 0.22	0.285 (0.345)	−0.315 to 0.723
	150°/s	0.90 ± 0.29	0.410 (0.164)	−0.182 to 0.784
	210°/s	0.83 ± 0.27	0.505 (0.078)	−0.063 to 0.826
	270°/s	0.83 ± 0.35	0.369 (0.238)	−0.260 to 0.778

$PP_{adjusted}$ = adjusted World Athletics competition performance points. * = statistically significant correlation ($p < 0.05$).