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Elongation differences between the sub-tendons of gastrocnemius medialis and lateralis during plantarflexion in different frontal plane position of the foot

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ABSTRACT

Background: Gastrocnemius medialis (GM) and lateralis (GL) act at the ankle complex in the sagittal and frontal planes and there is evidence that their actions can be somewhat uncoupled from each other. Some independence of GM and GL from each other could be advantageous, e.g. to stabilise the ankle complex in unstable walking conditions. Given the compartmentalised structure of the Achilles tendon, the sub-tendons of GM and GL may exhibit different elongation during plantarflexion contractions, particularly with the foot in different frontal plane positions.

Research Questions:

- Is elongation within a sub-tendon affected by frontal plane foot position?
- Does elongation between the two sub-tendons differ?
- Are elongation differences between the sub-tendons affected by frontal plane foot position?

Methods: Sub-tendon elongation was determined from 18 participants during ramped isometric plantarflexion contractions to 70% of their maximum voluntary contraction (MVC) level with the foot in neutral, inversion and eversion. One-dimensional statistical parametric mapping was applied to determine elongation differences.
Results: Elongation within a sub-tendon did not differ in the three foot positions. Elongation was similar between both sub-tendons at very low contraction levels, but GM sub-tendon elongation exceeded GL sub-tendon displacement significantly from 30% MVC. The elongation differences between the sub-tendons were not affected by foot position.
Significance: Greater GM sub-tendon elongation is likely caused by the greater force production capability of GM but may also indicate that the sub-tendons of GM and GL have different mechanical properties, which is currently unknown. Elongation differences were contraction level dependent suggesting that contributions of GM and GL to plantarflexion torque may also be contraction level dependent.

1. Introduction

Gastrocnemius medialis (GM) and lateralis (GL) are mainly considered as important plantarflexors, but also contribute substantially to frontal plane motion of the foot and can act relatively independent of each other [1]. Together with soleus, GM and GL insert into the Achilles tendon (AT), which consists of three sub-tendons each corresponding to one of these muscles. The sub-tendons may slide relative to each other during muscle contractions resulting in differential tissue displacement within the AT [2], which may be a possible mechanism for the gastrocnemii's relatively independent actions. Such actions could be advantageous for fine-tuning of movements and moments at the ankle complex in all three anatomical planes, for example to stabilise the ankle complex when walking on uneven or slippery surfaces and to control frontal plane movements and moments of the foot during the stance phase of gait [3,4]. Some evidence exists for diversity between the two gastrocnemii in terms of muscle architecture [5], function [6] and force producing capability [7], which may result in elongation

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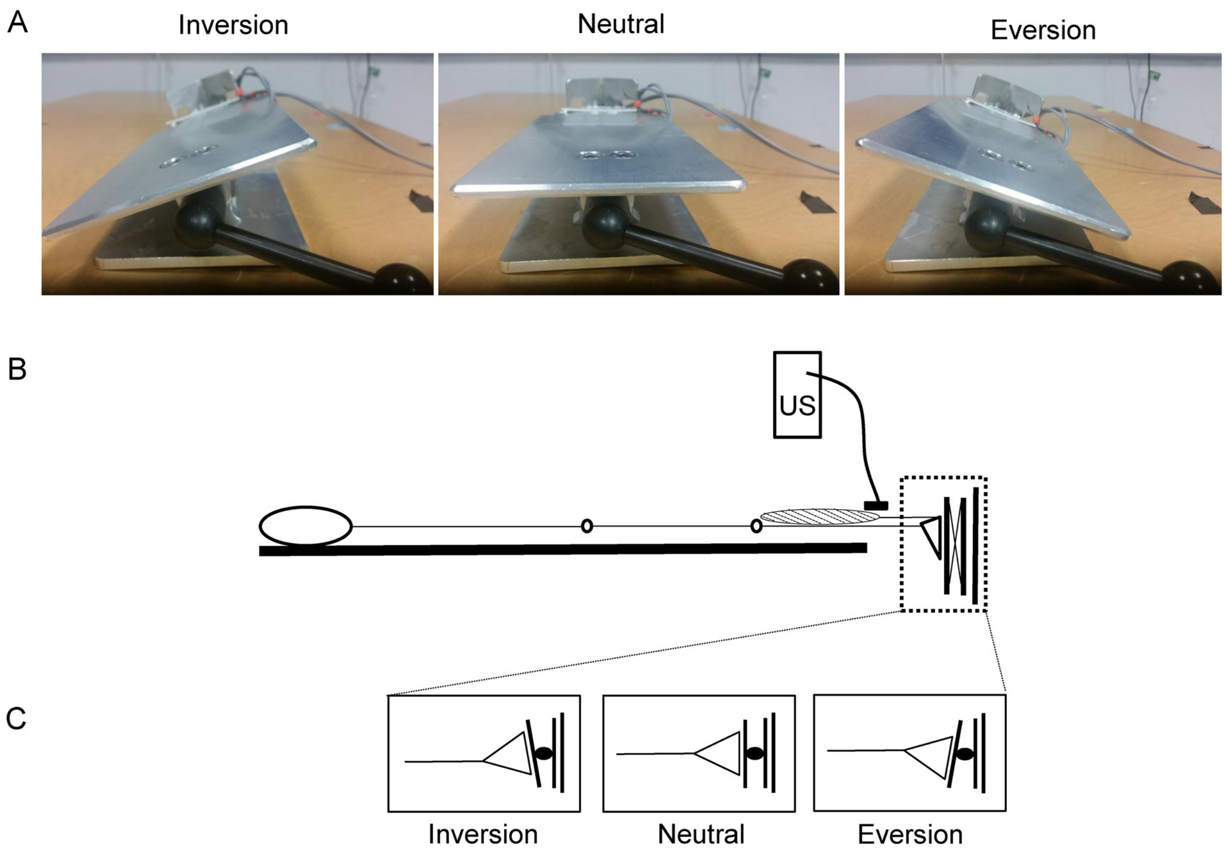

Fig. 1. (A) The custom-made footplate dismounted from the dynamometer foot adapter. (B) Schematic representation of participant positioning on the dynamometer bench showing the placement of the two ultrasound transducers and the custom-made footplate mounted to the dynamometer foot adapter. (C) Enlarged schematic representation of the foot and lower leg on the custom-made footplate in the three different positions (neutral, inversion, eversion) viewed from above. The footplate is mounted to the dynamometer foot adapter.

differences of their sub-tendons during muscle activation, but such elongation differences have not been investigated in vivo.

During submaximal force requirements, the relative force contributions of both gastrocnemii to plantarflexion (PF) contractions are dependent on the task requirements. For example, GL appears to be dominant during low-force PF contractions with GM being activated when the force requirements are higher [8]. During gait, both gastrocnemii act uniformly as plantarflexors, but when walking on slippery or uneven surfaces, GL activation is more modulated than GM activation [3], which has also been shown for cycling at different intensities and velocities [9].

Variations in the contributions of GM and GL to overall PF force may result in displacement differences of their respective sub-tendons. Displacement differences have previously been recognised in vivo between the gastrocnemii and soleus [10], which can largely be attributed to the greater force production capabilities of soleus compared to that of the gastrocnemii [11], as well as the functional differences of the mono-articular soleus and the bi-articular gastrocnemii [12]. For the gastrocnemii, Kawakami et al. [13] reported greater muscle belly shortening of GM than of GL during an isometric PF contraction to maximum without reporting possible tendon elongation. A recent modelling study predicts greater elongation of the sub-tendon of GM than that of GL [14], but this observation has not been reported in vivo to date.

Both gastrocnemii not only cross the ankle joint, but also the subtalar joint. During a PF contraction, both muscles are likely to exert an inversion or eversion moment in the frontal plane [1,15] as they have been shown to have a frontal plane moment arm [16]. In an in vivo study, GM and GL were shown to act synergistically as inverters in neutral and inversion foot positions but become antagonists when the foot is everted with GM acting as inverter and GL as everter [16]. Depending on the frontal plane position of the foot, GM and GL may contribute more to frontal plane moments of the foot while at the same time reducing their contribution to PF moment. In a modelling study, an inverted foot position reduced the PF potential of the gastrocnemii walking [17] but a distinction between GM and GL was not made. Thus, it is not known whether the elongation of the sub-tendons of GM and GL is affected by the inversion/eversion position of the foot.

In the present study, we aimed to investigate whether elongation differences exist within and between the sub-tendons of GM and GL during PF contractions of different intensities and in different frontal plane positions of the foot. We hypothesised that the elongation within the sub-tendons of GM and GL would show differences depending on the frontal plane position of the foot. We further hypothesised that GM sub-tendon elongation would exceed GL sub-tendon elongation and that elongation differences between the sub-tendons of GM and GL, if present, would occur at different contraction levels depending on the frontal plane position of the foot.

2. Methods

2.1. Participants and data acquisition

Data were collected from 18 participants (11 males, 7 females, age 39.8 ± 9.3 years, height 173.9 ± 8.2 cm, body mass 72.7 ± 11.0 kg) who reported to have sustained no musculoskeletal injury to their foot, ankle or lower leg within the previous six months. Written informed signed consent was obtained from each participant prior to taking part in the study. The procedures were approved by the ethics committee of the Department of Exercise and Sport Science at Manchester

Metropolitan University and conformed to the Declaration of Helsinki.

Participants were positioned prone on an isokinetic dynamometer (HUMAC®, NORM™ 770, Computer Sports Medicine Inc., Stoughton, MA, USA) with their hips and knees extended and the ankle perpendicular to the lower leg. A custom-built footplate allowing rotation of the foot in the frontal plane (inversion/eversion) was mounted onto the foot adapter of the dynamometer (Fig. 1). Foot position was altered by rotating the footplate into 0° neutral, 10° inversion or 10° eversion. The lateral malleolus was carefully aligned with the dynamometer axis of rotation and the ankle was firmly strapped into place to limit relative ankle joint rotation during plantarflexion efforts. The absence of relative ankle joint rotation was visually confirmed.

For pre-conditioning, participants performed five isometric submaximal PF contractions with the foot in neutral [18], followed by two maximum effort PF contractions which were averaged to determine individual maximum voluntary contraction (MVC) torque. Participants then performed ramped isometric PF contractions to 70% MVC by increasing their effort over four seconds. Visual feedback was provided in real-time to the participants, who were instructed to keep the torque indicator between two markers placed ± 5% of the target torque. After four to five practice trials, participants performed two sets each consisting of three trials in non-randomised order in neutral, inversion and eversion position. PF torque was sampled during each trial at a sampling rate of 2000 Hz using a 16 bit A/D card (USB 6210, National Instruments Corp., Austin, TX, USA) and custom-written LabVIEW code (v.8.6.1, National Instruments, Corp., Austin, TX, USA).

During the ramped plantarflexion efforts, displacement of the muscle-tendon junction (MTJ) of GM and GL in the sagittal plane was imaged using B-mode ultrasound (Echo Blaster, TELEMED, Vilnius, Lithuania). The GM MTJ was imaged during the first three trials and the displacement of the GL MTJ was imaged during the last three trials using a 60 mm long ultrasound transducer (LV.7.5/60/128Z-2) at a sampling frequency of 40 Hz. The transducer was inserted into a custom-made holder and strapped firmly to the lower leg using elasticated bandage (3 M Coban™, Neuss, Germany).

2.2. Data reduction

Displacement of the GM MTJ and GL MTJ was determined to estimate the elongation of the GM sub-tendon and the GL sub-tendon, respectively. The tracked MTJ displacement was considered to be representative of sub-tendon elongation since the foot was firmly strapped to the footplate preventing notable ankle rotations. It was further assumed that any possible small ankle rotations would be similar between the three foot positions. MTJ displacement was determined with a custom-written algorithm in Matlab (v. R2014b, MathWorks, Natick, USA) using a pyramidal implementation of the Kanade-Lucas-Tomasi feature tracking algorithm [19]. To track MTJ displacement, the MTJ location was first defined by placing a tracking marker on the image near the MTJ inside the muscle belly around which a pixel neighbourhood of 21 × 21 pixels was created. The displacement of the marker, representing the displacement of the MTJ from one frame to the following frame, was determined for the entire ultrasound video to obtain continuous displacement curves (Fig. 2). Automated tracking of MTJ displacement has been performed previously with a similar approach [20] and the repeatability of this method was reported to be 98% [20].

Sub-tendon elongation of GM and GL was extracted for each foot position from PF torque onset to 70% MVC and plotted as function of PF torque. The elongation-PF joint torque curves were time normalised to 200 data points resulting in six elongation-PF joint torque curves, one for each muscle in each foot position (neutral, inversion and eversion).

The sub-tendons of GM and GL have been reported to differ in their length [21], which could result in differences in strain experienced by each sub-tendon. We, therefore, determined strain-PF torque curves for each sub-tendon. Strain was calculated as sub-tendon elongation

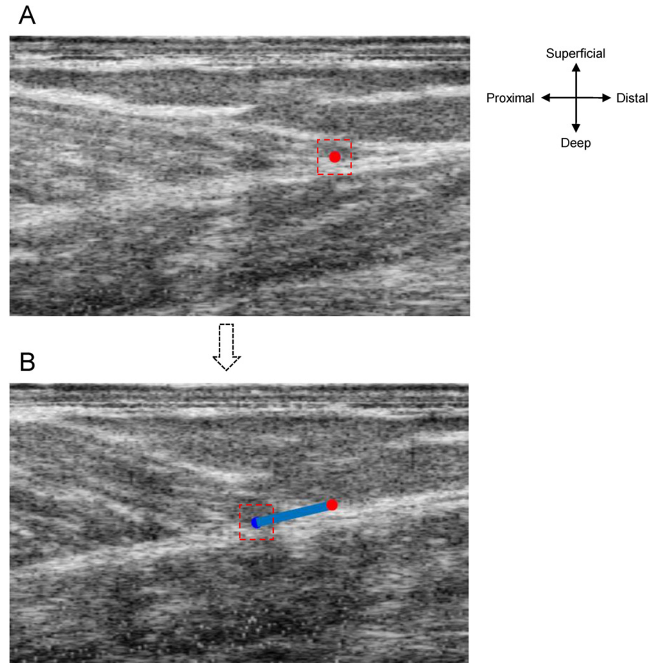

Fig. 2. Ultrasound video frames of the MTJ at torque onset (A) and at 70% MVC (B) illustrating the position of the tracking marker and its pixel neighbourhood at torque onset (red dot), at 70% MVC (blue dot) and the displacement of the tracking marker (light blue line) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

normalised to sub-tendon resting length measured using a tape measure as the distance between the AT insertion at the calcaneus and the MTJ of GM and GL (identified through ultrasonography), respectively. The participant's foot was in neutral position and at a right angle to the lower leg during these measurements.

2.3. Statistical analyses

For statistical analyses, the entire elongation-PF joint torque curves and strain-PF joint torque curves from rest to 70% MVC were considered. All analyses were conducted with one-dimensional statistical parametric mapping (1dSPM) using custom-written code in Python (Enthought Canopy v. 1.7.4, Enthought Inc., Austin, USA) and the open-source spm1d software package (v. 0.4, available at http://www.spm1d.org/Downloads.html). To test for significance, a critical threshold was calculated at the significance level $\alpha = 0.05$. A 1dSPM two-way repeated measures ANOVA with two main effects (muscle and foot position) and an interaction effect (muscle*foot position) was used to determine elongation differences within and between the sub-tendons of GM and GL. Differences in resting lengths of the GM and GL sub-tendons were determined with a paired, one-tailed t-test in SPSS (v. 22.0.0.1, IBM Corporation, USA) with a significance level of $\alpha = 0.05$.

3. Results

Mean isometric PF MVC torque was 101.03 ± 35.15 Nm. The sub-tendons of both GM and GL elongated from rest to 70% MVC in all three foot positions (Fig. 3A and Table 1). The 1dSPM ANOVA revealed no significant main effect of foot position, a significant main effect of muscle and no significant interaction effect of muscle*foot position (Fig. 3B). There was no difference in elongation within the sub-tendon of GM and within the sub-tendon of GL in all foot positions ($p > 0.05$). Elongation of the sub-tendons of GM and GL was similar at lower submaximal contraction levels, but GM sub-tendon elongation exceeded GL sub-tendon elongation from approximately 30% MVC to 70.00%

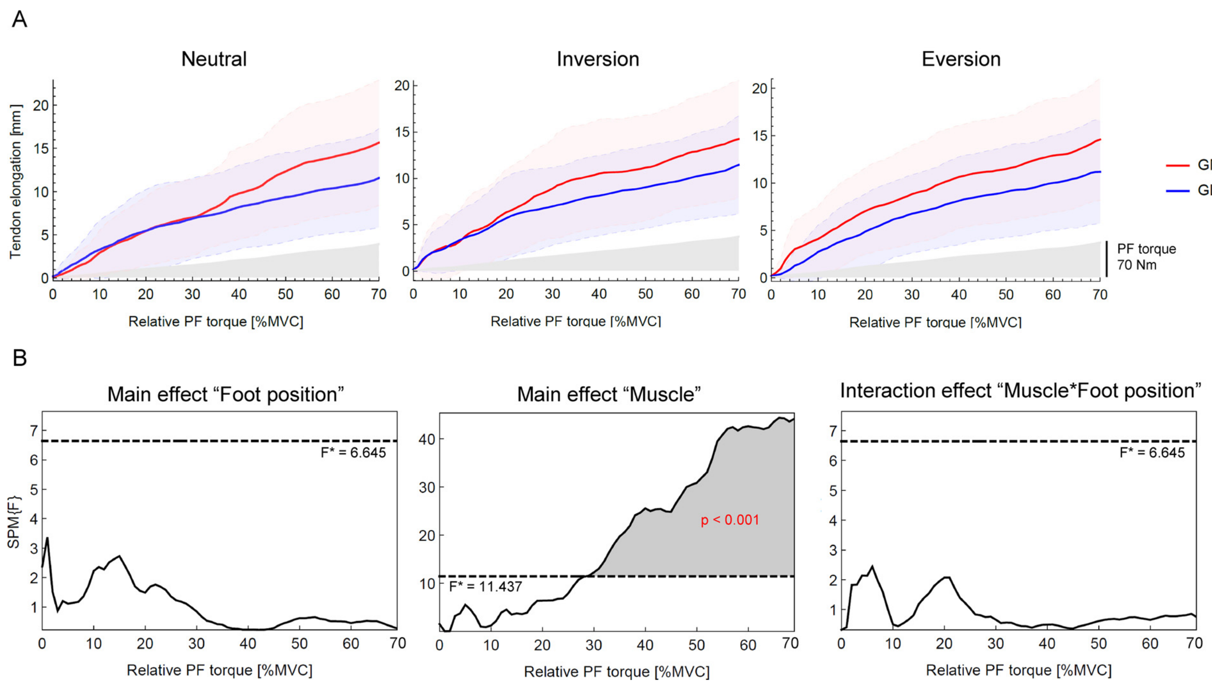

Fig. 3. (A) Mean sub-tendon elongation with standard deviation clouds for GM (red) and GL (blue) in neutral, inversion and eversion foot positions. In all three foot positions, displacement of the GM sub-tendon was greater than displacement of the GL sub-tendon. Mean torque for each foot position is indicated by the grey shaded area. (B) Results of the 1dSPM two-way repeated measures ANOVA revealed differences in elongation between the sub-tendons of GM and GL (significant main effect of muscle – left), but not within each of the sub-tendons of GM and GL (no significant main effect of foot position – centre). The grey shaded area indicates the contraction levels, at which GM sub-tendon elongation was greater than GL sub-tendon elongation. Foot position did not affect the elongation differences between the two sub-tendons (no significant interaction effect of muscle*foot position – right) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Mean sub-tendon elongation and standard deviations of GM and GL at 70% MVC in all foot positions and mean sub-tendon strain and standard deviations of GM and GL at the 70% MVC contraction level for the neutral foot position. Average elongation is average elongation across all three foot positions.

	Tendon elongation [mm]		Tendon strain	
	GM	GL	GM	GL
NEU	15.65 ± 7.23	11.56 ± 5.70	0.07 ± 0.03	0.05 ± 0.02
INV	14.23 ± 6.32	11.46 ± 5.25		
EV	14.61 ± 6.41	11.20 ± 5.45		
Average	14.83 ± 6.56	11.41 ± 5.36		

GM – gastrocnemius medialis, GL – gastrocnemius lateralis, NEU – neutral foot position, INV – inversion foot position, EV – eversion foot position.

MVC ($p < 0.001$). This elongation pattern was similar in all foot positions with GM sub-tendon elongation being greater than GL sub-tendon elongation, and was not affected by foot position ($p > 0.05$).

Mean resting length of the GM sub-tendon was smaller than mean resting length of the GL sub-tendon ($p < 0.001$, Fig. 4). Since there was no main effect of foot position and no interaction effect of muscle*foot on sub-tendon displacement, we calculated sub-tendon strain for the neutral foot position only and determined sub-tendon strain differences between GM and GL with a 1dSPM two-tailed paired *t*-test. The 1dSPM *t*-test showed that sub-tendon strain was similar between GM and GL at submaximal contraction levels up to 45%. GM sub-tendon strain was greater than GL sub-tendon strain between 45% and 70% MVC (Fig. 5 and Table 1).

4. Discussion

The present study investigated elongation and strain of the sub-

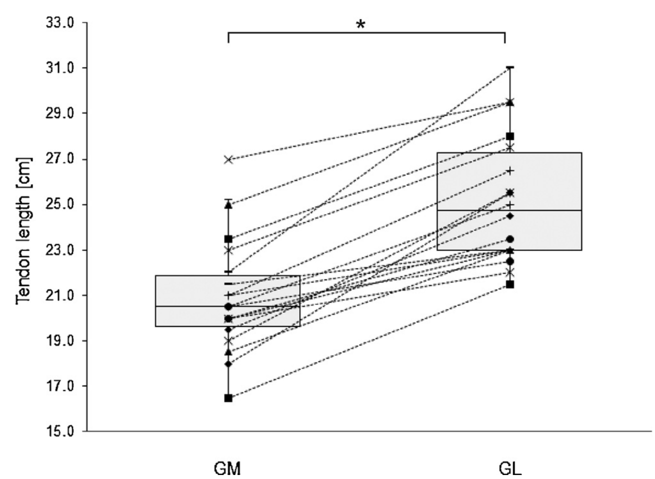

Fig. 4. Box-and-Whisker plot of tendon lengths of the GM and GL tendon portions. One box represents the data distribution of tendon length as first, median and third quartile. Whiskers represent the variability of the data as 1.5 times the interquartile range. Individual participants are represented as line graphs (*p < 0.001).

tendons of GM and GL during isometric submaximal PF in different frontal plane foot positions. In agreement with our hypothesis, elongation and strain was greater in the GM sub-tendon than the GL sub-tendon, which was dependent on the level of contraction. Contrary to our hypothesis, however, elongation within the sub-tendon of GM and the sub-tendon of GL was similar in all foot positions.

Elongation differences between the sub-tendons of GM and GL have not been reported previously but other studies have shown differential displacement within the free AT [10]. Clark and Franz [10] suggest that such differential displacement could be related to displacement

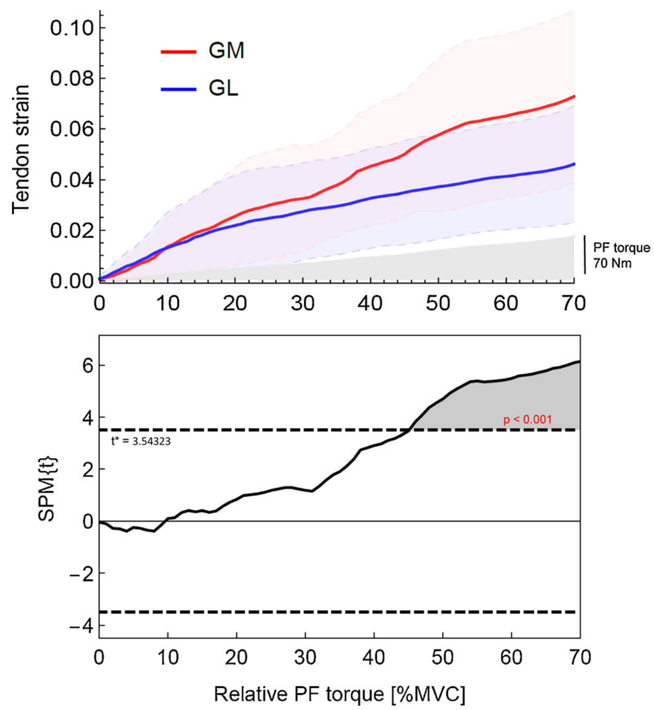

Fig. 5. Top panel: Strain for the GM sub-tendon (red) and GL sub-tendon (blue) with standard deviation clouds in the neutral foot position. Bottom panel: Result from the 1dSPM *t*-test comparing tendon strain between GM and GL in neutral foot position. The grey shaded area indicates at which contraction level GM sub-tendon strain was greater than GL sub-tendon strain (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

differences between the sub-tendons of gastrocnemius and soleus. One explanation for the observed sub-tendon elongation differences between GM and GL could be the force producing capability of GM and GL. Based on measurements of physiological cross-sectional area (PCSA), GM contributes about twice as much force to overall PF force than GL [7]. This could lead to greater elongation of the GM sub-tendon than the GL sub-tendon as shown in the present study, assuming that the stiffness of both sub-tendons is equal. This explanation, however, only holds true for maximum effort contractions, but the present study used a sub-maximal effort protocol up to 70% MVC. During very low sub-maximal PF contractions, Antonios and Adds [8] suggested that GL is activated before GM, which may result in the GL sub-tendon pulling the GM sub-tendon along resulting in the similar elongations of both sub-tendons as shown in the present study. Such pulling action is possible since the sub-tendons are not completely independent [22]. In addition, relative force contributions of GM and GL to overall PF force might be more similar at lower submaximal contraction levels. Masood et al. [23] demonstrated previously that GM and GL contribute similarly to PF force during sub-maximal isometric contractions up to 30% MVC. In our study, we observed differences in sub-tendon elongation between GM and GL at contraction levels above 30%. The relative contributions of GM and GL to plantarflexion force might be similar up to this contraction level but GM might contribute more than GL to overall plantarflexion force at contraction levels above 30% MVC resulting in the elongation differences observed in the present study.

Similarly, strain was greater in the GM sub-tendon than the GL sub-tendon at higher sub-maximal contraction levels. Resting length of the GM sub-tendon was significantly shorter than of the GL sub-tendon, which is in agreement with previous studies [8,21]. Since strain is defined as elongation relative to resting length, the shorter GM sub-tendon, therefore, likely experiences greater strain than the GL sub-tendon. Morrison et al. [21] reported that strain between the GM sub-tendon and GL sub-tendon was similar at MVC moment, which is in contrast to the results of the present study. It is unlikely that force output of GM would cease while GL force output continues to increase with an increase in contraction level. Furthermore, predictions based on the PCSA of GM and GL would suggest that GM force output is greater than GL force output at MVC moment [7], resulting in greater sub-tendon elongation and subsequently strain. It is possible, however, that the sub-tendons of GM and GL have different mechanical properties, but this is currently unknown.

The greater sub-tendon strain in GM compared to GL may indicate that the occurrence of GM strain injuries is higher than that of GL strain injuries. In fact, Millar [24] reported that MTJ ruptures of the GM make up 53% of all gastrocnemius strain injuries compared to only 3% of GL MTJ ruptures. Furthermore, strain differences are likely to occur during locomotion and may lead to shear strain and subsequently tissue degeneration and overuse injury [25]. AT overuse injuries were reported to occur predominately in relation to excessive eversion during the stance phase of walking and running [26] and an in vitro study showed greater strains on the medial side of the AT when the calcaneus is everted [27]. However, our study cannot provide support for this notion since sub-tendon elongation (and most likely strain) was unaffected by the frontal plane foot position.

A number of limitations in the present study should be noted. Firstly, inversion and eversion were achieved by rotating the foot in the frontal plane. Elongation differences between the sub-tendons of GM and GL might have occurred at other contraction levels if the foot had been rotated around the subtalar joint axis, which does not lie perpendicular to anatomical planes [28]. Secondly, we did not correct for possible ankle joint rotations during PF efforts. Ankle rotation results in greater measured MTJ displacement of approximately 0.7-0.8 mm for each degree of ankle rotation [7]. In our study, participants performed PF efforts up to 70% MVC. We applied tight strapping to the ankle to minimise ankle rotation and subsequent loss of inversion or eversion position of the rearfoot. We visually confirmed that ankle rotation did not occur and are, therefore, confident in our estimates of sub-tendon elongation. Thirdly, the results may have been affected by tendon creep resulting in greater tendon elongation in each subsequent trial [29], and pre-conditioning of at least five sub-maximal contractions has been suggested [18]. This is particularly noteworthy since conditions were not randomised and MTJ displacements were determined for GM and GL in separate trials. Elongation was almost identical for each sub-tendon in the different foot positions and it is, therefore, unlikely that tendon creep, if present, affected these results considerably. However, the sub-tendon elongation differences between GM and GL might have been affected. Since GM MTJ displacement was determined first, GM sub-tendon elongation might be underestimated compared to GL sub-tendon elongation, but this should have resulted in smaller sub-tendon elongation differences between GM and GL presented in our study. Fourthly, our findings do not allow us to conclude whether the observed elongation and strain differences also occur in the free AT since strain in the proximal AT is approximately half the strain in the free AT during a submaximal plantarflexion to 50% MVC [30]. The observed sub-tendon elongation and strain differences between GM and GL may, therefore, not be as pronounced in the free AT.

In conclusion, our study showed that elongation and strain is greater in the GM sub-tendon than the GL sub-tendon during ramped sub-maximal isometric plantarflexion contractions but only at higher sub-maximal contraction levels. This suggests that the relative contributions of GM and GL to overall PF force vary depending on the contraction level, provided that the mechanical properties of both sub-tendons are similar. The occurrence of muscle-dependent regional AT displacement differences should be investigated with the true position of the subtalar joint known and in isokinetic/isotonic protocols to gain further understanding of triceps surae muscle-tendon unit mechanics and AT injury mechanisms during locomotion.

Author contributions

Susann Wolfram: Conceptualisation, Methodology, Investigation, Formal Analysis, Writing- Original Draft Preparation.

Emma F. Hodson-Tole: Methodology, Formal Analysis, Writing- Review & Editing.

Christopher I. Morse: Conceptualisation, Methodology, Writing- Review & Editing.

Keith L. Winwood: Conceptualisation, Writing- Review & Editing.

Islay M. McEwan: Conceptualisation, Methodology, Supervision, Writing- Review & Editing.

Declaration of Competing Interest

The authors have no conflicts of interest.

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