Eight weeks of eccentric training at long-muscle length increases fascicle length independently of adaptations in passive mechanical properties

Running title: Skeletal muscle adaptations to eccentric exercise training

Authors: Baptiste Bizet[1,2,3], Antoine Nordez*[1,4], Tristan Tallio[1], Lilian Lacourpaille[1], Thomas Cattagni[1], Julian Colard[1], Yohan Betus[1], Sylvain Dorel[1], Aurélie Sarcher[1], Olivier Seynnes[5], Ricardo J. Andrade[1]

[1] Nantes Université, Mouvement - Interactions - Performance, MIP, UR 4334, F-44000 Nantes, France
[2] Department of Neurosciences, Biomedicine and Movement, University of Verona, Italy
[3] National PhD program in Kinesiology and Sport Sciences, University of Verona, Italy
[4] Institut Universitaire de France (IUF), Paris, France
[5] Department for Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway

ORCID:
Ricardo J Andrade (Orcid: 0000-0001-5316-7531)
Antoine Nordez (Orcid: 0000-0002-7276-4793)

Corresponding authors*:

*__Prof Antoine Nordez__, Nantes Université, Movement - Interactions - Performance, MIP, UR 4334, F-44000 Nantes, France

Email address: antoine.nordez@univ-nantes.fr
Mailing address: 23, rue du Recteur Schmitt Bât F0 44300 Nantes, France
Phone number: +33 251837208

*__Dr Ricardo Andrade__, Nantes Université, Movement - Interactions - Performance, MIP, UR 4334, F-44000 Nantes, France

Email address: ricardo.andrade@univ-nantes.fr
Mailing address: 23, rue du Recteur Schmitt Bât F0 44300 Nantes, France
Phone number: +33 251837241

Availability of data
The entire data set with raw data is available at https://entrepot.recherche.data.gouv.fr/dataset.xhtml?persistentId=doi:10.57745/SFBCL7. The dataset with the processed data is available from the corresponding author on reasonable request.

Conflict of interest statement:
No conflicts of interest, financial or otherwise, are declared by the authors.

Acknowledgements
We extend our gratitude to all participants who generously volunteered for the study. RJA was supported by the AFM-Téléthon (Grant ID#28643).

ABSTRACT

Eccentric exercise training is believed to induce an increase in muscle fascicle length. However, the mechanisms underlying this adaptation are not fully understood. This study aimed to determine if an increase in gastrocnemius medialis fascicle length following an 8-week eccentric training is linked to changes in muscle tissue and joint mechanical properties. Thirty-three physically active young adults were assigned to one of two training protocols targeting the plantar flexors: eccentric exercise at 1) long-muscle length or 2) short-muscle length. Fascicle length and muscle shear modulus of the gastrocnemius medialis were assessed using ultrasound imaging during passive ankle rotations, alongside measurements of passive ankle torque. A total of 27 participants successfully completed the training program and data processing stage (long-muscle length, n=15; short-muscle length, n=12). Maximal voluntary isometric torque increased significantly following the training programs (9.5%), with no differences between training groups. An increase in fascicle length (mean 8.5%) was observed in the long-muscle length group, from 39.5±0.7° to 36.8±0.8° in plantar flexion; but not in the short-muscle length group. Notably, this macrostructural adaptation was detected only at muscle lengths shorter than the slack length (i.e., absence of any muscle passive tension). The eccentric training did not alter the muscle shear modulus or slack length. Collectively, these findings suggest that fascicle length adaptations in response to eccentric training were unrelated to changes in passive muscle-tendon mechanical properties. Consequently, the increase in fascicle length may be attributed to an increase in sarcomere length and/or an addition of sarcomeres in series.

NEW & NOTEWORTHY

We demonstrate that an 8-week eccentric training program significantly increases gastrocnemius medialis fascicle length in humans, independent of any adaptions in passive muscle-tendon mechanical properties. Fascicle length adaptions were specific to the group that trained at long-muscle lengths, highlighting the importance of the muscle-tendon length range during eccentric exercise programs. This factor may be crucial for fine-tuning structural adaptations at the fascicle level, likely through the addition of sarcomeres in series.

KEYWORDS

Elastography, Tissue Elasticity Imaging, Ultrasonography, Skeletal Muscle, Strength Training

INTRODUCTION

Eccentric training is well-established as an efficient modality for enhancing muscle performance (1, 2). Numerous studies have reported increases in ultrasound-measured fascicle length following chronic eccentric training in humans (3–6). Based on animal studies demonstrating an increase in the number of the sarcomeres in series (7–9), the fascicle lengthening observed in humans has been interpreted as indicative of longitudinal fascicle growth (10–12). However, the training load in human studies is typically lower than in animals, suggesting potential differences in the underlying mechanisms. Furthermore, changes in fascicle length remain a very indirect marker of sarcomere number adaptation. Collectively, these factors highlight the need for a more comprehensive understanding of the adaptations resulting from strength training protocols commonly employed in sports and rehabilitation programs.

The association between increased ultrasound-measured fascicle length and serial sarcomere number has only recently been studied in humans by combining a minimally invasive microendoscopy method for in-situ sarcomere measurements alongside ultrasound imaging (13). This approach revealed an increase in ultrasound-measured fascicle length following a 3-week Nordic hamstring eccentric exercise training, without changes in the estimated serial sarcomere number of the biceps femoris. Therefore, increased fascicle length was attributed to an increase in sarcomere length. While the mechanisms underlying these findings remain unclear, it was suggested that connective tissue adaptations or changes in passive mechanical properties of the muscle-tendon unit may explain the changes in fascicle length after such a short training period.

Several human studies have demonstrated that mechanical properties of the muscle-tendon unit can be modified through chronic eccentric training (14, 15). However, the relationship between muscle-tendon mechanical properties and changes in fascicle length has not been studied. Additionally, fascicle length is often measured at a single joint angle, typically under passive muscle tension – e.g., with the foot perpendicular to the leg for the gastrocnemius muscle. The observed changes in fascicle length could therefore be partially attributed to adaptations in passive muscle-tendon mechanical properties (16), highlighting the importance of assessing muscle fascicle length across the full range of motion – both with and without passive tension.

Studies involving humans (4) and animal models (8) have suggested that the range of muscle length during eccentric exercise may influence muscle adaptations. Specifically, training at longer muscle lengths appears to promote the adaptions in muscle fascicle length. Therefore, manipulating the muscle length during the eccentric training could be relevant for better identifying the potential relationships between changes in muscle-tendon mechanical properties and adaptations in fascicle length.

The primary aim of this study was to determine whether changes in muscle fascicle length in response to chronic eccentric training are associated to adaptations in passive muscle mechanics. We implemented an 8-week eccentric training program targeting the plantar flexor muscle group. High-resolution ultrasound imaging and ultrasound shear wave elastography (SWE) methods were employed to simultaneously measure fascicle length and passive mechanical properties of the gastrocnemius medialis muscle across the entire ankle range of motion (ROM). Given the substantial animal evidence indicating an increase in the number of sarcomeres in series (9), we hypothesized that changes in fascicle length would not be related to adaptations in passive muscle mechanics. Instead of a control group, we tested two distinct eccentric training groups in which exercise was performed at 1) short-muscle length and 2) long-muscle length. We hypothesized that the increase in fascicle length would be greater for the group performing eccentric exercise at long-muscle length (4, 8). This comparison between groups could provide valuable insights into the relationship between fascicle length and passive muscle-tendon mechanical properties adaptations.

METHODS

Participants, Randomization, and Ethical Approval

Thirty-three healthy adults participated in this single blind randomized study (10 female; age 19.8 ± 1.5 years, height 174.3 ± 11.8 cm, weight 66.3 ± 10.9 kg). All participants were sport sciences students recruited from the local university. Inclusion criteria included being healthy and aged between 18 and 30 years. Exclusion criteria were as follows: 1) recent (< 3 years) musculoskeletal injury or disability in spine or lower limbs; 2) cardiovascular, neurological, or psychiatric disease; and 3) recent enrollment in any strength training program. Based on an effect size of 0.45 for fascicle length adaptations (11), a significance level of 0.05, and a power of 0.80, the required sample size for a two-way repeated measures analysis (with a within-between interaction) is 12 participants per group (G*Power software; Kiel University, Germany). Participants were randomly assigned to one of two distinct eccentric training conditions – short-muscle length or long-muscle length – using a coin toss, in a 1:1 ratio. Once one group reached half of the total sample size, all subsequent participants were assigned to the second group. Ethical approval was obtained from the local Institutional Review Board of the University (CERNI #06012023).

Experimental procedure

Ankle joint mechanics and range of motion. An isokinetic dynamometer (Con-Trex MJ, CMV AG, Dubendorf, Switzerland) was used to perform passive ankle rotations (Figure 1A). All measurements were performed on the right lower leg. The lateral malleolus was considered as the rotation center of the ankle and was aligned with the center of rotation of the dynamometer. Participants were positioned with their hips flexed at 50°, the right leg parallel to the floor, and their right knee fully extended. The ankle neutral position was set at 90° between the footplate and the shank. The foot, the leg and the ankle were carefully attached to minimize potential heel displacement. Before and during data collection, potential heel displacement was visually monitored, and adjustments to the strap system were made as needed. The ankle angle and torque were both recorded at 5000Hz using an analog-digital converter (LockLab, Vicon Motion Systems Ltf, Oxford, UK).

Muscle mechanics and architecture. B-mode and SWE clips were simultaneously acquired from the gastrocnemius medialis using an ultrafast ultrasound scanner (SuperSonic Imagine, v12, Aix-en-Provence, France) coupled with a linear array transducer (50mm, SuperLinear 4-15MHz, Vermon, Tours, France). The muscle shear modulus, as assessed by SWE, was used as an indicator of muscle stiffness (17). For all measurements, the ultrasound transducer was placed at the proximal third of the lower leg length, defined as the distance between the medial malleolus and the femur's medial epicondyle (18). The imaging plane was carefully aligned with the main muscle shortening direction and adjusted to avoid any blood vessels. The medio-lateral positioning was defined by the line connecting the bony landmarks, as described earlier. For post-training assessments, pre-training images were compared for each participant to guide probe placement. SWE settings, including temporal and spatial filters were set as described elsewhere (19). A custom-made transducer holder was attached to the skin with double-sided adhesive tape and secured with straps (applying minimal pressure) to prevent any displacement during ankle rotations. SWE and B-mode windows were simultaneously displayed and acquired on the ultrasound scanner for offline image processing (Figure 1A). To ensure that the region of interest was the same pre- and post-tests, B-mode images of the pre-test were used to place the probe during the post-test. The sampling rate for SWE and B-mode were 1.1-1.3Hz and 11Hz respectively.

Electromyography. Myoeletric activity was recorded for the gastrocnemius lateralis, soleus, and tibialis anterior muscles using surface electromyography (EMG; MiniWave, Cometa, Bareggio, Italy). The sampling rate was set at 5000 Hz, and data was recorded with an analog-digital converter. Electrodes were placed in accordance with the SENIAM guidelines (20).

Baseline and follow-up assessments

All participants were asked to refrain from any lower limb strength training for 48 hours prior to the testing sessions conducted before and after the training program. Pre-testing sessions were performed 48 hours before the commencing of the eccentric training program, whereas post-testing sessions were conducted 4 to 5 days after the last training session. Pre- and post-testing sessions were performed at the same period of the day (±4 hours). Investigators were blinded to group allocation during the pre-testing session but not during the post-testing session.

The testing session comprised five steps. First, the passive maximal ankle dorsiflexion range of motion (ROM) was assessed. Briefly, the ankle was passively rotated at a slow and constant velocity (~1°/s) from 40° of plantar flexion to the maximal dorsiflexion, defined as the onset of muscle stretching pain. Two trials were conducted with a 1 min rest interval. The highest score across trials was considered as the maximal dorsiflexion ROM. Second, five stretching cycles were performed at 5°/s between 40° of plantar flexion and 80% of the maximal dorsiflexion ROM for conditioning purposes (21). Third, a stretching cycle was performed at 1°/s within the same range of angular rotation. Passive torque, ankle angle, EMG, ultrasound SWE and B-mode clips were continuously recorded during the loading phase of the plantar flexion muscle group (axial) stretching. Throughout the preceding steps, participants were instructed to remain as relaxed as possible. Fourth, following a preliminary warm-up, participants were asked to perform two maximal voluntary isometric contractions (MVIC) in plantar flexion and dorsiflexion in neutral ankle position. Only the highest MVIC was used for the statistical analysis. Peak isometric torque was registered, and EMG signals were further used (offline) to normalize myoelectric activity during passive ankle rotations. Finally, two eccentric contractions from 40° of plantar flexion to 80% of the maximal ROM in dorsiflexion were performed at 30°/s to evaluate the peak eccentric torque. The highest peak eccentric torque measured during the pre-training assessment was used for further analysis. The post-training eccentric torque was then calculated at the same ankle angle at which the pre-training peak eccentric torque was measured. All contractions were performed with a rest interval of 90-s.

Intervention protocols

All participants performed twenty-four sessions of eccentric plantar flexor exercises over the course of eight weeks. The progressive nature of the training protocol was maintained by monitoring the changes in the maximum concentric repetition (1-RM) every other training session for each exercise. The eccentric workload was set at 100% of the concentric unilateral 1-RM. The training program was closely monitored and supervised. Each training session started with a 10-min warm-up specifically focused on the plantar flexor muscle group. The training sessions comprised: i) eccentric heel drops performed on a Smith machine (10 sessions; Figure 2A), or ii) eccentric heel drops executed on the oblique press (10 sessions; Figure 2B), or iii) eccentric plantar flexions performed on an isokinetic dynamometer (4 sessions: 6th, 12th, 18th and 24th; Figure2C).

For the sessions involving eccentric heel drops on the Smith machine, participants stood upright with the knees and hips straight, while a bar rested on their shoulders behind the neck (22). To safely execute the heel drops on the inclined leg press, participants were instructed to flex their hips at 90° and to maintain a slight flexion in their knees to prevent hyperextension during the movement. Both groups executed bilateral concentric plantar flexion followed by unilateral eccentric plantar flexion. The participants were carefully instructed to synchronize their movements with a 1-1-3-1 rhythm provided by a metronome. This rhythmic pattern consisted of 1-s for the bilateral heel rise, 1-s for the isometric hold, 3-s for the heel drop, (i.e. eccentric exercise) and 1-s of bilateral rest. Participants performed four sets of ten repetitions on both the right and the left side, alternating left and right sides, when their 1-RM was determined at the beginning of the session. Every other session, when the 1-RM was not tested, they completed five sets of ten repetitions for each leg. Each set was followed by a 90-s rest interval. The workload was adjusted to match the concentric 1-RM of the right foot (Table 1).

The ankle range of motion, and consequently, the length of the plantar flexor muscles, were the only parameters that differed between the two testing conditions: short-muscle vs. long-muscle lengths. The short-muscle length training group performed the eccentric plantar flexions from 30°

plantar flexion to 0° (neutral position, with the foot on the floor). The long-muscle length training group executed the eccentric plantar flexions from 0° (neutral position) to maximal dorsiflexion (~ 30° of dorsiflexion, depending on the participants' maximal dorsiflexion range of motion). To ensure that participants respected the range of motion set for each training condition, a measuring tape (in cm) was positioned on both the inclined smith squat and press machines. The tape was calibrated to the targeted range of motion based on joint angles previously measured in static conditions using a manual goniometer. Real-time guidance was provided by one of the investigators during the training session to ensure that range of motion was respected for each condition (short-muscle *versus* long-muscle lengths training group).

Data analysis

Data were processed using custom-made MATLAB (v.R2018a, MathWorks, Natick, Massachusetts, USA) scripts. All data remained coded to enable analysis to be conducted in a fully blinded manner.

Shear modulus. Shear modulus data were analyzed as described elsewhere (19). The region of interest was set to be the largest possible within the shear wave elastography map, excluding all non-muscle regions and saturation (Figure 1B). Consistency in this region was ensured across both pre- and post-testing. The slack angle was visually determined as the onset of increase in shear modulus during the passive muscle stretching (23).

Fascicle length. Two fascicles were analyzed from the B-mode clips, exported as DICOM files, using an adapted version of the 5.2 UltraTrack software (24). Fascicle length was defined as the distance between the insertions of the fascicle into the superficial and deep aponeuroses. Linear extrapolation was used where fascicle length exceeded the image. Manual corrections were made where the tracking algorithm did not track the fascicle length well. Briefly, for each clip of muscle axial loading, two fascicles were successfully linearly tracked and averaged for statistical analyses purposes (Figure 1C). The slack length was considered as the fascicle length at the slack angle.

Surface Electromyography. EMG data from gastrocnemius lateralis, soleus, and tibialis anterior muscles were band-pass (20-400Hz), and band-stop (50Hz) filtered with 2^{nd} order Butterworth. The root mean square of the EMG (EMG-RMS) was calculated on a 300 ms sliding window for both MVIC and throughout the loading phase of the stretching cycle. Muscle activation was then expressed as a percentage of the maximal EMG-RMS activity reached during MVIC (25).

Ankle torque and position. The ankle torque and joint angle were filtered by a 2^{nd} order Butterworth low-pass filter (5Hz). The torque was corrected for gravity effects of the dynamometer toolkit.

Synchronization. Myoelectric activity (EMG), mechanical (torque and angle) and ultrasound-based data (shear modulus, fascicle length) were synchronized using the trigger output generated by the ultrasound scanner at each SWE measurement. Pre- to post-comparisons of muscle geometrical (fascicle length) and mechanical (shear modulus and passive ankle torque) were conducted continuously between 40° plantar flexion and 80% of the common greatest maximal dorsiflexion ROM registered – for each participant – prior the training protocol (or following, in case where maximal dorsiflexion ROM decreased). To facilitate continuous statistical analysis and data visualisation, the relationships between ankle angle or fascicle length, and the muscle shear modulus and ankle passive torque were then interpolated every 5%, resulting in a 21-point curve (19). Muscle shear modulus was also analysed as a function of the raw ultrasound-measured fascicle length and the fascicle length normalized to the previously quantified slack length.

Statistical analysis

Two-way repeated measures analysis of variance (ANOVA) was used to investigate the effects of eccentric training conditions (short-muscle length *versus* long-muscle length) and time (pre-training *versus* post-training) on eccentric peak torque, gastrocnemius medialis slack angle and MVIC. Post-hoc analyses were performed using Bonferroni tests for multiple comparisons. Effect sizes are reported as partial *eta* squared (η_p^2). Effects of 0.01, 0.06, and 0.14 were small, medium, and large, respectively. A two-way analysis of variance (ANOVA-SPM) with repeated measures on one factor was performed in MATLAB (R2021a, The MathWorks Inc) using one-dimensional statistical parametric mapping (SPM, Version M.0.4.10 released 2021-09-23; www.spm1d.org) (26) to investigate the effects of eccentric training conditions (short-muscle length *versus* long-muscle length) and time (pre-training *versus* post-training) on ankle passive torque, gastrocnemius medialis fascicle length, and gastrocnemius medialis shear modulus as a function of ankle. We further examined the effects of eccentric training conditions and time on the gastrocnemius medialis shear modulus as a function of both fascicle length and fascicle length normalized to the slack length. Pairwise comparisons with Bonferroni corrections were applied where significant main or interaction effects were found. The normal distribution of the data was confirmed through the Shapiro-Wilk test prior each analysis of variance. The significance level for all statistical comparisons was set at $p < 0.05$. The ANOVAs and graphics were performed in GraphPad Prism (version 8; GraphPad Software, Inc., CA, US). Descriptive data are presented as mean ± standard deviation.

RESULTS

Of the initial 33 participants, four withdrew from the training protocol, and one did not commence participation. A total of 28 participants successfully completed the training program, with an adherence rate of 24.0 ± 0.8 sessions completed. Data from 27 participants were successfully analyzed (Figure 3): twelve in the short-muscle length group (5 women, age 19.2 ± 1.1 years, height 172.2 ± 10.9 cm, body mass 64.5 ± 10.8 kg, means ± SD) and fifteen in the long-length group (4 women, age 20.3 ± 1.7 years, height 174.1 ± 11.4 cm, body mass 66.3 ± 10.8 kg). One participant (short-muscle length group) was excluded from the statistical analysis because the mechanical data file from the post-testing session was incomplete due to a recording issue. Prior to participating in the training protocol, participants reported an average physical activity level of 2.6 ± 1.0 hours per week, engaging in physical activity approximately 4.7 ± 1.7 times each week.

[Figure 3]

Functional outcomes

There were no significant group*time interactions for the gastrocnemius medialis slack angle, plantar flexion MVIC and peak eccentric torque (Figure 4). However, a significant time effect revealed an increase of 9.5% in plantarflexion MVIC ($F=7.065$; $p<0.046$; $\eta_p^2=0.371$) following eccentric training. No effects of training or time were observed on the gastrocnemius medialis slack angle.

Muscle and joint adaptations

The averaged continuous relationships between ankle angle and gastrocnemius medialis fascicle length, shear modulus, and ankle passive torque are illustrated in Figure 5. They depict the eccentric training effects for both training groups and peak eccentric torque.

Fascicle length. Two-way ANOVA-SPM analysis revealed a significant group*time interaction between 39.5 ± 0.7° and 22.9 ± 1.6° of ankle plantar flexion ($p=0.045$). Post-hoc analyses indicated a significant increase in gastrocnemius medialis fascicle length following the eccentric training performed at long-muscle length, specifically between -39.8 ± 0.5° and -36.8 ± 0.8° in plantar flexion (Figure 5A; p=0.011). In the long-muscle length group, fascicle length measured prior to the training protocol were 4.23 ± 0.67cm at -39.8 ± 0.5° and 4.23 ± 0.66cm at -36.8 ± 0.8°. Following the training protocol, we observed an increase of 8.5 ± 10.0% (3.4 ± 4.2 mm) and 8.6 ± 10% (3.4 ± 4.2 mm) for both angles respectively. No changes were detected for the eccentric training performed at short-muscle length (Figure 5B).

Muscle shear modulus. There were no effects of the eccentric training protocols on gastrocnemius medialis shear modulus across the entire range of ankle motion (Figures 5C and 5D). Similarly, we did not observe any effects of eccentric training when evaluating the shear modulus as a function of fascicle length or fascicle length normalized to the slack length (Figures 6A and 6B). Additionally, SPM analyses did not detect any differences between the training conditions (short-muscle length *versus* long-muscle length).

Ankle passive torque. ANOVA-SPM analyses revealed a statistically significant time effect of eccentric exercise training on passive ankle torque at angles below the muscle slack length. Specifically, changes were observed from -39.7 ± 0.6° to -13.8 ± 2.8° in plantarflexion between pre- and post-training conditions. No group*time interaction was identified (Figure 5E and 5F).

EMG

There were no significant effects of group or time on the EMG-RMS of the gastrocnemius lateralis, soleus, and tibialis anterior muscles at any ankle angle. Activity levels across axial muscle loading were low: 0.3 ± 0.3% (maximum: 1.4%) for the gastrocnemius lateralis, 0.4 ± 0.3% (maximum: 1.4%) for the soleus, and 0.2 ± 0.3% (maximum: 1.4%) for the tibialis anterior. Specifically, only 2.0% of all data points for the gastrocnemius lateralis exceeded 1.0% of muscle activation. Similarly, 1.5% and 1.3% of all data points of the soleus and tibialis anterior exceeded 1.0% of muscle activation, respectively.

Discussion

This study demonstrates that an 8-week eccentric training program targeting the plantar flexor muscle group at a long-muscle length significantly increases gastrocnemius medialis fascicle length. This increase in fascicle length was not associated with adaptations in passive muscle mechanical properties, as evidenced by two primary findings. First, the relationships between ankle angle-muscle shear modulus and fascicle length-muscle shear modulus remained unchanged across the entire ankle ROM following the eccentric training. Second, the increase in fascicle length was significant only at plantarflexion angles below the slack length and hence in the absence of any passive muscle (axial) tension. These findings provide new insights into the mechanisms underlying the long-term macrostructural adaptations of the GM muscle in response to eccentric training.

The effects of the eccentric training on muscle strength are in line with those reported in the literature (1). In the present study, the long-term eccentric training led to overall improvements in peak isometric strength of 10.74 ± 26.76 N.m (mean increase of 9.5 %), which as on average 113.56 ± 31.35 N.m before the protocol. These findings align with previous studies that reported an average increase of 13 % in plantar flexors MVIC following eccentric training lasting 7 and 12 weeks (27, 28). Notably, the enhancements in muscle strength observed in this study did not differ between the short-muscle length and long-muscle length training groups. This observation suggests that adaptations in muscle length observed in the long-muscle length group were decoupled from changes in muscle strength. This reinforces the relevance of our methodological approach, comparing the effects of two different eccentric-based training stimuli on fascicle lengthening and passive tissue mechanics. There was no significant time effect for peak eccentric torque (p = 0.41). Notably, one participant in the long-muscle length group exhibited an unexpected decrease of 84.9 N·m in peak eccentric torque following the training protocol. Although this behavior might categorize the participant as an outlier for this specific variable, the participant was not excluded from the analysis because no outlier-like responses were detected in the primary outcome measures.

Eccentric training performed at both short- and long-muscle lengths did not alter ankle passive torque between 13.8°±2.8° in plantar flexion and 80% of the maximum dorsiflexion ROM. This is in line with previous observations (29). Similar findings have been reported across the full passive stretching cycle (14). In contrast, we found a significant decrease in ankle passive torque at plantar flexion angles around or below the slack angle (19.9 ± 4.4° in plantarflexion) following both eccentric training conditions. Passive ankle torque is influenced by multiple structures, including monoarticular plantarflexors (e.g., soleus), monoarticular dorsiflexors (e.g., tibialis anterior), and biarticular plantarflexors (e.g., gastrocnemii). Given that the GM shear modulus remained unaffected by training, and that passive torque changes occurred specifically below the GM muscle slack angle, it is likely that the decrease in passive torque in plantar flexion angles was unrelated to the GM muscle. Although the reasons underlying these changes remain unclear, they might be related to a decrease in passive tension of the soleus and/or an increase in passive tension of dorsiflexors (e.g., tibialis anterior). Considering that the maximum difference occurs at 40° of plantar flexion, it is likely attributed to ankle dorsiflexors rather than the soleus. The increase in passive tension of the ankle dorsiflexors may result from a decrease in slack length, an increase in muscle elastic modulus, and/or hypertrophy. These changes could be associated with isometric loading or the co-activation of these muscles during the eccentric exercise.

The increase in fascicle length in the long-muscle length group (mean increase of 8.5%) was in line with previous findings. For instance, Duclay *et al.* (2009) observed a 6.8% increase in ultrasound-measured fascicle length of the gastrocnemius medialis – assessed at neutral ankle position – following an eccentric training of similar duration and load (27). However, the increase in fascicle length observed in the present study was smaller compared to studies involving other muscles, such as the quadriceps, where increases typically range from 10% to 20% (30–33). Our unique approach enabled us to investigate, for the first time, the effects of eccentric training on fascicle length over a large range of muscle lengthening, rather than at a single joint angle (as commonly studied). Specifically, our findings indicate that fascicle length significantly increased only at plantar flexion angles between 39.5 ± 0.7° and 36.8 ± 0.8°. An important finding from the present study is that fascicle lengthening did not occur in the short-muscle length training group. This demonstrates that the range of muscle-tendon length at which eccentric training is performed is crucial for eliciting structural adaptations, potentially resulting from sarcomerogenesis. Additionally, in the long-muscle length training group, fascicle length increased only below the gastrocnemius medialis slack angle (i.e., absence of any passive axial tension). This indicates that muscle passive tension – and thus connective tissue adaptations – did not contribute to the increase in muscle fascicle length. This conclusion is further supported by the lack of significant changes in muscle shear modulus, which was measured at the same location as the fascicle length (Figure 1) across the stretching cycle (i.e., ankle ROM). Together, these results strongly suggest that the changes in fascicle length may be related to an increase in the number of sarcomeres in series or an increase in the sarcomere length, independent of changes in passive muscle mechanics. Considering the study of Pincheira *et al.* (2021), an increase in sarcomere length may be the preferential mechanism involved in these adaptations (13). However, the differences in training duration (3 weeks *versus* 8 weeks in the present study) and the muscles examined (biceps femoris *versus* gastrocnemius medialis) limit direct comparisons between the studies. It is possible that 3 weeks of eccentric training were insufficient to trigger an increase in the number of sarcomeres in series and that this increase may occur after 8 weeks of training. Finally, while it is feasible to measure the shear modulus of hamstrings during passive lengthening (34), tracking the fascicle length of these very long muscles remains challenging. This is the reason why the present study was focused on the gastrocnemius medialis muscle.

Comparing the effects of the eccentric training used in the present study with the chronic muscle-directed stretching protocol used by Andrade *et al.* (2020) reveals intriguing insights into the mechanical properties of the gastrocnemius medialis (19). While the 12-week stretching protocol resulted in a 13% decrease in shear modulus and an 8.2% increase in fascicle length at 0° of dorsiflexion, the 8-week eccentric training led to a similar magnitude of fascicle length increase but in the absence of muscle mechanical adaptations. Together, these observations suggest distinct mechanisms driving skeletal muscle adaptations in response to long-term loading stimuli (i.e., passive stretching *versus* eccentric contraction).

We acknowledge some limitations in this study. Firstly, we used a linear extrapolation method to measure fascicle length, which may introduce errors due to the potential curvature of the fascicle or aponeurosis (35). However, gastrocnemii fascicles typically exhibit a relatively linear arrangement, and measurement errors associated with fascicle curvature have been shown to be negligible in resting gastrocnemius medialis muscle (35–37). Furthermore, the typical length of the gastrocnemii fascicles is approximately equal to the size of the (linear) transducer used for the assessments (i.e., 5 cm). In this study, the average extrapolated fascicle length was 36.5% ± 10.0% at the highest plantar flexion angle (40°) and 40.1% ± 10.4% at 80% of the maximal dorsiflexion range of motion. Second, slight variations in probe location may have occurred due to training-induced hypertrophy and changes in muscle geometry. However, we ensured that images were captured in the same muscle region using bone references, applying minimal pressure, and rigorously positioning participants in the same manner in the isokinetic dynamometer system before and after the interventions. Additionally, we did not include a control group. Third, this study focused on the muscle mechanics and architectural adaptations of the gastrocnemius medialis. However, similar adaptations may have occurred in other plantar flexor muscles, particularly within the triceps surae. While adaptations in the gastrocnemius lateralis are likely, they may have been to a lesser extent than those in the gastrocnemius medialis (11). We speculate that adaptations in the monoarticular soleus were more limited, given the specific nature of the training configuration (i.e., knee extended). Forth, we experienced some technical issues with the EMG system during the post-training assessments, resulting in missing EMG data for four participants. To address these issues, we carefully inspected passive torque, muscle shear modulus, and B-mode images to confirm that no involuntary muscle activation occurred during the stretching cycles in post-training tests. Moreover, during the pre-training test session, none of these participants had an RMS-EMG activity >1% on the three measured muscles. Lastly, for the remaining participants, the RMS-EMG activity of the gastrocnemius medialis, soleus and tibialis anterior muscles was notably low, well below the 2% threshold identified as potential factor affecting muscle and joint stiffness (25). However, it is important to acknowledge that the primary muscle of interest in this study, the gastrocnemius medialis, was not assessed due to the practical challenges associated with obtaining EMG data concurrently with ultrasound imaging during a passive muscle stretching.

CONCLUSION

This study provides new insight into how the strength, macrostructure and mechanical properties of the gastrocnemius medialis muscle adapt over eccentric training performed at different muscle lengths. Eight weeks of eccentric training at both short-muscle or long-muscle lengths induced similar increases in isometric and eccentric peak force. Interestingly, only the eccentric training performed at long-muscle length led to significant increases in fascicle length, which occurred at plantar flexion angles below the muscle slack length (i.e., absence of any passive axial tension). This highlights the importance of the muscle-tendon length range during eccentric exercises for eliciting adaptations in fascicle length. Additionally, none of eccentric training groups exhibited changes in local muscle shear modulus, measured at the same site as the fascicle length. Therefore, the increase in fascicle length observed in our study may be attributed to an increase in sarcomere length and/or an increase in sarcomeres in series, which appears to occur independently of adaptations in passive muscle-tendon mechanical properties. Further studies are required to better understand the influence of training duration and the trained muscle on changes in muscle fascicle properties. Finaly, the design employed in the present study, investigating both short-muscle and long-muscle eccentric training groups, could be particularly relevant for assessing changes in muscle mechanics and fascicle adaptations independently of changes in muscle strength. Lastly, we acknowledge that our findings cannot be generalized to other skeletal muscles and do not intend to provide direct recommendations regarding the most effective eccentric training protocols for inducing structural changes at the tissue level. For example, the eccentric load was set at 1 maximal concentric repetition. Protocols done with higher loads may provide different results.

REFERENCES

1. **Douglas J**, **Pearson S**, **Ross A**, **McGuigan M**. Chronic Adaptations to Eccentric Training: A Systematic Review | SpringerLink [Online]. 2016. https://link.springer.com/article/10.1007/s40279-016-0628-4?platform=hootsuite&error=cookies_not_supported&code=6161c50d-7122-4ba3-8036-4756fb0c20d4 [19 Aug. 2022].

2. **Lieber R**. Biomechanical response of skeletal muscle to eccentric contractions | Elsevier Enhanced Reader. 2018.

3. **Blazevich AJ**, **Cannavan D**, **Coleman DR**, **Horne S**. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol Bethesda Md 1985* 103: 1565–1575, 2007. doi: 10.1152/japplphysiol.00578.2007.

4. **Guex K**, **Degache F**, **Morisod C**, **Sailly M**, **Millet GP**. Hamstring Architectural and Functional Adaptations Following Long vs. Short Muscle Length Eccentric Training. *Front Physiol* 7: 340, 2016. doi: 10.3389/fphys.2016.00340.

5. **Quinlan JI**, **Franchi MV**, **Gharahdaghi N**, **Badiali F**, **Francis S**, **Hale A**, **Phillips BE**, **Szewczyk N**, **Greenhaff PL**, **Smith K**, **Maganaris C**, **Atherton PJ**, **Narici MV**. Muscle and tendon adaptations to moderate load eccentric vs. concentric resistance exercise in young and older males. *GeroScience* 43: 1567–1584, 2021. doi: 10.1007/s11357-021-00396-0.

6. **Sharifnezhad A**, **Marzilger R**, **Arampatzis A**. Effects of load magnitude, muscle length and velocity during eccentric chronic loading on the longitudinal growth of the vastus lateralis muscle. *J Exp Biol* 217: 2726–2733, 2014. doi: 10.1242/jeb.100370.

7. **Lynn R**, **Talbot JA**, **Morgan DL**. Differences in rat skeletal muscles after incline and decline running. *J Appl Physiol* 85: 98–104, 1998. doi: 10.1152/jappl.1998.85.1.98.

8. **Lynn R**, **Morgan DL**. Decline running produces more sarcomeres in rat vastus intermedius muscle fibers than does incline running. *J Appl Physiol* 77: 1439–1444, 1994. doi: 10.1152/jappl.1994.77.3.1439.

9. **Morgan DL**, **Proske U**. POPPING SARCOMERE HYPOTHESIS EXPLAINS STRETCH-INDUCED MUSCLE DAMAGE. *Clin Exp Pharmacol Physiol* 31: 541–545, 2004. doi: 10.1111/j.1440-1681.2004.04029.x.

10. **Franchi MV**, **Ruoss S**, **Valdivieso P**, **Mitchell KW**, **Smith K**, **Atherton PJ**, **Narici MV**, **Flück M**. Regional regulation of focal adhesion kinase after concentric and eccentric loading is related to remodelling of human skeletal muscle. *Acta Physiol* 223: e13056, 2018. doi: 10.1111/apha.13056.

11. **Geremia JM**, **Baroni BM**, **Bini RR**, **Lanferdini FJ**, **de Lima AR**, **Herzog W**, **Vaz MA**. Triceps Surae Muscle Architecture Adaptations to Eccentric Training. *Front Physiol* 10: 1456, 2019. doi: 10.3389/fphys.2019.01456.

12. **Marušič J**, **Vatovec R**, **Marković G**, **Šarabon N**. Effects of eccentric training at long-muscle length on architectural and functional characteristics of the hamstrings. *Scand J Med Sci Sports* 30: 2130–2142, 2020. doi: 10.1111/sms.13770.

13. **Pincheira PA**, **Boswell MA**, **Franchi MV**, **Delp SL**, **Lichtwark GA**. Biceps femoris long head sarcomere and fascicle length adaptations after 3 weeks of eccentric exercise training. *J Sport Health Sci* 11: 43–49, 2022. doi: 10.1016/j.jshs.2021.09.002.

14. **Fouré A**, **Nordez A**, **Cornu C**. Effects of eccentric training on mechanical properties of the plantar flexor muscle-tendon complex. *J Appl Physiol* 114: 523–537, 2013. doi: 10.1152/japplphysiol.01313.2011.

15. **Mahieu NN**, **Mcnair P**, **Cools A**, **D'haen C**, **Vandermeulen K**, **Witvrouw E**. Effect of Eccentric Training on the Plantar Flexor Muscle-Tendon Tissue Properties. *Med Sci Sports Exerc* 40: 117–123, 2008.

16. **Aeles J**, **Lenchant S**, **Vanlommel L**, **Vanwanseele B**. Bilateral differences in muscle fascicle architecture are not related to the preferred leg in jumping athletes. *Eur J Appl Physiol* 117: 1453–1461, 2017. doi: 10.1007/s00421-017-3638-5.

17. **Hug F**, **Tucker K**, **Gennisson J-L**, **Tanter M**, **Nordez A**. Elastography for Muscle Biomechanics: Toward the Estimation of Individual Muscle Force. *Exerc Sport Sci Rev* 43: 125–133, 2015.

18. **Antonios T**, **Adds PJ**. The medial and lateral bellies of gastrocnemius: a cadaveric and ultrasound investigation. *Clin Anat N Y N* 21: 66–74, 2008. doi: 10.1002/ca.20533.

19. **Andrade R**, **Freitas S**, **Hug F**, **Le Sant G**, **Lacourpaille L**, **Gross R**, **Quillard J-B**, **McNair P**, **Nordez A**. Chronic effects of muscle and nerve-directed stretching on tissue mechanics. 2020.

20. **Hermens HJ**, **Freriks B**, **Disselhorst-Klug C**, **Rau G**. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol* 10: 361–374, 2000. doi: 10.1016/s1050-6411(00)00027-4.

21. **Nordez A**, **McNair P**, **Casari P**, **Cornu C**. Acute Changes in Hamstrings Musculo-Articular Dissipative Properties Induced by Cyclic and Static Stretching. .

22. **Bezerra de azevedo J**, **Massaroto Barros B**, **Peixoto Rosa Dos Santos LE**, **Aparecida Biasotto-Gonzalez D**, **Fidelis De Paula Gomes CA**, **Baker JS**, **Luksevicius Rica R**, **Sales Bocalini D**, **Politti F**. Activation of triceps Surae during exercises on leg press, Smith and seated calf raise machines. *J Phys Educ Sport* 23, 2023. doi: 10.7752/jpes.2023.08260.

23. **Le Sant G**, **Nordez A**, **Andrade R**, **Hug F**, **Freitas S**, **Gross R**. Stiffness mapping of lower leg muscles during passive dorsiflexion. *J Anat* 230: 639–650, 2017. doi: 10.1111/joa.12589.

24. **Farris DJ**, **Lichtwark GA**. UltraTrack: Software for semi-automated tracking of muscle fascicles in sequences of B-mode ultrasound images. *Comput Methods Programs Biomed* 128: 111–118, 2016. doi: 10.1016/j.cmpb.2016.02.016.

25. **Le Sant G**, **Gross R**, **Hug F**, **Nordez A**. Influence of low muscle activation levels on the ankle torque and muscle shear modulus during plantar flexor stretching. *J Biomech* 93: 111–117, 2019. doi: 10.1016/j.jbiomech.2019.06.018.

26. **Pataky TC**, **Robinson MA**, **Vanrenterghem J**. Vector field statistical analysis of kinematic and force trajectories. *J Biomech* 46: 2394–2401, 2013. doi: 10.1016/j.jbiomech.2013.07.031.

27. **Duclay J**, **Martin A**, **Duclay A**, **Cometti G**, **Pousson M**. Behavior of fascicles and the myotendinous junction of human medial gastrocnemius following eccentric strength training. *Muscle Nerve* 39: 819–827, 2009. doi: 10.1002/mus.21297.

28. **Geremia JM**, **Baroni BM**, **Lanferdini FJ**, **Bini RR**, **Sonda FC**, **Vaz MA**. Time course of neuromechanical and morphological adaptations to triceps surae isokinetic eccentric training. *Phys Ther Sport Off J Assoc Chart Physiother Sports Med* 34: 84–91, 2018. doi: 10.1016/j.ptsp.2018.09.003.

29. **Kay AD**, **Richmond D**, **Talbot C**, **Mina M**, **Baross AW**, **Blazevich AJ**. Stretching of Active Muscle Elicits Chronic Changes in Multiple Strain Risk Factors. *Med Sci Sports Exerc* 48: 1388, 2016. doi: 10.1249/MSS.0000000000000887.

30. **Franchi MV**, **Atherton PJ**, **Reeves ND**, **Flück M**, **Williams J**, **Mitchell WK**, **Selby A**, **Beltran Valls RM**, **Narici MV**. Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiol* 210: 642–654, 2014. doi: 10.1111/apha.12225.

31. **Baroni BM**, **Geremia JM**, **Rodrigues R**, **De Azevedo Franke R**, **Karamanidis K**, **Vaz MA**. Muscle architecture adaptations to knee extensor eccentric training: rectus femoris vs. vastus lateralis. *Muscle Nerve* 48: 498–506, 2013. doi: 10.1002/mus.23785.

32. **Reeves ND**, **Maganaris CN**, **Longo S**, **Narici MV**. Differential adaptations to eccentric versus conventional resistance training in older humans. *Exp Physiol* 94: 825–833, 2009. doi: 10.1113/expphysiol.2009.046599.

33. **Seynnes OR**, **de Boer M**, **Narici MV**. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol Bethesda Md 1985* 102: 368–373, 2007. doi: 10.1152/japplphysiol.00789.2006.

34. **Le Sant G**, **Ates F**, **Brasseur J-L**, **Nordez A**. Elastography Study of Hamstring Behaviors during Passive Stretching. *PloS One* 10: e0139272, 2015. doi: 10.1371/journal.pone.0139272.

35. **Van Hooren B**, **Teratsias P**, **Hodson-Tole EF**. Ultrasound imaging to assess skeletal muscle architecture during movements: a systematic review of methods, reliability, and challenges. *J Appl Physiol Bethesda Md 1985* 128: 978–999, 2020. doi: 10.1152/japplphysiol.00835.2019.

36. **May S**, **Locke S**, **Kingsley M**. Reliability of ultrasonographic measurement of muscle architecture of the gastrocnemius medialis and gastrocnemius lateralis. *PLOS ONE* 16: e0258014, 2021. doi: 10.1371/journal.pone.0258014.

37. **Muramatsu T**, **Muraoka T**, **Kawakami Y**, **Shibayama A**, **Fukunaga T**. In vivo determination of fascicle curvature in contracting human skeletal muscles. *J Appl Physiol Bethesda Md 1985* 92: 129–134, 2002. doi: 10.1152/jappl.2002.92.1.129.

FIGURES LEGEND

Figure 1. **A.** Setup for the ultrafast ultrasound imaging acquisitions; **B.** Example of a shear wave elastography map, with the region of interest for shear modulus measurements outlined in yellow; **C.** Example of fascicle length analysis using UltraTrack software (Farris & Litchwark, 2016).

Figure 2. Eccentric training exercises and ankle positions for each eccentric training condition. The first column corresponds to 30° of plantar flexion (starting position for short-muscle length group). The second column indicates the neutral position (end position for short-muscle length training group and starting position for long-length training group). The third column illustrates the maximal dorsiflexion position (end position for the long-length training group); **A.** Heel drop exercise preformed on the smith machine; **B.** Heel drop exercise performed on the oblique press; **C.** Isokinetic eccentric plantar flexion exercise.

Figure 3. Flow chart illustrating the study enrollment, allocation, and analysis process.

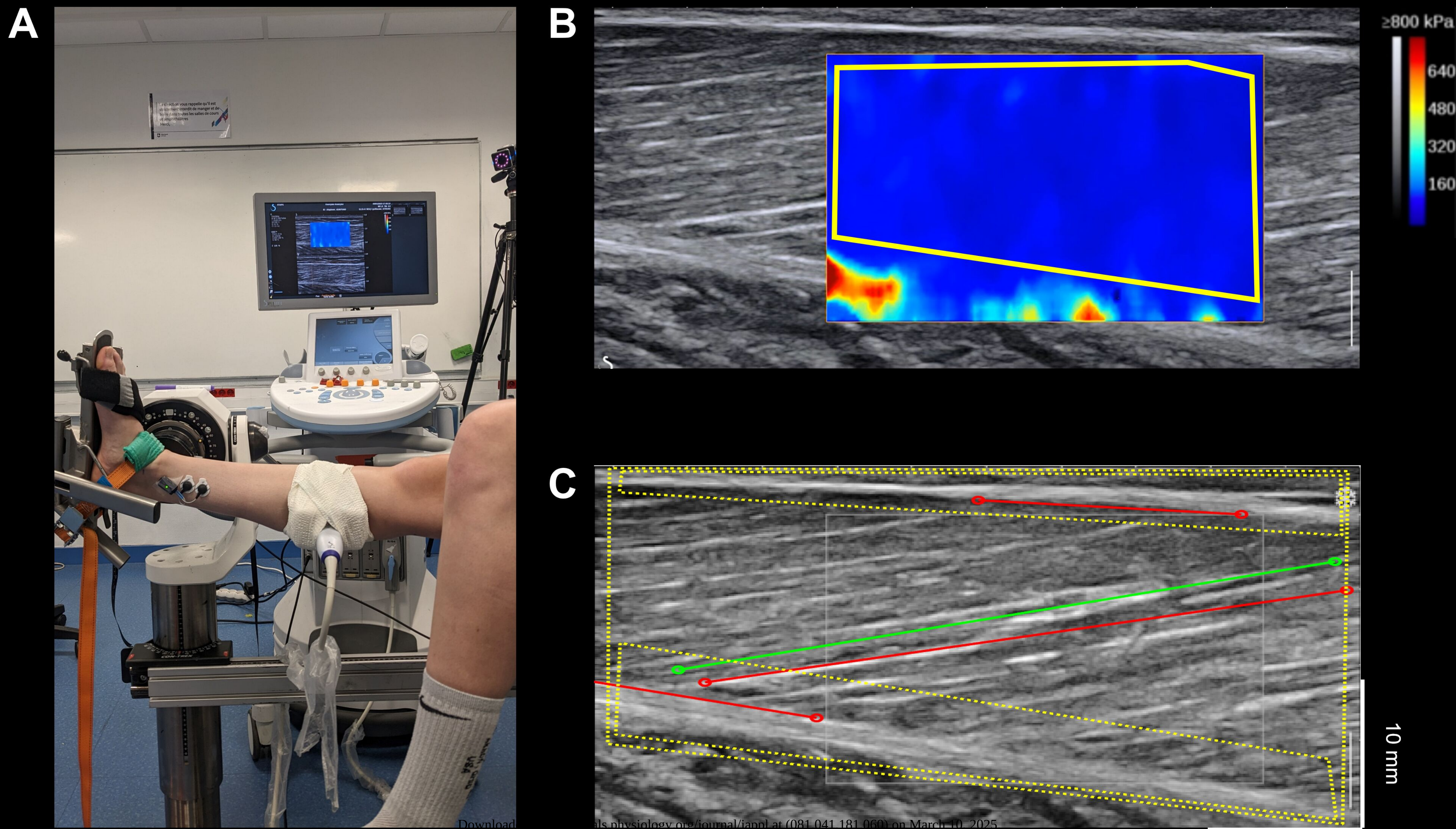
Figure 4. Pre- to post-training effects of eccentric training performed at long-muscle and short-muscle lengths on plantar flexion maximal voluntary isometric contraction (MVIC) **(A)**, peak eccentric torque in plantar flexion **(B)** and gastrocnemius medialis slack angle **(C)** per training condition (short-muscle length *versus* long-muscle length). There were no significant group*time interactions for the gastrocnemius medialis slack angle, plantar flexion MVIC and peak eccentric torque. A significant time effect revealed an increase of 9.5% in plantarflexion MVIC ($p<0.046$) following eccentric training. No effects of training or time were observed on the gastrocnemius medialis slack angle and peak eccentric torque. Individual data points are represented by red square (pre-training, □) and blue triangles (post-training, △). MVIC: maximal voluntary isometric contraction; GM: gastrocnemius medialis.

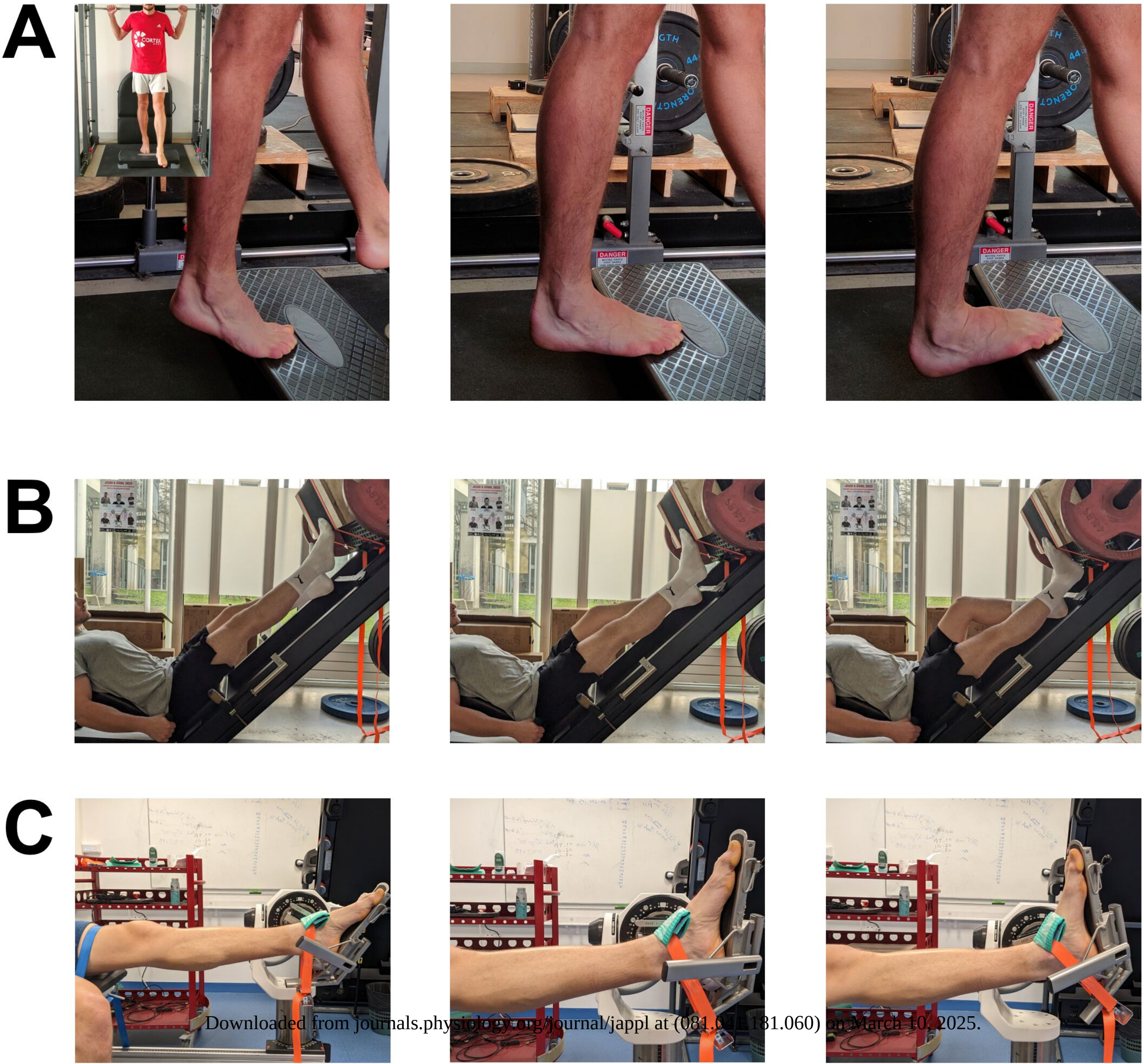
Figure 5. Effects of 8-week eccentric training at long-muscle length and short-muscle length on gastrocnemius medialis (GM) fascicle length **(A & B)**, gastrocnemius medialis muscle shear modulus **(C & D)**, and ankle passive torque **(E & F)** as a function of ankle angle. Panels **A**, **C**, and **E** correspond to long-muscle length training, while panels **B**, **D**, and **F** represent short-muscle length training. Individual data are illustrated as red squares (pre-training, ■) and blue triangles (post-training, ▲). GM: gastrocnemius medialis; Fl: Fascicle length; *denotes $p<0.05$.

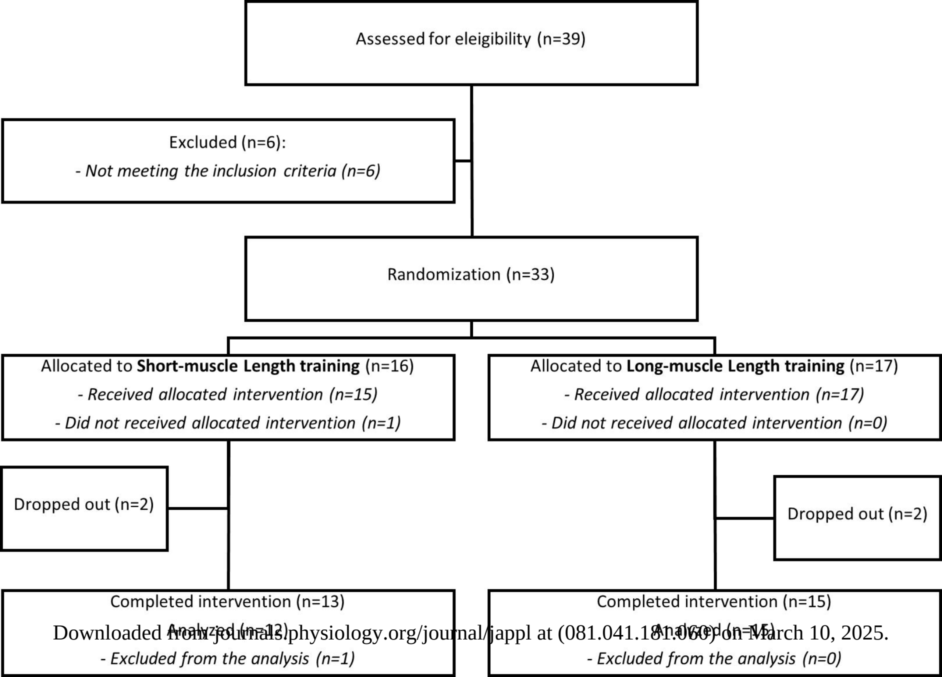
Figure 6. Gastrocnemius medialis muscle shear modulus as a function of fascicle length normalized to the slack length, pre- and post-training for the long-muscle length **(A)** and the short-muscle length **(B)** conditions. Individual data are illustrated as red squares (pre-training, ■) and blue triangles (post-training, ▲). GM: gastrocnemius medialis; Fl: fascicle length; Fl_0: slack length; $Fl-Fl_0$: fascicle length normalized to the slack length).

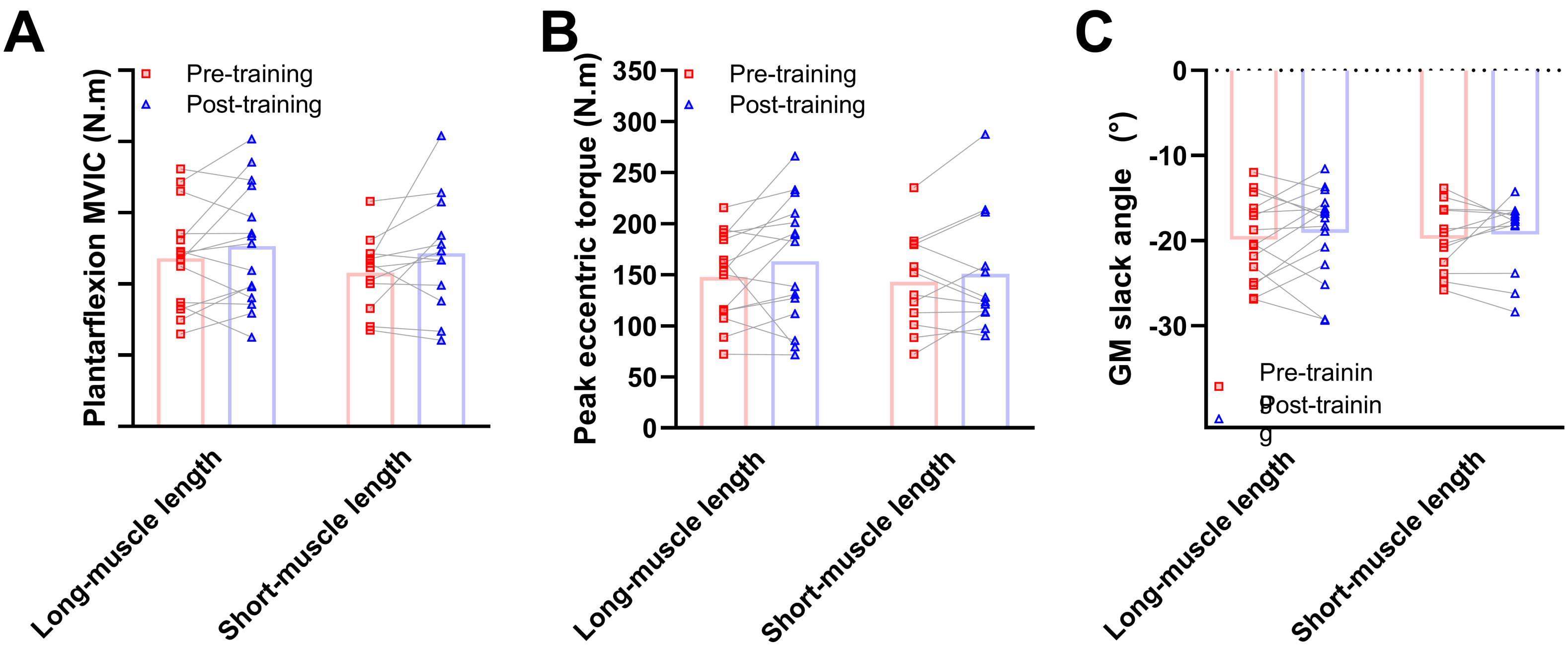
TABLES LEGEND

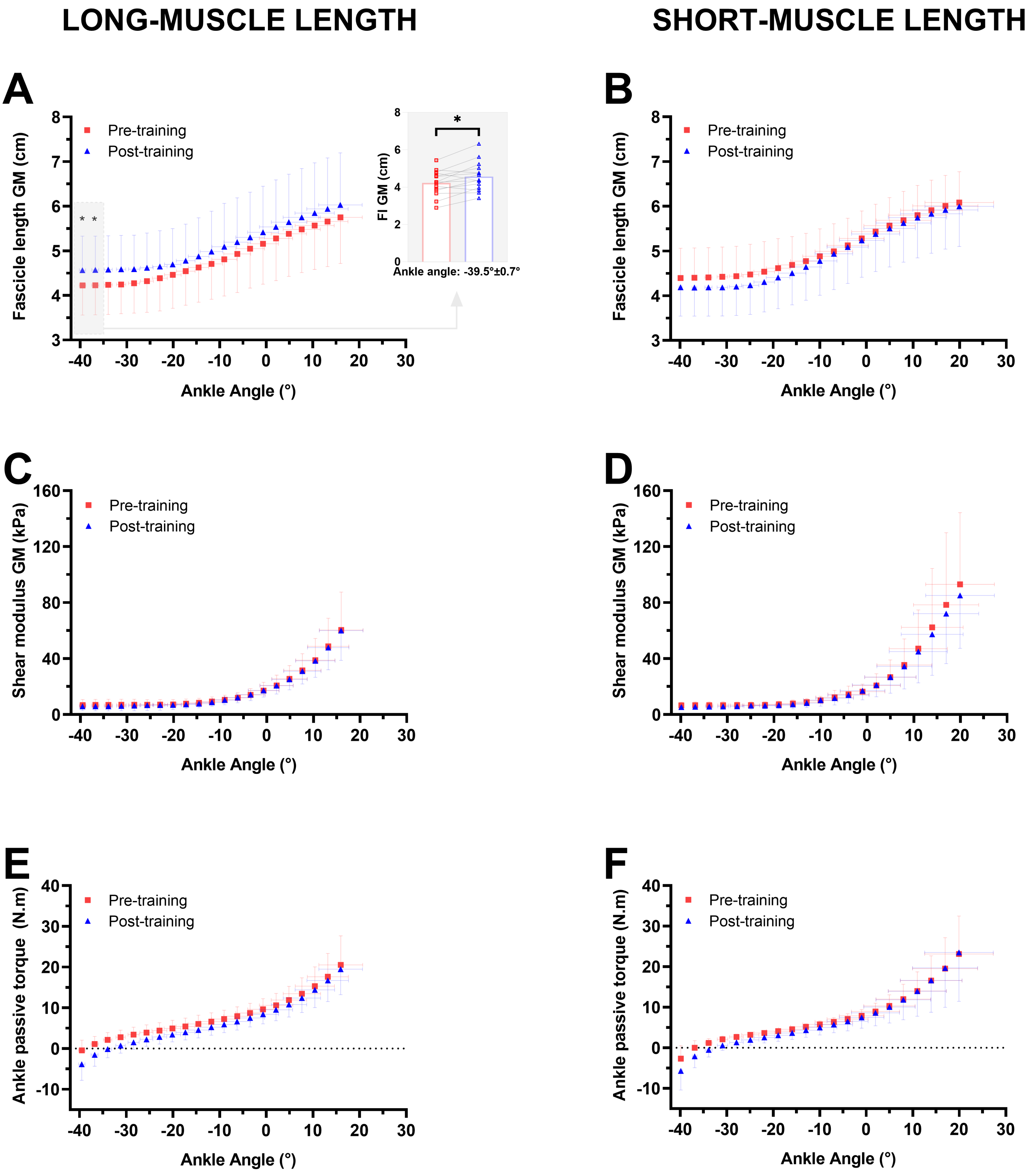
Table 1. Summary of the eccentric training protocol for each testing condition. 1-RM: one repetition concentric maximum; Con: concentric Ecc: eccentric; Isom: isometric. Note that the concentric part was performed bilaterally and, that for eccentric, right and left sides were involved alternatively.


A
B
C
≥800 kPa
640
480
320
160
10 mm


A
B
C
DANGER


Assessed for eleigibility (n=39)
Excluded (n=6):
- Not meeting the inclusion criteria (n=6)
Randomization (n=33)
Allocated to Short-muscle Length training (n=16)
- Received allocated intervention (n=15)
- Did not received allocated intervention (n=1)
Allocated to Long-muscle Length training (n=17)
- Received allocated intervention (n=17)
- Did not received allocated intervention (n=0)
Dropped out (n=2)
Dropped out (n=2)
Completed intervention (n=13)
Analyzed (n=12)
- Excluded from the analysis (n=1)
Completed intervention (n=15)
Analyzed (n=15)
- Excluded from the analysis (n=0)


A
Plantarflexion MVIC (N.m)
Pre-training
Post-training
Long-muscle length
Short-muscle length
B
Peak eccentric torque (N.m)
350
300
250
200
150
100
50
0
Pre-training
Post-training
Long-muscle length
Short-muscle length
C
GM slack angle (°)
0
-10
-20
-30
Pre-trainin
g
Post-trainin
g
Long-muscle length
Short-muscle length



LONG-MUSCLE LENGTH
SHORT-MUSCLE LENGTH
A
B
C
D
E
F
Pre-training
Post-training
Fascicle length GM (cm)
Fl GM (cm)
Ankle angle: -39.5°±0.7°
Shear modulus GM (kPa)
Ankle passive torque (N.m)
Ankle Angle (°)

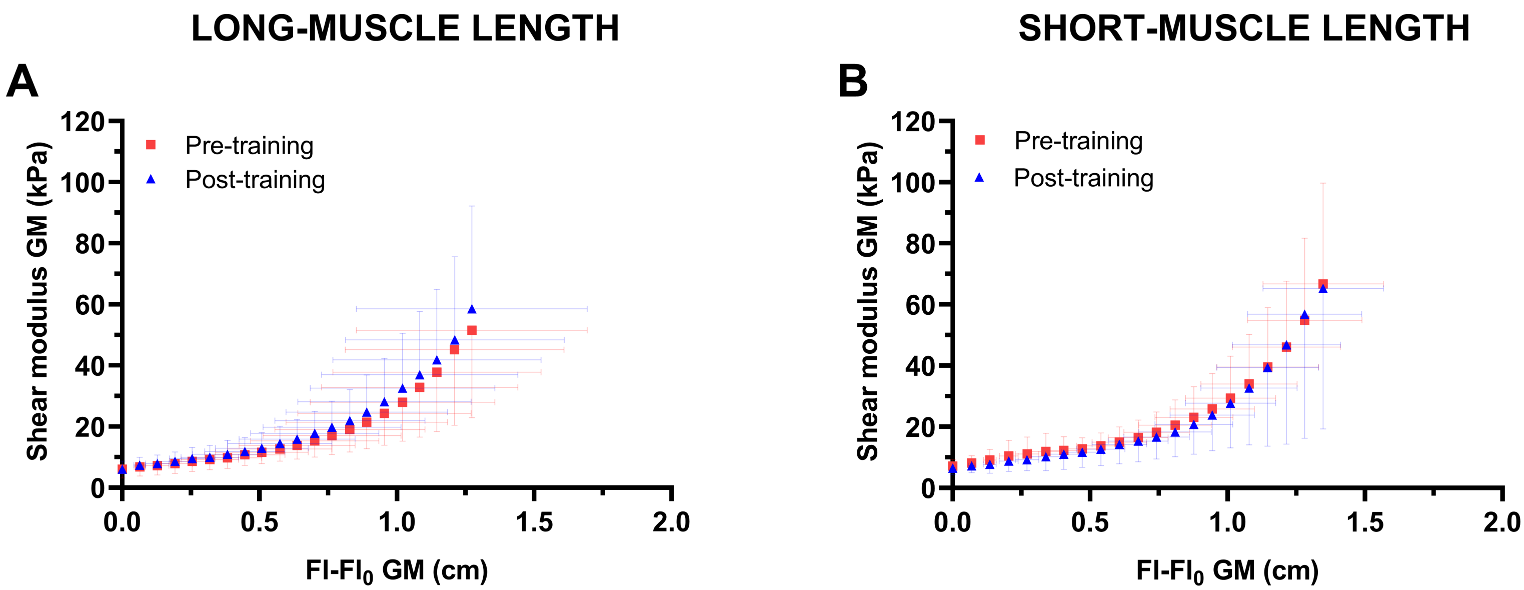

LONG-MUSCLE LENGTH
SHORT-MUSCLE LENGTH
A
B
Pre-training
Post-training
Shear modulus GM (kPa)
Fl-Fl0 GM (cm)
0
20
40
60
80
100
120
0.0
0.5
1.0
1.5
2.0

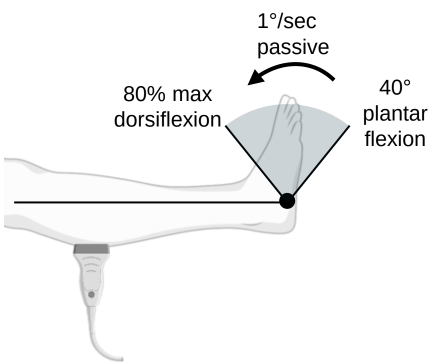
Table 1. Summary of the eccentric training protocols used in the short-muscle and long-muscle length groups. Note that the concentric phase was performed bilaterally, whereas the eccentric phase involved alternating between the right and left sides. Abbreviations: 1-RM: one repetition concentric maximum; Con: concentric; Ecc: eccentric; Isom: isometric.

Modality	Apparatus	Number of sessions	Prescription	Tempo (s) con-isom-ecc-rest	Recovery between series (s)	Loading dose
Isotonic	Heel drop on the Smith machine	5	5x10	1-1-3-1	90	100% of Concentric 1-RM
		5	1-RM assessment 4x10	1-1-3-1	90	100% of Concentric 1-RM
	Heel drop on the oblique press	5	5x10	1-1-3-1	90	100% of Concentric 1-RM
		5	1-RM assessment 4x10	1-1-3-1	90	100% of Concentric 1-RM
Isokinetic	Dynamometer	4	5x10	1-1-3-1	90	100% Eccentric

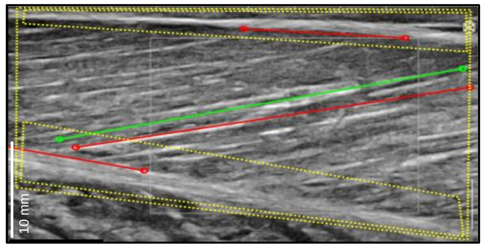
Eight weeks of eccentric training at long muscle length increase gastrocnemius medialis fascicle length without altering passive mechanics

METHODS

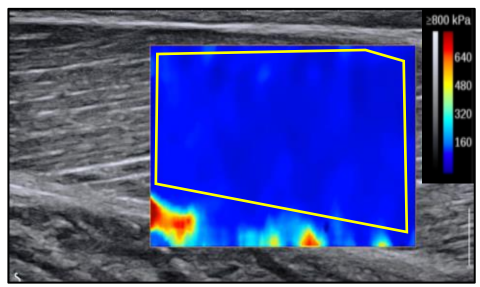
Outcomes measures:



Fascicle length

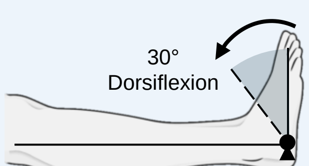


Shear modulus (stiffness)



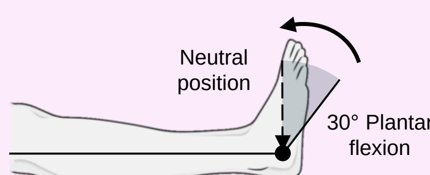
Eccentric training groups:

Long-muscle length (n=15)



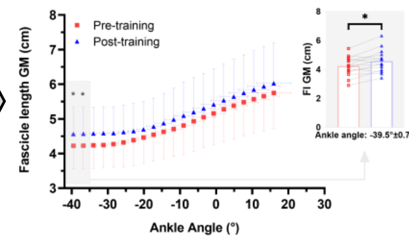
VS

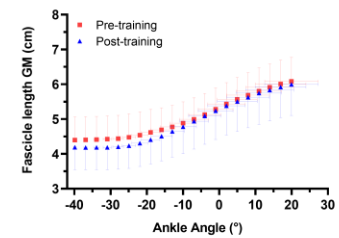
Short-muscle length (n=13)

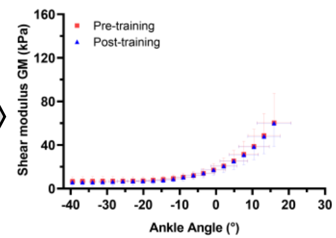


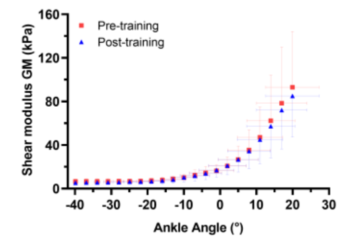
OUTCOMES

Long-muscle length | **Short-muscle length**









Fascicle length increased in the long-muscle length group, but only at plantar-flexed angles (i.e., without passive tension), while shear modulus remained unchanged

CONCLUSION

Fascicle length adaptations to eccentric training occurred independently of changes in passive muscle-tendon properties, likely reflecting increased sarcomere length and/or the addition of sarcomeres in series