

Research article

Morphological and Functional Adaptations of the Triceps Surae Complex to Eccentric Quasi-Isometric versus Eccentric Resistance Exercise in Healthy, Regularly Trained Adults: A Randomised Controlled Trial

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Abstract

Eccentric quasi-isometric (EQI) contractions combine isometric holding with subsequent eccentric (ECC) lengthening. Although EQI exercise has gained attention, its chronic effects remain unclear. This study compared morphological and functional adaptations to EQI and ECC resistance exercise. Forty-eight healthy, regularly trained adult participants were randomly allocated (sex-stratified) to EQI, ECC, or control groups ($n = 16$ per group; age 22.91 ± 4.70). The intervention groups completed a six-week training program with matched load and time under tension. Outcomes assessed pre- and post-intervention included Achilles tendon properties, gastrocnemius architecture, ankle range of motion, and plantar flexor strength. Both EQI and ECC training increased Achilles tendon thickness, gastrocnemius fascicle length and muscle thickness, and lateral gastrocnemius pennation angle compared to control (all $p \leq 0.001$; $\eta^2 = 0.53 - 0.79$), with no differences between protocols ($p = 0.227 - 0.965$). Ankle dorsiflexion (open and closed kinetic chain) and concentric, ECC, and isometric strength improved in both intervention groups compared to control ($p \leq 0.019$; $\eta^2 = 0.33 - 0.77$), without between-group differences ($p = 0.561 - 0.976$). Only ECC training increased EQI time under tension and torque impulse ($p = 0.012 - 0.020$), while tendon stiffness, medial gastrocnemius pennation angle, and EQI angular velocity did not change ($p \geq 0.065$). EQI and ECC training produced comparable improvements in muscle-tendon morphology, strength, and ankle dorsiflexion when load and time under tension were matched, while EQI training was associated with lower muscle soreness.

Key words: Ankle plantar flexors, eccentric quasi-isometric contraction, eccentric contraction, muscle and tendon morphology, strength.

Introduction

Recently, scientific literature has been increasingly addressing the challenge of optimising exercise protocols designed to prevent and treat musculoskeletal injuries or improve muscle performance. Research has focused primarily on adjusting exercise volume (Oranchuk et al., 2019), intensity (Luan et al., 2019), and/or the type of muscle contraction (Henderson et al., 2025; Oranchuk et al., 2021b; Wiesinger et al., 2015). Muscle contractions can generally be classified as isometric, concentric, and eccentric (ECC) contractions (Radovanović et al., 2022). Isometric contraction is defined as the generation of force with the muscle-tendon complex remaining at a constant length (Radovanović et al., 2022). In contrast, during concentric con-

traction, the muscle-tendon complex shortens while generating force, whereas during ECC contraction, it lengthens (Lindstedt et al., 2018). During ECC contraction, the external load exceeds the force produced by the muscle to maintain the position, resulting in active lengthening of the muscle-tendon complex (Lindstedt et al., 2018). In addition to these forms, isotonic and isokinetic lengthening are also common in practice, involving a sequence of concentric and ECC phases, with constant external resistance in one movement direction in the former and constant velocity of movement in the latter (Thompson, 2025).

A combined form of muscle exercise that has been gaining recognition in recent years is eccentric quasi-isometric (EQI) action (Oranchuk et al., 2019). EQI action combines isometric and ECC contraction; specifically, the initial position in the weaker part of the range of motion (RoM) (i.e., where the muscle is shortened) is maintained until isometric failure, followed by maximum resistance in the subsequent ECC phase and an attempt to re-establish isometric contraction (Oranchuk et al., 2019). Due to low angular velocities of movement, EQI action allows training at high (submaximal or maximal) loads without the risk of a sudden increase in mechanical stress on the tendon and joint (Magnusson and Kjaer, 2019). To date, only a limited number of studies have been conducted to examine the characteristics (Henderson et al., 2023; Križaj et al., 2025b; Ličen et al., 2024; Lin et al., 2026; Oranchuk et al., 2021a) and acute (Križaj et al., 2025a; Lin et al., 2026; Oranchuk et al., 2021b) or chronic effects of EQI exercise (Henderson et al., 2025). Previous EQI studies have examined knee extensors and flexors (Ličen et al., 2024; Oranchuk et al., 2021a), elbow flexors (Henderson et al., 2023; 2025; Lin et al., 2026), and ankle plantar flexors (Križaj et al., 2025a; 2025b). It was found that the magnitude of angular impulse decreased during successive EQI actions (Henderson et al., 2023; Oranchuk et al., 2021a), which is most pronounced between the first and the second repetition (Henderson et al., 2023). Meanwhile, two studies examining the effects of four EQI repetitions on strength reported divergent findings. Ličen et al. (2024) observed significant reductions in concentric strength of the knee extensors and flexors, whereas Križaj et al. (2025b) found no change in isometric strength of the ankle plantar flexors. These discrepancies may reflect differences in the muscle groups investigated and in the type of strength outcomes that were assessed (concentric and isometric, respectively). It was also found that the performance of five EQI actions resulted in a 3.5-

times longer time under tension compared to five series of ECC-only contractions that were executed until failure (Lin et al., 2026). At the same time, the execution of EQI protocol caused lower maximal voluntary contraction (MVC) and RoM decrease compared to ECC-only protocol (Lin et al., 2026). This is also supported by data showing that biochemical markers of muscle damage were significantly higher following the ECC protocol than following the EQI protocol, with a faster recovery after EQI exercise (Lin et al., 2026).

Short-term effects, defined as effects assessed within less than four weeks (Mitham et al., 2021), have been examined in only two previous studies that compared EQI to ECC (Oranchuk et al., 2021b) and isokinetic heavy slow resistance (IHSR) exercise (Križaj et al., 2025a). Both studies found that EQI exercise caused a smaller decrease in the maximum strength of the trained muscle group and also a lower level of delayed muscle soreness than ECC or IHSR (Križaj et al., 2025a; Oranchuk et al., 2021b). In addition, the total torque impulse in the study on knee extensors was equal between the protocols (Oranchuk et al., 2021b), whereas in the study by Križaj et al. (2025a), an attempt to equalise the total torque impulse on the ankle plantar flexors was unsuccessful; specifically, a higher total torque impulse was achieved in the EQI group.

Meanwhile, medium-term effects, defined as effects assessed over a period of 4 - 12 weeks (Mitham et al., 2021), were examined in the only study to date (Henderson et al., 2025). Henderson et al. (2025) has examined the differences in the medium-term effects of EQI and isotonic exercise (on elbow flexors), where participants completed 23 training sessions within an eight-week program. The total load during the sessions of both protocols was equal (Henderson et al., 2025). The results showed that an eight-week traditional isotonic exercise program caused significantly greater increases in muscle thickness and estimated one-repetition maximum (1 RM) compared to the protocol based on EQI action (Henderson et al., 2025). But, in the case of the latter study (Henderson et al., 2025), the load that the subjects had to overcome and the duration or number of repetitions remained unchanged throughout the entire protocol; the results obtained must be interpreted with caution.

Based on the inconclusive results shown by Henderson et al. (2025) and previous research that suggests that ankle plantar flexor muscles are particularly sensitive to the type of contraction and the amount of tension (Wiesinger et al., 2015), additional studies on ankle plantar flexors are needed. Importantly, although previous studies have examined the acute effects of EQI exercise on the ankle plantar flexors, it remains unknown whether repeated EQI exercise induces chronic adaptations in the morphological and performance-related properties of the ankle plantar flexor muscle-tendon complex. Moreover, no previous study has directly compared the effects of a multi-week EQI exercise programme with traditional ECC exercise in this muscle group. Therefore, the present study aims to extend the existing literature by providing the first direct comparison of EQI- and ECC-induced adaptations in the ankle plantar flexor morphology and contraction-specific strength following a six-week exercise intervention. Given that EQI

exercise has previously been associated with lower short-term reductions in strength and muscle soreness than ECC and IHSR exercise, despite comparable or greater total torque impulse (Križaj et al., 2025a; Oranchuk et al., 2021b), the present study aims to determine whether these acute characteristics translate into distinct chronic morphological adaptations and improvements in the ankle plantar flexors' performance following a six-week EQI protocol compared to traditional ECC training. Regardless of the previous findings of ankle plantar flexor sensitivity, we hypothesised that there would be no statistically significant differences between the intervention groups in terms of changes in the morphological properties of the muscle-tendon complex of the ankle plantar flexors, while a statistically significant increase in concentric and ECC strength in the ECC group, and isometric strength in the EQI group was expected.

Methods

The trial was prospectively registered in the International Standard Randomised Controlled Trial Number (ISRCTN) registry (ISRCTN35199955). The study was conducted at the Faculty of Health Sciences, University of Primorska, Izola, Slovenia, between November 2025 and January 2026.

Participants

For the study, 48 healthy adults (26 male and 22 female) were recruited and equally divided into three groups. The sample size was calculated using the G*Power tool (version 3.1.9.7) for the interaction in a mixed analysis of variance, assuming an effect size $f = 0.25$, corresponding to a partial $\eta^2 = 0.06$, a standard error $\alpha = 0.05$, and statistical power 0.80 (Morrissey et al., 2011). The participants were recruited via social media and personal contacts and were eligible if they had no ankle or lower-limb injury in the past year, no lower back or neuropathy problems in the last six months, and no musculoskeletal injuries outside the lower limb within the previous three months, and with at least moderate experience of resistance exercise (participants who performed a systematic strengthening program of the lower limb at least twice a week in the last six months). According to the resistance-training classification proposed by McKay et al. (2022), all participants were classified as Tier 1 (Recreationally Active). Exclusion criteria were participants with: 1) chronic infectious diseases; 2) a diagnosis of neurological disorders (e.g., multiple sclerosis, etc.); 3) cardiovascular or respiratory diseases that limit physical activity; 4) individuals who use medications that affect physical performance; and 5) pregnancy. Before entering the study, all participants signed an informed consent form. All methods were carried out in accordance with the relevant guidelines and regulations, including the Declaration of Helsinki and the ethical standard approved by the Commission of the University of Primorska for Ethics in Human Subjects Research (approval number: 4264-19-6/23) and by the National Medical Ethics Committee of the Republic of Slovenia (approval number: 0120-489/2024-2711-5).

Study design

This study was a three-arm parallel-group randomised controlled trial with a 1:1:1 allocation ratio, using a pre-post repeated-measures design to evaluate the effects of a six-week exercise intervention. Within each sex stratum, a random allocation sequence was generated using the RAND function in Microsoft Excel (Microsoft Corp., Redmond, WA, USA) with a 1:1:1 allocation ratio into one of the three groups (EQI, ECC or control). To avoid data variability, differences in foot dominance between subjects (whether the dominant side is the take-off or the kicking side) and in order to obtain more comparable results, in all participants, only the right limb was assessed.

Measurement protocol

The measurement protocol consisted of separate morphological, ankle mobility and strength measurements. A detailed outline of all measurement procedures is available in Supplementary file 1 (<https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>). The whole protocol began with the ultrasound measurements executed using an ultrasound device (Resona 7, Mindray, China) and was carried out using the L11 - 3U ultrasound probe. During ultrasound measurements, all participants were lying in a prone position with their ankle over the edge of the therapeutic table (Supplementary file 1 - Figure S1A; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>).

The ultrasound protocol comprised three Achilles tendon thickness (Supplementary file 1- Figure S1B; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>) and stiffness measurements (Supplementary file 1 - Figure S1C; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>) (Mifsud et al., 2023), and two medial and lateral gastrocnemius thickness, fascicle length and pennation angle measurements based on a panoramic image (Supplementary file 1- Figure S2; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>).

Tendon properties were measured approximately five cm above the insertion of the Achilles tendon on the heel where we determined the thickness using a distance function and the stiffness using the shear wave quantitative mode with a fixed region of interest measuring 3 mm x 3 mm, positioned within the tendon tissue. All muscle measurements were performed using iScope View mode, which allowed us to capture panoramic images of both the medial and lateral gastrocnemius. From these images we manually determined the fascicle length, pennation angle and muscle thickness (two measurements for each parameter) using distance and angle functions. An example of a panoramic image is shown in Supplementary file 1- Figure S2 (<https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>).

All panoramic images of both the medial and lateral gastrocnemius muscles were taken along the same line, as shown in Figure 1A. To ensure greater accuracy, all muscle scans were performed jointly by two researchers, with one conducting the measurement using the aforementioned ultrasound probe. At the same time, the other monitored the scan on the screen, supervised the measurement process and image quality, and recorded the obtained values. Meanwhile, ankle mobility measurements consisted of ankle plantar and dorsal flexion RoM measurements in open

and closed kinetic chain (Jakovljević and Hlebš, 2023).

Before the strength measurements, which focused on measuring concentric, ECC and isometric maximal voluntary contraction and three EQI actions, each participant executed a standardised warm-up protocol. The protocol consisted of three minutes of light jogging (on a treadmill) and four minutes of stepping onto a 10-centimetre-high platform (alternating with each leg for 60 seconds, increasing the stepping velocity in the second series) followed by dynamic stretching exercises and ten repetitions of active strengthening exercises (jumping jacks, squats, push-ups, and heel raises with both feet without additional weight). After the participant finished with a warm-up, they moved to the isokinetic dynamometer (HumacNorm, Computer Sports Medicine Inc., Stoughton, MA, USA), where we initially adjusted the settings of the seat and footrest part of the dynamometer (i.e., the backrest, knee and lumbar support, plantar support, etc.) and straps, following our previous studies (Supplementary file 1 - Figure S3) (Križaj et al., 2025a; 2025b). The seat and footrest settings were carefully recorded so that the position could be replicated during the second measurement. The additional RoM assessment was carried out on the dynamometer, followed by the gravity effect correction in the neutral ankle position (i.e., 0°). The measurement protocol began with two warm-up sets of five isokinetic ankle plantar flexor repetitions (at ~50 % and ~70 - 80 % of maximal effort) with three-minute rest in between. Warm-up repetitions were followed by performing five consecutive maximal voluntary concentric and ECC contractions of the ankle plantar flexors at a movement velocity of 60 °/s. After a three-minute break, the dynamometer was configured to isometric mode, so the participants were able to perform three additional maximal voluntary isometric ankle plantar flexor contractions in the neutral ankle position. The break between each repetition lasted 30 s. Participants received continuous real-time visual feedback in the form of a time-torque curve, and verbal encouragement was given during every repetition. The thigh and both foot straps were loosened and removed, and then securely fastened again before the next contraction. After measuring isometric MVC, all participants performed three EQI actions, with a three-minute break in between. The EQI testing was performed in accordance with our previous studies (Križaj et al., 2025a; 2025b), with the load during the EQI actions set at 75% of the predetermined isometric MVC (Križaj et al., 2025b). The determined load was the same in all three repetitions. Each participant completed two identical measurements - the first (baseline) and second (post) measurement; with an interval of seven weeks between them.

Intervention protocol

After the baseline measurement, participants in the control group had to continue their normal physical activity, but without any direct exercise that would affect changes in the ankle plantar flexors (i.e., exercises for direct strengthening or stretching of the ankle plantar flexors; plyometric exercise, etc.) until the execution of the post-measurement. Meanwhile, the EQI and ECC group participants executed a six-week exercise protocol that consisted of 12 exercise sessions, which had to be performed twice a week, with at

least two days of rest between sessions. The exercise protocol began five days after the baseline measurement, while the post-measurement was then performed three days after the last exercise session. The exercise session began with the same warm-up (Supplementary file 3 - Figure S4; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>) as in the case of the baseline measurement. Then, in both protocols, heel raise repetitions had to be performed on a Smith machine. The repetitions began in a standing position on a higher platform (or stepper) with an Olympic barbell (and additional weights) placed across the trapezius muscle. The subjects had the distal third of their feet (including the footpads) in contact with the higher platform. In both protocols, participants executed bilateral heel raise to the highest position with their knees extended (Supplementary file 3 - Figure S5A; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>). In the EQI group, participants unilaterally attempted to hold the reached position isometrically (Supplementary file 3 - Figure S5B; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>), while the ankle gradually moved into increasingly greater dorsal flexion that the subjects resisted. The end of the contraction was determined when the ankle plantar flexors were unable to overcome the load or the ankle reached its final RoM (the participants touched the ground with their heel or began to overcome the load with the help of the other, passive leg) (Supplementary file 3 - Figure S5C; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>). Meanwhile, the participants in the ECC group executed controlled three-second unilateral heel drop in the direction of ankle dorsal flexion, which was followed by a repeat of the repetition until the end of the set. All exercise sessions were executed on the right leg only. Both interventions were matched in load and time under tension. A load equal to 1 RM was set for each participant. The performance value was measured for all individuals, regardless of group, in accordance with an adapted version presented in the NSCA's "Essentials of Strength and Conditioning, 4th Edition" (Haff and Triplett, 2016). All participants first performed one warm-up set of unilateral heel-raises on a Smith machine with a low load (10 repetitions), followed by a one-minute rest, and then performed a second set with a higher load (three-five repetitions). After a two-minute rest, the researcher determined the participant's approximate maximum load for two-three repetitions, followed by a four-minute rest and a trial 1 RM measurement. If the attempt was successful, the load was gradually increased, and the procedure was repeated until the participant could no longer perform another repetition.

The load corresponded to the individual's 1 RM and was re-assessed following the same procedure before sessions 1, 5, and 9; therefore, Load 1 was used in sessions 1 - 4, Load 2 in sessions 5 - 8, and Load 3 in sessions 9 - 12. Time under tension progressively increased from 90 s in sessions 1 - 2 to 135 s in sessions 3 - 6 and 180 s in sessions 7 - 12. In the EQI group, participants repeated EQI actions with two-minute breaks until the prescribed time under tension was achieved. In the ECC group, the corresponding volume was 2×15 repetitions in sessions 1 - 2, 3×15 repetitions in sessions 3 - 6, and 4×15 repetitions in sessions 7 - 12 (See Supplementary File 3 - Table S2 for details;

<https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>).

The suitability of implementing the intervention protocol on the Smith machine, and protocols' load and RoM were predetermined based on the previously conducted pilot study with 8 participants (4 men, 4 women) (See Supplementary file 2 for details; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>). The results of the pilot study (Supplementary file 2; <https://www.jssm.org/SM/Man9545-2026SupplMaterials.pdf>) showed that the dynamics of EQI actions on the Smith machine, without RoM restriction and at a load equal to 1 RM, are most comparable to those achieved on an isokinetic dynamometer.

All exercise sessions were supervised by the researchers, who corrected the execution of the movement task if needed, videorecorded the repetitions and measured the time under tension and resting time (especially in the EQI group). The repetitions were recorded using a high-resolution camera positioned to provide a clear view of the movement in the sagittal plane. Reflective markers were placed on the relevant anatomical landmarks (i.e., slightly distal to the medial malleolus, on the medial tibial condyle and on the head of the first metatarsal bone) by a researcher who was present during the exercise session. The EQI repetitions were analysed in the Kinovea tool. A semi-automatic analysis function was used to identify the marker positions and determine the starting and final ankle angles in the sagittal plane and the time under tension of a single contraction. Based on these values, the angular velocity at which the participant performed the contraction was calculated. Although the semi-automatic function was used for the analysis, each video recording was carefully reviewed by the researcher. Whenever any deviation or error in marker detection or tracking was identified, the marker position was manually corrected before the angular velocity was calculated, thus ensuring the accuracy of the analysed data. At the beginning of each exercise session, the participants had to report the level of delayed muscle soreness they felt in the triceps surae region, while after completing the exercise protocol, they had to report the effort score for that exercise session. Both variables were rated on a 10-point scale, where a higher value meant a higher level of pain or effort that the person felt.

Data processing

Ultrasound measurements were averaged across repetitions, using the mean values for tendon thickness and stiffness, and gastrocnemius muscle fascicle length, pennation angle and thickness. All signals obtained using an isokinetic dynamometer (time, ankle position, torque and angular velocity), were sampled at 100 Hz frequency and analysed without prior filtering (Oranchuk et al., 2021a). Meanwhile, only the greatest torque from the concentric, ECC and isometric voluntary contraction was considered as the dependent variable. The beginning and end of EQI actions were determined in accordance with previous studies (Križaj et al., 2025a; 2025b). Each EQI action was visually inspected to remove any artefacts that might affect the accurate identification of contraction onset or terminal. The analysis focused on the following four primary outcomes: 1) time under tension (s); 2) total RoM (°); 3) total angular impulse; (Nm·s); and (4) average angular velocity

(°/s). RoM was included to account for fatigue-related differences in contractions between repetitions. Processing of strength, EQI and RoM data was performed using MATLAB software (version R2024a; The MathWorks Inc., Natick, MA, USA).

Statistical analysis

The per-protocol population comprised participants who completed post-intervention testing and, in the intervention groups, attended ≥ 10 of 12 supervised sessions ($\geq 83\%$). The per-protocol approach was prioritized to assess physiological adaptations following sufficient exposure to the prescribed exercise intervention. As a sensitivity analysis, all randomized participants were included in linear mixed-effects models with group, time, and group $\times$ time as fixed effects and participant as a random effect, using all available observations without imputation of missing data. No interim analyses were performed, no stopping guidelines were pre-specified, and no changes to the pre-specified outcomes were made after trial commencement. We presented the data as means $\pm$ standard deviation. We checked the normality of the data distribution using the Shapiro-Wilk test and visual inspection of histograms and Q - Q plots. The threshold for statistical significance was set at $p < 0.05$. We checked the baseline differences between groups with a unifactorial analysis of variance (ANOVA). Mixed-model ANOVA was used to check the differences according to group (EQI, ECC and control group; between-subjects factor), time (baseline and post-measurements; within-subjects factor), and the interaction between group and time. We calculated the effect size as partial η^2 , which was interpreted as trivial (< 0.01), small ($0.01 - 0.06$), medium ($0.06 - 0.14$), or large (> 0.14) (Richardson, 2011).

Following significant group $\times$ time interactions, within-group changes were examined using one-way repeated-measures ANOVAs, with time as the within-subject factor and Bonferroni correction applied to multiple comparisons. In addition, when the primary 3×2 ANOVA revealed a significant group $\times$ time interaction, a separate 2×2 mixed ANOVA including only the EQI and ECC groups was conducted to determine whether the interaction also reflected differences in changes between the two intervention protocols. A general linear model with group as a between-subject factor and repetition as a within-subject factor was used to assess repetition-by-repetition differences in time under tension, ankle dorsiflexion, total torque impulse and angular velocity. All analyses were performed using SPSS statistical software (version 25.0, IBM, Armonk, NY, USA).

Results

Of the 48 randomised participants, 46 completed the study and were included in the per-protocol analysis (EQI, $n = 15$; ECC, $n = 15$; control, $n = 16$). Two participants withdrew during the intervention period; one of them dropped out of the study early due to a lack of time, while the other did so because of an injury unrelated to the ankle or to exercising on the Smith machine. No intervention-related adverse events were reported. Baseline demographic and outcome measures did not differ between groups (all $p \geq 0.166$). Participant flow is shown in Figure 1. Baseline characteristics are shown in Table 1. The sensitivity analysis including all 48 randomized participants yielded conclusions consistent with the primary per-protocol analysis, with no changes in the statistical significance of group $\times$ time interactions and is not further reported.

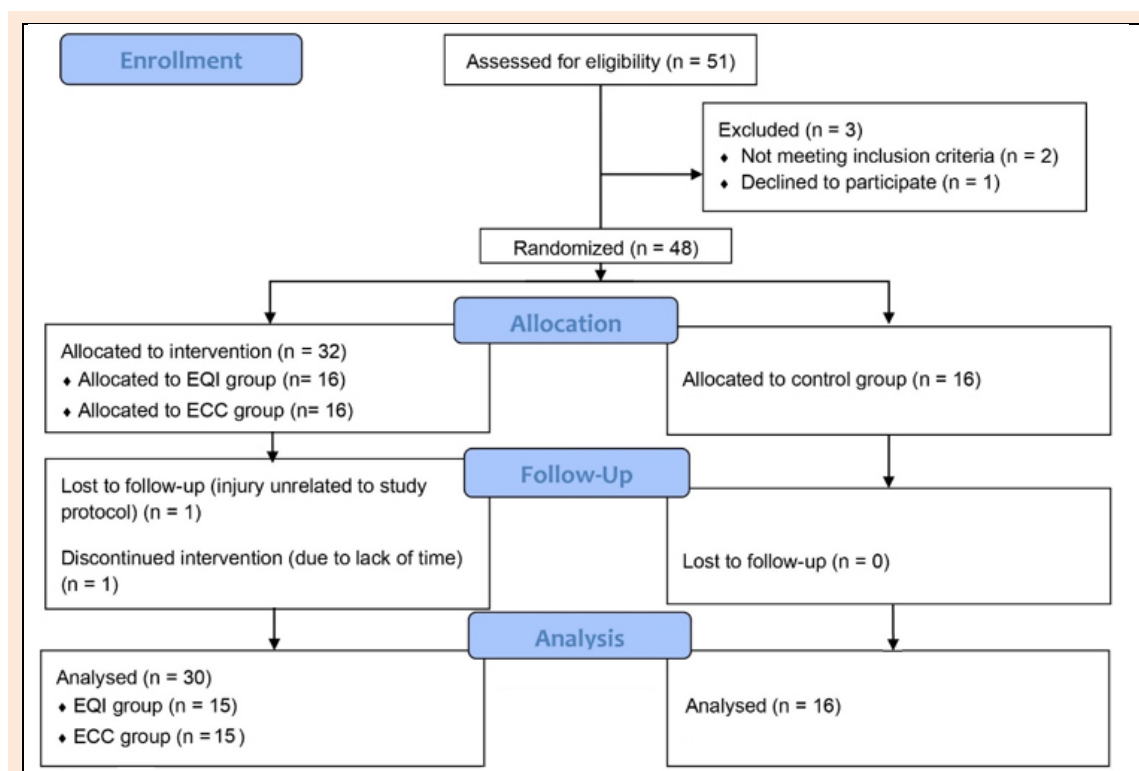


Figure 1. CONSORT flow diagram illustrating the enrollment, allocation, follow-up, and analysis of participants across the three study groups (EQI, ECC, and control).

Table 1: Comparison of baseline variables between the EQI, ECC and control group.

Outcome Variables	EQI Group (n = 15)		ECC Group (n = 15)		Control Group (n = 16)		Difference	
	Mean	SD	Mean	SD	Mean	SD	F-Value	p
ATT (mm)	4.782	0.526	4.880	0.496	4.760	0.648	0.196	0.823
ATS (kPa)	127.044	22.853	117.551	15.364	115.640	12.831	1.870	0.166
MGFL (cm)	5.118	0.911	4.983	0.703	5.210	0.606	0.359	0.701
MGPA (°)	20.9	2.063	20.033	2.310	19.438	2.489	1.578	0.218
MGT (cm)	1.959	0.337	1.843	0.340	1.876	0.262	0.546	0.583
LGFL (cm)	5.339	0.560	4.993	0.737	5.499	0.883	1.870	0.166
LGPA (°)	14.000	3.793	14.100	2.123	13.188	1.948	0.524	0.596
LGT (cm)	1.407	0.446	1.178	0.243	1.279	0.249	1.871	0.166
ODF (°)	10.600	3.019	12.670	4.776	12.560	4.993	1.075	0.350
CDF (°)	18.930	5.824	20.130	4.172	21.560	7.865	0.702	0.501
CS (Nm)	228.387	51.503	237.434	58.882	228.592	62.260	0.121	0.886
ES (Nm)	221.372	50.077	232.705	62.823	222.979	64.004	0.161	0.852
IS(Nm)	194.256	49.299	195.824	47.654	194.186	51.156	0.005	0.995
Time under tension (s)	122.639	46.702	113.127	34.743	109.398	44.934	0.396	0.676
Total torque impulse (Nm s/MVIC)	93.173	37.141	86.249	26.307	82.720	34.560	0.399	0.674
Angular velocity (°/s)	-1.181	0.711	-1.075	0.243	-1.166	0.459	0.194	0.825

ATS – Achilles tendon stiffness; ATT – Achilles tendon thickness; CDF – closed kinetic chain ankle dorsiflexion; CS – concentric strength; ECC – eccentric; EQI – eccentric quasi-isometric; ES – eccentric strength; IS – isometric strength; LGFL – lateral gastrocnemius fascicle length; LGPA – lateral gastrocnemius pennation angle; LGT – lateral gastrocnemius thickness; MGFL – medial gastrocnemius fascicle length; MGPA – medial gastrocnemius pennation angle; MGT – medial gastrocnemius thickness; ODF – open kinetic chain ankle dorsiflexion; SD – standard deviation

Intervention characteristics

The EQI group required approximately two repetitions to achieve 90 s of total time under tension, two to three repetitions to achieve 135 s, and three to four repetitions to achieve 180 s. Mean angular velocity during Smith-machine EQI exercise ranged from -0.448 to $-0.608^{\circ}\cdot\text{s}^{-1}$.

Muscle and tendon adaptations

Significant group $\times$ time interactions were observed for Achilles tendon thickness and most gastrocnemius architecture outcomes ($p \leq 0.001$; partial $\eta^2 = 0.30 - 0.56$). Achilles tendon thickness, medial and lateral gastrocnemius fascicle length, muscle thickness, and lateral gastrocnemius pennation angle increased in both intervention groups (all $p < 0.001$; partial $\eta^2 = 0.53 - 0.79$). Changes did not differ between EQI and ECC training ($p = 0.227 - 0.965$) (Figure 2).

Achilles tendon stiffness and medial gastrocnemius pennation angle did not show significant group $\times$ time interactions ($p = 0.157 - 0.767$). Although a small increase in lateral gastrocnemius fascicle length was also observed in the control group ($p = 0.048$; partial $\eta^2 = 0.24$), the corresponding effects were larger in the EQI and ECC groups (both $p < 0.001$; partial $\eta^2 = 0.71 - 0.76$) (Figure 2).

Range of motion and strength

Open-chain ankle dorsiflexion increased in the EQI and ECC groups ($p = 0.014 - 0.019$; partial $\eta^2 = 0.33 - 0.36$), but the group $\times$ time interaction was not significant ($p = 0.148$). Closed-chain dorsiflexion showed a significant group $\times$ time interaction ($p = 0.029$; partial $\eta^2 = 0.15$) and increased in all groups ($p = 0.003 - 0.045$; partial $\eta^2 = 0.24 - 0.61$). Changes in either dorsiflexion outcome did not differ between EQI and ECC training ($p = 0.648 - 0.885$) (Figure 3).

Significant group $\times$ time interactions were observed for concentric, eccentric, and isometric plantar-flexor strength (all $p < 0.001$; partial $\eta^2 = 0.30 - 0.43$). All three

strength outcomes increased in both intervention groups ($p \leq 0.001$; partial $\eta^2 = 0.58 - 0.77$), whereas no significant changes were observed in the control group ($p = 0.193 - 0.954$). Improvements did not differ between EQI and ECC training ($p = 0.561 - 0.976$) (Figure 3).

Eccentric quasi-isometric performance

There were significant main effects of time for EQI time under tension and total torque impulse ($p = 0.002 - 0.003$; partial $\eta^2 = 0.19 - 0.21$), but no significant group $\times$ time interactions ($p = 0.170 - 0.229$). Within-group analyses showed increases after ECC training ($p = 0.012 - 0.020$; partial $\eta^2 = 0.33 - 0.37$), but not after EQI training or in the control group ($p = 0.084 - 0.382$). Changes did not differ between the EQI and ECC groups ($p = 0.958 - 0.961$). EQI angular velocity remained unchanged, with no significant time, group, or interaction effects ($p = 0.246 - 0.805$) (Figure 3).

Pain and perceived effort

Pain scores were significantly lower after executing EQI than ECC training (1.29 vs 1.69 points; $p = 0.004$; partial η^2 for the group effect = 0.15), although pain remained low in both groups. Perceived effort was moderate to high and did not differ between interventions (6.11 - 6.68 points; $p = 0.229$). A small effect of time was observed for perceived effort ($p = 0.012$; partial $\eta^2 = 0.09$), without a significant group $\times$ time interaction ($p = 0.737$) (Figure 4).

Discussion

The results showed that both interventions induced increases in Achilles tendon thickness, gastrocnemius fascicle length (medial and lateral head), gastrocnemius thickness (medial and lateral head), lateral gastrocnemius pennation angle, dorsiflexion RoM, and plantarflexion strength compared to the control group, while the statistically significant differences between protocols were not

detected. Meanwhile, the improvements in EQI time under tension and total torque impulse were observed only following ECC training according to within-group analysis; however, between-group differences were not statistically significant.

Previous studies (Lazarczuk et al., 2022; Radovanović et al., 2022) found that tendon adaptations are independent of the type of muscle contraction as long as the minimum threshold of mechanical load is exceeded. To achieve sufficient adaptations, the training load on the Achilles tendon must exceed approximately 75 % of 1 RM, which corresponds to 4.0 - 4.5% Achilles tendon strain (McCrum et al., 2018). Since the load and time under tension in our study were equal in EQI and ECC groups (i.e., 100% 1 RM, and 90, 135 or 180 seconds, respectively) and large enough to exceed the aforementioned strain value,

our findings are consistent with this body of evidence. Increased tendon thickness results may reflect a morphological adaptation that could be associated with greater tendon capacity to withstand mechanical loading (Milgrom et al., 2014). However, whether this adaptation translates into improved mechanical properties, greater tolerance of high forces at higher velocities, or reduced injury risk remains uncertain and cannot be directly inferred from tendon thickness (Milgrom et al., 2014). Nevertheless, both EQI and ECC protocols increased tendon thickness compared to baseline, while there were no statistically significant differences between these protocols. Different conclusions were reached in a previous study (Sanz-López et al., 2016), which reported that a six-week ECC overload training did not result in a statistically significant increase in Achilles tendon thickness.

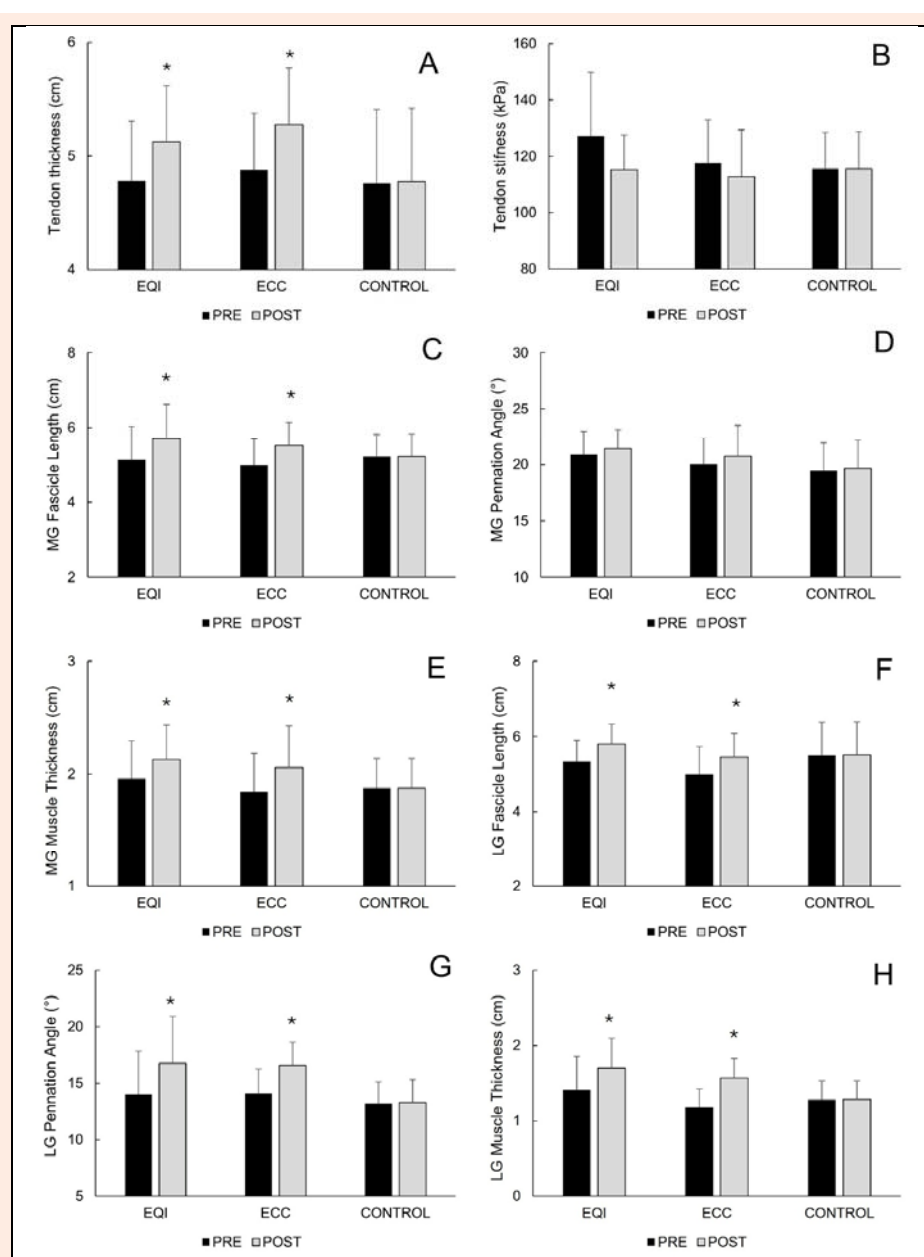


Figure 2. Differences in PRE-POST morphological values between groups: Achilles tendon thickness (A); Achilles tendon stiffness (B); medial gastrocnemius fascicle length (C); medial gastrocnemius pennation angle (D); medial gastrocnemius thickness (E); lateral gastrocnemius fascicle length (F); lateral gastrocnemius pennation angle (G); and lateral gastrocnemius thickness (H).

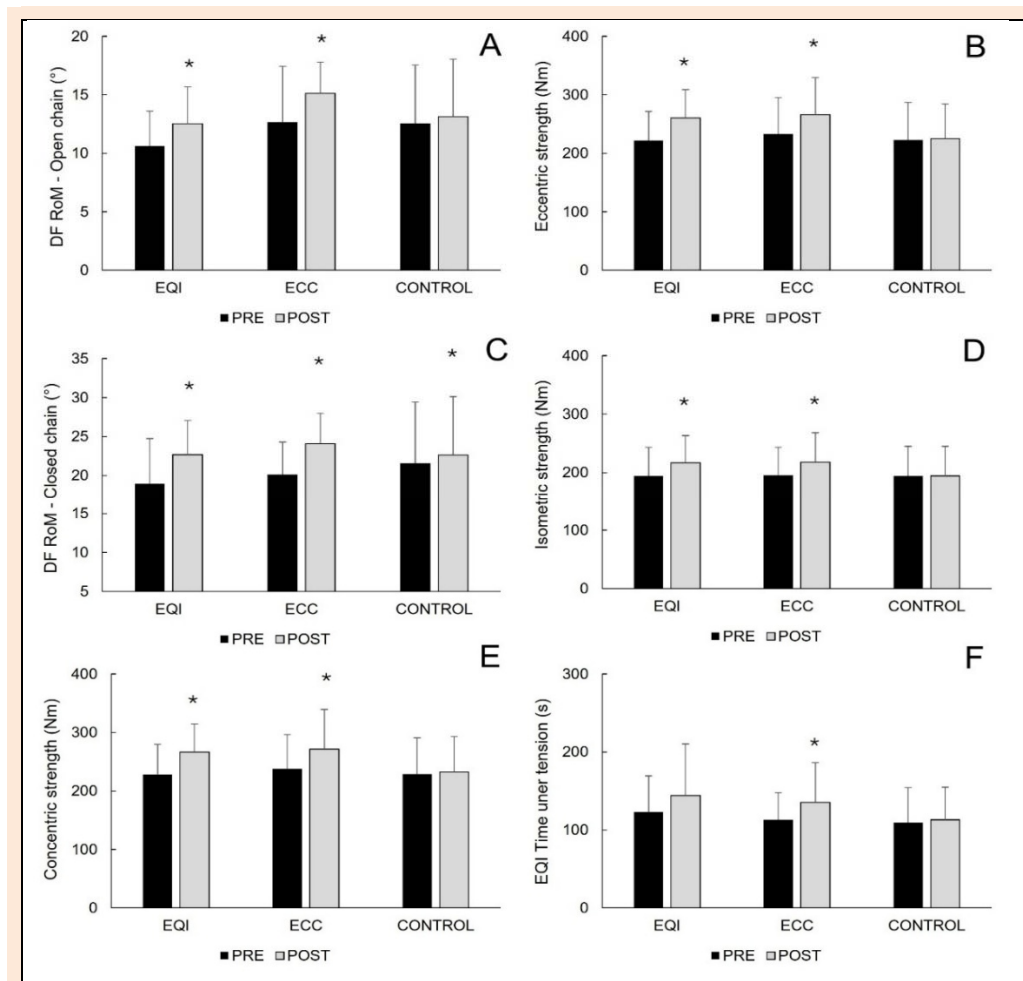


Figure 3. Differences in PRE-POST performance values between groups: open kinetic chain ankle dorsiflexion (A); closed kinetic chain ankle dorsiflexion (B); maximal voluntary concentric contraction (C); maximal voluntary eccentric contraction (D); maximal voluntary isometric contraction (E); EQI combined time under tension (F).

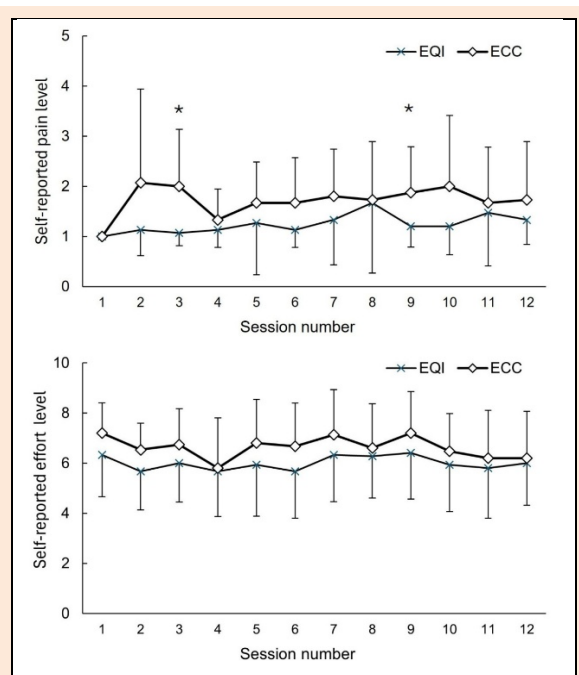


Figure 4. Changes in pain level caused by exercise sessions (top chart); changes in effort level during exercise sessions (bottom chart). * statistically significant between group difference for a given session ($p < 0.05$).

There could be several reasons for conflicting findings in this case. In the previous study, thickness was measured at two points - one and three cm above the tendon insertion on the heel (Sanz-López et al., 2016), while in our case, it was measured five cm above the insertion. In addition, instead of direct exercises to strengthen the ankle plantar flexors, the previous study used an exercise where the muscle is only synergistically active (i.e., squat), and the exercise was performed on a flywheel device, which uses inertial resistance and, from a load perspective, is not the most precise exercise (Sanz-López et al., 2016). While in our case, the exercise directly targeted the plantar flexors on a Smith machine with a predetermined load, which we adjusted three times during a six-week protocol. Our study also showed that neither EQI nor ECC protocol caused either improvement or reduction of Achilles tendon stiffness. Similar conclusions in the case of the Achilles tendon were reached by Kubo and Ikebukuro (2012), who found that stiffness did not change in the first eight weeks of the training protocol after isometric exercise, despite a 19 % increase in muscle strength, while stiffness increased significantly after 12 weeks of the exercise protocol. Slightly different findings were reported in another study (Geremia et al., 2018), which reported a statistically significant increase in Achilles tendon stiffness after four, eight and 12

weeks of ECC protocol. In that study (Geremia et al., 2018), the subjects did not participate in any systematic program for strengthening and/or resistance of the lower limbs in the 6 months prior to the start of the study, while in our case, all participants had to be included in a systematic strengthening program of the lower limb at least twice a week in the last six months. Based on these findings, we assume that an increase in tendon stiffness can occur within 6 - 8 weeks of performing the exercise protocol, but the changes are small and may be affected by previous physical activity status (Wiesinger et al., 2015).

An increase in the fascicle length and pennation angle of the gastrocnemius is directly related to an increase in strength (Narici et al., 2005; 2016) and the ability to shorten the muscle at higher speeds (Narici et al., 2005). An increase in muscle thickness indicates hypertrophy, which is an expected consequence of exposure to high mechanical tension during ECC loads (Oranchuk et al., 2019). The results of our study showed that the execution of either EQI or ECC exercise similarly increased fascicle length and thickness of both gastrocnemius muscles, and lateral gastrocnemius pennation angle, while none of the protocols caused a statistically significant increase in medial gastrocnemius pennation angle. The results obtained are consistent with those of a previous study (Alonso-Fernandez et al., 2020), which investigated how ECC heel drop exercise affects the architecture of both heads of the gastrocnemius in physically active young adults. They found that performing an eight-week protocol statistically significantly increased the fascicle length of both the lateral ($d = 2.78$) and medial gastrocnemius ($d = 2.54$), as well as the thickness of the medial ($d = 2.22$) and lateral gastrocnemius ($d = 2.86$) (Alonso-Fernandez et al., 2020). Meanwhile, Alonso-Fernandez et al. (2020) reported increases in pennation angle in both gastrocnemius heads, with a considerably larger effect size for the lateral gastrocnemius ($d = 1.88$) than for the medial gastrocnemius ($d = 0.53$). Similarly, Kudo et al. (2020) found that performing a long-term ECC calf raises exercise significantly increased the fascicle length and thickness of the medial gastrocnemius, but not the pennation angle. In that case, the first effects of exercise protocol on fascicle length and muscle thickness were noticeable after just six weeks, while an increase in pennation angle was not noticeable even after 12 weeks (Kudo et al., 2020). Interestingly, the medial gastrocnemius is characterised by being slightly more active than the lateral gastrocnemius during walking, but the latter has greater potential in terms of lengthening (Hamard et al., 2021). This can be linked to the findings of Lai et al., (2019), who found that during walking (and most likely also during exercise), the muscle fibres of the medial gastrocnemius alternately perform negative and positive work (acting as a spring due to elastic energy), while the muscle fibres of the lateral head of the gastrocnemius behave closer to isometric mode. Since the muscle-tendon complex of the ankle plantar flexors does not act as an elastic spring during controlled EQI and ECC exercise, but rather as a more "rigid" and stabilizing structure, these architectural differences between gastrocnemius heads may partly contribute to the observed adaptation pattern. However, as muscle behaviour during the present exercise protocols was not directly

assessed, this interpretation remains speculative and should be confirmed in the future studies.

Meanwhile, Henderson et al. (2025) came to slightly different conclusions about the effects of EQI exercise on elbow flexors. They found that isotonic training had a greater effect on increasing the thickness of the biceps brachii muscle than EQI training (Henderson et al., 2025). Although the load was the same in both cases (70% of the previously measured estimated 1 RM) and remained unchanged throughout the protocol, the time the muscle-tendon complex was under tension was uneven between the protocols, since this depended on the participant's abilities (Henderson et al., 2025). The number of isotonic repetitions depended on the subject's abilities and fitness (how many they could perform at a given load), while the duration of EQI actions depended on the participant's endurance (Henderson et al., 2025). Based on these data, we can most likely conclude that the differences between the protocols were mainly due to different training volumes and not solely to the type of muscle contraction.

The increase in ankle dorsiflexion RoM as a result of EQI or ECC training is consistent with the findings of previous study (Rout et al., 2024). Such adaptations are most likely due to the final RoM achieved by each participant during the exercise protocols, since it is well known that resistance training at long muscle lengths can increase the joint RoM (Kay et al., 2023). In the case of the ECC protocol, participants achieved the final RoM dynamically and multiple times within the exercise session (30 - 60 times per session), while in the case of the EQI protocol, they achieved the final RoM fewer times (1 - 6 times per session), but the time of maintaining of the greater stretches (close to the final range of dorsiflexion) was longer than in the case of the ECC protocol.

The results of the study showed that both protocols, EQI and ECC, increased concentric, ECC and isometric strength of the ankle plantar flexors, without any detected differences between protocols. Although EQI exercise is performed at a lower angular velocity than ECC-only contraction, both protocols are based on ECC contraction. Previous evidence suggests that strength increase after ECC exercise is velocity-independent when overall time under tension and load magnitude are matched between the protocols (Marzilger et al., 2019; Santos et al., 2025), which is consistent with the comparable strength adaptations in both groups observed in the present study. Meanwhile, many studies reported that ECC exercise has a significant effect on increasing all three types of strength - concentric (Malliaras et al., 2013), ECC and isometric (Farup et al., 2014; Franchi et al., 2014). Such results in the case of ECC contraction are most likely due to lower muscle activation and energy demands to achieve similar torque production compared to other types of contractions (Lastayo et al., 2025), while its maximal force is about 40% greater than the maximal concentric force (Nuzzo et al., 2023). However, the results obtained were not consistent with the findings of Henderson et al., (2025), who reported that isotonic exercise significantly increased elbow flexion strength compared to EQI exercise, similarly to the muscle thickness parameter. It is, as mentioned, most likely due to the different elbow flexors exercise time under tension and unchanged

load during the protocols.

Regardless of the fact that the results showed a statistically significant increase in the time under tension and total torque impulse of EQI action only in the ECC group, but not in the EQI group, the between-group analysis showed that there were no statistically significant differences between the protocols. These results were most likely due to (statistically insignificant) differences in the baseline, where, on average, the participants in the EQI group achieved both higher times under tension and higher total torque impulse values. In addition, minor positive changes in the ECC group or insignificant changes in the aforementioned parameters in the case of the EQI group, with a simultaneous increase in isometric strength (which we used to calculate the load that the subjects overcame), are already associated with progress in itself, as the participant overcame the higher load in the same (or longer) time. It should be noted that there were most likely no noticeable changes in the total torque impulse, as the value was not determined solely by trapezoidal integration of the area under the torque curve and time, but as the calculated trapezoidal integration divided by the isometric strength, which was higher in the post-measurement case than in the baseline measurement case. Similarly, we can also understand why there was no reduction in the angular velocity of EQI action in any of the groups.

The study showed that the protocols differ statistically significantly in terms of the level of pain caused by EQI or ECC contractions. These results are most likely due to the higher number of repetitions and higher movement velocities to which the ECC group participants were exposed (Chapman et al., 2006). At the same time, there were no differences between the protocols in the level of effort required to perform either the EQI or ECC protocol. The effort was most likely comparable between the groups since in both cases the contraction occurs throughout the entire range of ankle motion (Lindstedt et al., 2018), while the time under tension (i.e., 90, 135, or 180 s) and load (i.e., 1 RM) were equal between the exercise sessions (Oranchuk et al., 2021b).

Based on the present findings, several directions for future research can be identified. First, extending the duration of the intervention would help determine whether EQI and ECC differ in their long-term effects. Second, incorporating multiple intermediate and follow-up assessment time points would allow a more detailed characterisation of the time course and retention of adaptations. Third, future studies should include additional functional performance outcomes, such as squat jump and countermovement jump performance. Finally, the applicability of EQI training should be examined in pathological populations, particularly individuals with Achilles tendinopathy.

Limitations

Several limitations of this study should be acknowledged. First, laboratory-based outcomes were assessed only at baseline and post-intervention, limiting insight into the temporal progression of adaptations. Second, the findings cannot be readily generalised to the broader population, as the sample consisted exclusively of young, healthy, and physically active individuals. Third, the results cannot be

extrapolated to populations with Achilles tendon pathologies. Fourth, due to the nature of the exercise interventions, participant and therapist blinding was not possible, which may have introduced performance bias despite standardised supervision and testing procedures. In addition, because analyses were conducted per-protocol and excluded participants who withdrew, the estimated effects may be sensitive to attrition-related bias. Finally, pain and effort outcomes were derived from subjective self-reports and may have been influenced by individual pain tolerance and prior training experience.

Conclusion

This study provides evidence that EQI and traditional ECC training can induce positive adaptations in the triceps surae muscle-tendon unit when load and time under tension are matched, while statistically significant differences were not detected. These findings are relevant for sports medicine and rehabilitation because EQI exercise may offer a controlled high-load stimulus with lower perceived muscle soreness than ECC exercise, while producing similar improvements in plantar flexor strength, ankle dorsiflexion, and muscle-tendon morphology. The results therefore support EQI exercise as a potentially useful alternative to conventional ECC loading in contexts where high mechanical tension is desired but excessive soreness or repeated faster eccentric actions may be undesirable. Future studies should determine whether these findings extend to athletes, older adults, and patients with Achilles tendon disorders, and whether longer interventions reveal protocol-specific differences in tendon stiffness, functional performance, or symptom responses.

Acknowledgements

Datasets generated during the current study are not publicly available but are available from the corresponding author upon reasonable request. The authors declare that they have no conflict of interest. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was carried out. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript. The authors declare that financial support was received by the Slovenian Research and Innovation Agency (ARIS) through the post-doctoral project EQI-TRAIN: Establishing scientific foundations for eccentric quasiisometric resistance training (Z5-50181 (B)) and research program KINSPO - Kinesiology for the effectiveness and prevention of musculoskeletal injuries in sports (P5-0443).

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Key points

- Six weeks of EQI and ECC training induced improvements in gastrocnemius muscle architecture, Achilles tendon thickness, plantar flexor strength, and ankle dorsiflexion.
- No statistically significant differences in morphological or functional adaptations were detected between EQI and ECC training when load and time under tension were matched.
- Neither training protocol significantly altered Achilles tendon stiffness or medial gastrocnemius pennation angle.
- EQI training was associated with lower muscle soreness than ECC training, despite comparable perceived effort.
- EQI exercise may represent a viable alternative to conventional ECC training for improving plantar flexor muscle-tendon properties while limiting exercise-induced soreness.

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