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Eccentric Quasi-Isometric Exercise Produces Greater Impulse with Less Pain than Isokinetic Heavy–Slow Resistance Exercise in Ankle Plantar Flexors: Quasi-Randomized Controlled Trial

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Abstract

Recently, there has been growing interest in optimizing exercise protocols in sports training and rehabilitation, with particular attention to eccentric quasi-isometric (EQI) contractions, which involve maintaining joint position until isometric failure and then resisting the subsequent eccentric phase. Evidence directly comparing EQI with other contraction modes remains scarce. This quasi-randomized controlled trial examined the short-term effects of EQI versus isokinetic heavy–slow resistance (IHSR) exercises on ankle plantar flexors, focusing on pain, range of motion (RoM), and strength performance. Thirty-two physically active participants were allocated to EQI (n = 16) or IHSR (n = 16) groups and assessed at baseline, immediately post-exercise, and 24 and 48 h later. Both groups performed three exercise sets with 3 min breaks. The protocols were designed to approximate matched loading, based on preliminary testing. Nevertheless, the EQI group achieved a significantly greater total impulse (p = 0.028), a shorter time under tension (p = 0.001), and lower effort scores (p < 0.001). Group × time analysis revealed less decline in maximal voluntary isometric contraction torque (p = 0.002; η^2 = 0.16), as well as lower general (p < 0.001; η^2 = 0.32) and activity-related pain (p < 0.001; η^2 = 0.32) in the EQI group, with no significant differences in dorsiflexion RoM (p = 0.893). In conclusion, EQI produced a higher torque impulse while inducing less fatigue and post-exercise pain than IHSR, suggesting it may be a more efficient loading strategy for the ankle plantar flexors. The results contribute to the understanding of contraction-specific efficiency, and may inform the design of future training and rehabilitation protocols targeting the ankle plantar flexors.

Keywords: eccentric quasi-isometric contraction; isokinetic heavy–slow resistance contraction; ankle plantar flexors; impulse; pain; range of motion

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Academic Editor: Arkady Voloshin

Received: 1 October 2025
Revised: 16 October 2025
Accepted: 17 October 2025
Published: 18 October 2025

Citation: Križaj, L.; Kozinc, Ž.; Šarabon, N. Eccentric Quasi-Isometric Exercise Produces Greater Impulse with Less Pain than Isokinetic Heavy–Slow Resistance Exercise in Ankle Plantar Flexors: Quasi-Randomized Controlled Trial. *Appl. Sci.* **2025**, *15*, 11177. https://doi.org/10.3390/app152011177

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1. Introduction

Over the last decade, there has been a growing interest in optimizing exercise protocols in the scientific literature, with research focusing on exercise intensity [1–3], volume [4,5], and the type of muscle contraction [2,6–9]. The latter is broadly categorized as either isometric, concentric, or eccentric contraction. Additionally, when both concentric and eccentric contractions are combined, the terms isotonic (constant load) or isokinetic (constant velocity) contraction are used [10]. Isometric contraction is defined as generating a force without changing the length of the muscle–tendon complex [11]. Eccentric contraction refers to the generation of force during the lengthening of the muscle–tendon complex,

where the force produced by the muscle is less than the external load [12]. Isotonic contraction defines the combination of concentric contraction, where force is generated by shortening the muscle–tendon complex, and eccentric contraction, while the external load is constant [10,13]. Meanwhile, an isokinetic contraction is defined as a transition between concentric and eccentric tension, where the angular velocity is constant throughout the range of motion (RoM) of the joint [10].

To further optimize existing exercise protocols, especially to achieve a higher total impulse with a concomitant lower pain and fatigue level, the concept of eccentric quasi-isometric (EQI) contraction has been increasingly emerging in the scientific literature of the last few years [7,9]. EQI contraction involves sustaining a fixed joint position until the point of isometric failure, after which the individual maximally resists the ensuing eccentric movement and attempts to regain the isometric hold [2]. In other words, EQI is a combined type of contraction in which active muscles transition between a slow eccentric phase and an isometric contraction, continuing until the end of RoM [2]. EQI contraction allows the application of high loads, either submaximal or maximal, without the risk of sudden increases in mechanical stress on tendons and joints [14,15].

Only a limited number of studies have investigated the effects of EQI contractions. These studies have focused on the biomechanical characteristics of EQI contractions in knee extensors [7–9], knee flexors [9], and elbow flexors [6]. However, only one of them [7] investigated the short-term responses of the muscle after performing an EQI contraction with another form of contraction (eccentric contraction). In that study, the total angular impulse (integral of knee extension torque over time) between the two limbs was matched [7]. They found that a comparable total angular impulse in the knee extensor example was achieved with 1 EQI contraction or approximately 25 eccentric contractions [7]. However, the participants achieved, on average, a higher torque with the eccentric contraction (i.e., average peak torque in the case of eccentric contraction was 215 $\pm$ 54 Nm, while mean peak torque in the case of EQI contraction was 179 $\pm$ 28.5 Nm) [7]. Furthermore, while the eccentric protocol resulted in a greater pain increase in the distal and medial regions of the vastus lateralis and distal rectus femoris muscles, the EQI protocol resulted in a greater swelling of the distal and medial regions of the vastus intermedius muscle [7]. In addition, the execution of the EQI protocol caused a smaller decrease in maximal voluntary isometric contraction (MVIC) than the eccentric protocol. Beyond the limited number of studies directly examining EQI, several investigations have compared distinct contraction modes in other muscle groups. For example, Royer et al. [16] compared the isometric, concentric, and eccentric contractions of the knee extensors matched for the torque–time integral, demonstrating contraction-specific fatigue and neuromuscular responses. Similarly, Chapman et al. [17] observed greater muscle damage and soreness after fast-velocity eccentric contractions compared to slower ones. For the ankle plantar flexors, Ferri et al. [18] and Wiesinger et al. [19] examined strength and tendon adaptations following different loading regimes, highlighting the sensitivity of these muscles to contraction type and strain magnitude. These findings emphasize that contraction mode, load intensity, and velocity critically influence both the mechanical output and subsequent adaptations. These factors guided the present comparison between EQI and IHSR protocols.

Based on the previous research and the current lack of studies comparing the effects of the EQI protocol with other contraction types on ankle plantar flexors, our study aims to expand the understanding of the short-term effects of EQI contractions, particularly in terms of pain, performance, and RoM in the healthy, regularly exercising, active adults' population. In the case of our study, we compared the EQI protocol with the isokinetic heavy–slow resistance (IHSR) protocol, since the heavy–slow resistance protocol is currently considered an equivalent or even better exercise or exercise therapeutic protocol than an

isolated eccentric exercise, for both healthy and pathological plantar flexors of the ankle and Achilles tendon. The IHSR protocol was selected as the comparison condition because heavy–slow resistance training has been shown to produce similar or sometimes even superior clinical and structural improvements compared with traditional eccentric exercise in patients with mid-portion Achilles tendinopathy [5,20,21]. IHSR allows for greater control of movement velocity and consistent loading throughout the entire range of motion, making it a suitable and widely accepted benchmark for high-load tendon rehabilitation. We hypothesized that the EQI contractions of plantar ankle flexors would result in a greater total impulse (integral of the ankle plantarflexion torque over the time of the contraction; Nm·s) while causing less fatigue and post-exercise pain compared to the IHSR protocol. Additionally, it was expected that the EQI protocol would lead to a smaller decline in the MVIC torque.

2. Materials and Methods

2.1. Participants

For the study, 32 healthy adults (16 men and 16 women) were recruited. The sample size was calculated using G*Power (version 3.1.9.7) (for the interaction in a mixed analysis of variance, with effect size f = 0.25 (calculated from partial η^2 = 0.06), standard error α = 0.05, and statistical power 0.80). Recruitment was carried out via announcements on social media and personal contacts. Participants were eligible if they had had no musculoskeletal injuries within the previous three months, no history of ankle injury or lower-limb surgery in the past year, and had engaged in regular resistance training (at least two sessions per week on average during the preceding six months). Exclusion criteria included patients with chronic noncommunicable diseases (e.g., cardiovascular, neurological, musculoskeletal, tumours, etc.), pregnancy, and people with prior experience with EQI-based training. Before participation in 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 standards approved by the Commission of the University of Primorska for Ethics in Human Subjects Research (approval number: 4264-19-6/23).

2.2. Study Design and Procedures

The study was a quasi-randomized controlled trial. Participants were stratified by gender to ensure equal representation in both groups. Within each gender, participants were randomly allocated to either the experimental or comparison group, until the required number of eight men and eight women per group was reached. To ensure allocation concealment, group assignments were stored in sequentially numbered, opaque, sealed envelopes, which were prepared by an investigator. The personnel who enrolled participants and assigned them to interventions had access to the random allocation sequence, and allocation was not concealed or blinded. In order to reduce variability in the data, avoid subjective individual differences in dominance (whether the dominant side is the kicking or takeoff side), and to improve comparability of results, in all participants, only the right limb was assessed. To compare the short-term effects of EQI or isokinetic contractions on pain, RoM and strength performance, a parallel group and a repeated measures approach was used, with each participant attending the laboratory on three consecutive days, at the same time of day ($\pm$30 min). The first visit involved baseline measurements, the exercise protocol (either EQI or IHSR), and another set of measurements immediately following the exercise protocol (post). On the second and third visits, the participants were tested again (post24 and post48, respectively) with the same procedures once again, but there was no exercise protocol. The intervention comprised three sets of 30 IHSR (total = 90) contractions

(at a velocity of 30°/s) or three EQI contractions with 3 min breaks between series. The two protocols were designed to achieve approximate load matching. In the pilot phase (n = 5), the within-subject comparisons were used to determine the number of repetitions producing comparable torque–time integrals between EQI and isokinetic heavy–slow resistance (IHSR) contractions performed at 30°/s. Each pilot participant completed one EQI contraction and a series of IHSR contractions (random order, with a 10 min break in between) until the cumulative torque–time integral of the IHSR matched that of the EQI contraction. This procedure indicated that approximately 30 IHSR repetitions were needed to match 1 EQI contraction, and this finding informed the design of the main parallel group study. However, since the experimental trial compared independent groups of different participants, the between-subject variability in strength and contraction characteristics was expected to contribute to the imperfect matching of total impulse. Therefore, the comparison should be interpreted in the context of matched loading intent rather than exact mechanical equivalence. The angular velocities of the isokinetic contractions were determined based on the results of a previous study [18], which found that a velocity of 30°/s can produce the maximum ankle torque during plantar flexion of the ankle. The number of 30 repetitions was determined through a pilot study (n = 5) that showed that similar angular impulse can be achieved by performing either 30 slow IHSR contractions or 1 EQI contraction (at a load equal to 75% of the participant's MVIC). Since it was found that the total torque impulse of the EQI contraction of ankle plantar flexors is greater in the case of 75% of premeasured MVIC intensity compared to 90% of premeasured MVIC, the lower load was selected [22]. Furthermore, applying a load corresponding to approximately 70–75% of MVIC typically produces an Achilles tendon strain of about 4–4.5% [19]. This strain magnitude is regarded as sufficient to elicit adaptive responses in tendon mechanical properties (such as increases in stiffness, cross-sectional area, and Young's modulus) when sustained over longer training durations (e.g., 12 weeks) [19,23,24].

The primary outcome variables were plantar flexion MVIC, dorsal flexion RoM, and pain scores, with a focus on time × group interaction. Pain scores included a subjective assessment of the general pain score in the triceps surae complex, and a separate assessment of activity-related pain, which was reported after performing three unilateral concentric toe raises with eccentric descent below the level of the higher ground. Secondary analysis compared the total torque impulse, time under tension, as well as comfort and effort between the exercise protocols. Comfort was measured using a short questionnaire on comfort during the protocol, the sensation of tightness in the active leg (due to the position), and the degree of tightness and blistering on the dynamometer. The variable was obtained as the mean value of the individual questions, with each question containing a 10-point scale, where a lower value represented a higher level of comfort. Meanwhile, the participants also rated the effort on a 10-point scale, but in this case, a higher value meant a higher level of effect that the person felt upon the implementation of the protocol. All measurements were carried out in the biomechanical laboratory at the Faculty of Health Sciences of the University of Primorska.

2.3. Ankle Range of Motion and Pain

Ankle RoM in the sagittal plane (plantar and dorsiflexion) was measured using a manual goniometer. The subject lay supine on a massage table with an extended knee and an ankle over the edge of the table [25]. The axis of the goniometer was slightly distal to the lateral malleolus [25]. The stationary arm was parallel to the longitudinal axis of the fibula, directed towards the medial condyle of the tibia, while the movement arm was directed towards the head of the first metatarsal bone [25]. We measured only the active RoM

(achieved by muscular activation of the ankle plantar or dorsal flexors of the participant, respectively) [25].

Meanwhile, pain was assessed on a 10-point numerical rating scale, with the participants providing a subjective assessment of the level of general pain and activity-related pain. While general pain level was determined as the subjective assessment of the overall ankle region, ankle plantar flexors, and Achilles tendon pain, the activity-related pain level was determined as the subjective assessment of the ankle region, ankle plantar flexors, and Achilles tendon caused by the execution of three unilateral toe rises on a higher ground. A score of one indicated the absence of pain, while a score of ten indicated the greatest degree of pain. As mentioned above, the measurements were performed before the execution of the protocol, immediately after the protocol and at the two follow-ups (24 and 48 h later). Also, participants were instructed to report any adverse symptoms or unusual discomfort during and after the exercise protocols.

2.4. Maximal Voluntary Isometric Contraction

The measurement of MVIC was performed on an isokinetic dynamometer (HumacNorm, Computer Sports Medicine Inc., Stoughton, MA, USA). All participants performed the measurements and the protocol at a recline angle of 80° (Figure 1). As the dynamometer does not allow for the adjustment of the additional lumbar tilt, the lumbar support of all participants was provided by the additional use of pads. This ensured that the lumbar region was slightly curved, thus maintaining the natural arch of the lower back. All other dynamometer position settings were individually adjusted to ensure the correct positioning of the participant. We ensured that the participant's right leg was aligned with the dynamometer plantar support (Figure 1), while the knee was planted and slightly flexed (i.e., approximately 10–15°, in order to reduce any negative effects of a potentially uncomfortable position that might affect the results). Both the ankle rotation axis and the foot support axis were at the same level. We strapped the participants across the shoulders, pelvis, and distal part of the femur of the measured limb. The fixations were refined through pilot testing, with the aim of minimizing the activation of the knee extensors and flexors, and the gluteal muscles. Participants were wearing sports shoes during the protocol.

After the fixation of the participant, an additional RoM assessment was performed on the dynamometer. Then, before starting the MVIC measurements in the neutral ankle position (i.e., 0°), the gravity effect was corrected. Initially, participants performed three trial contractions (first repetition at 50%, second at 75%, and third at 90% of maximum effort), followed by performing three repetitions of MVIC in the neutral ankle position. There was a 30 s break between each repetition. Real-time visual feedback (the time–torque curve) was provided throughout and participants were verbally encouraged during each repetition. We also unstrapped their thigh between each repetition and strapped it back before performing the contraction. Following the execution of either the EQI or IHSR protocol, the procedure was immediately repeated, without pairing trials, to assess the effects of fatigue. The same MVIC measurement protocol, without performing the EQI or IHSR protocol, was also performed at 24 and 48 h follow-ups.



Figure 1. Participant's position and fixation in the dynamometer (top chart) and a close-up of ankle and foot fixation.

2.5. Eccentric Quasi-Isometric Contractions

The dynamometer was configured to isotonic mode, providing a constant external resistance in a single direction (ankle dorsiflexion in this study). Participants resisted this load through the EQI contraction, which produced alternating phases of isometric holding and slow eccentric lengthening. The average torque was set at 119.4 $\pm$ 35.7 Nm (as a 75% MVIC load). Each EQI contraction consisted of one repetition which started in maximal dorsal flexion. At the beginning, participants performed a concentric burst against the direction of the resistance (i.e., in ankle plantar flexion direction), followed by holding the position and resisting the eccentric contraction by maintaining maximal voluntary isometric plantarflexion torque for as long as possible. When the participant could no longer provide the torque to overcome the dynamometer in a certain position, the ankle moved to a more dorsiflexed position. The change in position stretched the plantar flexors, resulting in a greater ankle plantarflexion torque capacity. This allowed the participant to maintain the new position for a longer time, despite previously being unable to cope with the strain in a greater plantar flexion position. This alternation of slow eccentric and isometric contraction continued until maximal dorsal flexion RoM was reached. The

available RoM was the same as that determined from the MVIC measurements for each participant. While the final ankle position was equal to the RoM of maximal voluntary dorsiflexion, the total RoM during EQI contraction was lower (as in the case of voluntary plantar flexion) because the participants failed to push the dynamometer to full RoM against resistance. Participants were verbally stimulated throughout the contractions and could also follow visual signals on the screen (the time–torque curve). The rest period between each repetition lasted 3 min.

2.6. Isokinetic Heavy–Slow Resistance Contractions

Meanwhile, when performing IHSR contractions, the dynamometer was set to isokinetic mode, which allows for constant slow movement velocity (at 30°/s) throughout the whole RoM (i.e., in the direction of ankle dorsal and plantar flexion). Each participant that performed the IHSR protocol executed three series of 30 IHSR repetitions with a 3 min break in between. At the beginning of each series, participants executed two trial isokinetic contractions. After 30 s of rest, they then performed 30 IHSR repetitions. Participants performed a concentric contraction in the direction of plantar flexion, overcoming the dynamometer, while resisting the dynamometer as the plantar support moved into dorsiflexion, thereby performing an eccentric contraction of the ankle plantar flexors. The participant's RoM was defined as between 35° of the plantar and 10° of the dorsiflexion of the ankle. The ankle RoM was determined based on the results of a pilot study, which showed that the technically correct completion of a total of 90 repetitions was not possible with a larger range of motion. During repetitions, participants were verbally encouraged and could observe a screen displaying the time–torque curve in real-time. The break between sets lasted 3 min.

2.7. Data Processing

Data processing was performed in MATLAB (version R2024a; The MathWorks Inc., Natick, MA, USA). Signals of time, ankle position (plantarflexion and dorsiflexion angles), angular velocity, and torque were sampled at 100 Hz and analyzed without prior filtering [8]. For the MVIC assessment, the peak torque obtained from the highest-performing trial was used as the dependent variable.

The onset of the EQI contraction was defined as the first local maximum in the torque–angle trace (corresponding to maximal plantar flexion), whereas the end point was identified either when (1) torque values fell below 50% of the target threshold, or (2) the ankle reached the end of the range of motion. Each EQI trial was visually checked to exclude artefacts that could interfere with the accurate detection of contraction onset or termination. To minimize type I error and the risk of false discovery, the analysis focused on the following four primary outcome variables: (1) total angular impulse (area under the torque–time curve, determined via trapezoidal integration; Nm·s), (2) contraction duration (s), (3) total range of motion (°), and (4) mean angular velocity (°/s). Including range of motion as a dependent variable for the EQI contractions was essential to capture the overall differences between repetitions, since fatigue from earlier trials could reduce the participant's ability to reach the same initial plantarflexion angle at the start of the concentric phase.

In the secondary analysis (i.e., comparison of the EQI and IHSR protocol characteristics), we focused on total torque impulse (defined as the area under the torque–time curve, determined using trapezoidal integration and the time under tension (contraction duration)). To account for potential baseline strength differences, the total torque impulse was normalized by dividing it by the peak MVIC torque.

2.8. Statistical Analysis

Data are reported as means ± standard deviations. The normality of each variable's distribution was assessed using the Shapiro–Wilk test, complemented by visual inspection of histograms and Q–Q plots. We used an independent samples t-test to check the differences between the groups for body height, body mass, age, baseline MVIC, total torque impulse, and time under tension. Effort levels and comfort scores were compared using Mann–Whitney test. To compare the effects of EQI and IHSR on primary outcome measures, a general linear model with a group (EQI and IHSR, between-subjects factor) and time (baseline, post, post 24 h, and post 48 h, within-subjects factor) was used. The effect size was calculated as a partial η^2 and interpreted as indicating no effect (<0.01), or small (0.01–0.06), medium (0.06–0.14), and large effects (>0.14) [26]. Muschly's test was used to assess sphericity, and the Greenhouse–Geisser correction was used to adjust for possible sphericity violations. In the case of statistically significant group × time interactions, further unifactorial analyses, using Bonferroni correction, were performed to discern group-specific differences in time. A general linear model with group (between-subject factor) and repetition (within-subject factor) was also used for repetition-by-repetition differences in torque impulse, while a unifactorial model (repetition, within-subject) was used to compare the mean angular velocity among repetitions within the EQI group. The statistical significance threshold was set at $\alpha < 0.05$ and all analyses were performed using SPSS statistical software (version 25.0, IBM, Armonk, NY, USA).

3. Results

The results are presented in sections covering (1) baseline comparisons between groups, (2) mechanical outcomes derived from torque–time analysis, and (3) changes in performance, pain, and range of motion across time points. Descriptive statistics are followed by inferential analyses, to provide a comprehensive overview of group differences and temporal effects. All participants (n = 32) successfully completed the intervention and attended all follow-up measurement sessions. Demographic data and baseline MVIC are shown in Table 1. There were no statistically significant differences between the EQI and IHSR group for any of these variables (p = 0.251–0.768). Additionally, no severe adverse events or injuries were observed or reported during the course of study.

Table 1. Demographic characteristics of the participants.

Outcome Variable	EQI Group (n = 16)		IHSR Group (n = 16)		Difference	
	Mean	SD	Mean	SD	t-Value	p
Body height (cm)	176.1	11.3	173.9	11.2	0.55	0.586
Body mass (kg)	75.2	15.1	69.5	12.3	1.17	0.251
Age (years)	26.3	5.3	25.6	5.1	0.40	0.687
Baseline MVIC (Nm)	159.3	47.7	163.9	38.8	−0.297	0.768

EQI—eccentric quasi-isometric; IHSR—isokinetic heavy–slow resistance; MVIC—maximal voluntary isometric contraction; SD—standard deviation.

3.1. Intervention Characteristics

The comparison between the EQI and IHSR groups is summarized in Table 2. Significant differences were observed between the two groups in several variables. Total impulse (Nm·s/MVIC) was significantly higher in the EQI group (144.2 ± 108.2) compared to in the IHSR group (80.9 ± 18.0) (p = 0.028). Time under tension was significantly lower in the EQI group (177.3 ± 118.0) compared to in the IHSR group (290.6 ± 40.6) (p = 0.001). The effort level was also significantly lower in the EQI group (4.7 ± 1.7) compared to in

the IHSR group (7.6 ± 1.3) ($p < 0.001$). Although the comfort score was lower (indicating better comfort) in the EQI group (5.0 ± 1.9) compared to in the IHSR group (6.3 ± 1.8), this difference was not statistically significant ($p = 0.068$).

Table 2. Comparison between the EQI and IHSR interventions.

Outcome Variable	EQI Group (n = 16)		IHSR Group (n = 16)		Difference	
	Mean	SD	Mean	SD	t	*p*
Total torque impulse (Nm·s/MVIC)	144.2	108.2	80.9	18.0	2.31	0.028
Time under tension (s)	177.3	118.0	290.6	40.6	−3.632	0.001
Effort level (1–10)	4.7	1.7	7.6	1.3	−5.347	<0.001
Comfort (1–10)	5.0	1.9	6.3	1.8	−1.89	0.068

EQI—eccentric quasi-isometric; IHSR—isokinetic heavy–slow resistance; MVIC—maximal voluntary isometric contraction; SD—standard deviation.

With regard to torque impulse, there was a statistically significant repetition × group interaction (F = 10.1; $p < 0.001$; $\eta^2 = 0.25$), as well statistically significant repetition (F = 27.3; $p < 0.001$; $\eta^2 = 0.47$) and group effects (F = 6.5; $p = 0.016$; $\eta^2 = 0.18$). Further analyses revealed that torque impulse was progressively lower from repetition one to repetition three within the EQI group (main effect: $p < 0.001$, $\eta^2 = 0.63$; all pairwise comparisons: $p \leq 0.002$) but was not statistically significantly different among repetitions in the IHSR group ($p = 0.072$; $\eta^2 = 0.18$). The descriptive statistics for repetition-by-repetition analysis are included in Supplementary Table S1.

Within the EQI, the mean angular velocity was increased with each repletion (repetition one: 0.27 ± 0.13°/s; repetition two: 0.38 ± 0.21°/s; repetition three: 0.45 ± 0.21°/s), with a statistically significant main effect (F = 9.2; $p = 0.001$; $\eta^2 = 0.38$) with a pairwise comparison showing a statistically significant increase only between repetition one and two ($p = 0.037$), but not repetition two and three ($p = 0.510$).

3.2. Pain Scores

Figure 2 displays the general (top chart) and activity-related (bottom chart) scores. There were no differences, in general, in pain scores between groups at baseline ($p = 1.000$). There was a statistically significant group × time interaction (F = 14.3; $p < 0.001$; $\eta^2 = 0.32$), as well as statistically significant effects of time (F = 31.15; $p < 0.001$; $\eta^2 = 0.51$) and group (F = 41.8; $p < 0.001$; $\eta^2 = 0.58$). The pairwise comparison revealed elevated pain at post, post24, and post48 compared to baseline (all $p < 0.001$), with post48 showing lower values than post and post24 ($p = 0.001$–0.004), with no difference between post and post24 ($p = 1.000$). Unifactorial analyses showed a statistically significant time effect in both groups (F = 9.41 and 25.2, both $p < 0.001$), but the effect size was smaller in the EQI group ($\eta^2 = 0.39$) compared to the IHSR group ($\eta^2 = 0.63$). The differences between groups were statistically significant at post, post24, and post48 (Mann–Whitney's U = 13.0–37.0; all $p < 0.001$), with lower pain scores in the EQI group compared to the HSR group.

There were no differences in activity-related pain (Figure 2, bottom chart) scores between the groups at baseline ($p = 1.000$). Similarly to general pain scores, there was a statistically significant group × time interaction (F = 14.4; $p < 0.001$; $\eta^2 = 0.32$), as well as statistically significant effects of time (F = 27.7; $p < 0.001$; $\eta^2 = 0.48$) and group (F = 45.1; $p < 0.001$; $\eta^2 = 0.60$). The pairwise comparison revealed elevated pain at post, post24, and post48 compared to baseline (all $p < 0.001$), with post48 showing lower values than post and post24 ($p = 0.003$–0.012), with no difference between post and post24 ($p = 1.000$). Similarly to general pain scores, unifactorial analyses again showed a statistically significant time effect in both groups (F = 6.44 and 23.5, both $p < 0.001$), with a smaller effect size in the EQI

group (η^2 = 0.30) compared to IHSR group (η^2 = 0.61). The differences between groups were statistically significant at post, post24, and post48 (Mann–Whitney's U = 21.0–37.0; all $p < 0.001$), with lower pain scores in the EQI group compared to the IHSR group.

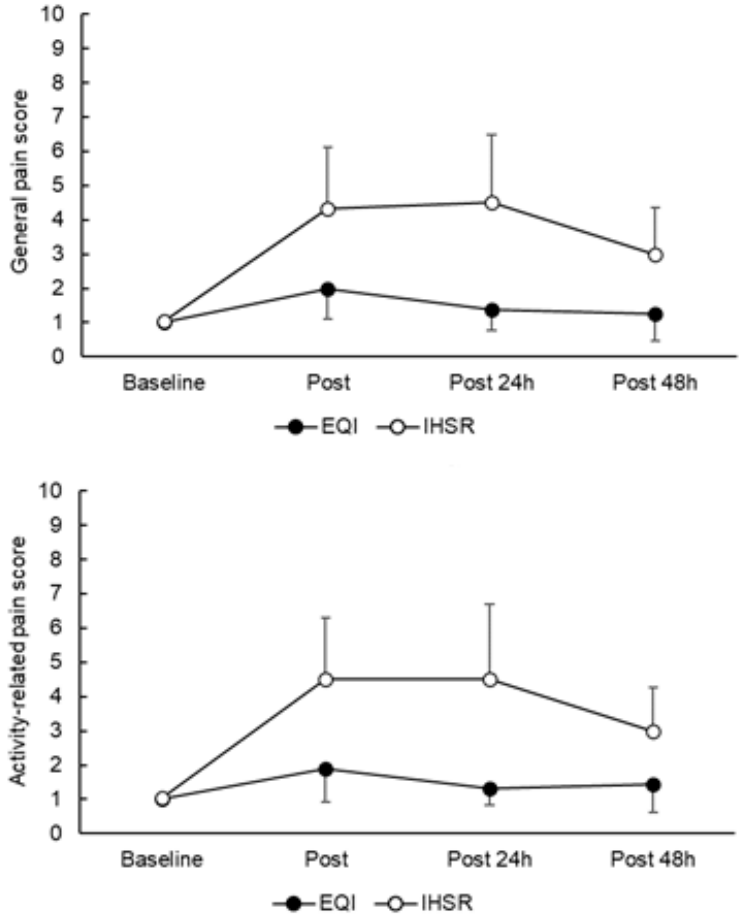


Figure 2. General pain scores (top chart) and activity-related pain scores (bottom chart) across timepoints and groups (n = 16 per group). EQI—eccentric quasi-isometric; IHSR—isokinetic heavy–slow resistance.

3.3. Maximal Voluntary Isometric Contraction Torque

There were no statistically significant differences in the MVIC torque (Figure 3, top chart) at baseline between the groups (p = 0.768). There was a statistically significant group × time interaction (F = 5.5; p = 0.002; η^2 = 0.16), as well as a statistically significant effect of time (F = 4.1 p = 0.009; η^2 = 0.12), but no statistically significant effect of group (F = 0.5; p = 0.479). The pairwise comparison revealed reduced MVIC torque at post (p = 0.004) and post24 (p = 0.032) compared to baseline, with no statistically significant difference between baseline and post48 (p = 1.000). There were also no statistically significant pairwise differences among post, post24, and post48 (p = 0.322–1.000). Unifactorial analyses showed a statistically significant time effect in the IHSR group (F = 15.6; $p < 0.001$, η^2 = 0.51), but not in the EQI group (F = 0.8; p = 0.501). Within IHSR, pairwise comparisons showed statistically significantly reduced MVIC at post ($p < 0.001$), post24 (p = 0.003), and post48 (p = 0.016) compared to baseline, with no statistically significant differences among post, post24, and post48 (p = 0.060–1.000).

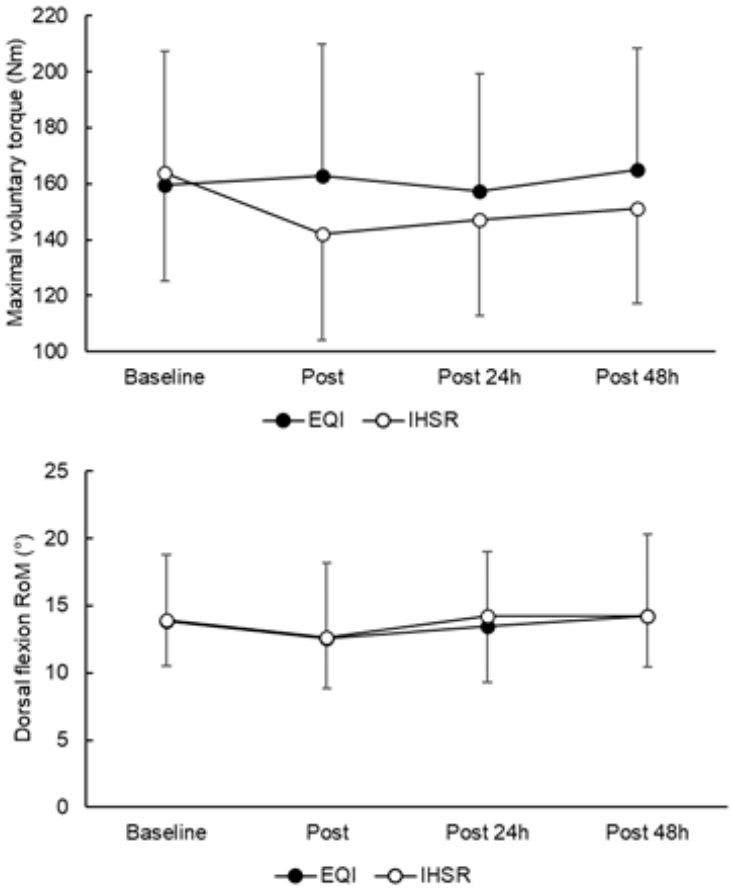


Figure 3. Maximal voluntary torque (top chart) and range of motion (bottom chart) across timepoints and groups (n = 16 per group). EQI—eccentric quasi-isometric; IHSR—isokinetic heavy–slow resistance.

3.4. Range of Motion

There were no statistically significant differences in dorsiflexion RoM (Figure 3, bottom chart) at baseline between the groups ($p = 0.967$). The main analysis showed no statistically significant group × time interaction (F = 0.2; $p = 0.893$) and no statistically significant effect of group (F = 0.23; $p = 0.890$). There was a statistically significant effect of time (F = 3.3; $p = 0.023$; $\eta^2 = 0.10$), with post hoc tests showing a statistically significant difference only between post and post48h ($p = 0.043$).

4. Discussion

This study aimed to extend the understanding of the short-term effects of EQI contractions, particularly in the context of pain, RoM, and strength performance of ankle plantar flexors in comparison to the IHSR protocol. The analysis of the results showed that the EQI group produced a greater total torque impulse with a concomitant lower time under tension and effort compared to the IHSR group. At the same time, the execution of the EQI protocol also caused lower general and activity-related pain scores, and a lesser decline in the MVIC torque, while there were no statistically significant differences between groups in terms of changes in ankle dorsiflexion RoM. Based on the results obtained, our hypotheses can be confirmed.

Our findings can be compared to those of knee extensors, where it has been confirmed that the EQI protocol has a higher efficiency compared to the isokinetic eccentric-only protocol in accumulating high torque impulse [7]. They reported that the performance of 1 EQI contraction on knee extensors was comparable to approximately 26 isokinetic eccentric-

only repetitions (on an isokinetic dynamometer with a velocity determined at 30°/s) [7]. It should be noted that this type of variation in the number of contractions needed to match one set of EQI, is most likely due to both the difference in the RoM and the different muscle contractions performed by the muscle group under investigation. Participants in the previously mentioned study performed EQIs over 80° RoM (i.e., between 30 and 110° of knee flexion) [7], while the mean RoM in our study ranged between 19.52° (in the case of the first EQI contraction) and 17.55° (in the case of the third EQI contraction), or 43.06 to 43.91° in the case of the IHSR contractions, respectively. Thus, we can observe an almost one-fold lower RoM when comparing isokinetic eccentric-only contractions of the knee extensors and IHSR contractions of the plantar flexors of the ankle [7]. Moreover, in our study, participants performed both concentric and eccentric contractions at an angular velocity of 30°/s, whereas in the case of the study on the knee extensors, only eccentric contractions were performed [7]. Although our study aimed for approximate load matching based on pilot data, the EQI group ultimately achieved a greater total impulse while reporting lower exertion and pain. Rather than contradicting the study rationale, this finding strengthens the interpretation that EQI represents a more mechanically efficient contraction mode, capable of producing higher overall work with less pain and lower MVIC reduction afterwards. Speculatively, this may reflect that the controlled transition between the isometric and eccentric phases allows sustained torque generation without excessive muscle damage. Nevertheless, it should be acknowledged that the protocols were not perfectly load-matched, and future work should consider normalization metrics, such as impulse per contraction or impulse per second, to enhance comparability.

Since group × time interaction for MVIC was statistically significant, the time effect in each group was checked, with a statistically significant decrease found only in the IHSR group. Within IHSR, pairwise comparisons showed statistically significantly reduced MVIC at post, post24, and post48 compared to baseline, with no statistically significant differences among post, post24, and post48. The persistent reduction in MVIC observed in the IHSR group even after 48 h may reflect the delayed recovery associated with greater muscle damage and prolonged excitation–contraction coupling impairment [27]. High-repetition eccentric actions performed under slow velocity and wide range of motion are known to induce microstructural disruptions within muscle fibres [28], accompanied by inflammatory processes and swelling that can persist for several days [29,30]. These mechanisms likely contributed to the sustained strength deficit observed in the IHSR group. In contrast, the EQI protocol, despite the higher mechanical impulse, may have induced less fibre disruption due to the more gradual force development and reduced muscle lengthening velocity. From a practical standpoint, this suggests that EQI loading might facilitate faster recovery and lower cumulative fatigue. The complete absence of MVIC decline in EQI was somewhat unexpected, given that EQI contraction is based on the maintenance of the position until isometric failure [2], which means that it can be associated with greater muscle fatigue. Comparably, when measuring concentric peak torque, it was also found that the drop in torque after performing the isokinetic eccentric-only protocol was greater than after performing the EQI protocol, but it almost restores as early as 72 h after performing the protocol [7]. Similarly, none of the MVIC measurements (neither at 70 nor 100° of knee flexion) resulted in a change in the MVIC of the knee extensors [7], as in the ankle plantar flexors situation. The execution of isometric, concentric or eccentric contraction with an equalized total torque impulse also resulted in a decrease in maximal voluntary contraction of the knee extensors [7,16]. In addition, it was found that an increase in maximal voluntary contraction over the baseline measurement was observed only in the group performing concentric contraction (5.0 ± 11.0%), whereas this did not occur within the isometric (−5.5 ± 7.9%) and eccentric groups (−12.9 ± 14.8%) [16].

The IHSR protocol resulted in higher pain (considered as a marker of delayed onset muscle soreness [DOMS] at post24 and post48) compared to the EQI protocol at all time points (immediately post-protocol, 24 h post-protocol, and 48 h post-protocol). While the EQI group experienced the highest level of pain immediately post-protocol (2.00-points on a 10-point scale), the subjects in the other group experienced the highest level of DOMS 24 h after the protocol (4.50-points on a 10-point scale). The higher DOMS after the IHSR protocol could be due to the different characteristics between the two contractions, which are as follows: (1) performing eccentric contraction at much higher angular velocities results in higher DOMS levels [17]; and (2) eccentric exercise occurs over a wider RoM [12]. The first characteristic could partially explain our results, as the angular velocity during the IHSR contractions ($\omega = 30^\circ/s$) was significantly higher compared to the EQI protocol ($\omega = -0.279 - -0.458^\circ/s$), while the execution of eccentric contraction over a wider RoM causes higher tensions at longer muscle lengths, which result in greater muscle damage and consequently greater DOMS [12]. The results can also be partly explained by comparing the duration of the contractions, as the mean total time of the three EQI contractions was 177.33 s, whereas the mean total time in the IHSR group was 290.62 s. Similar findings were also reached by the knee extensors [7].

The study showed that the execution of neither the EQI nor IHSR protocol caused statistically significant differences in ankle RoM. Only a statistically significant difference was observed between measurements performed immediately after the execution of either one of the protocols and at a 48 h follow-up. As the decrease in RoM is associated with DOMS [31], it can be assumed that the differences between these two measures are mainly due to the latter. This finding is also supported by the fact that DOMS starts to develop 6 to 12 h after overload exercise, while ultrastructural damage gradually increases until peak muscle soreness is reached, between 48 and 72 h post-exercise [32].

In the EQI group, a gradual decrease in the contraction duration and the associated higher velocity of the movement with each repetition was observed between the first and last contraction. At the same time, most probably due to fatigue, participants were able to achieve a smaller RoM each time during the concentric contraction, which marked the onset of the EQI contraction. Shorter contraction duration (and associated higher velocities) and lower RoM resulted in lower mean angular impulse. Thus, the average angular impulse after the first EQI repetition was 8796.11 Nm, whereas, compared to the first, the average angular impulse of the last contraction was almost 40% lower (5337.48 Nm). Similar results in knee extensors have not been reported, with participants exhibiting progressive shorter contraction times within the fixed RoM [7].

4.1. Practical Application

While the current findings suggest that EQI may represent an efficient and well-tolerated loading strategy, its potential application in individuals with Achilles tendinopathy remains speculative. Further research is required to verify whether similar benefits would be observed in symptomatic populations. Therefore, future clinical studies should directly compare EQI with established rehabilitation protocols (e.g., eccentric or heavy–slow resistance training) to determine its safety, feasibility, and long-term efficacy in tendon pathology management. The practical value of the study can be identified mainly in the context of improved exercise or exercise therapeutic interventions for ankle plantar flexors, potentially serving as an alternative approach for treating Achilles tendon pathologies, such as Achilles tendinopathy. Based on previous evidence, adaptations of injured tendons can occur with different contraction modes, provided that a minimum threshold of mechanical stress on the tendon and joint is reached [11,33], In light of the present findings, which showed that the EQI protocol produced a greater total torque impulse

with less pain than the IHSR protocol, it is reasonable to speculate that EQI training might hold potential for use in patients with Achilles tendinopathy. However, this assumption remains hypothetical, and future clinical studies are required to confirm whether such benefits translate to symptomatic populations. While EQI contractions can theoretically be performed without specialized equipment, such applications require further validation to ensure comparable loading conditions and safety before being implemented in training or rehabilitation practice.

4.2. Limitations

Some limitations of our study should be acknowledged. Contrary to our pilot study, the analysis showed that the execution of 1 EQI contraction on the ankle plantar flexors exceeds the total angular impulse produced by 30 IHSR contractions. Interestingly, the effort was lower in participants performing the EQI contraction (mean: 4.69/10) than in the case of those performing the IHSR contractions (mean: 7.56/10-point). Based on a further calculation, the equated total angular impulse on the ankle plantar flexors could be achieved with 1 EQI contraction and approximately 49 IHSR contractions. The study sample consisted of young, healthy, and regularly active participants, which restricts the generalizability of the findings. The observed responses may differ in older adults or clinical populations, where neuromuscular characteristics, pain perception, and recovery capacity could substantially vary. Consequently, any clinical implications should be interpreted with caution until validated by dedicated trials. The findings of the study, due to inclusion and exclusion criteria, are also not directly transferable to a population with Achilles tendon pathologies. The subjective assessment of pain after the protocol is also a limitation, as we observed that participants who train the lower limb (or more specifically the ankle plantar flexors) more frequently did not experience any DOMS, even after performing 90 IHSR contractions. Additionally, since neither participants nor the personnel conducting the interventions and assessments were blinded to group allocation, a potential performance and measurement bias cannot be fully excluded. Pain outcomes were based on subjective self-report and may have been influenced by individual pain tolerance or prior training experience. Although standardized instructions were used, variability in pain perception between participants cannot be fully excluded. Finally, the quasi-randomized allocation procedure may have introduced some degree of selection bias, as group assignment was not entirely random. Although stratification by sex helped to balance participant characteristics, residual confounding effects cannot be fully excluded. Although the quasi-randomized design allows for inference of short-term cause–effect relationships between the applied interventions and measured outcomes, the absence of full randomization warrants cautious interpretation. Thus, while the study supports preliminary causal conclusions, further fully randomized and longer-term trials are needed to strengthen causal inference.

5. Conclusions

Based on the findings on the ankle plantar flexors, we can conclude that the implementation of the EQI protocol is likely to be more efficient in the short-term than the implementation of the IHSR or the eccentric-only protocol for ankle plantar flexors. Also, the execution of the EQI protocol did not result in an acute decrease in MVIC, whereas the IHSR protocol caused a decrease in MVIC. The drop in MVIC values in the IHSR group was noticeable even after 48 h. Moreover, the IHSR protocol resulted in a higher level of pain than the EQI protocol at all time points. The EQI protocol caused the short-term effect of improving ankle RoM, while the IHSR protocol did not produce comparable positive changes. It should be noted that, most likely due to the onset of fatigue, there was a shortening of the contraction duration and an increase in the contraction velocity during

successive EQI repetitions. Fatigue also affected the RoM performed by the participants in the EQI group and the associated reduction in angular impulse between repetitions. We believe that our results have laid the foundations for further research that could focus on the effects of EQI protocols in pathological populations (such as Achilles tendinopathy).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app152011177/s1. Table S1: Descriptive statistics for repetition-by-repetition analysis.

Author Contributions: Conceptualization, Ž.K. and N.Š.; Methodology, Ž.K. and N.Š.; Investigation, L.K. and Ž.K.; Resources, Ž.K.; Data Curation, Ž.K. and L.K.; Formal Analysis, Ž.K. and N.Š.; Project Administration, Ž.K.; Supervision, Ž.K.; Writing—Original Draft, L.K.; Writing—Review and Editing, Ž.K. and N.Š. All authors have read and agreed to the published version of the manuscript.

Funding: The study was supported by the Slovenian Research Agency through post-doctoral project EQI-TRAIN: Establishing scientific foundations for eccentric quasi-isometric resistance training (Z5-50181 (B)), and research programme KINSPO—Kinesiology for the effectiveness and prevention of musculoskeletal injuries in sports (P5-0443).

Institutional Review Board Statement: The research methods and interventions used were non-invasive and approved by the Commission of the University of Primorska for Ethics in Human Subjects Research (approval number: 4264-19-6/23).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient in Figure 1 to publish this paper.

Data Availability Statement: Raw data is freely available in Zenodo database (https://zenodo.org/records/15689820 (accessed on 18 June 2025).

Acknowledgments: During the preparation of this manuscript/study, the author(s) used ChatGPT (Version 5.0; Open AI) for the purposes of grammar checking. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

DOMS	Delayed onset muscle soreness
EQI	Eccentric quasi-isometric
IHSR	Isokinetic heavy–slow resistance
MVIC	Maximal voluntary isometric contraction
RoM	Range of motion
RM	Repetition maximum
SD	Standard deviation
SPSS	Statistical Package for the Social Sciences
η^2	Partial eta squared

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