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ORIGINAL ARTICLE

Strength gains and absence of hypertrophy and cross-education in knee extensors following short-term low-volume eccentric training in untrained young men

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Abstract

This study investigated the effects of a short-term, low-volume eccentric training protocol on knee extensor strength and thickness in untrained young men, including the potential cross-education effect. Twenty-six healthy male participants with no resistance training experience were assigned to the training ($n=14$) or control ($n=12$) group. The training group performed five maximal voluntary eccentric contractions of the knee extensors on the dominant leg, twice weekly for 2 weeks. Maximal voluntary contraction torque in isometric (MVIC), concentric (MVCC), and eccentric (MVEC) modes, along with quadriceps muscle thickness, were measured before and after the intervention. Significant increases in the MVIC (15.7% ± 24.8%, d = 0.66), MVCC (8.8% ± 7.3%, d = 0.65), and MVEC (22.1% ± 16.4%, d = 0.87) torques were observed in the trained legs (all $p<0.05$). MVIC, MVCC, and MVEC torque showed no significant changes in the untrained legs and the control group. The muscle thickness remained unchanged across all groups. In conclusion, a 2-week protocol involving five maximal eccentric contractions twice weekly effectively increased knee-extensor strength in untrained individuals, while no hypertrophic changes were detected. However, the minimal protocol did not elicit cross-education, suggesting that a higher training volume or longer duration may be necessary to induce this effect. Such a time-efficient strategy may be suitable for early-stage rehabilitation or for populations with limited training capacity.

Keywords Maximal voluntary contraction · Muscle thickness · Isokinetic dynamometer · Resistance training · Rehabilitation · Lower limb

Abbreviations

ANOVA	Analysis of variance
ES	effect size
ICC	Intraclass correlation coefficient
MVC	Maximal voluntary contraction
MVCC	Maximal voluntary concentric contraction
MVEC	Maximal voluntary eccentric contraction
MVIC	Maximal voluntary isometric contraction
NTL	Non-trained leg
POST	Post-training
PRE	Pre-training
RF	Rectus femoris
SD	Standard deviation
TL	Trained leg
VI	Vastus intermedius
VL	Vastus lateralis
VM	Vastus medialis

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Introduction

Increasing muscle strength through resistance training is of paramount importance for health and quality of life (Khodadad Kashi et al. 2023). Its effectiveness depends on factors such as contraction type, exercise intensity, volume, and frequency (Mcleod et al. 2024). Notably, eccentric (muscle lengthening) contractions induce greater muscle adaptations than isometric or concentric (muscle shortening) contractions (Roig et al. 2009; Douglas et al. 2017; Sato et al. 2022a, b; Nakamura et al. 2025). This advantage has prompted a growing interest in whether eccentric contractions can be leveraged even in minimal-dose, time-efficient protocols (Nuzzo et al. 2024).

Increasing attention is being given to resistance training strategies that maximize strength gains with minimal time commitment, addressing the lack of time as a common barrier to physical activity (Behm et al. 2024; Nuzzo et al. 2024; Kirk et al. 2025). In particular, low-volume and high-frequency eccentric exercise has emerged as a promising approach. Nuzzo et al. (2024) reviewed minimal-intensity protocols and found that eccentric training can effectively increase muscle strength with lower training volumes. Similarly, Kirk et al. (2025) demonstrated that just 5 min of daily home-based eccentric-biased exercises over 4 weeks led to a 13% increase in isometric strength in sedentary middle-aged individuals. These findings suggest that even brief, low-volume eccentric training can substantially improve muscle strength.

Previous studies supports these observations (Sato et al. 2022a; Yoshida et al. 2024a). Sato et al. (2022a) showed that a single maximal voluntary eccentric contraction of the elbow flexors for 3 s per day, five times a week for 4 weeks (totaling 60 s), increased isometric, concentric, and eccentric peak torque by 10%–13%, without changing muscle thickness. Conversely, a single maximal isometric or concentric contraction did not yield similar effects (Sato et al. 2022a). Yoshida et al. (2024a) found that training frequency is critical: strength gains from single maximal eccentric contractions were minimal with 2–3 weekly sessions (0%–3%) but increased to 11% with five sessions per week. However, these studies focused on the elbow flexors, limiting generalizability to other muscle groups that are essential for daily function and athletic performance, such as the quadriceps femoris muscles (Cinarli et al. 2024). Lower-limb muscles that are exposed to gravity on a daily basis may exhibit slower or smaller hypertrophic responses to eccentric training compared with upper-limb muscles (Bottaro et al. 2011; da Silva et al. 2025). Nevertheless, strength gains, largely driven by neural adaptations, can emerge earlier and more robustly than morphological changes, particularly under eccentric loading (Douglas et al. 2017). Thus, developing effective, low-volume eccentric training protocols specifically for the quadriceps represents a critical next step in determining whether time-efficient approaches can elicit meaningful strength gains in large lower-limb muscles.

Additionally, eccentric training produces greater strength gains in the untrained contralateral limb, a phenomenon called the cross-education effect (Manca et al. 2017, 2021). To maximize this effect, previous reviews have highlighted the importance of high-intensity training, the inclusion of eccentric contractions, and intervention durations of at least 4–6 weeks, as these conditions are considered essential for producing functionally meaningful contralateral adaptation (Manca et al. 2021). Kidgell et al. (2015) found that unilateral eccentric training reduced intracortical inhibition and increased corticospinal excitability on the untrained side, resulting in greater strength gains compared to concentric training (47% vs. 28%). Maroto-Izquierdo et al. (2022) reported similar cross-education effects in the lower limbs after 12 sessions of high-intensity accentuated eccentric training (untrained leg press one-repetition maximum increased by 26.2%, comparable to the trained side's 27.4%). Nevertheless, the potential of low-volume high-intensity unilateral eccentric training to induce cross-education in lower-limb muscles remains unclear. Addressing this gap is essential for establishing whether short-term, time-efficient eccentric training can extend its benefits beyond the trained limb, thereby providing a practical strategy for both rehabilitation and performance enhancement.

This study aimed to investigate changes in knee extensor strength and muscle thickness in the trained and contralateral untrained limbs following a short-term, low-volume eccentric training protocol. We hypothesized that strength would increase in the trained limb, whereas muscle thickness would show minimal change. Furthermore, despite the brief duration and limited training volume, we postulated that the contralateral untrained limb could also demonstrate measurable strength gains, given that high-intensity eccentric contractions may facilitate cross-education.

Methods

Participants and study design

Maximal voluntary isometric (MVIC), concentric (MVCC), and eccentric (MVEC) contractions of the knee extensors and quadriceps muscle thickness were measured the week before and the week after the 2-week training intervention. For the pre-training (PRE) and post-training (POST) measurements, ultrasonography was performed immediately before muscle strength tests. To eliminate potential learning effects and ensure reliable strength assessment, participants completed one familiarization session using the isokinetic dynamometer one week before the PRE measurement, during which they were familiarized with the isometric, concentric, and eccentric testing procedures. A non-training control group was included to consider the time-dependent variability of the outcomes (Hammert et al. 2024). Additionally, POST measurements were performed at least 2 days after the last training session. A single non-blinded trained investigator performed all measurements to minimize the potential for inter-rater variability.

Twenty-six healthy male university students were recruited for this study. The inclusion criteria were as follows: free from orthopedic disorders of the lower extremities, having no history of neuromuscular or chronic diseases, and had not undergone any regular resistance training in the 6 months before participation. Participants were randomly assigned to either the training group ($n=14$) or the control group ($n=12$) using a computerized random number function in Microsoft Excel (Microsoft Corp., Washington, WA, USA). Because of this allocation procedure, the number of participants was not balanced between groups. None of the participants withdrew from the study and there were no missing data throughout the intervention and testing periods. The required sample size for a two-way repeated-measures analysis of variance (ANOVA) was estimated using G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany). Because pilot data were not collected in the present study, the effect size was derived from the pre-post change in maximal voluntary contraction torque reported in a previous study by Sato et al. (2022a). In that study, early strength gains were induced by short-term low-volume maximal voluntary eccentric contractions, which were conceptually comparable to the present intervention. Based on the reported pre-post changes in maximal voluntary contraction torque, the effect size was set at $f=0.40$, with an alpha level of 0.05 and statistical power of 0.80. This calculation indicated that a minimum of 12 participants were required per group.

Participants in the training group performed five maximal voluntary eccentric contractions of the dominant leg, twice a week for 2 weeks (a total of 4 sessions). In the training group, the dominant (trained leg, TL) and contralateral (non-trained leg, NTL) legs were assessed to evaluate the cross-education effect. The dominant leg was determined as the preferred leg used to kick the ball. In the control group, measurements were performed in the dominant leg at the baseline and after a 2-week interval. There were no significant differences ($p>0.05$) in average age, height, and body mass between the training (21.3 ± 0.7 y, 169.9 ± 4.9 cm, 64.5 ± 10.3 kg) and control groups (21.0 ± 0.8 y, 172.3 ± 4.4 cm, 69.3 ± 12.2 kg). This study was conducted in accordance with the Declaration of Helsinki and was approved by Nishikyushu University, Saga, Japan.

Training protocol

All participants performed MVEC training on the dominant limb side twice a week for 2 weeks. All participants performed the training with at least 48 h of rest between sessions. The MVEC training was performed in the same manner as the MVEC torque measurements, with five consecutive MVEC sessions. Specifically, the participants were instructed to maximally resist the movement of the dynamometer lever as it moved from 0° to 90° of knee flexion at an angular velocity of 60°/s. After each eccentric contraction, the lever arm of the isokinetic dynamometer passively returned the knee joint to the starting position (0° knee angle) at 10°/s, providing a 9-second rest between contractions.

Dependent variables

Maximal voluntary contraction (MVC) torque

All MVC torque measurements were performed using an isokinetic dynamometer. The torque of each contraction was monitored and recorded using an analog-to-digital converter (PowerLab 8/30, AD Instruments, Colorado Springs, CO, USA) on a personal computer with the analysis software (LabChart 7, AD Instruments). Participants were seated on a dynamometer chair (Biodex System 3.0; Biodex Medical Systems Inc., Shirley, NY, USA) with a hip flexion angle of 80° and adjustable Velcro straps fixed over the trunk, pelvis, and thigh of the exercised limb. The knee joint on the measurement side was aligned with the dynamometer's axis of rotation. MVIC torque was measured at a knee angle of 90° using a dynamometer, with gravity correction performed in the fully extended knee position (0°). The participants were instructed to perform a maximal contraction for 3 s at each angle twice with a 60-second rest between each set, and the average value was adopted for further analysis (Kasahara et al. 2023). MVCC and MVEC were measured at an angular velocity of 60°/s for a range of motion of 90° (0°–90° knee angle) for three continuous maximal voluntary concentric or eccentric contractions in the knee-extension direction. For the MVEC measurements, the upper torque threshold was set to the maximum allowable value defined by the manufacturer's safety settings. No additional or artificial torque limit was imposed, and the participants were allowed to exert maximal voluntary effort throughout the eccentric contractions. The highest value among the three trials was used for further analyses (Nakamura et al. 2020; Kasahara et al. 2023). Verbal encouragement was consistently provided during all tests.

Muscle thickness

B-mode ultrasonography (Venue Fit; GE Healthcare Japan, Tokyo, Japan) with a 5.2 cm linear array probe (8-MHz) was used to evaluate the thickness of the quadriceps muscles. For the quadriceps muscle, we measured the muscle thickness of the rectus femoris (RF), vastus intermedius (VI) in the middle and lateral portions, vastus lateralis (VL), and vastus medialis (VM) with the participants in a supine position with a 0° hip and knee angle for each muscle based on a previous study (Ema et al. 2013) (Fig. 1). The longitudinal ultrasound images were obtained for the VL, RF, and VI muscles, and the muscle thicknesses of the RF and VL were determined as the mean of the distances between the deep and superficial aponeuroses measured at both image ends (Blazevich et al. 2006; Ema et al. 2013). In addition, the muscle thickness of the VI at the lateral and middle portions was determined as the mean of the distances between the aponeurosis at the boundary with the VL and RF, respectively, and the bone. The measurement site was set at the midpoint between the anterior superior iliac spine and the superior border of the patella (Pardo et al. 2018). Regarding the VM muscle, as we could not monitor the deep and superficial aponeuroses on the longitudinal image, transverse ultrasound images were obtained. The measurement site was set on the VM muscle area, medially displaced from the 30% distal between the greater trochanter and lateral femoral tuberosity (Taniguchi et al. 2023). To ensure imaging at the same location before and after the training period, the same operator with more than 15 years of ultrasound measurement experience performed the measurements. In addition, during ultrasonographic images obtained at POST, several landmarks, such as fat, connective tissues, and blood vessels, were carefully visualized in the same position while referencing images acquired during the PRE measurement.

Statistical analyses

SPSS (version 24.0; IBM Corp., Armonk, NY, USA) was used for statistical analyses. The normal distribution of the data was confirmed using the Shapiro–Wilk test. The baseline dependent variables were compared among the legs using one-way ANOVA. The test–retest reliability of muscle strength and thickness measurements was determined using the intraclass correlation coefficient (ICC) in six healthy men (age: 21.7 ± 0.5 years; height, 169.8 ± 3.7 cm; and body weight, 68.8 ± 11.4 kg), with a 2-week interval. A split-plot ANOVA with two factors (legs [TL vs. NTL vs. control] × time [pre vs. post-training]) was used to compare the legs for changes in dependent variables. When significant interactions were observed, post-hoc pairwise comparisons with Bonferroni adjustment were performed. In addition, paired t-tests with Bonferroni adjustment were applied to explore within-leg changes from PRE to POST for descriptive purposes. Effect size (ES) was calculated as the difference in the mean value between the PRE and POST measurement values divided by the pooled SD (Cohen 1988). The ES (d) of 0.00–0.19 was considered trivial, 0.20–0.49 as small, 0.50–0.79 as moderate, and ≥0.80 as large. The ES for the split-plot ANOVA (η_p^2) was classified as small ($\eta_p^2 < 0.01$), medium (0.02–0.1), or large (>0.1) (Cohen 1988). Statistical significance was defined as $p < 0.05$. Descriptive data are reported as mean ± SD.

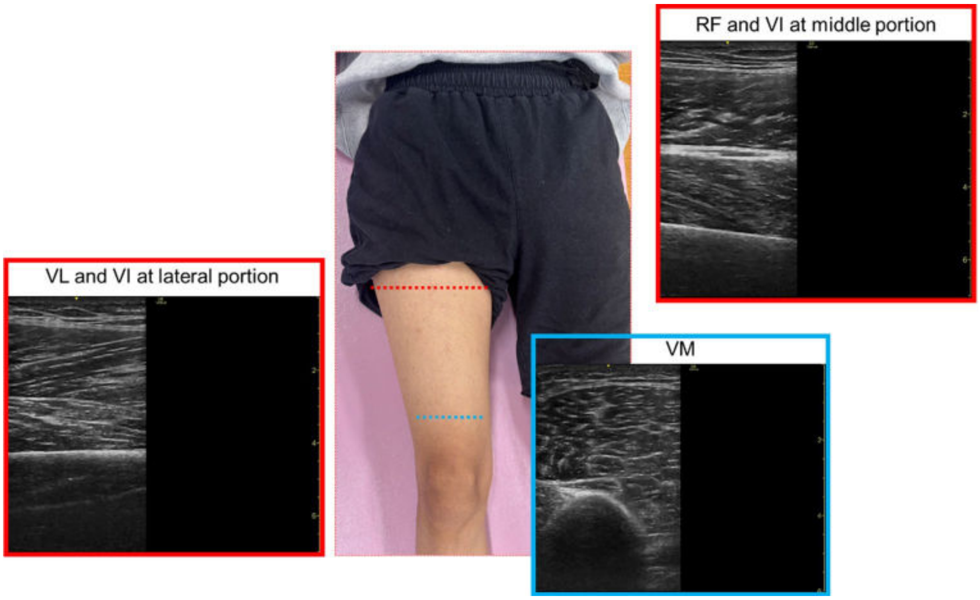

Fig. 1 Position of ultrasound assessment and examples ultrasound images
VL vastus lateralis, VM vastus medialis, RF rectus femoris, VI vastus intermedius

Results

Baseline values

No significant differences were found between the TL, NTL, and control legs in the experimental and control groups for any of the baseline variables.

Test–retest reliability of the outcome measures

The ICC values for the MVIC, MVCC, and MVEC torques were 0.990, 0.987, and 0.816, respectively, with typical errors of 3.1 Nm, 2.6 Nm, and 10.4 Nm, respectively. In addition, the ICCs for muscle thickness measurements of the RF, VI in the middle portion, VL, VI in the lateral portion, and VM were 0.838, 0.940, 0.932, 0.954, and 0.944, respectively. The corresponding typical errors for these muscle thickness measurements were 1.8 mm, 1.2 mm, 0.6 mm, 0.6 mm, and 0.8 mm, respectively.

Changes in the variables after training

Figure 2 shows the changes in MVIC, MVCC, and MVEC torques from pre- to post-training for each participant, along with the average (±SD) of 14 participants for the TL and NTL and of 12 participants for the dominant leg in the control group. A significant interaction effect was evident for MVIC (F [2, 48] = 3.990, $p = 0.027$, $\eta p^2 = 0.177$), MVCC (F [2, 48] = 6.671, $p = 0.003$, $\eta p^2 = 0.265$), and MVEC torque (F [2, 48] = 4.698, $p = 0.015$, $\eta p^2 = 0.203$) between the legs in the experimental group and the dominant leg in the control group. A significant increase in MVIC ($p = 0.042$, d = 0.66), MVCC ($p = 0.001$, d = 0.65), and MVEC ($p < 0.001$, d = 0.87) torque was observed only for the TL. No significant changes were detected in the NTL and control groups.

Table 1 presents the pre- and post-training values of muscle thickness for the RF, VI, VL, and VM in the TL and NTL of the training group ($n = 14$) and the dominant leg of the control group ($n = 12$). Two-way split-plot ANOVA revealed no significant interaction effects (leg × time) or main effects of time on any of the quadriceps muscle thickness variables ($p > 0.05$). In addition, Fig. 2 (bottom right) depicts the individual data for mean quadriceps muscle thickness (calculated as the average across RF, VI, VL, and VM), further illustrating the absence of systematic changes in any group.

Discussion

In the present study, we investigated the effects of a low-volume, high-intensity eccentric training intervention on the muscle strength and thickness of the knee extensors. Performing five maximal eccentric contractions twice per week over 2 weeks (total contraction time: 60 s) increased MVIC (15.7 ± 24.8%), MVCC (8.8 ± 7.3%), and MVEC (22.1 ± 16.4%) torques in the trained limb, while no detectable changes in muscle thickness were observed. No significant changes were observed in the contralateral untrained

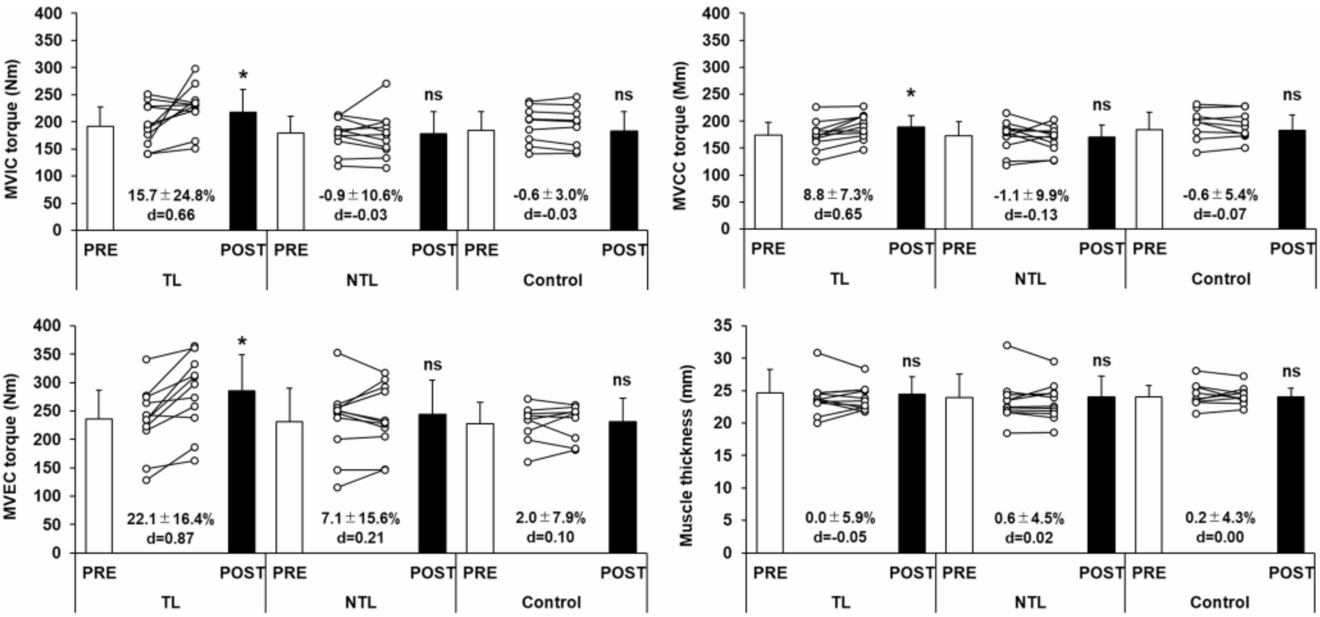

Fig. 2 Changes (mean ± SD) in maximal voluntary isometric contraction (MVIC), maximal voluntary concentric contraction (MVCC), maximal voluntary eccentric contraction (MVEC) torques, and average muscle thickness of quadriceps muscle (vastus lateralis, vastus intermedius, rectus femoris, and vastus medialis) before (PRE) and after (POST) in 2-week intervention maximal eccentric contraction trained (TL) and non-trained (NTL) legs and the dominant leg in the control group. The average (±SD) magnitude of change (%) is included, and "Cohen's d" for the difference between PRE and POST values is also shown. *: significantly ($P < 0.05$) different from the PRE value

Table 1 Mean ± SD muscle thickness (mm) of quadriceps muscle (vastus lateralis, vastus intermedius, rectus femoris, and vastus medialis) in 2 weeks maximal eccentric contraction trained (TL) and non-trained legs (NTL) and the dominant leg in the control group. Cohen's d effect size. The split-plot analysis of variance (ANOVA) results (T: time effect, C x T: condition x time interaction effect; F-value) and partial η^2 (η_p^2) are shown in right column

	TL		NTL		Control		ANOVA results
	PRE	POST	PRE	POST	PRE	POST	P value, F value, η_p^2
Vastus Lateralis	24.4±4.0	24.1±3.7	23.4±4.3	23.2±3.7	22.5±3.3	22.2±2.9	T: $p=0.493$, F=0.481, $\eta_p^2=0.013$
	d = -0.08		d=0.01		d = -0.09		C x T: $p=0.996$, F=0.004, $\eta_p^2<0.01$
Vastus Intermedius at lateral portion	18.3±4.2	19.0±2.9	17.9±3.0	17.8±3.2	17.4±2.2	17.1±2.4	T: $p=0.823$, F=0.05, $\eta_p^2<0.01$
	d = -0.08		d = -0.06		d = -0.12		C x T: $p=0.748$, F=0.293, $\eta_p^2=0.02$
Rectus Femoris	26.1±2.5	25.8±2.5	24.1±3.1	24.4±2.8	24.1±2.2	24.8±2.1	T: $p=0.401$, F=0.721, $\eta_p^2=0.019$
	d = -0.13		d=0.10		d=0.36		C x T: $p=0.308$, F=0.109, $\eta_p^2=0.06$
Vastus Intermedius at middle portion	20.6±5.1	20.2±5.4	21.5±5.2	21.5±4.7	22.5±3.3	22.4±3.1	T: $p=0.706$, F=0.144, $\eta_p^2<0.01$
	d = -0.08		d=0.01		d = -0.02		C x T: $p=0.897$, F=0.109, $\eta_p^2<0.01$
Vastus Medialis	33.8±5.9	33.5±6.0	32.9±6.5	33.2±6.7	33.8±4.36	33.7±4.3	T: $p=0.905$, F=0.01, $\eta_p^2<0.01$
	d = -0.05		d=0.04		d = -0.02		C x T: $p=0.756$, F=0.282, $\eta_p^2=0.015$

PRE, before resistance training program; POST, after resistance training program

limb or the control group ($p>0.05$). Despite the considerable inter-individual variability in training responses, increases in MVC torque were evident in most participants in the training group, with 11 of 14 participants showing increases in MVIC torque and 13 of 14 participants showing increases in both MVCC and MVEC torque (Fig. 2). These findings suggest that even a very short duration of eccentric training can induce notable strength gains, although these increases occurred in the absence of detectable hypertrophy. However, the present results also indicate that this minimal-volume eccentric training protocol was insufficient to elicit a cross-education effect, contrary to our hypothesis.

In line with a previous study (Sato et al. 2022a), the lack of detectable hypertrophic changes, despite marked strength gains, suggests that neural adaptation may have played a primary role in the observed improvements. Short-term strength gains after resistance training are commonly attributed to increased motor unit recruitment efficiency, elevated firing frequency, and improved coordination of synergistic muscles (Pearcey et al. 2021). Notably, eccentric contractions modulate cortical and spinal excitability (Tallent et al. 2017; Douglas et al. 2017; Lepley et al. 2017). For example, Tallent et al. (2017) reported greater increases in corticospinal excitability and V-wave amplitudes following eccentric versus concentric training of the tibialis anterior muscle at 80% MVC. Although they used a higher training volume and lower exercise intensity, their results highlight the superior neural adaptations associated with eccentric contraction.

Interestingly, in the present study, strength gains were observed in eccentric, isometric and concentric muscle contractions, despite training involving only eccentric contractions. Although this may seem inconsistent with the principle of contraction-type specificity, research has documented cross-type strength gains after eccentric-only isokinetic training (Colson et al. 1999; Walker et al. 2016; Sato et al. 2022a, b; Yoshida et al. 2022, 2024b; Spudić and Nosaka 2025). Such a generalization likely reflects the broader neural adaptations induced by high-intensity (i.e., 100% MVC) eccentric contractions. Sato et al. (2022a) reported that performing one maximal voluntary eccentric contraction of the elbow flexors for just 3 s daily, five times a week over 4 weeks, resulted in improvements in isometric, concentric, and eccentric torques of the elbow flexors by 10%, 13%, and 12%, respectively. Conversely, Tallent et al. (2017) reported contraction–type–specific increases following moderate-intensity eccentric training (80% MVC), performed as five sets of six repetitions per session, three times a week for 4 weeks. These differences may result from variations in training intensity and volume. Therefore, our protocol utilized maximal eccentric contractions with markedly lower volumes, potentially eliciting a more robust stimulus for generalized strength gains.

Despite the observed increase in muscle strength, no significant alterations in muscle thickness were detected on the trained leg. This outcome is likely attributable to the brief duration of the intervention period and low overall training volume (total session time under tension: 60 s), which may have been inadequate to elicit muscle hypertrophy. This finding is consistent with those of previous studies suggesting that a certain minimum weekly training volume is necessary to stimulate hypertrophic adaptations (Schoenfeld et al. 2017). Interestingly, in previous studies, we observed increases in muscle thickness of the elbow flexors following low-volume eccentric training (Yoshida et al. 2022). Yoshida et al. (2022) reported similar increases in muscle thickness following a 4-week intervention, wherein one group performed six maximal eccentric contractions per day, five days a week, and the other completed 30 contractions in a single weekly session. These findings suggest that an extended intervention period or a higher weekly training volume may be necessary to induce increases in lower-limb muscle thickness through low-volume eccentric training.

Although previous studies have demonstrated the efficacy of eccentric training in increasing the cross-educational effect (Kidgell et al. 2015; Manca et al. 2021; Maroto-Izquierdo et al. 2022), the isokinetic eccentric-only training regimen employed in this study did not result in a muscle strength increase in untrained legs. The protocol, which involved a maximum of five eccentric contractions per session over a 2-week period, may have been inadequate to produce a plausible cross-education effect on non-trained limbs. The magnitude of the cross-education effect is influenced by several factors, including intensity, volume, and frequency of training, type of contraction, and duration (Manca et al. 2017). Additionally, research suggests that training protocols should encompass at least 13–18 sessions or a period of 4–6 weeks to achieve functionally significant strength gains in the untrained limb (Manca et al. 2021). Consequently, the findings of our study underscore the significance of absolute training duration and volume in facilitating the cross-education effect. Future research should investigate whether extending the training duration or increasing the frequency of contractions per week or within each session can improve strength gains in the untrained limb, even in the context of low-volume (i.e., microdosing) eccentric training.

From a mechanistic perspective, the dissociation between robust strength gains in the trained limb and the absence of meaningful strength changes in the contralateral untrained limb may reflect differences in the sensitivity and thresholds of neuromuscular adaptations to training volume and frequency. Strength improvements in the trained limb are likely driven by relatively localized and early neural adaptations, which can occur rapidly in response to high-intensity voluntary effort even under minimal training volume (Pearcey et al. 2021; Škarabot et al. 2021). In contrast, cross-education, which has often been reported to reach approximately 50% of the strength gains observed in the trained limb (Manca et al. 2017, 2021), appears to depend on more central and widespread neural plasticity, including bilateral cortical reorganization, and the modulation of interhemispheric inhibition (Kidgell et al. 2015). Such centrally mediated adaptations likely require a greater cumulative training stimulus to exceed the neural threshold necessary for contralateral transfer. Accordingly, although the present low-volume and short-duration protocol was sufficient to elicit limb-specific neural adaptations and strength gains in the trained limb, it was likely inadequate to induce the magnitude of central neuroplastic changes required for meaningful strength expression in the untrained limb. This interpretation suggests that cross-education is not determined solely by exercise intensity but is strongly influenced by the accumulation of neural adaptations over time. From this perspective, the importance of training frequency may also be interpreted through concepts of motor learning, where distributed practice has been shown to promote motor cortex-dependent processes and learning retention more effectively than massed practice (Kantak and Winstein 2012). This suggests that more frequent eccentric training could facilitate central neural adaptations through repeated neural inputs. Although speculative in the absence of direct neurophysiological measurements, this framework offers a physiologically plausible explanation for why strength changes in the untrained limb were limited and highlights the importance of training volume, frequency, and duration when minimal-dose eccentric training protocols are intended to elicit cross-education.

This study demonstrated that engaging in five maximal eccentric contractions twice weekly over 2 weeks can significantly improve knee-extensor strength in untrained young men, even without changes in muscle thickness. Such low-volume high-intensity protocols present a time-efficient strategy for individuals with constraints related to time, motivation, or physical capacity (Behm et al. 2024; Nuzzo et al. 2024). Given the neural-driven gains observed without hypertrophy in young, untrained men, this approach may have potential relevance for early-stage rehabilitation or older populations requiring minimal joint loading, although such implications remain speculative. Its simplicity supports its implementation in home-based and digital training programs. However, the absence of cross-education and hypertrophy indicates that this protocol should be considered an entry-level approach, rather than a comprehensive solution. For broader and more sustained adaptations, progressive increases in volume or integration with other modalities are recommended.

The present study has several limitations. First, the findings may not be generalizable to other populations such as older adults, clinical populations, or highly trained individuals. The participants in this study were healthy young men with no prior experience in resistance training; therefore, the observed effects may differ among groups with distinct baseline neuromuscular characteristics. Untrained individuals tend to experience more pronounced neuromuscular adaptations from resistance training than trained individuals (Škarabot et al. 2021; Pearcey et al. 2021). This may have contributed to the relatively large increases in muscle strength observed in this study. Second, direct neurophysiological assessments such as transcranial magnetic stimulation, electromyography, or V-wave recording were not conducted. Although neural adaptation was inferred from performance outcomes and supported by previous studies (Tallent et al. 2017; Lepley et al. 2017; Pearcey et al. 2021), the lack of objective neural measurements limits our ability to draw mechanistic conclusions regarding the underlying neuromuscular changes. Third, although this study utilized isokinetic eccentric training, more practical training modalities such as free weight exercises or bodyweight-based training are more commonly employed in real world settings. A previous study demonstrated that eccentric training can be effectively implemented using simple equipment, for example, by lifting a load concentrically with both limbs and lowering it eccentrically with a single limb, thereby enabling both supramaximal and submaximal eccentric loading in a practical manner (Krentz et al. 2017). Therefore, future studies should examine whether similar low-volume eccentric protocols that use more accessible methods can elicit comparable neuromuscular adaptations. Fourth, in this study, ultrasound assessment was used to measure muscle hypertrophy at only one location per muscle. Previous studies have demonstrated that muscle thickness measured by ultrasound assessment is a valid indicator for cross-sectional area and muscle volume measurements (Tourel et al. 2020; Högelin et al. 2022), and is a valid indicator in resistance training as described above (Ema et al. 2013; Franchi et al. 2018). However, we were unable to use extended-field-of-view ultrasound to directly quantify cross-sectional area or muscle volume, which would have provided a more comprehensive assessment of architectural adaptations (Sarto et al. 2021). On the other hand, the muscle hypertrophy effect of resistance training is heterogeneous, and hypertrophy may differ between muscle sites (Ema et al. 2013; Matta et al. 2015; Nunes et al. 2024). Thus, the ultrasound assessment of a single site per muscle used in this study may not have been sensitive enough to detect subtle early changes in muscle morphology. Future research will require the use of imaging techniques such as computed tomography and magnetic resonance imaging to more accurately assess hypertrophic changes, examining alterations at multiple sites and muscle volume. Fifth, the leg conditions were not fully balanced between the training and control groups. In the training group, the dominant leg was designated as the trained limb and the non-dominant leg as the untrained limb to examine the cross-education effect, whereas only the dominant leg was assessed in the control group. Although this design was aligned to evaluate cross-education, the potential influence of limb dominance on neuromuscular responses cannot be completely ruled out and should be considered when interpreting the findings. Finally, the intervention period was intentionally limited to 2 weeks to evaluate the effects of short-term, low-volume eccentric training. However, to capture longer-term adaptations such as muscle hypertrophy and the cross-education effect, future studies should extend the intervention's duration to at least 4–6 weeks and evaluate the time course of these physiological changes.

In conclusion, performing five maximal eccentric contractions twice per week over 2 weeks was associated with an observable increase in knee-extensor strength on the trained side, while no measurable changes in muscle thickness were detected. By contrast, strength gains were not evident in the untrained limb, suggesting that this minimal protocol may be insufficient to elicit a cross-education effect. These findings indicate that short-term, low-volume eccentric training has the potential to enhance muscle strength in a time-efficient manner, possibly through neural rather than structural mechanisms, although direct neurophysiological evidence is required to substantiate this interpretation. From an applied perspective, such an approach could be valuable in rehabilitation contexts or in settings with limited training opportunities, where rapid improvements in voluntary strength are desirable without imposing substantial mechanical load.

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Author contributions SS and MN designed the study. SS and MN collected the data and analyzed the data. All authors drafted and revised the manuscript and approved the final version of the manuscript and agreed to be accountable for all aspects of this work.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Informed consent Informed consent was obtained from all participants involved in the study.

Research involving human participants All procedures in the study were in accordance with the ethical standards of the 1964 Helsinki Declaration and its later amendments. This study was approved by the Ethics Committee of the Nishikyushu University, Saga, Japan (approval number: 23JXD08).

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