Received: 28 May 2021 | Revised: 20 November 2021 | Accepted: 27 November 2021

DOI: 10.1111/sms.14108

ORIGINAL ARTICLE

WILEY

Cross-education effects of unilateral accentuated eccentric isoinertial resistance training on lean mass and function

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Funding information
Ministerio de Educación, Cultura y Deporte, Gobierno de España, Grant/Award Number: FPU014/05732

Abstract

Purpose: We investigated the effects of three different unilateral isoinertial resistance training protocols with eccentric overload on changes in lean mass and muscle function of trained (TL) and contralateral non-trained (NTL) legs.

Methods: Physically active university students were randomly assigned to one of three training groups or a control group ($n = 10$/group). Participants in the training groups performed dominant leg isoinertial squat training twice a week for 6 weeks (4 sets of 7 repetitions) using either an electric-motor device with an eccentric phase velocity of 100% (EM100) or 150% (EM150) of concentric phase velocity or a conventional flywheel device (FW) with the same relative inertial load. Changes in thigh lean mass, unilateral leg-press one-repetition maximum (1-RM), muscle power at 40–80% 1-RM, and unilateral vertical jump height before and after training were compared between the groups and between TL and NTL.

Results: No changes in any variable were found for the control group. In TL, all training groups showed similar increases ($p < 0.05$) in 1-RM strength (22.4–30.2%), lean tissue mass (2.5–5.8%), muscle power (8.8–21.7%), and vertical jump height (9.1–32.9%). In NTL, 1-RM strength increased 22.0–27.8% without significant differences between groups; however, increases in lean mass ($p < 0.001$) were observed for EM150 (3.5%) and FW (3.8%) only. Unilateral vertical jump height (6.0–32.9%) and muscle power (6.8–17.5%) also increased in NTL without significant differences between training groups.

Conclusion: The three eccentric-overload resistance training modalities produced similar neuromuscular changes in both the trained and non-trained legs, suggesting that strong cross-education effects were induced by the eccentric-overload training.

KEYWORDS
cross-education effect, eccentric overload, muscle mass, muscle strength, one-leg vertical jump, one-repetition maximum

1 | INTRODUCTION

Unilateral exercise training affects not only the muscles of a trained limb but also the muscles of the non-trained contralateral limb, which is known as the cross-education or cross-transfer effect.[1–5] In particular, unilateral resistance exercise training improves strength in both the trained ipsilateral limb and the homologous muscles in the non-trained contralateral limb.[2,5,6] The magnitude of the cross-education effect on muscle strength is ~20%, with a greater effect in lower limb (27%) than upper limb muscles (13%).[1–3] Although the mechanisms underpinning this cross-education effect have not been fully elucidated,[7] both neurological and muscular mechanisms have been proposed.[1]

Several studies have shown that resistance training (RT) using eccentric (lengthening) muscle actions increases strength in the non-trained contralateral limb,[2,3] even when movement velocity[8,9] or contraction mode differs between the test and the training regimens.[10] For example, Hortobagyi et al.[11] showed that 12 weeks of eccentric-only or concentric-only isokinetic training produced significant increases in maximal voluntary isometric contraction strength of the non-trained contralateral limb muscles (39% and 22%, respectively), potentially indicating that RT with eccentric muscle actions produces greater cross-education effect on the non-trained homologous muscle than concentric-based exercise.[9,12] Furthermore, Tseng et al.[12] reported that 5 weeks of progressive isokinetic eccentric-only RT led to greater cross-education in isometric contractions than isokinetic concentric-only RT in young men (muscle strength of the contralateral non-trained elbow flexors increased 11% and 5%, respectively).

In traditional RT modalities, concentric and eccentric contractions are usually coupled and performed repetitively, so the load is determined by an individual's maximal concentric muscle strength, that is, the ability to lift rather than lower the load.[13] Thus, the stimulus applied to muscles during the eccentric phase is usually suboptimal, since muscles can produce greater maximum eccentric than concentric forces due to the well-described force-velocity characteristics of muscles.[14] Thus, overloading the eccentric phase in RT may be useful to enhance neuromuscular adaptations during traditional eccentric-concentric training.[15] To promote eccentric overload during RT, non-gravity-dependent technology such as isoinertial flywheel devices (FWs) or electric-motor devices have been introduced.[16] These technologies allow for greater loads to be imposed during the eccentric phase either by using the energy stored in the system during the concentric phase (ie, inertial kinetic energy) or directly by a motor controlled by a software applying during the eccentric phase.[16]

Flywheel devices require maximal concentric contractions to be performed in order to induce momentum in the flywheel to then allow the greatest resistance in the eccentric phase, and subsequently for the greatest active braking forces to be produced in the short period of time at the end of the eccentric phase.[17] Thus, eccentric overload is provided largely toward the end range of motion (ROM) with muscles at longer lengths,[18] which in turn provides an ideal stimulus for muscle hypertrophy[19] and promotes a specialized motor unit activation pattern.[20] Indeed, flywheel RT has been shown to produce rapid and significant neuromuscular adaptations, which appear to be greater than those achieved by conventional weight-stack RT for some functional, anatomical (ie, muscle size), and physiological parameters.[18,21,22] Electric-motor devices, on the contrary, are capable of generating eccentric overload throughout the full ROM at different eccentric movement velocities.[16] Similar effects have been observed for flywheel and electric-motor devices regardless the amount of eccentric overload and eccentric phase length used.[16] Notwithstanding, whether the amount of eccentric overload and the ROM at which the overload is applied impacts cross-education in the non-trained contralateral leg remains unknown. To the best of our knowledge, no study has reported the effects of unilateral RT with eccentric overload on the contralateral untrained limb.

Therefore, the aim of the present study was to investigate the cross-education effect induced by accentuated eccentric isoinertial RT and to compare the effects between flywheel RT and isoinertial motor-driven eccentric RT on changes in lower limb lean mass and muscle function of trained and non-trained legs in physically active men. Given the evidence that eccentric RT of one limb produces a strong cross-education effect on the contralateral limb,[2] it was hypothesized that a greater eccentric overload during RT would evoke greater increases in muscle strength, power and mass of the non-trained contralateral leg.

2 | MATERIALS AND METHODS

2.1 | Participants and study design

Male sports science undergraduate students ($n = 40$) volunteered for the study and were randomly allocated to one of the three training groups (training with an electric-motor device with an eccentric phase velocity of 100%: EM100, or 150%: EM150, and training with a conventional flywheel device: FW) or a non-training control group ($n = 10$ per group). No significant differences in age (EM100: 21.3 ± 1.1 y; EM150: 21.1 ± 0.6 y; FW: 21.4 ± 2.2 y; control: 22.7 ± 3.4 y), body mass (EM100: 76.8 ± 8.2 kg; EM150:

74.8 ± 6.6 kg; FW: 75.1 ± 8.9 kg; control: 76.7 ± 11.1 kg), or height (EM100: 180.0 ± 4.6 cm; EM150: 179.1 ± 6.0 cm; FW: 175.8 ± 5.9 cm; control: 175.3 ± 5.1 cm) were evident between the groups. Participants were moderately active and healthy, and engaged in 6–8 h of recreational physical activities per week. They had no history of regular lower limb strength training and no muscle joint or bone injury in the last 6 months. They were informed of the purposes and risks involved in the study before giving their informed written consent to participate. They were asked not to change their exercise habits and not to perform resistance exercises for the opposite leg from the trained leg. The participants in the control group continued with their daily activities, without any RT for the leg muscles. The Ethics Committee of the University of León approved the study protocols (ETICA-ULE-009-2018). All participants completed all the protocols, including two familiarization sessions, the prescribed training program, and the pre- and post-training tests.

Sample size was estimated using the data from a previous study[9] in which the cross-education effect on strength was investigated for lower limb muscles. Based on the effect size of 1.0 for a possible difference in muscle strength changes between the ipsilateral and contralateral limbs, it was estimated that at least eight participants were necessary for each group, with the alpha level of 0.05 and power ($1-\beta$) of 0.80 by G*Power (G*Power 3.1.9.2, Heinrich-Heine-Universitat Dusseldorf, Dusseldorf, Germany; http://www.gpower.hhu.de/). Considering possible dropouts and an estimation error, 10 participants were recruited for each group.

The training groups completed 12 sessions of unilateral single-leg squat resistance exercise over 6 weeks (2 sessions per week) with the dominant leg, as detailed in the next section. Outcome measures included thigh lean mass, maximal dynamic leg press strength (1-RM), vertical jump performance (countermovement jump: CMJ, squat jump: SJ, and drop jump: DJ), and muscle power at different relative intensities of 1-RM for both training leg (TL) and non-training leg (NTL). These measures were taken one week before the first training session and 1 week after the last training session, and were also taken from both legs in the control group. Changes in the variables from pre- to post-training for the trained and non-trained legs were compared between groups.

2.2 | Training protocols

The training protocols were described in detail previously.[16] Briefly, participants in the three training groups performed 12 sessions of a single-leg squat resistance exercise with at least 48 h of rest between sessions over 6 weeks. Each session consisted of 4 sets of 7 maximal unilateral squat movements with coupled concentric and eccentric muscle actions of the dominant leg, which was determined by the leg to shoot a ball on a target.[23] One group used a conventional flywheel device (FW) (Kinetic Box, Kbox, Exxentric AB TM), and the other two groups used an electric-motor device (Exentrix, SmartCoach™) configured in isoinertial mode at two different velocities during the eccentric phases: 100% (EM100) or 150% (EM150) of the concentric phase speed. Participants in FW used the flywheel device with one 4.2-kg flywheel (0.05 kg m^2). They were instructed to resist gently during the first two-thirds of the ROM in the eccentric phase and thereafter to apply maximal braking force to stop the movement at about 110º of knee flexion. EM100 and EM150 performed a similar exercise to that described for the flywheel exercise but used the electric-motor device with a load of 37 inertial units (also 0.05 kg m^2). The software was configured to set the eccentric phase at 150% faster than the concentric phase velocity for EM150 and at the concentric phase speed (100%) for EM100. The electric-motor device produced eccentric overload through the entire ROM in both groups. Therefore, the instruction given to EM100 and EM150 participants was to stop the movement before reaching the end of the ROM. ROM was set up for each participant from 0° of knee flexion to 110° using a goniometer before each session. In the case of the electric-motor device, participants were allowed to apply braking force through the entire ROM. In the case of the flywheel device, participants were instructed to resist gently, and thereafter to apply maximal breaking force to try stopping the movement between 90º and 110° knee flexion. To ensure that participants employed the same squat depth at each repetition, an adjustable tripod with a telemetric photocell (Microgate) was placed at the side of the flywheel. The telemetry photocell emitted a sound when the knees reached the individual set height fixed at 90º knee flexion. In both EM and FW exercises, the instep of the non-trained leg (NTL) was placed on a 40-cm box located 60–80 cm from the front foot (TL foot). TL foot was positioned in such a way that the ankle malleolus was at the same height as the cable outlet. A point of support was established at the height of the baldness of each participant, in which they were allowed to place two fingers of each hand (see Figure S1). Participants were instructed not to use the back leg to produce force.

Electromyography (EMG) activity in vastus lateralis, rectus femoris, biceps femoris, and gluteus medius in the non-training leg was measured in a small subset of individuals, and EMG amplitudes were found to be ~20–30% of those observed in the training leg (see Figure S2); these were considered too low to evoke an adaptive response. Power was measured by a rotary encoder during each repetition (concentric and eccentric muscle actions; SmartCoach™ in the case of FW and Exentrix PC Interface-V2.4, SmartCoach™ in the case of EM100 and EM150), and real-time feedback was provided on a computer monitor to ensure that each repetition was performed with the maximum movement intention and that the development of concentric peak power remained stable during each set and between sets in each training session. All participants were familiarized over two sessions (the first familiarization session consisted of 4 non-maximal sets of 7 reps with an inertial load of 0.025 kg m^2, and the second familiarization session consisted of 1 non-maximal and 2 maximal sets of 7 reps with an inertial load of 0.05 kg m^2) with the single-leg squat exercise ~1 week before the first training session.

2.3 | Dependent variables

2.3.1 | Lean tissue mass

Dual-energy X-ray absorptiometry (DXA) was performed ~1 week before the first training session and 1 week after the last training session, at the same time of the day, using a Lunar Prodigy® whole-body scan (GE Medical Systems) accordingly with the protocols described by Nana et al.[24] and Tavoian et al.,[25] that is, participants were encouraged to have a similar sleeping time and eating for both scans and to avoid any exercise on the morning of the scan. They were advised to report to the laboratory in a euhydrated state, fasted overnight and with the bladder voided. They were asked to wear underwear and to remove all jewelry and metal objects. Care was taken to follow The International Society for Clinical Densitometry guidelines for positioning during the scan.[26] A manual analysis was performed to estimate total thigh lean mass of each leg following the protocol described by Fernandez-Gonzalo and colleagues.[27] Lean tissue mass estimation in each thigh was calculated using the device's software (Encore® 2009 software, Lunar Corp.). The error attributable to manual positioning of the region of interest limits, assessed from repeated analysis of the scans of twenty random subjects, was 1.0%.

2.3.2 | Unilateral maximal dynamic force

Twenty-four hours after DXA scanning, the unilateral one-repetition maximum (1-RM) load in the leg press exercise was assessed on a 45º inclined leg press device (Gerva-Sport). Each participant performed the 1-RM test from full knee extension (0°) to 90º flexion and then extending to full extension with a load corresponding to approximately 3-RM. The load was increased by 10 kg if the participant succeeded or decreased 5 kg if they failed. Testing ended when each participant was unable to overcome a given load in two successive trials. Unilateral 1-RM load was achieved between 3 and 6 attempts, and trials were interspersed by a 2-min recovery. Participants were asked to place the untested leg with the knee flexed and the foot propped on the ground. The 1-RM test was performed twice for each leg; 3–5 days before and 3–5 days after the training period. A warm-up of 5-min cycling, 25 repetitions of skipping, 25 repetitions of butt kicks, and one set at ~8 RM load preceded the 1-RM test. The partial reliability (intraclass correlation coefficient, ICC) was 0.98 (95% CI: 0.93–0.99) for the TL and 0.94 (95% CI: 0.84–0.98) for the NTL.

2.3.3 | Unilateral maximal dynamic power

Forty-eight hours after the 1-RM test, each participant completed six sets of three unilateral repetitions from full knee extension (lowered with control) to 90º flexion and then extending to full extension (0º) in the leg press, as described above, with a 2-min recovery between sets. To avoid use of the stretch-shortening cycle, each repetition started from a static position (load was individually locked at the exact point of 90º knee flexion by a security strap). The warm-up protocol described for the 1-RM test was also performed before the muscle power test. Sets were performed at 40%, 60%, and 80% of 1-RM, and the order of the sets and the limb assessed were individually randomized before testing and replicated at post-training testing. Participants were asked to perform the concentric phase of each repetition as fast as possible. Concentric mean power data for each repetition were captured at 1000 Hz using an encoder (T-FORCE Dynamic Measurement System, Ergotech Consulting S.L.) and the associated software (T-Force v. 2.28). The best repetition performed at each load was used for data analysis. Partial reliability (ICC) for unilateral concentric mean power was high across all loads (40%: 0.91 [95% CI: 0.81–0.96]; 60%: 0.93 [95% CI: 0.86–0.97]; 80%: 0.90 [95% CI: 0.80–0.96]).

2.3.4 | Unilateral vertical jump performance

Vertical jump tests were completed immediately after the DXA scan. A warm-up of 5-min cycling, 25 repetitions of high knee, 25 repetitions of butt kicks, and 1 set of 10 repetitions of body-weight squat exercise were completed before the tests. Jump height was measured for three jump types performed unilaterally on a contact platform (Globus Ergotester®, Globus): squat jump (SJ), countermovement jump (CMJ), and drop jump (DJ). SJ was performed from a 90º knee flexion with hands on the hips. For CMJ, participants started in a standing straight position and were instructed to jump as high as possible with hands on the hips. In DJ, participants stepped off the platform of a box of 45 cm above the ground and then jump as high as possible immediately after landing. Jump height (and DJ contact time: DJ CT) was recorded to the nearest 0.1 cm (0.05 s for contact time) with a partial reliability (ICC) of 0.98 (95% CI: 0.95–0.99). Three trials, with 30 s recovery, were allowed and the best result was included in the data analysis.

2.4 | Magnitude of cross-education effect

The magnitude of the cross-education effect from TL to NTL for each variable was calculated using the following formula[5]:

$$\text{Cross} - \text{education effect of training} = \frac{\text{NTL \% gain}}{\text{TL \% gain}} \text{x} \, 100$$

2.5 | Statistical analyses

Statistical analyses were performed using SPSS v.20.0 (SPSS Inc.). Data distribution was examined for normality using the Shapiro-Wilk test. A three-way analysis of variance with repeated measures (group × time × leg) and Bonferroni post hoc tests were used to investigate differences in variables after training within participants and between groups. The effect size (ES) was calculated for interactions between groups using Cohen's guidelines. Threshold values for ES were >0.2 (small), >0.6 (large), and >2.0 (very large).[28] According to Carroll et al.,[6] the size of cross-education effect of training was given by the difference between the mean change in any variable of NTL and was expressed as a percentage of the initial variable magnitude in NTL before training. In order to quantify the magnitude of the cross-education effect from the trained to non-trained leg, data from participants in the three training groups ($n = 30$) were pooled to make an "eccentric overload" training group (EO), since no significant differences in the changes in most outcome measures were detected between the training groups (see Results) and equality of variances between groups were observed (Levene's test). A three-way mixed analysis with repeated measures (group × time × leg) followed by Bonferroni post hoc testing was performed for this group to assess changes in the dependent variables from pre- to post-training. In addition, Pearson's r was used to examine correlations between TL and NTL for the percent changes in each dependent variable from pre- to post-training for the participants in the three training groups. For all statistical analyses, a significance level was set at $p < 0.05$. Results are reported as mean ± SD.

3 | RESULTS

3.1 | Training

The average peak power for the concentric phase increased ($p < 0.01$) from the first to the last training session, but the increases were similar between EM100 (523.6 ± 154.0–792.0 ± 149.1 W, Δ51%), EM150 (559.9 ± 86.9–785.2 ± 98.3 W; Δ40%), and FW (468.0 ± 117.7–712.0 ± 180.0 W; Δ52%). In all training sessions, the mean eccentric overloads in terms of power relative to the concentric average peak power were −13.3 ± 7.6% in EM100 (CON: 683.2 ± 67.9 W; ECC: 595.3 ± 96.6 W), 114.0 ± 5.2% in EM150 (CON: 698.0 ± 71.5 W; ECC: 1493.9 ± 153.6 W), and 44.7 ± 16.8% in FW (CON: 582.4 ± 62.7 W; ECC: 843.0 ± 161.9 W), which were significantly ($p < 0.001$) different each other. The average peak forces generated in the eccentric phase relative to the concentric average peak force were 17 ± 4.1% in EM100 (CON: 685.4 ± 79.9 N; ECC: 800.1 ± 125.8 N) and 50.7 ± 6.5% in EM150 (CON: 696.6 ± 73.3 N; ECC: 1053.3 ± 66.0 N). Eccentric overload in terms of average peak force was not reported by the flywheel device. The mean concentric velocity (0.95 ± 0.07 m/s) and peak concentric phase velocity (1.52 ± 0.10 m/s) were similar between the training groups, but the peak eccentric phase velocity was faster ($p < 0.01$) in EM150 (1.88 ± 0.19–2.35 ± 0.17 m/s) and FW (1.82 ± 0.24–2.29 ± 0.19 m/s) than EM100 (1.36 ± 0.19–1.70 ± 0.15 m/s).

3.2 | Lean tissue mass

All training groups (FW, EM100, and EM150) increased total thigh lean mass ($p < 0.01$) after the 6-week training period, but no significant changes were found for the control group. The thigh lean mass increased by 2.6–5.1% ($p < 0.01$) for all training groups in TL (95% CI: 84.8–308.0, $F_{1,29}$ = 12.1–48.7, ES: 0.23–0.44). A significant ($p < 0.001$) increase in NTL thigh lean mass was also found in EM150 (3.5%, 95% CI: 82.3–310.2, $F_{1,29} = 14.0$, ES = 0.27) and FW (3.8%, 95% CI: 178.9–394.9, $F_{1,29} = 15.7$, ES = 0.32) (Figure 1A). When comparing the lean tissue mass changes between TL and NTL, no interaction effect was observed for any group (Figure 1A).

When the three training groups were combined into an "eccentric-overload training" group (EO) (Table 1),

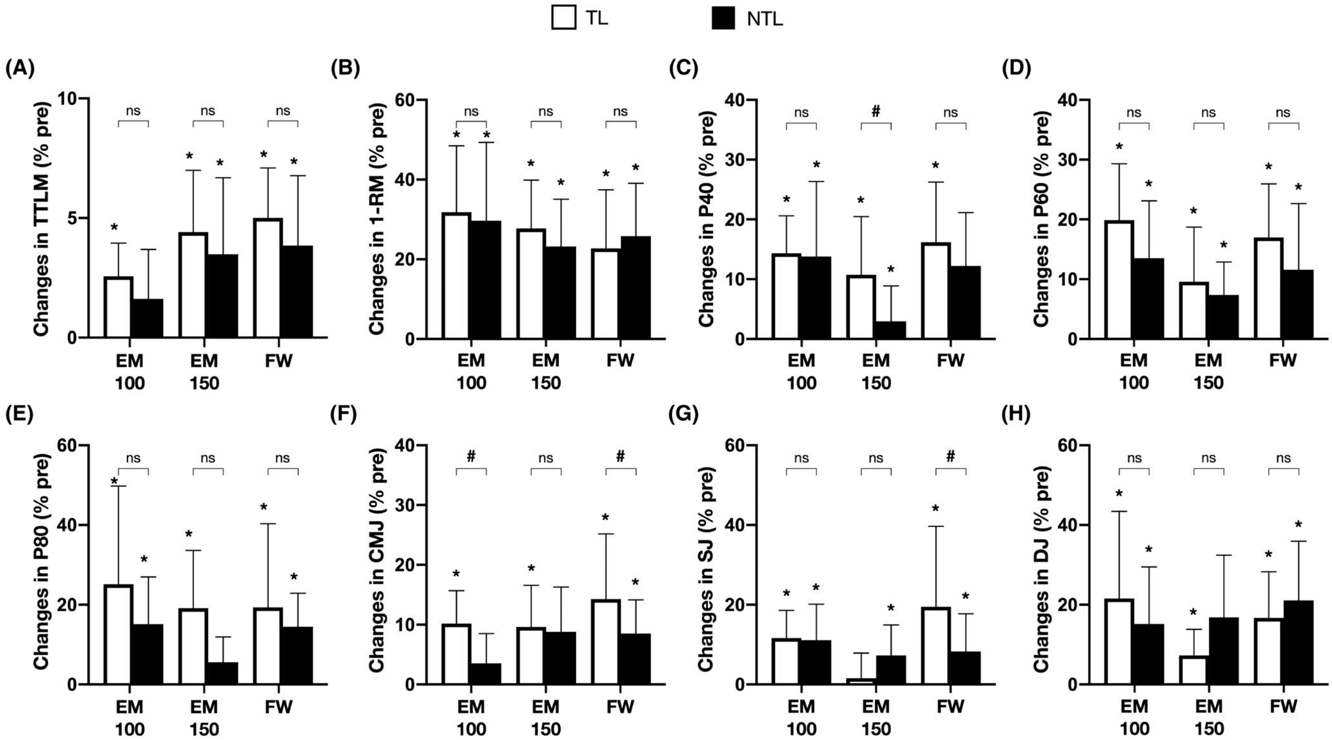

FIGURE 1 Relative changes from the baseline values (mean ± SD) in thigh lean mass (TTLM, A), one-repetition maximal of one leg press (1-RM, B), concentric mean power at 40% (P40, C), 60% (P60, D) and 80% of 1-RM (P80, E), countermovement jump height (CMJ, F), squat jump height (SJ, G) and drop jump height (DJ, H) for the trained leg (white) and non-trained leg (black) in the EM100, EM150, and FW groups. *A significant ($p < 0.05$) change from the baseline. #A significant ($p < 0.05$) difference from the trained leg. ns: no significant difference between groups for the trained leg

significant ($p < 0.001$) increases in lean thigh mass were observed after training in both TL (4.1%, 95% CI: 212.8–335.2, $F = 83.0$, ES = 0.33) and NTL (3.1%, 95% CI: 123.4–273.4, $F_{1,39} = 28.9$, ES = 0.25); however, the increase was greater ($p = 0.008$, $F_{1,39} = 8.3$) in TL than NTL. A significant ($p < 0.001$) correlation between TL and NTL was found for the change in lean thigh mass ($r = 0.76$, Figure 2A).

3.3 | 1-RM strength

Similar 1-RM increases ($p < 0.001$) were observed in TL (EM100: 30.2 ± 16.6%, 95% CI: 39.6–73.8, $F_{1,29} = 45.7$, ES = 1.49; EM150: 27.6 ± 12.9%, 95% CI: 31.8–65.9, $F_{1,29} = 34.1$, ES = 1.39; FW: 21.9 ± 15.6%, 95% CI: 29.0–63.2, $F_{1,29} = 30.3$, ES = 1.20) and NTL (EM100: 27.8 ± 20.8%, 95% CI: 34.2–66.9, $F_{1,29} = 39.6$, ES = 1.32; EM150: 22.0 ± 12.6%, 95% CI: 23.1–55.8, $F_{1,29} = 24.1$, ES = 1.32; FW: 24.7 ± 14.0%, 95% CI: 32.5–65.3, $F_{1,29} = 37.1$, ES = 1.30) (Figure 1B), but the control group did not show statistical change. When comparing TL and NTL, no significant ($p>0.05$) differences were found in the 1-RM change (Figure 1B).

In EO, both TL and NTL showed similar increases in 1-RM ($p < 0.001$, 95% CI: 40.8–60.2 and 36.9–55.6; $F_{1,39} = 113.3$ and 102.5, respectively), as shown in Table 1. A significant ($p < 0.001$) correlation was found between TL and NTL for the changes in 1-RM strength ($r = 0.84$) (Figure 2B), but no statistical difference was detected for the magnitude of the increase (93.9%) between TL (27.4 ± 14.6%) and NTL (26.3 ± 15.0%).

3.4 | Unilateral maximal dynamic power

As shown in Figure 1C–E, all training groups showed significant ($p < 0.01$) increases in power at 40% 1-RM (EM100: 14.2%, 95% CI: 33.6–93.2, $F_{1,29} = 17.9$, ES = 0.68; EM150: 9.5%, 95% CI: 14.5–77.1, $F_{1,29} = 8.9$, ES = 0.41; FW: 16.0%, 95% CI: 43.3–105.9, $F_{1,29} = 23.7$, ES = 0.91), 60% 1-RM (EM100: 18.6%, 95% CI: 60.4–121.4, $F_{1,29} = 37.1$, ES = 1.04; EM150: 8.8%, 95% CI: 16.7–77.7, $F_{1,29} = 10.0$, ES = 0.44; FW: 15.8%, 95% CI: 52.1–113.0, $F_{1,29} = 30.6$, ES = 0.79), and 80% 1-RM (EM100: 20.4%, 95% CI: 36.4–145.8, $F_{1,29} = 11.6$, ES = 0.89; EM150: 16.8%, 95% CI: 10.6–140.1, $F = 10.2$, ES = 0.79; FW: 15.3%, 95% CI: 14.6–130.7, $F_{1,29} = 6.5$, ES = 0.62) in TL. Power also increased ($p < 0.001$) in NTL at all loads tested in EM100 (13.2–13.9%, 95% CI range 29.5–33.8 to 86.7–98.8, $F_{1,29}$ range 15.2–19.4, ES range 0.50–0.77)

TABLE 1 Changes (mean ± SD) in unilateral total thigh lean mass (TTLM), one-repetition maximal strength (1-RM), muscle power at different loads of the 1-RM (40%, 60%, and 80% 1-RM loads, P40, P60, and P80, respectively), countermovement (CMJ), squat (SJ) and drop jump (DJ) heights and DJ contact time (DJ CT) for the trained and non-trained legs for the training group (combination of the three groups: EO, $n = 30$) and control group ($n = 10$) before (pre) and after training (Post). p value for the comparison between pre- and post-training values by Bonferroni test, and effect size (ES) for the changes, the magnitude of change (%) are shown for each leg. The magnitude of cross-education effect based on the ratio between the trained (TL) and non-trained legs (NTL) for the change of each variable from pre- to post-training is shown on the right column (100% means that the magnitude of the change was the same between the TL and NT, and 50% means that the magnitude of the change in the NTL was 50% of that of the TL)

	Trained leg					Non-trained leg					Cross-education effect (%)
	Pre	Post	p	ES	%	Pre	Post	p	ES	%	
EO group											
TTLM (g)	6744.5 ± 802.0	7018.5 ± 866.1	<0.001	0.33	4.1^	6627.3 ± 776.3#	6825.6 ± 807.9#	<0.001	0.25	3.1*	75.6
1-RM (kg)	191.6 ± 38.9	242.2 ± 37.2	<0.001	1.33	26.4^	186.5 ± 35.0# ^	232.8 ± 36.0#	<0.001	1.30	24.8^	93.9
P40 (W)	467.9 ± 91.6	529.7 ± 96.9	<0.001	0.67	13.2^	472.3 ± 100.0	514.0 ± 103.5	<0.001	0.41	8.8^	66.7
P60 (W)	515.4 ± 103.9	588.9 ± 92.4	<0.001	0.75	14.3^	515.1 ± 102.2	568.8 ± 98.3	<0.001	0.54	10.4^	72.7
P80 (W)	477.0 ± 125.4	560.5 ± 86.4	<0.001	0.78	17.5^	496.6 ± 93.2	549.4 ± 85.6	<0.001	0.59	10.6* ^	60.6
CMJ (cm)	21.5 ± 3.6	23.8 ± 3.1	<0.001	0.68	10.7^	21.6 ± 4.0	22.4 ± 3.6#	0.003	0.21	3.7*	34.6
SJ (cm)	20.5 ± 3.6	22.9 ± 2.9	<0.001	0.73	11.7^	20.1 ± 3.6	21.6 ± 3.7#	<0.001	0.41	7.5^	64.1
DJ (cm)	18.3 ± 3.8	21.5 ± 2.8	<0.001	0.96	17.5^	18.3 ± 4.3	20.1 ± 3.8#	0.001	0.44	9.8^	56.0
DJ CT (ms)	0.534 ± 0.13	0.402 ± 0.07^	<0.001	1.26	−24.7^	0.553 ± 0.15	0.439 ± 0.09# ^	0.002	0.76	−20.6^	83.4
Control group											
TTLM (g)	6783.0 ± 1103.0	6684.3 ± 995.1	0.092	0.09	−1.5	6725.7 ± 1168.1	6669.9 ± 989.8	0.449	0.05	−0.8	-
1-RM (kg)	225.0 ± 40.3	225.7 ± 46.9	0.941	0.02	0.3	222.1 ± 41.1	225.7 ± 46.9	0.698	0.08	1.6	-
P40 (W)	518.0 ± 140.9	500.6 ± 88.8	0.324	0.14	−3.3	497.7 ± 108.6	509.4 ± 98.9	0.446	0.11	2.4	-
P60 (W)	530.6 ± 146.4	543.9 ± 127.8	0.438	0.1	2.5	557.9 ± 129.3	538.4 ± 84.5	0.311	0.18	−3.5	-
P80 (W)	508.7 ± 124.9	519.4 ± 130.5	0.727	0.08	2.1	512.4 ± 136.0	526.4 ± 118.9	0.397	0.11	2.7	-
CMJ (cm)	23.8 ± 7.4	21.4 ± 5.3	0.015	0.37	−10.1	21.4 ± 5.4	20.6 ± 5.1	0.119	0.15	−3.7	-
SJ (cm)	22.8 ± 7.9	20.8 ± 4.3	0.071	0.31	−8.8	21.5 ± 6.2	21.0 ± 5.1	0.389	0.08	−2.3	-
DJ (cm)	19.9 ± 4.1	18.9 ± 3.8	0.339	0.25	−5.0	19.4 ± 5.6	18.5 ± 4.1	0.341	0.18	−4.6	-
DJ CT (ms)	0.528 ± 0.07	0.524 ± 0.13	0.942	0.04	−0.8	0.507 ± 0.08	0.539 ± 0.11	0.529	0.33	6.3	-

#Significant ($p < 0.05$) difference from the trained leg.

*Significant ($p < 0.05$) difference in the magnitude of change between TL and NTL.

^Significant ($p < 0.05$) difference from the control group.

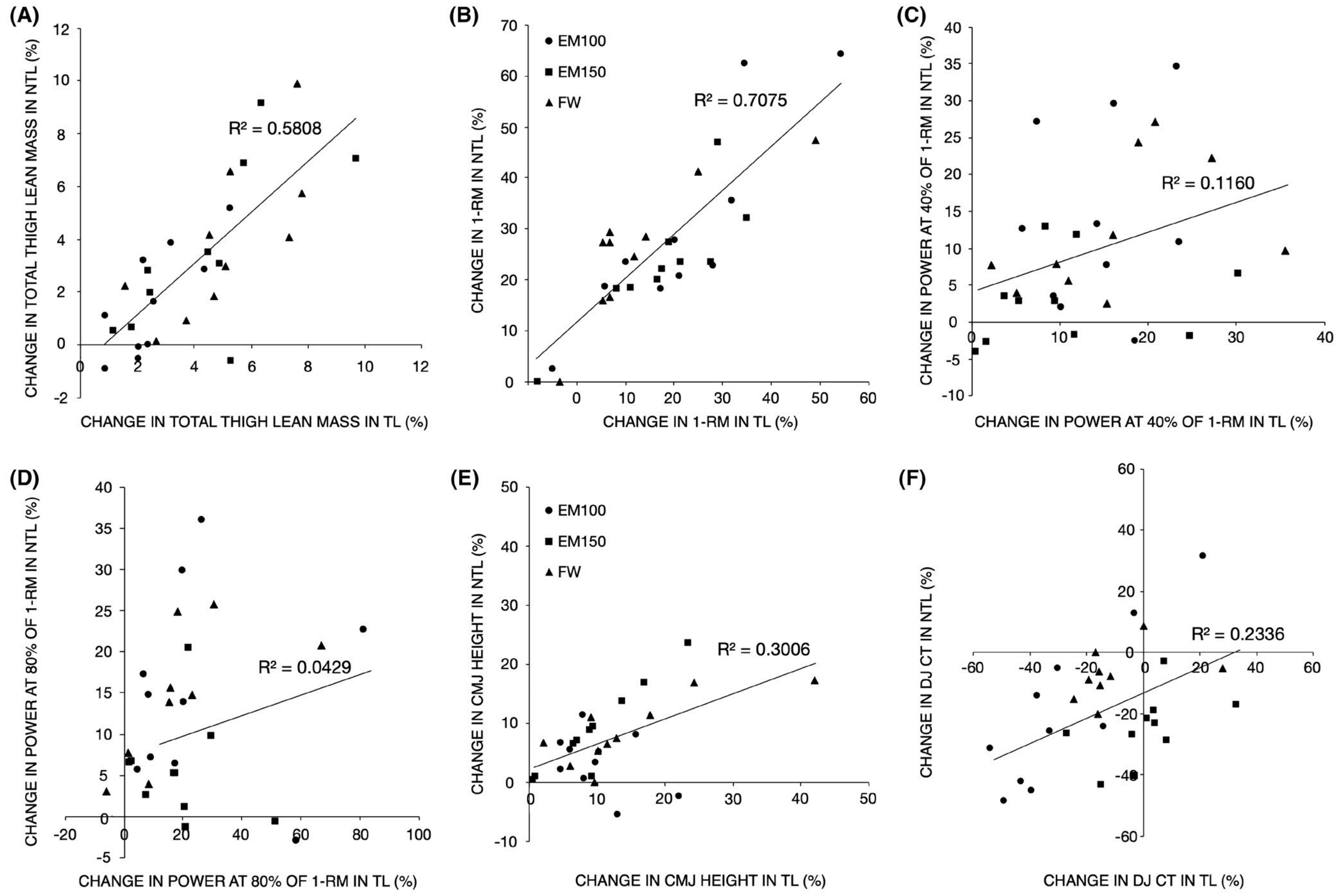

FIGURE 2 Correlations between the trained (TL) and non-trained legs (NTL) for the magnitude of changes in total thigh lean mass (A), one-repetition maximal (1-RM) strength of one leg press (B), power at 40% (C) and 80% of 1-RM (D), countermovement jump (CMJ) height (E) and drop jump contact time (DJ CT) (F) following unilateral resistance training for all participants in the three training groups (EM100, EM150, and FW) combined ($n = 30$)

and FW (11.9–13.9%, 95% CI range 24.6–36.6 to 81.8–98.9, $F_{1,29}$ range 12.4–19.8, ES range 0.49–0.79), but a statistical ($p < 0.05$) increase was evident only at 60% 1-RM (6.8%, 95% CI: 3.7–71.6, $F_{1,29} = 5.1$, ES = 0.41) for EM150. Moreover, significant differences between TL and NTL were found in EM150 at 40% 1-RM ($p < 0.05$, $F_{1,29} = 4.9$) (Figure 1C). No significant changes were detected in the control group.

In EO, similar changes were observed between TL (13.2–15.5%, 95% CI ranged 43.8–55.2 to 60.2–91.9, $F_{1,39}$ range 29.8–67.0, ES range 0.67–0.78) and NTL (8.8–10.6%, 95% CI ranged 24.2–34.9 to 59.2–73.1, $F_{1,39}$ range 23.6–36.5, ES range 0.41–0.59), as shown in Table 1. However, TL showed greater ($p = 0.022$, 95% CI: 52.2–114.6, $F_{1,39} = 6.0$) increases in muscle power at 80% of 1-RM than NTL, although no significant differences between the legs were evident for other loads (Table 1). In addition, no significant correlations were found between TL and NTL for muscle power at any load ($r = 0.21$–0.36, Figure 2C,D).

3.5 | Unilateral vertical jump performance

Significant ($p < 0.05$) increases in vertical jump height were observed for all tests performed in TL (Figure 1F–H) in EM100 (CMJ: 9.7%, 95% CI: 0.4–3.9, $F_{1,29} = 6.1$, ES = 0.65; SJ: 11.2%, 95% CI: 0.3–4.2, $F_{1,29} = 5.8$, ES = 0.67; DJ: 18.0%, 95% CI: 1.6–5.0, $F_{1,29} = 15.4$, ES = 0.89) and FW (CMJ: 12.8%, 95% CI: 0.9–4.5, $F_{1,29} = 9.8$, ES = 0.73; SJ: 17.3%, 95% CI: 1.4–5.2, $F_{1,29} = 12.4$, ES = 1.03; DJ: 17.5%, 95% CI: 1.3–5.0, $F_{1,29} = 12.4$, ES = 1.33). For EM150, significant ($p < 0.05$) increases were observed for CMJ (9.2%, 95% CI: 0.2–3.7, $F_{1,29} = 5.3$, ES = 0.59) and DJ (16.3%, 95% CI: 1.2–4.7, $F_{1,29} = 12.2$, ES = 0.81). In NTL, EM100 (SJ: 21.3%, 95% CI: 0.9–2.9, $F_{1,29} = 6.4$, ES = 1.16; DJ: 14.7%, 95% CI: 0.8–4.3, $F_{1,29} = 8.6$, ES = 0.99) and FW (CMJ: 7.7%, 95% CI: 0.7–2.4, $F_{1,29} = 14.4$, ES = 0.35; SJ: 7.5%, 95% CI: 0.5–2.5, $F_{1,29} = 9.0$, ES = 0.42; DJ: 14.0%, 95% CI: 0.5–4.2, $F_{1,29} = 6.7$, ES = 0.60) showed statistical ($p < 0.01$) increases in all variables; however, EM150 increased ($p < 0.05$) only in SJ (6.0%, 95% CI: 0.2–2.3, $F_{1,29} = 6.4$, ES = 0.33). DJ contact time was significantly ($p < 0.01$) reduced after training in both legs in EM100 (TL: −33.1%, 95% CI: −0.27 to −0.11, $F_{1,29} = 25.4$, ES = 1.51; NTL: −25.6%, 95% CI: −0.24 to −0.63, $F_{1,29} = 12.1$, ES = 1.05) and EM150 (TL: −27.1%, 95% CI: −0.21 to −0.58, $F_{1,29} = 12.9$, ES = 1.47; NTL: −26.6%, 95% CI: −0.23 to −0.51, $F_{1,29} = 10.2$, ES = 1.16), but not in FW (TL: $p = 0.136$, 95% CI: −0.14 to 0.02, $F_{1,29} = 2.3$; NTL: $p = 0.379$, 95% CI: −0.04 to 0.05, $F_{1,29} = 0.8$). When comparing the magnitude of changes in TL and NTL, significant differences were found in EM100 in CMJ ($p < 0.01$, $F_{1,29} = 9.2$) and in FW in CMJ ($p < 0.05$, $F_{1,29} = 7.4$) and SJ ($p < 0.05$, $F_{1,29} = 6.7$) (Figure 1F–G). No statistical differences were found for any variable in any leg in the control group.

In EO, both TL (10.7–17.5%, 95% CI ranged 1.2–2.2 to 3.3–4.1, $F_{1,39}$ ranged 18.3–42.3, ES = 0.68–1.26) and NTL (3.7–9.8%, 95% CI ranged 0.3–0.8 to 1.3–2.8, $F_{1,39}$ ranged 10.3–29.9, ES = 0.21–0.92) increased ($p < 0.01$) in all tests (Table 1). Significant ($p < 0.05$; $F_{1,39}$ ranged 6.5–7.5) differences between TL and NTL were found at post-training in vertical jump height in all tests as well as DJ contact time, with greater increases observed in TL than NTL. Significant ($p < 0.01$) correlations between legs were observed for CMJ ($r = 0.55$, Figure 2E) and DJ contact time ($r = 0.48$, Figure 2F), but no significant correlations were found between legs for SJ ($r = 0.24$) or DJ tests ($r = 0.18$). TL showed greater ($p = 0.001$, $F_{1,39} = 12.5$) increases in CMJ height than NTL, but no statistical differences between the legs were detected for other variables (Table 1).

3.6 | Magnitude of cross-education effect

The magnitude of the cross-education effect on each variable was calculated by the ratio between the NTL to TL for the magnitude of the increase from pre- to post-training. The effect varied between the variables, ranging from 34.6% to 93.9% (see Table 1).

4 | DISCUSSION

The present study examined the effects of eccentric-overload unilateral isoinertial RT protocols on changes in function and lean tissue mass of the trained (TL) and non-trained legs (NTL). After 12 sessions of the three eccentric-overload training protocols (EM100, EM150, and FW), comparable increases in lean tissue mass, maximum unilateral dynamic strength, unilateral muscle power at different loads, and unilateral vertical jump height were found in both TL and NTL (Table 1, Figure 1). These results, together with the significant correlations found between the magnitude of the changes in 1-RM and lean tissue mass between TL and NTL (Figure 2), indicate a strong cross-education effect of unilateral isoinertial RT with eccentric overload.

Short-term RT (ie, several weeks) with isoinertial devices such as flywheel and electric-motor systems effectively increase muscle strength,[18,21] power, lean mass, and vertical jump performance in the trained limb.[16] However, the effects of unilateral isoinertial RT on the non-trained contralateral limb have not previously been explored. Nonetheless, it is well known that unilateral RT increases muscle strength of contralateral non-trained homologous muscles, that is, it induces a cross-education or cross-transfer effect.[1–5] In a recent review, Green and Gabriel[5] reported that the magnitude of the increase in muscle strength in the contralateral non-trained limb ranged from 52 to 80% of that of the trained limb. To the best of our knowledge, at least nine studies have shown that a cross-education effect on non-trained contralateral limb strength was induced by isokinetic[8,9,11,12,29–31] or isotonic[10,32] eccentric RT. Manca et al.[2] showed that the contralateral isometric, concentric, and eccentric strength gains were, on average, greater after an isolated eccentric regime with isokinetic devices (20–77%) than by an isotonic concentric/eccentric regime (20–35%). In the present study, the mean magnitude of the cross-education effect ranged from 34.6% to 93.9% between the variables, with NTL achieving more than 70% of the gain made TL in some variables (Table 1).

In the present study, similar increases in 1-RM were observed between TL (22–30%) and NTL (22–28%) in the three experimental groups after 6 weeks (12 sessions) of unilateral isoinertial RT. Farthing & Chilibeck[30] compared faster ($180^{o}\cdot s^{-1}$) and slower ($30^{o}\cdot s^{-1}$) velocity eccentric RT and reported that the faster RT program induced greater increases in peak concentric force of the elbow flexors for the trained (30% at $180°\cdot s^{-1}$ and 34% at $30°\cdot s^{-1}$) and non-trained (24% at $180°\cdot s^{-1}$ and 17% at $30°\cdot s^{-1}$) limbs than the lower-velocity program (trained limb: −2% at $180°\cdot s^{-1}$ and −4% at $30°\cdot s^{-1}$, non-trained limb: −18% at $180°\cdot s^{-1}$ and −20% at $30°\cdot s^{-1}$) after 8 weeks of eccentric-only RT performed 3 times a week. However, an effect of training velocity was not found in the present study, with both EM100 and EM150 achieving similar improvements in 1-RM in both TL and NTL (Figure 1B). A high correlation ($r = 0.84$) was observed between strength changes in TL and NTL (Figure 2B), indicating that those who achieved the greatest increases in strength of the trained limb also showed greater improvements in the non-trained limb. This correlation was slightly lower than those previously reported after unilateral isolated eccentric training protocols ($r = 0.97$) but higher than those found after unilateral concentric-only protocols ($r = 0.55$).[22] It should be noted that when data for all three training groups were combined (ie, an "eccentric overload" group: EO), no differences in 1-RM changes were observed between the trained (27.4%) and non-trained (26.2%) legs, showing similar unilateral leg press 1-RM gains (Table 1). In addition, the changes observed in the present study were slightly greater than in previous studies in which 1-RM strength was tested after lower limb concentric-eccentric unilateral RT. This may possibly be explained by the use of absolute maximal concentric phases and a higher relative eccentric intensity achieved with the accentuated eccentric loading in the present study. For example, Latella et al.[13] reported that single-leg RT performed 3 times a week for 4 weeks with 78 to 88% of 1-RM resulted in strength gains of 21.2% in TL and 17.4% in NTL, confirming that the magnitudes of the contralateral gains were strongly associated with those obtained ipsilaterally.[2]

Regarding muscle power, changes in TL were similar to previous studies using bilateral flywheel RT.[27,33,34] In the present study, EM100 and FW increased concentric mean power under all loads tested in NTL, showing a moderate-large cross-education effect (ES: 0.49–0.98). These groups, in which eccentric overload (in terms of peak power) was lower or nil, also showed moderate to large cross-education effects on vertical jump height (ES: 0.35–1.15). However, EM150 showed increases in concentric mean power only under medium loads and differences between legs changes at low loads (Figure 1C). Therefore, despite the fact that there were no differences between groups, it seems that lower percentages of eccentric overload may be associated with greater increases in muscle power, not only in the ipsilateral TL[16] but also in the contralateral NTL. In addition, DJ contact time was reduced in both legs in EM100 and EM150, probably due to the short eccentric-concentric transition time provided by the electric-motor device, indicating an enhancement in stretch-shortening cycle performance. EO (ie, combined data from the training groups) showed similar muscle power and vertical jump height enhancements in both legs, with differences between TL and NTL changes only at 80% of 1-RM. These results suggest that the magnitude of cross-education on muscle power may be associated with ipsilateral gains.

The similar magnitude of increases in muscle function between TL and NTL in the present study may be attributed to neural adaptations according to the previous study findings.[1,30] However, the precise locations of those adaptations remain unclear.[3] Although cross-education effect is likely to be attributed to increases in corticospinal excitability in both contralateral and ipsilateral primary motor cortexes,[3] decreased inhibition in the ipsilateral cortex not directly involved in the motor task,[35,36] and the development of new motor engrams due to new motor learning.[37,38] With specific respect to eccentric exercise, it has been postulated that eccentric training uniquely modulates corticospinal excitability and inhibition of the untrained limb to a greater extent than concentric training, which may induce a shift in motor unit recruitment[39] and an enhancement in α-motoneuron excitability[40] in the contralateral limb muscles. This may be accentuated when the eccentric stimulus is applied at higher speed,[7,30] as occurs in isoinertial RT. The results of the present study suggest that the maximal nature of each concentric contraction and the higher load provided during lengthening might induce greater neural responses (eg, via enhanced neural drive). Thus, additional to task-specific differences in contraction type and alterations in motor units recruitment strategies, isoinertial accentuated eccentric loading may provide a unique stimulus promoting greater neural adaptations compared with traditional loading,[15] thus leading to a higher cross-education effect. However, further research is warranted to explicitly test this hypothesis by comparing to an isoinertial non-eccentrically overloaded group.

Although early (within weeks) contralateral increases in muscle force are not associated with muscle hypertrophy,[1,3] EM150 and FW increased thigh lean mass similarly in TL (4.5% and 5.1%, respectively) and NTL (3.5% and 3.8%, respectively) in the present study. Although the increase in NTL (3.0%) was smaller than in TL (4.0%) in EO, a significant correlation ($r = 0.76$) was observed between changes in lean mass in the legs (Figure 2A), suggesting that the increase in NTL was associated with that of TL. Thus, unilateral eccentrically accentuated exercises with high eccentric overload led to a higher cross-education effect on lean mass. One explanation for this finding is that the training evoked a small increase in muscle mass in NTL, which might be explained by growth factor- and myokine-induced muscle remodeling, activation of myoblast proliferation, or muscle proteome modifications after eccentric exercise, which may systematically enhance the anabolic environment.[1,41] However, other explanations must also be considered. Although DXA-derived lean mass measurements are strongly correlated with magnetic resonance imaging-derived measures of muscle volume,[25] DXA presents several limitations, including its inability to separate muscle groups or provide isolated muscle volume analysis, being only able to quantify the lean tissue mass of a given transverse section of the body. Moreover, error in repeated measurements is not only attributed to machine and evaluator error but also to exercise training or dietary interventions.[25] These changes can impact X-ray attenuation by influencing the relative composition profile of lean tissue mass (especially with respect to fluid content), thus limiting DXA accuracy to quantify muscle-specific gains.[25] Nonetheless, in the present study, one week was allowed between the last training session and the post-training DXA scan to re-establish muscle water content levels and allow residual blood to be removed. Furthermore, increases in NTL water content after unilateral RT have not been shown previously. Another possibility is that the low muscle activation achieved in NTL might have stimulated lean mass increase. Although rectus femoris in particular would be activated eccentrically at long muscle lengths (ie, ideal conditions for hypertrophy), EMG activity during exercise in NTL was low (~20–30% of TL, Figure S1) and it is unlikely this would have triggered a similar hypertrophic effect as observed in TL. However, it is possible that this involvement of the untrained leg to provide stability to the exercise may have promoted greater cross-education effects not only in functional variables but also in lean mass. It might be that the NTL activation of 20–30% with respect to the TL recorded during isometric contractions in which the anterior thigh muscles remained elongated to provide stability (producing an average of ~25 N, a peak of ~100 N [~12.5% of TL eccentric peak force], Figure S3), contributed to the effects.[42] A final possibility is that training-related TL fatigue led to increased use of NTL during daily activities, including in the days before DXA scan, triggering either muscle hypertrophy or at least increased blood flow and water accumulation. Indeed, increases in the muscle fiber water content in NTL would also contribute to enhanced force production in that leg,[43] and this should be considered in future research. It is important to consider the above possibilities within future research designs. It is also of interest to repeat the experiments using muscle groups that do not commonly perform daily activities and for which a bilateral compensation would not be likely (eg, upper limb muscles). In addition, due to the practically relevant nature of the training paradigm, it should be considered that global stabilizing musculature was highly involved during training.[44] This could imply global adaptations, especially in the lumbo-pelvic musculature, that contribute to transfer effects in tasks such as unilateral vertical jump that do not isolate a single muscle group. Although more research is needed to corroborate this, including functional exercises may be a key approach in the practical field to enhance the cross-transfer effect.

Several other potential delimitations are worthy of mention. The study was conducted over 6 weeks (training twice per week), and while relatively large improvements in muscle function were observed it would be of interest to test adaptations after longer training periods. Also, because the sample was homogeneous with respect to age, sex, strength level, and training experience, it is not known whether similar results would be found in women or individuals of older or younger chronological or exercise training ages. Finally, a comparison of the magnitude of the cross-education between traditional concentric-eccentric, eccentric-only and eccentrically accentuated isoinertial RT is warranted.

In conclusion, the present study demonstrated that 6 weeks (12 sessions) of RT with eccentric overload induced significant and similar gains in muscle strength, muscle power at different loads, vertical jump performance, and lean mass in both ipsilateral TL and contralateral NTL in physically active young men. The amount of eccentric overload did not appear to affect the increases in muscle function in NTL. However, the cross-education effect on DXA-derived lean mass estimates was greater after RT with higher eccentric overload, while lower eccentric overload seemed to be more beneficial for increases in explosive muscle function in NTL.

5 | PERSPECTIVE

It is well known that unilateral RT triggers a significant cross-education effect, increasing the strength of the contralateral non-trained homologous muscles.[5] However, the present study is the first to show the cross-education effects of eccentric-overload RT protocols on muscle function and lean tissue mass. Regardless of the amount of eccentric overload and ROM used, accentuated eccentric isoinertial RT led to comparable increases in unilateral leg-press one-repetition maximum (1-RM), muscle power at 40–80% 1-RM, unilateral vertical jump height, and lower limb lean tissue mass in both trained and non-trained legs. Thus, isoinertial eccentric-overload RT can promote a strong cross-education effect in which the effects on the non-trained leg were not largely different from those on the trained leg. Although further studies are needed to confirm its feasibility, it is likely that unilateral eccentric-overload RT is effective for rehabilitation and increasing muscle strength of athletes. Future studies should compare the magnitude of the cross-education effect between eccentric-overload and other RT modalities, examine other muscle groups, and investigate neurophysiological mechanisms underlying the cross-education effects.

ACKNOWLEDGMENTS

Dr Sergio Maroto-Izquierdo was supported by the Ministry of Education of Spain (FPU014/05732).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Maroto-Izquierdo S, Nosaka K, Blazevich AJ, González-Gallego J, de Paz JA. Cross-education effects of unilateral accentuated eccentric isoinertial resistance training on lean mass and function. *Scand J Med Sci Sports*. 2022;32:672–684. doi:10.1111/sms.14108