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ORIGINAL ARTICLE

Comparison between concentric-only, eccentric-only, and concentric–eccentric resistance training of the elbow flexors for their effects on muscle strength and hypertrophy

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Abstract

Purpose This study compared concentric–eccentric coupled (CON-ECC), concentric-only (CON), and eccentric-only (ECC) resistance training of the elbow flexors for their effects on muscle strength and hypertrophy.

Methods Non-resistance-trained young adults were assigned to one of the four groups: CON-ECC ($n = 14$), CON ($n = 14$) and ECC ($n = 14$) training groups, and a control group ($n = 11$) that had measurements only. The training group participants performed dominant arm elbow flexor resistance training in extended elbow joint angles (0°–50°) twice a week for 5 weeks. The total training volume (dumbbell weight × number of contractions) in CON-ECC (5745 ± 1020 kg) was double of that in CON (2930 ± 859 kg) and ECC (3035 ± 844 kg), because 3 sets of 10 contractions were performed for both directions in CON-ECC. Maximum voluntary isometric (MVC-ISO), concentric (MVC-CON), and eccentric contraction (MVC-ECC) torque of the elbow flexors and biceps brachii and brachialis muscle thickness (MT) were measured at baseline, and 3–9 days post-last training session.

Results No significant changes in any measures were evident for the control group. The CON-ECC and ECC groups showed increases ($P < 0.05$) in MVC-ISO (12.0 ± 15.7% and 11.3 ± 10.8%, respectively) and MVC-ECC torque (12.5 ± 18.3%, 16.2 ± 11.0%) similarly. Increases in MVC-CON torque ($P < 0.05$) were evident for the CON-ECC (17.5 ± 13.5%), CON (10.5 ± 12.8%), and ECC (14.2 ± 10.4%) groups without a significant difference among groups. MT increased ($P < 0.01$) after CON-ECC (10.6 ± 5.4%) and ECC (9.7 ± 7.2%) similarly, but not significantly after CON (2.5 ± 4.8%).

Conclusions ECC training increased muscle strength and thickness similarly to CON-ECC training, despite the half training volume, suggesting that concentric contractions contributed little to the training effects.

Keywords Eccentric contraction · Concentric contraction · Maximum voluntary contraction torque · Range of motion · Muscle hypertrophy

Abbreviations

ANOVA	Analysis of variance
CON-ECC	Concentric-eccentric coupled contraction
CON	Concentric-only contraction
ECC	Eccentric-only contraction
ES	Effect size
MT	Muscle thickness
MVC	Maximum voluntary contraction
MVC-ISO	Maximum voluntary isometric contraction

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MVC-CON	Maximum voluntary concentric contraction
MVC-ECC	Maximum voluntary eccentric contraction
ROM	Range of motion
SD	Standard deviation

Introduction

Muscle contraction type, intensity, number of repetitions and sets, and range of motion (ROM) all affect muscle adaptations in resistance training (Roig et al. 2009; Schoenfeld 2010; Mangine et al. 2015; Douglas et al. 2017; Schoenfeld et al. 2017a, b). Regarding muscle contraction type, many studies have shown that resistance training consisting of eccentric (lengthening) contractions induces greater muscle adaptation responses than that consisting of mainly isometric or concentric contractions (Chen et al. 2017; Maeo et al. 2018; Tseng et al. 2020; Valdes et al. 2021; Sato et al. 2021a). For example, Sato et al. (2021a) compared eccentric-only and concentric-only training of the elbow flexors performed twice a week for 5 weeks, and found that muscle thickness of biceps brachii and brachialis increased after the eccentric-only training (7.1%), although maximum voluntary contraction (MVC) torque of the elbow flexors increased similarly after the eccentric-only (22.5%) and concentric-only training (26.0%). Valdes et al. (2021) showed that increases in MVC strength of the elbow flexors and upper arm circumference were greater after eccentric-only training (20.9% and 2.9%, respectively) than concentric–eccentric coupled training (13.7% and 0.6%, respectively) when they were performed three times a week for 4 weeks in a matched training volume.

Regarding the ROM, Sato et al. (2021b) reported that elbow flexor resistance training at extended elbow joint angles (0°–50°) increased biceps and brachialis muscle thickness significantly greater (8.9%) when compared with that (3.4%) at flexed elbow joint angles (80°–130°). They also showed that maximum voluntary isometric (MVC-ISO), concentric (MVC-CON), and eccentric (MVC-ECC) contraction torque of the elbow flexors increased after the training at the extended joint angles (16.2%, 21.1%, and 19.6%, respectively) but not after the flexed angle training. However, no previous study has compared concentric–eccentric coupled contraction (CON-ECC), concentric-only (CON), and eccentric-only (ECC) training of the elbow flexors performed at long muscle lengths for changes in muscle strength and hypertrophy. Understanding the combined effects of muscle contraction type and ROM on muscle adaptations is important to prescribe a resistance exercise training.

Therefore, the present study compared CON-ECC, CON, and ECC training performed in long muscle lengths of the elbow flexors for changes in elbow flexor MVC torque in different muscle contraction modes and biceps brachii and brachialis muscle thickness (MT) before and after a 5-week training protocol. The training duration was short in the present study, but the 5-week CON and ECC protocols were shown to increase the MVC torque and MT (Sato et al. 2021b). Thus, we thought that the 5-week training period was adequate to compare the three training protocols. Based on the previous studies mentioned above (Tseng et al. 2020; Valdes et al. 2021; Sato et al. 2021b), we hypothesized that the increases in the MVC torque and MT would be greater after ECC training than CON-ECC or CON training.

Methods

Study design

A randomized repeated-measures experimental design was used to compare three unilateral elbow flexor resistance training groups with different muscle contraction configurations and a control group for changes in MVC torque and MT after 10 training sessions in 5 weeks. The dependent variables consisted of MVC-ISO torque at 50° elbow flexion, MVC-CON and MVC-ECC torque at 60°/s, and MT of biceps brachii and brachialis.

Participants

A total of 53 (25 male and 28 female) healthy university students (age: 20.9 ± 1.1 years, height: 163.5 ± 7.9 cm, body mass: 58.9 ± 8.7 kg), who were free from any orthopedic disorder of the upper extremity, had no history of previous neuromuscular or chronic diseases and had not performed a structured resistance training in the past 6 months, participated in the present study. They were allocated to one of the four groups considering the gender balance as follows: CON-ECC group (7 male, 7 female), CON group (6 male, 8 female), ECC group (7 male, 7 female), and control group (5 male, 6 female). There were no significant differences in age (CON-ECC: 21.1 ± 1.5 years, CON: 20.6 ± 1.0 years, ECC: 20.8 ± 1.0 years, and control: 21.2 ± 0.6 years), height (165.1 ± 8.2 cm, 163.5 ± 8.3 cm, 162.4 ± 8.3 cm, and 162.9 ± 6.0 cm), and body mass (57.9 ± 10.0 kg, 59.2 ± 8.7 kg, 61.1 ± 8.3 kg, and 57.0 ± 6.9 kg) among the groups.

The sample size was estimated from our previous study (Sato et al. 2021a) in which CON and ECC elbow flexor training effects were compared, showing the effect size of 0.60 for the difference in changes in MVC torque. With a power ($1 - \beta$) of 0.80 and an α of 0.05, it was shown that at least 7 participants per group were necessary. Considering an estimation error and possible dropouts, 14 participants were recruited for each training group, and 11 participants were recruited for the control group. Among the

53 participants, all except one in the control group were right-hand dominant based on the Edinburgh Handedness Inventory (Oldfield 1971). All participants were briefed on the study purpose and procedures, and a written consent was obtained from each participant. This study was approved by the Ethics Committee of Niigata University of Health and Welfare and was conducted in conformity with the policy statement regarding the use of human subjects by the Declaration of Helsinki.

Familiarization session

A familiarization session was set 1 week prior to the baseline measurements in all groups, and all participants practiced the MVC-ISO, MVC-CON, and MVC-ECC torque measurements. The resistance training was performed twice a week with at least 48 h between sessions for 5 weeks by the training group participants (Sato et al. 2021a, b). All participants were instructed to refrain from any systematic training outside the study for the experimental period.

Resistance training protocols

The resistance training was performed by the dominant arm. The training intensity was increased progressively from 30% (1st session) to 50% (2nd and 3rd sessions), 70% (4th and 5th sessions), 80% (6th and 7th sessions), 90% (8th and 9th sessions), and 100% (10th session) of the MVC-ISO torque at 50° measured at baseline for all training groups (Sato et al. 2021b). In the training, the dominant arm of each participant was placed on a preacher curl bench in a seated position, with 45° shoulder flexion and forearm supination to hold a dumbbell (Nunes et al. 2020; Sato et al. 2021b). Each session consisted of 3 sets of 10 repetitions, but it should be noted that the number of concentric or eccentric contractions for the CON or ECC was 30 in a session, but the number of concentric and eccentric contractions for the CON-ECC was 60 (30 concentric and 30 eccentric contractions). A metronome indicated the contraction tempo, and each participant in the CON-ECC group was instructed to move the dumbbell for the concentric phase and the eccentric phase in 2 s each. In contrast, each participant in the CON group was instructed to lift a dumbbell for the concentric phase in 2 s, and each participant in the ECC group lowered a dumbbell in 2 s, and the investigator set the dumbbell in the starting position (0° for CON, 50° for ECC) after each contraction, which provided a 2-s rest between contractions. The ROM was 50° (between 0° and 50° elbow flexion) for all training groups (Nosaka et al. 2005; Sato et al. 2021b). If a participant had difficulty controlling the dumbbell movement during training at a higher intensity (80–100% MVC-ISO torque), the investigator assisted the participant for weaker elbow joint angles. The rest time between sets was 3 min. The total lifting weights of the dumbbell for 10 sessions were calculated for each participant.

Maximum voluntary isometric, concentric, and eccentric torque

MVC-ISO torque was measured at 50° elbow flexion in 45° shoulder flexion, with the trunk and pelvis being secured to a chair of an isokinetic dynamometer (Biodex System 3.0, Biodex Medical Systems Inc., Shirley, NY, USA) by straps. Each contraction lasted for 3 s, and two measurements were taken for each angle with a 45-s interval (Tseng et al. 2020; Sato et al. 2021b), and the average of the two measures was used for further analysis. The isokinetic dynamometer was also used to measure MVC-CON and MVC-ECC torque of the elbow flexors in the same setting as that on MVC-ISO measures. MVC-CON torque was measured first five times, followed by MVC-ECC torque five times, and both were measured at 60°/s. The rest time between measurements was 120 s. The range of motion was 120° for the measurements, the starting angle was 0° for MVC-CON, and 130° elbow flexion for MVC-ECC torque (Colson et al. 1999). Among the five measurements, the highest torque for MVC-CON and MVC-ECC, respectively, was used for the subsequent analysis. During all measurements, the investigator gave verbal encouragement to the participants.

Muscle thickness

A total of biceps brachii and brachialis MT were measured using B-mode ultrasonography with an 8-MHz linear probe (LOGIQ e V2; GE Healthcare Japan, Tokyo, Japan). The investigator minimized the probe's pressure against the skin as much as possible, and the same investigator took all measurements. The measurement sites were 50%, 60%, and 70% of the lateral epicondyle of the humerus from the acromion. Each participant lay supine on a bed with the arms placed at each side and the forearm supinated while relaxing the arms. Ultrasound measurements of the transverse axis were repeated twice. The MT of biceps brachii plus brachialis was measured as the distance from the inner edge of the fascia to the humerus (Abe et al. 2000; Sato et al. 2021a, b). The average value of the MT at the 50%, 60%, and 70% sites was also calculated and used for further analysis (Sato et al. 2021b).

Statistical analyses

Statistical analyses were performed using the SPSS version 24.0 (IBM Japan, Inc., Tokyo, Japan). The normality of the data was assessed using a Shapiro–Wilk test. The variables at baseline were compared among the groups by a one-way analysis of variance (ANOVA) for each variable. A split-plot ANOVA with two factors (group

[CON-ECC vs CON vs ECC vs control] × time [pre- vs. post-training]) was used to compare among the groups for changes in MVC-ISO, MVC-CON, MVC-ECC torque, and MT from pre- to post-training. Classification of effect size for the split-plot ANOVA results was based on η_p^2, and less than 0.01 was considered a small, 0.02–0.1 was considered a medium, and over 0.1 was considered a large effect size (Cohen 1988). A paired *t* test with Bonferroni correction was used to determine significant differences between pre- and post-training values when significant effects were found. Furthermore, when significant differences were found between pre- and post-training values, the magnitude of the change in each variable from pre- to post-training was compared between groups using an independent t test with Bonferroni correction. The magnitude of the change in each variable from pre- to post-training was calculated by [post-training value] – [pre-training value]/[pre-training value] × 100. Effect size (ES) was calculated as a difference in the mean values between pre- and post-training divided by the pooled SD, and ES was categorized as trivial (0–0.19), small (0.20–0.49), moderate (0.50–0.79), and large (≥ 0.80) (Cohen 1988). In addition, an independent *t* test with Bonferroni correction was used to compare the total dumbbell weight lifted over the 10 sessions between all training groups. The differences were considered statistically significant at an alpha level of 0.05. Descriptive data are shown as mean ± standard deviation (SD).

Results

Training volume

All participants in the three training groups completed all training sessions as planned. The average dumbbell weight used for the 10 training sessions was similar between the CON-ECC (9.6 ± 1.7 kg), CON (9.8 ± 2.9 kg), and ECC (10.1 ± 2.8 kg) groups. However, the number of muscle contractions performed over the 10 sessions in the CON-ECC group ($n = 600$) was twice as much as that of the other two groups ($n = 300$). Thus, the total dumbbell weight lifted over the 10 training sessions (training volume) was significantly greater for the CON-ECC group (5745 ± 1020 kg) than the CON (2930 ± 859 kg) and ECC (3035 ± 844 kg) groups, without a significant difference between CON and ECC.

MVC-ISO, MVC-CON, and MVC-ECC torque and MT

No significant differences in the outcome measures were found between groups at the baseline. Changes in MVC-ISO, MVC-CON and MVC-ECC torque, and MT from pre- to post-training are shown in Table 1. Significant interaction effect was evident for MVC-ISO ($P = 0.023$, $F = 3.47$, $\eta_p^2 = 0.175$), MVC-CON ($P = 0.005$, $F = 4.81$, $\eta_p^2 = 0.228$), MVC-ECC ($P = 0.007$, $F = 4.51$, $\eta_p^2 = 0.213$) torque, and MT ($P < 0.001$, $F = 13.42$, $\eta_p^2 = 0.451$). No significant changes in all variables were observed for the control group.

Table 1 Maximum voluntary isometric (MVC-ISO), concentric (MVC-CON), eccentric (MVC-ECC) contraction torque, and average muscle thickness of three sites (MT) before (Pre) and after (Post) 5-week training (mean ± SD) for coupled concentric and eccentric (CON-ECC), eccentric-only (ECC), concentric-only contractions (CON) groups, or no training group (Control)

Variable	Group	Pre	Post	Effect size	ANOVA
MVC-ISO torque (N m)	CON-ECC	33.2 ± 7.8	36.9 ± 8.3*	0.46	$F = 3.47$ $P = 0.023$
	ECC	34.5 ± 10.8	38.7 ± 13.2*	0.35	
	CON	34.0 ± 10.4	35.6 ± 11.4	0.15	
	Control	38.7 ± 12.9	38.1 ± 13.7	− 0.05	
MVC-CON torque (N m)	CON-ECC	28.2 ± 6.1	33.2 ± 8.3*	0.69	$F = 4.81$ $P = 0.005$
	ECC	30.7 ± 7.8	35.3 ± 10.1*	0.51	
	CON	29.0 ± 8.4	32.3 ± 10.9*	0.35	
	Control	32.2 ± 8.0	31.5 ± 9.5	− 0.07	
MVC-ECC torque (N m)	CON-ECC	38.7 ± 10.1	43.0 ± 10.6*	0.41	$F = 4.51$ $P = 0.007$
	ECC	45.6 ± 12.8	52.7 ± 14.1*	0.53	
	CON	46.5 ± 13.5	50.1 ± 15.1	0.25	
	Control	47.2 ± 14.9	46.6 ± 12.8	− 0.05	
Muscle thickness (mm)	CON-ECC	21.5 ± 4.1	23.7 ± 3.8*	0.55	$F = 13.42$ $P < 0.001$
	ECC	23.4 ± 3.5	25.6 ± 4.1*	0.60	
	CON	23.4 ± 3.9	23.9 ± 3.9	0.14	
	Control	21.7 ± 3.8	21.4 ± 4.0	− 0.08	

Effect size (*d*) of the change in each group, and *F* and *P* values of a split-plot ANOVA comparing among the groups for the changes (Group × Time interaction effect) for each variable are shown

*Significant ($P < 0.05$) deference from the pre-training value

The magnitude of the changes in MVC torque variables from pre- to post-training is shown in Fig. 1. No significant changes ($P = 1.00$) in any of the MVC torque were evident for the control group. MVC-CON torque increased similarly after CON-ECC ($P = 0.006$, $d = 0.69$), CON ($P = 0.039$, $d = 0.35$), and ECC training ($P = 0.002$, $d = 0.51$). However, increases in MVC-ISO and MVC-ECC torque were evident for the CON-ECC (MVC-ISO: $P = 0.044$, $d = 0.46$; MVC-ECC: $P = 0.038$, $d = 0.41$) and ECC groups ($P = 0.009$, $d = 0.35$; $P = 0.001$, $d = 0.53$), but not for the CON group. Figure 2 shows the magnitude of the change in MT (average of three sites) from pre- to post-training. A significant increase in MT was found for CON-ECC ($P < 0.001$, $d = 0.55$) and ECC ($P = 0.001$, $d = 0.60$) only. When looking at the individual responses, a large variability in the changes in the MVC torques was found among them. However, most of the participants in the CON-ECC and ECC groups showed increases in MVC-ISO, MVC-CON, and MVC-ECC torques (Fig. 1). This was also the case for MT (Fig. 2).

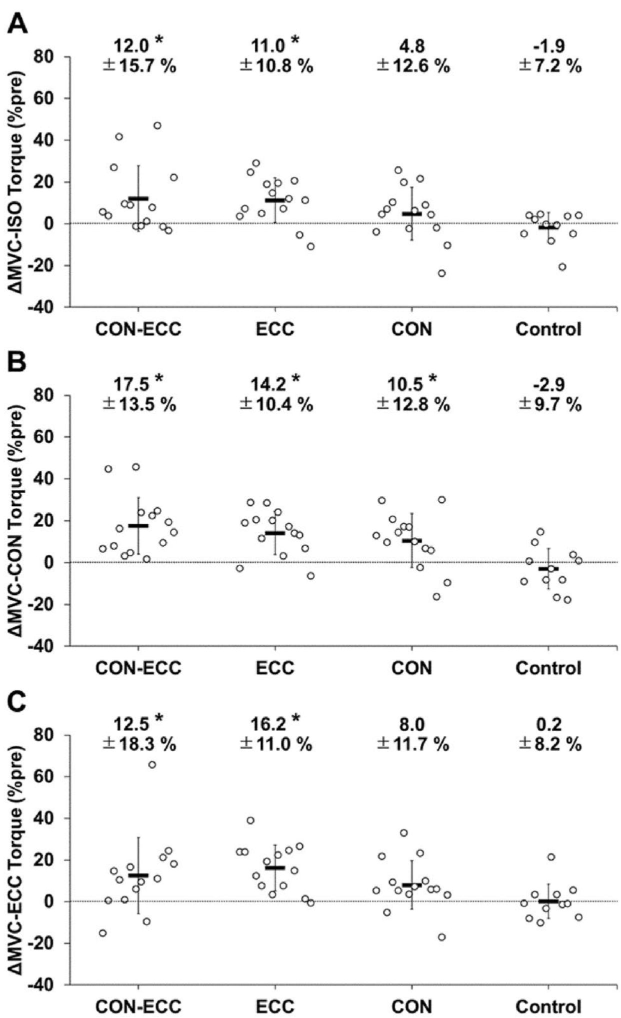

Fig. 1 Percent changes (individuals and mean ± SD) in maximum voluntary isometric (**A**), concentric (**B**), and eccentric contraction torque (**C**) from before to after 5-week training for coupled concentric and eccentric contractions (CON-ECC), eccentric-only contractions (ECC), concentric-only contractions (CON) groups, and no training (control) group. *Significant ($P < 0.05$) change from the baseline

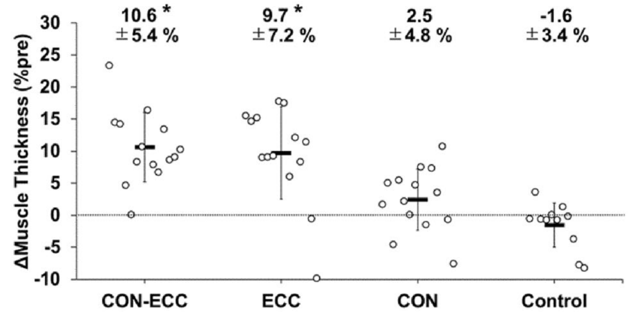

Fig. 2 Percent changes (individuals and mean ± SD) in average muscle thickness at three sites from before to after 5-week training for coupled concentric and eccentric contractions (CON-ECC), eccentric-only contractions (ECC), concentric-only contractions (CON) groups, and no training (control) group. *Significant ($P < 0.05$) change from the baseline

Discussion

The results were in line with the hypothesis, but the difference between CON-ECC and ECC training was smaller than expected. Valdes et al. (2021) reported that increases in MVC-ISO strength of the elbow flexors were greater after eccentric-only (20.9%) than concentric–eccentric training (13.7%) that were performed three times a week for 4 weeks in the same total training volume (the intensity of muscle contractions was greater for the eccentric-only training, but the number of contractions was greater for the concentric–eccentric than eccentric-only training). In the present study, the total training volume in the ECC group (3035 ± 844 kg) was half of that of the CON-ECC group (5745 ± 1025 kg). Despite this, the ECC and CON-ECC groups showed similar increases in all MVC torque (Fig. 1) and MT (Fig. 2). It is important to note that the CON group showed an increase in MVC-CON torque only, although its training volume was the same as that of the ECC group. The increase in MVC-CON torque after CON training could be explained by the training specificity. It appears that loading concentric contractions in resistance training contributed little to the increases in muscle strength and muscle size.

Herzog (2018) has documented that passive tension and spring action of titin contribute to the greater force exertion at a lower metabolic cost in eccentric than isometric or concentric contractions. This is advantageous in resistance training, since eccentric contractions could provide greater mechanical stimulus to the muscle and tendon when they are performed maximally, or less fatigue to muscle in repetitive contractions, when compared with concentric contractions. Hortobágyi et al. (1996b) reported a greater increase in the amplitude of electromyography in the vastus lateralis muscle after ECC training (86%) than CON training (12%) when they were performed at maximal intensity. It has been suggested that ECC training increases corticospinal excitability with inhibition of spinal reflexes greater than CON training (Lepley et al. 2017). Thus, emphasizing eccentric contractions in resistance training may induce greater adaptations in the supraspinal and spinal levels. This may have contributed to the greater increases in muscle strength of all contraction modes in the ECC group.

Hortobágyi et al. (1996a) compared the effects of concentric-only and eccentric-only resistance training of the knee extensors that were performed 4 times a week for 6 weeks on an isokinetic dynamometer and assessed isometric, concentric, and eccentric MVC torque. They reported that the concentric-only training increased concentric (36%) than eccentric MVC torque (13%) greater, whereas the eccentric-only training increased eccentric (42%) than concentric MVC torque (13%) greater, and the increase in isometric MVC torque was greater after eccentric-only (30%) than concentric-only training (18%). The present study also found that ECC training increased not only MVC-ECC torque (16.2%) but also MVC-ISO (11.3%) and MVC-CON torque (14.2%), even though no isometric and concentric contractions were performed in the ECC training. It appears that ECC training is more versatile for muscle strengthening than CON training.

It should be noted that a large variability in responses to the training was seen among the participants in the same group (Fig. 1). As reported in previous studies (Erskine et al. 2010; Pickering and Kiely 2019), there were always responders and non-responders to a training intervention, and this was not an exception for the present study. However, the number of the participants who showed more than 10% increase in MVC-ISO, MVC-CON, and MVC-ECC torque was 8, 10, and 9, respectively, for the ECC group, but for the CON-ECC group, it was 4, 8, and 8, respectively. Thus, the number of responders appeared to be larger for the ECC than CON-ECC group. This might be related to the familiarness to concentric–eccentric contractions that were already experienced by the participants in their daily activities and previous exercises, which provided a narrow room for improvement. In contrast, it is possible that the “unaccustomed” nature of eccentric-only contractions provided greater stimulus to the participants in the ECC group, producing the larger number of responders. It is likely that the increases in muscle strength observed in the present study were related to neural adaptations. Therefore, it is interesting to investigate neurophysiological differences between responders and non-responders in future studies.

As shown in Fig. 2, MT increased after CON-ECC (10.6%) and ECC training (9.7%) similarly, but not after CON training (2.5%). This was also in line with the previous studies reporting greater muscle hypertrophic effect by eccentric than concentric resistance exercises (Farthing and Chilibeck 2003; Sato et al. 2021a). For example, Farthing and Chilibeck (2003) showed 13% increase in MT of biceps brachii plus brachialis after fast velocity (180°/s) isokinetic eccentric training of the elbow flexors performed three times a week for 8 weeks (24 sessions in total), but no significant MT increase after isokinetic concentric training at the same velocity. It is important to note that the magnitude of increase in MT was similar between the CON-ECC and ECC groups (Fig. 2). Since no significant increase in MT was found after CON training, it is likely that the increase in MT was induced mainly by eccentric contractions in the CON-ECC. However, the small number of training sessions ($n = 10$) in a short training duration (5 weeks) and limited ROM in the present study might have contributed to the lack of increase in MT after CON training. Franchi et al. (2017) concluded in their review article that eccentric and concentric resistance training would increase muscle size similarly when they were matched for the volume or work, but which appeared to be regulated by different myogenic and molecular responses. Further investigation is necessary to elucidate myogenic and molecular mechanisms underpinning the MT increase by CON-ECC and ECC, but not by CON.

In the present study, a small ROM at long muscle lengths was used in the resistance training. A recent systematic review (Pallarés et al. 2021) concluded that resistance training in full ROM produced greater increases in muscle strength and lower limb muscle hypertrophy when compared with resistance training in partial ROM. On the other hand, Sato et al. (2021b) reported that resistance training in elbow extended joint angles (0°–50°) increased biceps and brachialis muscle thickness greater (8.9%) when compared with that in elbow flexed (80°–130°) angles (3.4%). In addition, the study (Sato et al. 2021b) found that MVC-ISO, MVC-CON, and MVC-ECC torque of the elbow flexors increased only after the resistance training in the extended joint angles (16.2%, 21.1%, and 19.6%, respectively). It seems that ECC training performed at extended muscle lengths is more effective than that at shortened muscle lengths when performed for a partial ROM, and the long muscle length ECC training is at least similarly effective as that in full ROM. It is necessary to further investigate the effect of ROM on muscle strength and muscle hypertrophy in ECC training.

There are several limitations in the present study. First, the total training volume was smaller (a half) for the CON and ECC than CON-ECC, although the number of concentric and eccentric contractions in the CON and ECC, respectively, was the same as that in the CON-ECC. Thus, greater increases in MVC torque and MT could have been observed in the CON and ECC groups, if the number of contractions had been matched with that of CON-ECC (i.e., 60 contractions, e.g., 6 sets of 10 repetitions per session). It is important to note that the ECC showed similar effects on MVC torque and MT as those of the CON-ECC, despite the smaller training volume, but this was not found for the CON. It is interesting to investigate whether the CON will increase MVC torque and MT in the same magnitude of that was shown after CON-ECC, when the training volume of the CON is matched with that of CON-ECC. Second, the intervention period in this study was short (5 weeks). Therefore, it is possible that a longer intervention period could clarify muscle adaptations by CON-ECC vs. ECC vs. CON better. Third, MT was used as a parameter of muscle hypertrophy, but magnetic resonance or computed tomography imaging is the gold standard method for measuring muscle volume. Fourth, only the elbow flexors in untrained young adults were investigated in the present study; thus, future studies should examine whether similar results can be found for other muscle groups and in older adults and more trained individuals. Finally, neurophysiological measurements such as electromyography and transcranial magnetic stimulation, and molecular investigation were not included in the present study, so the central or peripheral mechanisms underpinning the findings were not explored.

From a practical point of view, eccentric-only resistance training seems to be effective in rehabilitation and sports training, because ECC produced the same training effects as CON-ECC did, despite a half of the number of muscle contractions, and ECC increased MVC torque in all muscle contraction types (11.3–16.2%) and MT (9.7%) in a short period. It appears that eliminating concentric contractions in resistance training may be a choice when a specific device to perform eccentric-only contractions is available. Thus, it is necessary to develop a less-expensive and safe training device that allows eccentric-only contractions with eliminating load for the concentric phase. It is also interesting to investigate further the effects of eccentric-only training at different ROM and movement velocity.

In conclusion, eccentric contractions in long muscle lengths provided potent stimulus for muscle strength increases and muscle hypertrophy. Since eccentric-only contractions induced similar muscle adaptations to coupled concentric–eccentric contractions in which the total number of muscle contractions was doubled, it appears that eccentric-only contractions are more efficient for the training adaptations, and concentric contractions in the coupled concentric–eccentric contractions had little effect on the muscle adaptations. It is necessary to investigate the mechanisms underpinning the superior effects of ECC than ECC-CON or CON in future studies.

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Author contributions SS designed the study, performed data collection, drafted, and revised the manuscript. RY, FM, YS, KY, KK, and MN contributed to the data collection and revisions of the manuscript. JPN, KN, and MN were involved in designing the study, analyzing, and interpreting the data, and revised the manuscript. All authors approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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Data availability All data generated or analyzed during this study are included in the article. However, if any additional data are necessary, it will be provided upon proper request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants All the procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This study was approved by the Ethics Committee of Niigata University of Health and Welfare (#18442).

Informed consent Informed consent was obtained from all participants.

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