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ORIGINAL ARTICLE

Weekly minimum frequency of one maximal eccentric contraction to increase muscle strength of the elbow flexors

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Abstract

Purpose Our previous study showed that one 3-s maximal eccentric contraction a day performed 5 days a week for 4 weeks (5DW) increased maximal voluntary contraction (MVC) strength of the elbow flexors more than 10%. The present study examined whether muscle strength would still increase when the frequency was reduced to 2 days or 3 days per week.

Methods Twenty-six healthy young adults were recruited in the present study and placed to two groups (n = 13/group) based on the weekly frequency of the one 3-s maximal eccentric contraction for two (2DW) or three days per week (3DW) for 4 weeks. Changes in MVC-isometric, MVC-concentric, MVC-eccentric torque of the elbow flexors, and muscle thickness of biceps brachii and brachialis (MT) before and after the 4-week training were compared between 2DW and 3DW groups, and also compared to the 5DW group in the previous study.

Results The 2DW group showed no significant changes in MVC torque. Significant ($P < 0.05$) increases in MVC-concentric (2.5 ± 10.4%) and MVC-eccentric (3.9 ± 4.9%) torque were observed for the 3DW group, but the magnitude of the increase was smaller ($P < 0.05$) than that presented by the 5DW group (12.8 ± 9.6%, 12.2 ± 7.8%). No significant changes in MT were evident for any of the groups.

Conclusion These results suggest that at least three days a week are necessary for the one 3-s maximal eccentric contraction to be effective for increasing muscle strength, and more frequent sessions in a week (e.g., 5 days) appear to induce greater increases in muscle strength.

Keywords Lengthening contraction · Training frequency · Maximal voluntary contraction torque · Muscle thickness

Abbreviations

ANOVA	Analysis of variance
CSP	Cortical silent period
ES	Effect size
MT	Muscle thickness
MVC	Maximal voluntary contraction
MVC-CON	Maximum voluntary concentric contraction
MVC-ECC	Maximum voluntary eccentric contraction
MVC-ISO	Maximum voluntary isometric contraction
RMS	Root mean square
SD	Standard deviation
WHO	World Health Organization
2DW	Two days a week
3DW	Three days a week
5DW	Five days a week

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Introduction

Previous studies have shown that resistance training focusing on eccentric (lengthening) contractions is more effective than that focusing on concentric (shortening) contractions for increasing muscle strength and muscle size (Roig et al. 2009; Chen et al. 2017; Sato et al. 2022a; Čretnik et al. 2022). We reported that one 3-s maximal eccentric contraction session performed 5 days a week (Monday – Friday) for 4 weeks increased maximal voluntary isometric (MVC-ISO), concentric (MVC-CON), and eccentric contraction (MVC-ECC) torques by 10.2 ± 6.4%, 12.8 ± 9.6%, and 12.2 ± 7.8%, respectively, without increasing muscle thickness in the biceps and brachialis muscles (Sato et al. 2022b). However, this was not found after one 3-s maximal isometric or concentric contraction in the same format. It is interesting that only 60 s of eccentric contraction in total (3 s × 20 sessions) still produce a muscle strength increase in 4 weeks.

Our another study (Yoshida et al. 2022) showed that six 3-s maximal eccentric contractions a session performed 5 days a week (Monday–Friday) for 4 weeks increased MVC-ISO (9.3 ± 5.5%), MVC-CON (11.2 ± 7.4%), and MVC-ECC (13.5 ± 11.5%) torques, and the muscle thickness (10.4 ± 4.4%). However, when 30 maximal eccentric contractions (3-s per contraction) were performed in one session a week for 4 weeks, no increases in any of the MVC torque were found, although the muscle thickness was increased by 8.0 ± 5.8% (Yoshida et al. 2022). Interestingly, the magnitude of increases in MVC torque was not significantly different from that of the previous study (Sato et al. 2022b) in which only one maximal eccentric contraction in a session was performed 5 days a week for 4 weeks.

These findings suggest the importance of session frequency in the small volume eccentric contraction training. Since our previous study (Sato et al. 2022b) found that six 3-s maximal eccentric contractions performed one day a week did not increase muscle strength, it was assumed that one 3-s maximal eccentric contraction a week would not increase muscle strength either. From our previous studies (Yoshida et al. 2022) it was not known whether a reduced weekly frequency of the one 3-s maximal eccentric contraction training would increase muscle strength as shown in the 5 sessions per week protocols. Therefore, the present study examined the effects of one 3-s maximal eccentric contraction training of two different weekly frequencies; two days per week (2DW) and three days per week (3DW) on changes in MVC-ISO, MVC-CON, and MVC-ECC torque of the elbow flexors and muscle thickness of biceps brachii plus brachialis in comparison to the changes after five days per week (5DW) in the previous study (Sato et al. 2022b). We hypothesized that 2DW would show no significant increases in the MVC torque, but 3DW would increase the MVC torque but the magnitude of the increase would be smaller than that had been shown by 5DW, without any changes in muscle thickness for all conditions.

Methods

Participants

A total of 26 (19 male and 7 female) young healthy adults were recruited for this study, and 13 participants (9 males and 4 females) included in the present study were from our previous study (Sato et al. 2022b) in which one maximal eccentric contraction in a session was performed five days a week for 4 weeks (5DW). All participants were free from orthopedic disorders of the upper extremities, had no history of neuromuscular or chronic diseases, and had not performed any regular resistance training of the arms in the past 6 months before participating in the study. The 26 participants were randomly placed into one of the two groups (n = 13 per group) who performed one maximal eccentric contraction in a session with a different training frequency in a week; two days a week (2DW) or three days a week (3DW). The training duration was 4 weeks for all groups (Fig. 1). There were no significant differences in the physical characteristics among the three groups (2DW: 9 males, 4 females, age: 21.8 ± 0.5 y, height: 166.7 ± 6.9 cm, body mass: 63.6 ± 11.3 kg; 3DW: 10 males, 3 females, 21.6 ± 0.7 y, 167.1 ± 9.0 cm, 61.9 ± 10.2 kg; 5DW: 9 males, 4 females, 21.1 ± 0.6 y, 168.0 ± 9.2 cm, 62.4 ± 10.0 kg). In the present study, the same investigators to the previous studies (Yoshida et al. 2022; Sato et al. 2022b) took the measurements, and the participants were recruited from the same population, and instructions to the participants such as physical activity and diet during the experimental period were the same as those of the previous studies.

Since we had not known a possible difference between the groups for changes in maximal voluntary contraction (MVC) strength for the current study, the same sample size (n = 13 per group) as that of the previous study (Sato et al. 2022b) that compared the effects of one 3-s maximal eccentric, concentric and isometric contraction performed in a session for 5 days a week for 4 weeks was used.

All participants were informed about the study purpose and procedures, and written consent was obtained from each participant. All participants were instructed to refrain from any systematic training outside the study during the experiment period. This study was approved by the Ethics Committee of Niigata University of Health and Welfare (#18305), and the study was conducted in conformity with

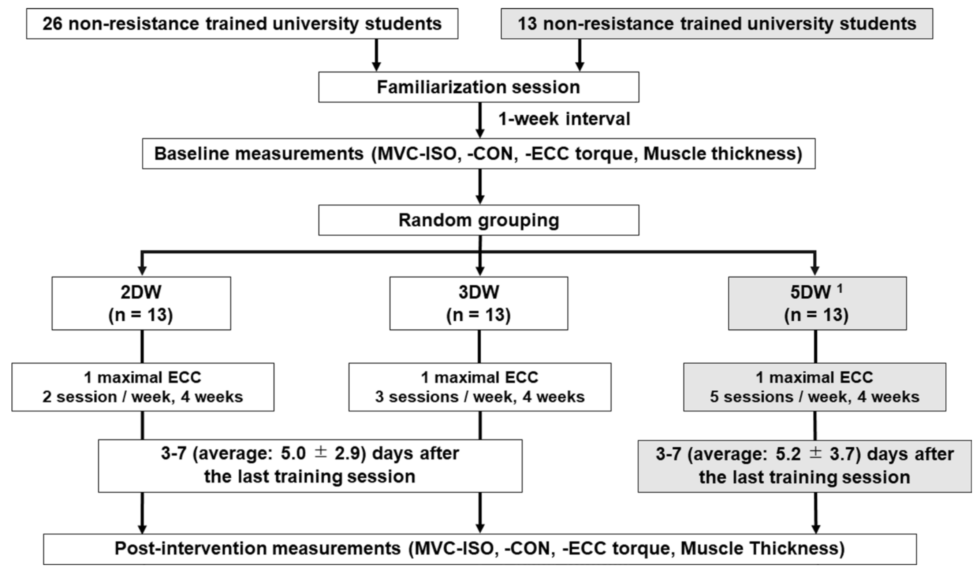

Fig. 1 Experimental design and protocol. A total of 26 healthy university students were placed to one of the two training groups; 3DW group that performed one maximal eccentric contraction a day for 3 days a week, and 2DW that performed one maximal eccentric contraction in two day a week (n = 13 per group). The 5DW group that performed one maximal eccentric contraction in 5 day a week was from the previous study (Sato et al. 2022b). For all groups, a familiarization session was held one week before the baseline assessments. Before the first intervention session and 3–7 days after the last intervention session, maximum voluntary isometric, concentric and eccentric contraction (MVC-ISO, MVC-CON, and MVC-ECC) torque and muscle thickness of the biceps brachii and brachialis was measured.

the policy statement regarding the use of human subjects by the Declaration of Helsinki.

Study design

To investigate the effects of one eccentric contraction training frequency on changes in muscle strength and muscle size, three training frequency protocols were compared: two days a week (2DW), three days a week (3DW), and five days a week (5DW). The dependent variables consisted of maximal voluntary isometric contraction (MVC-ISO) torque at three different elbow joint angles (20°, 55°, 90°), concentric (MVC-CON), and eccentric contraction (MVC-ECC) torque at two angular velocities (30°/s, 180°/s), and biceps brachii and brachialis muscle thickness, following our previous studies (Yoshida et al. 2022; Sato et al. 2022b). These measurements were taken from the trained arm only before and after the 4-week training.

A familiarization session was set at one week before the baseline measurements in which all participants performed the MVC-ISO, MVC-CON, and MVC-ECC torque measurements (Fig. 1). The number of maximal voluntary contractions was six for isometric, six for concentric, and six for eccentric torque measures. The baseline measures were taken 1 week after the familiarization session, and the post-training measurements were taken between three and seven (2DW group: 5.3 ± 3.3, 3DW group: 4.5 ± 1.2, 5DW group: 5.2 ± 3.7) days after the last training session, without a significant difference between groups. The range was due to the restriction by COVID-19 pandemic (e.g., no university campus access was allowed for some days).

Training protocol

The participants performed one maximal voluntary eccentric contraction of the elbow flexors using their dominant arms on an isokinetic dynamometer (Biodex System 3.0, Biodex Medical Systems Inc., Shirley, NY, USA) either two days a week (2DW group), three days a week (3DW group), or five days a week (5DW group) for 4 weeks. In the 2DW, at least two days were separated between sessions in a week (e.g., Monday and Thursday, Tuesday and Friday), and for the 3DW, the one maximal eccentric contraction was performed on Monday, Wednesday, and Friday, or Tuesday, Thursday, and Saturday. The 5DW performed it every day from Monday to Friday.

The shoulder joint was set at 45° flexion, and the trunk and pelvis were fixed with belts to the dynamometer chair. Each participant was instructed to resist maximally against the movement of the dynamometer lever arm moving from 100° to 10° of elbow flexion at the angular velocity of 30°/s. After each eccentric contraction, the lever arm of the isokinetic dynamometer passively returned the elbow joint to the starting position (100° flexion angle) at 10°/s, which provided a 9-s rest between contractions.

Dependent variables

All dependent variables in the present study were the same as those of the previous studies (Yoshida et al. 2022; Sato et al. 2022b).

Maximum voluntary contraction (MVC) torque

All MVC torque measures were taken using the isokinetic dynamometer. The MVC-ISO torque measurements at 20° (MVC-ISO_{20}), 55° (MVC-ISO_{55}), and 90° (MVC-ISO_{90}) were performed in random order. Each contraction lasted for 3 s, two measurements were taken for each angle with a 45-s interval, and the larger value of the two measures was used for further analysis. After the MVC-ISO torque measures, MVC torque of concentric (MVC-CON) and eccentric contraction (MVC-ECC) of the elbow flexors were measured in the same setting of the dynamometer to that of the MVC-ISO torque measures. MVC-CON torque was measured at 30°/s (MVC-CON_{30}) and 180°/s (MVC-CON_{180}), and MVC-ECC torque was also measured at 30°/s (MVC-ECC_{30}) and 180°/s (MVC-ECC_{180}) in this order. The rest time between measurements was 120 s. The range of motion was 100° for the MVC-CON and MVC-ECC torque measurements, the starting angle was 10° for MVC-CON, and 100° elbow flexion for MVC-ECC, where the fully extended elbow joint was defined as 0°. In the case of MVC-CON torque measurement, each participant was instructed to perform MVC from 10° to 100° of elbow flexion only, and the arm was returned to the starting angle (10° elbow flexion) passively while relaxing. For the MVC-ECC torque measurement, after performing eccentric MVC from 100° to 10° of elbow flexion, the arm was returned to the starting angle (100° elbow flexion) in a passive motion. In the MVC-CON torque measure, each participant performed MVC three times consecutively with a 120-s rest between contractions for each angular velocity, and the maximum torque obtained was used for the subsequent analysis. This was also the case for the MVC-ECC measures. During all measurements, verbal encouragement was provided to the participants. The torque of each contraction was monitored and recorded via an analog-to-digital converter (PowerLab 8/30, AD Instruments, Colorado Springs, CO, USA) to a personal computer with the analysis software (LabChart 7, AD Instruments).

The average of MVC-ISO_{20}, MVC-ISO_{55}, and MVC-ISO_{90} was calculated as MVC-ISO_{ave}, the average of MVC-CON_{30} and MVC-CON_{180} torque was calculated as MVC-CON_{ave} torque, and the average of MVC-ECC_{30} and MVC-ECC_{180} torque was also calculated as MVC-ECC_{ave} torque. Then, the mean value of MVC-ISO_{ave}, MVC-$CON_{ave,}$ and MVC-ECC_{ave} was obtained (MVC_{ave}) for each participant.

Muscle thickness

A total of biceps brachii and brachialis muscle thickness (MT) of the dominant (trained) arm was measured using B-mode ultrasonography with an 8-MHz linear probe (LOGIQ e V2; GE Healthcare Japan, Tokyo, Japan). The ultrasound intensity was 78.0, the frequency was 8.0 MHz, the depth was 6.0 cm, which was consistent over measurements at different time points across participants. 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 in the supine position on a bed with the dominant arm placed at each side with the forearm being supinated while relaxing the arm. Ultrasound measurements of the transverse-axis were repeated twice, and the MT of biceps brachii plus brachialis was measured as the distance from the inner edge of the fascia to the humerus. The average of the two measurements was used for further analysis. In addition, the average value (MT_{ave}) of the MT at the 50%, 60%, and 70% sites was calculated and used for further analysis.

Statistical analyses

Statistical analyses were performed using the SPSS version 28.0 (IBM Japan, Inc., Tokyo, Japan). The normality of the data was checked by a Shapiro–Wilk test. The baseline measures were compared among the three groups by a one-way analysis of variance (ANOVA). The sum of the peak torques produced in the training sessions was compared among the three groups by one-way ANOVA followed by an independent t-test with Bonferroni correction for two group comparisons. A split-plot ANOVA with two factors (group: 2DW, 3DW, 5DW x time: pre-, post-training) was used to compare the groups for the changes in the dependent variables. The magnitude of the change in each variable from pre- to post-training was compared between the groups using multiple comparisons with Bonferroni correction. Effect size (ES) was calculated as a difference in the mean values between pre- and post-training divided by the pooled SD. The ES (d) of 0.00–0.19 was considered trivial, 0.20–0.49 was small, 0.50–0.79 was moderate, and ≥ 0.80 was large (Cohen 2013). The ES for the split-plot ANOVA (η_p^2) was classified as small ($\eta_p^2 < 0.01$), medium (0.02–0.1) and large (> 0.1) based on (Cohen 2013). The differences were considered statistically significant at an alpha level of 0.05. Descriptive data are shown as mean ± SD.

Based on the data obtained from the present and previous studies (Yoshida et al. 2022; Sato et al. 2022b), the relationship between the weekly frequency of the training and the rate of increase in elbow flexion strength from pre- to post-training was examined using a simple linear regression analysis with a quadratic function. This result is shown in the Discussion.

Results

Training

All participants reported to the laboratory to perform the training without any missing sessions. Figure 2 shows the average (± SD) torque produced in each session and total training volume (total torque in 4 weeks) of the groups of the present study (2DW, 3DW) and the group from the previous study (5DW). The average torque in the first session was not significantly different between the 2DW (49.3 ± 10.2 Nm), 3DW (55.0 ± 12.3 Nm) and 5DW (54.3 ± 15.8 Nm) groups. The torque increased ($P < 0.01$) from the first session to the last session (62.8 ± 18.6 Nm) for the 5DW group (Δ15.7 ± 10.5%), but this was not the case for the 2DW and 3DW groups. The total torque in the training sessions was greater ($P < 0.01$) for the 5DW group (3658 ± 1051 Nm s) than the 3DW (2070 ± 508 Nm s) and 2DW groups (1233 ± 257 Nm s), and for the 3DW than the 2DW group (Fig. 2D).

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

A significant interaction effect was evident for changes in MVC-ISO_{20} ($F [2, 36] = 3.471$, $P = 0.042$, $\eta_p^2 = 0.162$), MVC-ISO_{55} ($F [2, 36] = 8.783$, $P < 0.001$, $\eta_p^2 = 0.328$), MVC-ISO_{90} ($F [2, 36] = 9.846$, $P < 0.001$, $\eta_p^2 = 0.354$), MVC-CON_{30} ($F [2, 36] = 10.686$, $P < 0.001$, $\eta_p^2 = 0.373$), MVC-ECC_{30} ($F [2, 36] = 11.543$, $P < 0.001$, $\eta_p^2 = 0.391$), and MVC-ECC_{180} ($F [2, 36] = 4.567$, $P < 0.001$, $\eta_p^2 = 0.202$) torques. The post-hoc test showed no significant increases in any of the MVC variables for the 2DW group (Fig. 3). Increases in MVC-ISO_{55} ($P < 0.01$, $d = 0.35$), MVC-ISO_{90} ($P < 0.01$, $d = 0.35$), and MVC-CON_{30} ($P < 0.01$, $d = 0.48$) torque were evident only for the 5DW group. MVC-ISO_{20} ($P = 0.02$, $d = 0.22$; $P < 0.01$, $d = 0.23$) and MVC-ECC_{180} ($P = 0.03$, $d = 0.23$; $P < 0.01$, $d = 0.37$) increased similarly for the 3DW and 5DW groups. MVC-ECC_{30} increased greater ($P < 0.01$) for the 5DW ($P < 0.01$, $d = 0.44$) than the 3DW group ($P = 0.03$, $d = 0.15$).

Figure 4 shows changes in MVC-ISO_{ave}, MVC-CON_{ave}, MVC-ECC_{ave}, and MVC_{ave} torque of individual participants in each group from baseline to 4 weeks later, compareing the changes between the groups. A significant interaction effect was evident for MVC-ISO_{ave} ($F [2, 36] = 12.759$, $P < 0.01$, $\eta_p^2 = 0.415$), MVC-CON_{ave} ($F [2, 36] = 5.180$, $P = 0.011$, $\eta_p^2 = 0.223$), MVC-ECC_{ave} ($F [2, 36] = 9.588$, $P < 0.01$, $\eta_p^2 = 0.348$), and MVC_{ave} torque ($F [2, 36] = 15.486$, $P < 0.01$, $\eta_p^2 = 0.462$). The post-hoc test showed that MVC-ISO_{ave} torque ($P < 0.01$, $d = 0.32$) increased only for the 5DW group, but MVC-CON_{ave}, MVC-ECC_{ave} and MVC_{ave} torque increased for the 3DW ($P < 0.05$, $d = 0.12$; $P < 0.05$, $d = 0.19$; and $P < 0.01$, $d = 0.13$, respectively) and 5DW ($P < 0.01$, $d = 0.42$; $P < 0.01$, $d = 0.41$; and $P < 0.01$, $d = 0.39$, respectively). However, the increases were greater ($P < 0.01$) for the 5DW than for the 3DW group.

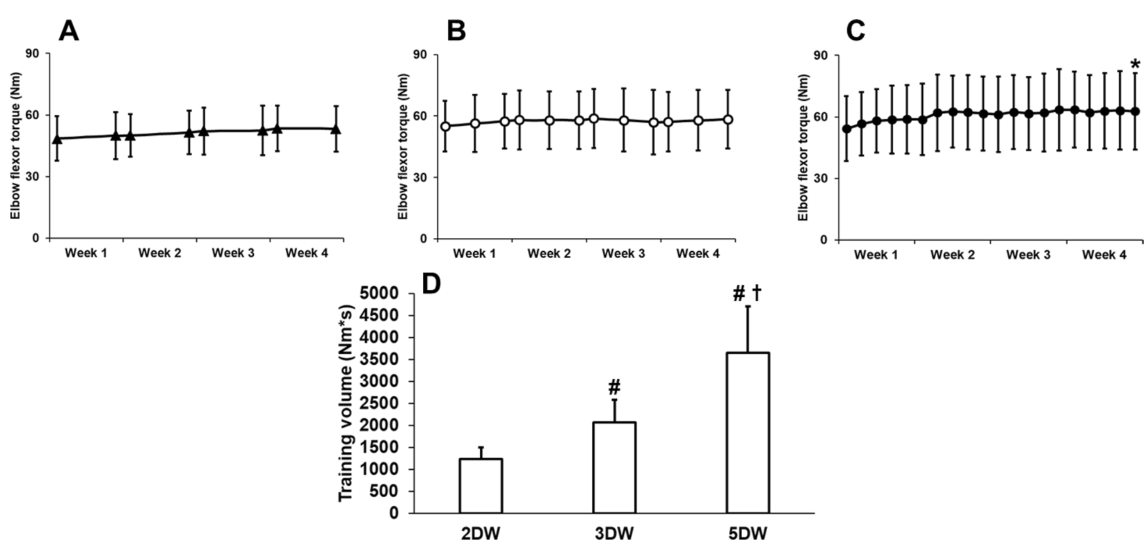

Fig. 2 Changes (mean ± SD of 13 participants) in peak eccentric contraction torque produced in each session of 4-week period in the group that performed one maximal eccentric contraction a session in two days a week (2DW) (**A**), three days a week (3DW) (**B**) and five days a week (**C**), and total peak torque (**D**) of each group. *: Significantly ($P < 0.05$) different from the first session, #: significantly ($P < 0.05$) different from 2DW, †: significantly ($P < 0.05$) different from 3DW

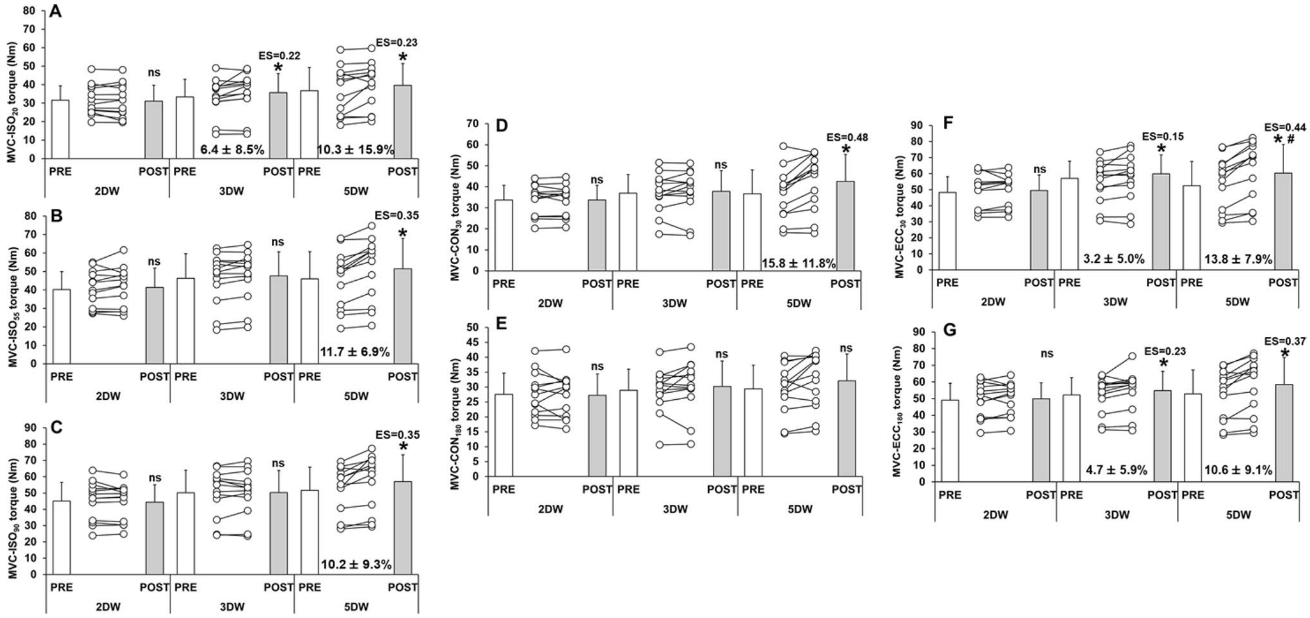

Fig. 3 Changes in maximum voluntary isometric contraction torque at three different angles (20°: **A**, 55°: **B**, and 90°: **C**), maximum voluntary isokinetic torque at two velocities (30°/s, 180°/s) for concentric (**D**, **E**) and eccentric contraction of the elbow flexors (**F**, **G**) from baseline (PRE) to post-intervention (POST) for the individuals and their average (±SD) of the group that performed one maximal eccentric contraction a session in two days a week (2DW), three days a week (3DW), and five days a week (5DW) for 4 weeks. *: Significantly ($P<0.05$) different from the PRE value. #: Significantly ($P<0.05$) different from the 3DW group (3DW vs 5DW). ns: no significant difference from the PRE value. The average (±SD) magnitude of change (%) is included for the significant ($P<0.05$) change and Cohen's d effect size (ES) is also provided for a significant change

Biceps brachii plus brachialis muscle thickness

The baseline MT values at 50%, 60%, and 70% sites and their average value (MTave) were not significantly different between the 2DW (50%: 26.6 ± 4.7 mm, 60%: 26.8 ± 4.9 mm, 70%: 29.3 ± 4.5 mm, and MT_{ave}: 27.7 ± 4.6 mm), 3DW (25.8 ± 4.4 mm, 27.1 ± 4.0 mm, 29.3 ± 4.3 mm, and 27.4 ± 4.2 mm), and 5DW groups (23.4 ± 3.8 mm, 23.4 ± 4.1 mm, 25.5 ± 3.3 mm, and 24.0 ± 3.7 mm). No significant changes in the MT at each site and MT_{ave} were evident for any of the groups.

Discussion

The results showed that the 2DW group had no significant increases in any of the MVC torque measures, while the 3DW group had significant increases in MVC-CON and MVC-ECC torques, but the magnitude of the increases was significantly smaller than that of the 5DW group (Figs. 3, 4). None of the groups showed any changes in muscle thickness (Fig. 5). These results supported the hypothesis that the 2DW would show no significant increases in MVC torque, but the 3DW group would show some increased MVC torque, but the magnitude of the increase would be smaller than that of the 5DW group.

In the 5DW group, the torque at the 20th session was significantly higher than the torque at the first session (Fig. 2). However, no significant increase in torque over sessions was observed for the 2DW and 3DW groups. The total peak torque in the 5DW group was significantly greater than that of the 2DW and 3DW groups, and the 3DW group had greater total peak torque than the 2DW group. These reflected the difference in the number of training sessions.

The 3DW group showed small but significant increases in $MVC\text{-}CON_{ave}$ (2.5%), $MVC\text{-}ECC_{ave}$ (3.9%), and MVC_{ave} torque (3.0%) without a significant increase in $MVC\text{-}ISO_{ave}$ torque (Fig. 4). When considering the possible MVC torque measurement errors, an increase of more than 5% was considered to be an actual increase (Sato et al. 2022b; Yoshida et al. 2022). In the 3DW group, 4, 5, 5, and 7 out of 13 participants showed more than 5% increases in the $MVC\text{-}CON_{30}$, $MVC\text{-}CON_{180}$, $MVC\text{-}ECC_{30}$, and $MVC\text{-}ECC_{180}$ torque, respectively (Fig. 3). For the MVC_{ave} torque, 4 participants showed more than 5% increases in the 3DW group (Fig. 4). However, the number of participants who showed more than 5% increases in MVC_{ave} torque was only two in the 2DW group. In contrast, 10, 9, 11, and 9 out of 13 participants in the 5DW group showed more than 5% increases $MVC\text{-}CON_{30}$, $MVC\text{-}CON_{180}$, $MVC\text{-}ECC_{30}$, and $MVC\text{-}ECC_{180}$ torque, respectively (Fig. 3), and 10 participants showed more than 5% increases in MVC_{ave} torque (Fig. 4).

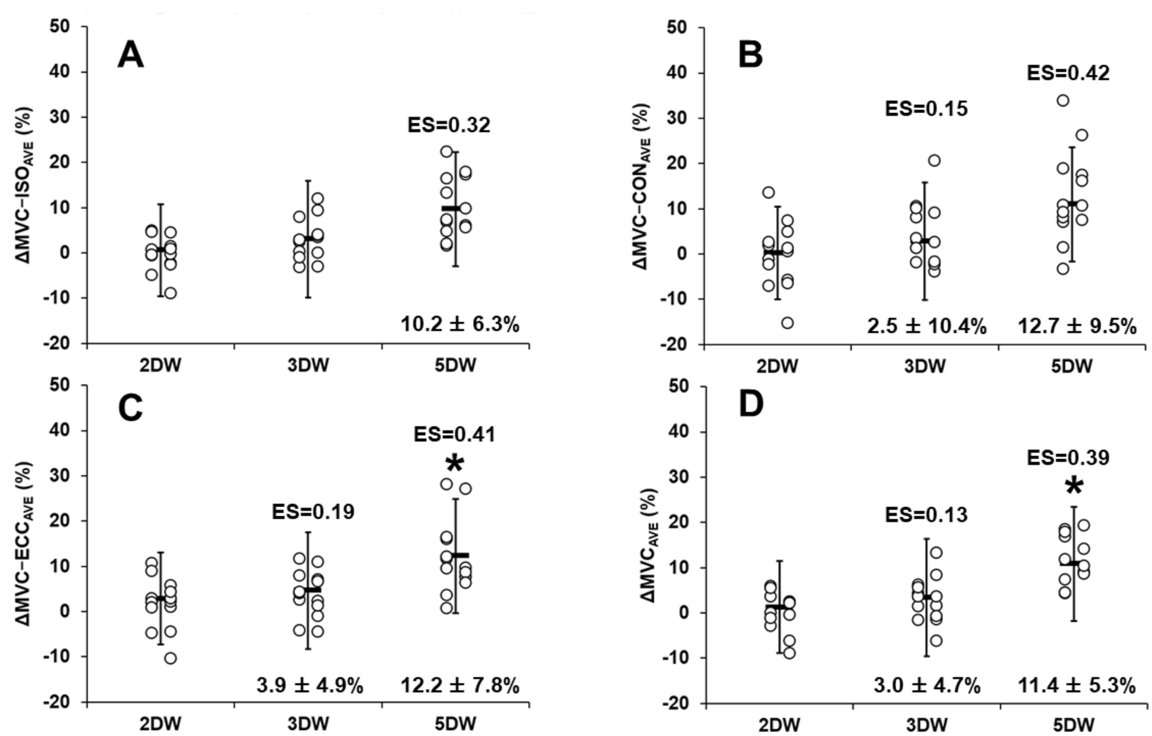

Fig. 4 Normalized changes in average maximum voluntary isometric contraction torque at three different angles (MVC-ISO$_{AVE}$: **A**), and average maximum voluntary concentric (MVC-CON$_{AVE}$: **B**) and eccentric contraction torque at two different velocities (MVC-ECC$_{AVE}$: **C**), and the average of all torque measures (MVC$_{AVE}$: **D**) from baseline (PRE) to post-intervention (POST) for the individuals and their average (± SD) of the group that performed one maximal eccentric contraction a session in two days a week (2DW), three days a week (3DW), and five days a week (5DW) for 4 weeks. *: Significantly ($P < 0.05$) different from the PRE value. *: Significantly ($P < 0.05$) different from 3-time/w group. ns: no significant difference from the PRE value. The average (± SD) magnitude of change (%) is included for the significant ($P < 0.05$) change and Cohen's d effect size (ES) is also provided for a significant change

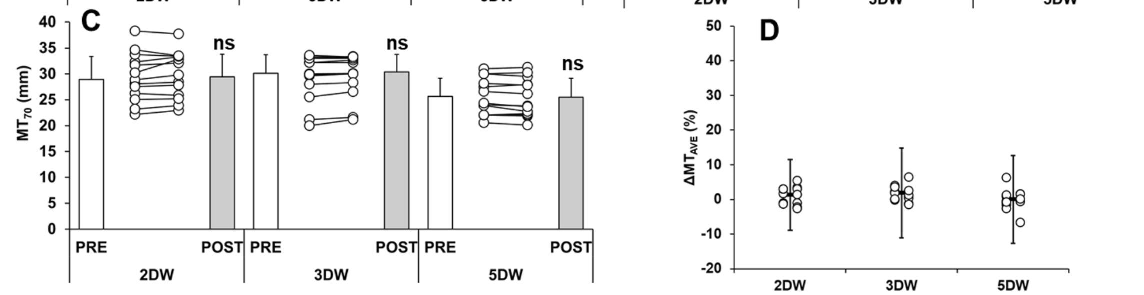

Fig. 5 Changes in biceps brachii plus brachialis muscle thickness (MT) at three different sites between the lateral epicondyle of the humerus from the acromion (50%: **A**, 60%: **B,** and 70%: **C**), and normalized changes in the average MT of the three sites from baseline (PRE) to post-intervention (POST) for the individuals and their average (± SD) in the group that performed one maximal eccentric contraction a session in two days a week (2DW), three days a week (3DW), and five days a week (5DW) for 4 weeks. ns: no significant difference from the PRE value

It should be noted that the increases in the MVC torques of the 5DW group (MVC-ISO$_{ave}$: 10.2%; MVC-CON$_{ave}$: 12.7%; MVC-ECC$_{ave}$: 12.2%, MVC$_{ave}$: 11.4%) were greater than those of the 3DW group (i.e., 3.1%, 2.5%, 3.9%, and 3.0%, respectively).

In the present study, multiple torque measurements such as the MVC-ISO torque at three elbow joint angles (20°, 55°, 90°), two angular velocities (30°/s and 180°/s) for the MVC-CON and MVC-ECC torques were taken according to our previous studies (Yoshida et al. 2022; Sato et al. 2022b). The inclusion of the several MVC measures was to examine if changes in MVC torque varied between contraction modes and elbow joint angles in the MVC-ISO torque measure. Since the training velocity (30°/s) was slow, we included two angular velocities (30°/s, 180°/s) for the MVC-CON and MVC-ECC torque measurements to examine training specificity. Although the principle of specificity in training is well known, eccentric contraction training has been reported to produce increases in strength in various contraction modalities (Yoshida et al. 2022; Sato et al. 2021, 2022a; Roig et al. 2009; Chen et al. 2017). In fact, the present study showed that the eccentric training increased all MVC measures except MVC-CON$_{180}$ in the 5DW group, but the 3DW group showed significant increases for MVC-ISO$_{20}$ only in addition to MVC-ECC$_{30}$ and MVC-ECC$_{180}$ (Fig. 3). This may suggest that when the session frequency is lower, the eccentric training effect follows the training specificity more strictly.

Our previous study (Yoshida et al. 2022) showed that six maximal eccentric contractions a session performed 5 days a week increased the MVC torque of the elbow flexors, but 30 maximal eccentric contractions a session performed once a week for 4 weeks did not increase any of them. This suggests the importance of the frequency of the training sessions. Mathews et al. (1957) compared four frequencies (two, three, four, and five sessions a week) of three 6-s maximal voluntary isometric contractions of the elbow flexors for changes in maximal voluntary isometric contraction strength of the elbow flexors after 4 weeks. They reported that the protocol of five sessions a week was most effective in increasing muscle strength followed by four, three, and two sessions per week, based on the number of participants who showed an increase. They concluded that five sessions a week exercise program was most beneficial in terms of strength gains. Our previous study (Sato et al. 2022b) showed no increase in MVC torque after one 3-s maximal isometric or concentric contraction in a session was performed 5 days a week for 4 weeks, suggesting the superiority of eccentric contraction to other contraction types in terms of muscle strength enhancement effects.

Based on the results from the present and previous (Sato et al. 2022b) studies, the relationship between the session frequency in a week and the rate of increase in MVCave torque was estimated (Fig. 6). It appears that increasing the intervention frequency from four to five times per week resulted in a nearly twice as large increase in MVC torque such that 6.7% in the four sessions per week, and 11.5% in the five sessions per week. Unfortunately, the present study did not include a group that performed the one maximal eccentric contraction 4 days per week due to the difficulty in recruiting participants in the COVID-19 pandemic period. The regression estimated that 24.7% increase in MVC strength could be obtained if one maximal eccentric contraction is performed every day, 7 days a week for 4 weeks. It is interesting to investigate whether the prediction is supported.

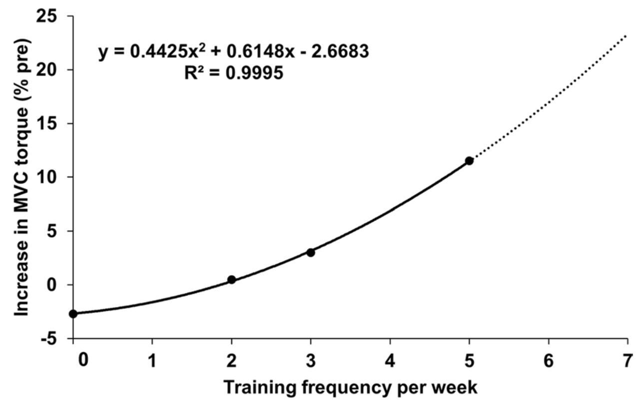

Fig. 6 Relationship between training frequency of one 3-s maximal eccentric contraction in a week and the magnitude of its effect on average maximal voluntary contraction (MVC) toque of isometric, concentric and eccentric contraction of the elbow flexors, based on the results from the present study and the previous studies (Sato et al. 2022b) in which no 3-s maximal eccentric contraction was performed (i.e., control condition)

Any of the groups showed no changes in MT of biceps brachii and brachialis (Fig. 5). Schoenfeld et al. (2019) reported that the amount of training per week, not the frequency of training per week, was important for increasing muscle mass in resistance training. Previous studies (Sato et al. 2022a; Chen et al. 2017; Tseng et al. 2020) showed eccentric contraction-only training-induced muscle hypertrophy of the elbow flexors with 30 contractions a session with one or two sessions a week. Our previous study found that MT of biceps brachii and brachialis increased by approximately 10% when 6 maximal eccentric contractions a session were performed 5 days a week, or 30 maximal eccentric contractions a session were performed 1 day a week for 4 weeks (Yoshida et al. 2022). Therefore, it is likely that the training volume in the present study was insufficient to induce muscle hypertrophy detected by the MT measurement.

It has been reported that relatively short-term resistance training, such as 6 weeks or less, produces primarily neural rather than morphological adaptations in muscle (Pearcey et al. 2021). The increase in muscle strength during the initial phase of resistance training is mainly due to neural adaptations such as increased excitability of corticospinal tracts and increased number of excitatory synapses in spinal motoneurons resulting in increased motor unit mobilization, discharge rate, and firing frequency (Lepley et al. 2017). Compared to concentric contractions, eccentric contractions have been shown to have superior neural adaptations (Douglas et al. 2017). Eccentric resistance training induces unique neural adaptations in the supraspinal and spinal cord, such as increased motor cortex excitability associated with the suppression of spinal reflexes (Moritani et al. 1987; Enoka 1996). Thus, it is possible that the increases in MVC torque induced by the maximal eccentric contractions in the 3DW and 5DW groups were associated with such neural adaptations. Latella et al. (2017) reported a decrease in cortical silent period (CSP) up to 48 h after an acute resistance exercise of the elbow flexors (3 repetitions × 5 sets) at 90–95% of one repetition maximum in 14 recreationally resistance-trained individuals who had 6–12 months experience in resistance training at least twice a week. Christie et al. (2014) showed an increase in MVC muscle strength (17.4%) and a decrease in CSP (12 ms) in their study investigating an ankle dorsiflexion short-term training performed 3 times a week for 2 weeks. These findings suggest that a decrease in CSP, a measure of cortical inhibition, may be involved in the increase in muscle strength. Therefore, it might be that the interval between training sessions was too long in the 2DW group (72–96 h) for sustaining a decrease in CSP, since the next session was performed when CSP was already returned to the baseline levels. On the other hand, the 3DW group trained at the interval of 48–72 h, and the 5DW group trained at intervals of 24 h. Therefore, the cumulative effect of resistance training could have increased muscle strength. The mechanisms underpinning the effects of resistance training frequency in neuromuscular adaptations warrant further studies.

Several limitations of the present study need to be considered in designing future studies. First, the participants in this study were sedentary young adults, and the sample size was considered adequate but not necessarily large. Future studies should increase the sample size to see if similar results can be obtained with older adults, children, and clinical populations. Second, in this study, the training frequency was set to 2 or 3 times per week. It is interesting to investigate other frequencies, such as 4, 6, or 7 days a week, to check whether the prediction shown in Fig. 6 is correct in the future studies. It is also necessary to extend the training period for longer than 4 weeks to see whether muscle strength continues to increase when the training is continued for a longer period. Third, the target muscle group in the present study was the elbow flexors. Therefore, it is important to examine lower limb and trunk muscles in future studies. Fourth, no muscle thickness changes were induced in any of the groups in the present study, although our previous study (Yoshida et al. 2022) showed that muscle thickness increased when 30 maximal eccentric contractions per week were performed. It is interesting to examine the minimum number of contractions per session that could induce muscle hypertrophy in the 3DW or 5DW protocol. Fifth, maximal eccentric contraction is difficult to perform without a constant velocity dynamometer or other special devices. Maximal eccentric contraction may not be possible in elderly patients or clinical populations, and it may be unsafe. Therefore, the effects of submaximal eccentric contraction, such as 2/3 or 1/3 of maximal strength, should be examined to determine the strength at which muscle strength gains occur. Sixth, the participants were a mixed-gender group, with more male participants. Since the small sample size did not allow us to make comparisons between male and female participants, further research is needed to investigate the differences in response to eccentric contraction training between sexes. Seventh, the post-training measurements were taken between three and seven days after the last training session. Although it is assumed that post-training measures would not change largely within a week, it would have been better to take the measurements in the same interval among all participants. Eighth, no blinding in the measurements nor grouping was made in the present study, although most of the items in the the PEDro checklist (Maher et al. 2003) were fulfilled in the present study. Finally, the neurophysiological and molecular biological mechanisms underlying the effects of maximal eccentric contraction training should be investigated using transcranial magnetic stimulation, electromyogram, and muscle biopsy in future studies.

The World Health Organization (WHO Guidelines 2020) and other organizations such as the American College of Sports Medicine (Nelson et al. 2007) recommend that muscle-strengthening activities that involve all major muscle groups should be performed in two or more days a week. However, many people do not appear to meet this recommendation (Bennie et al. 2020). The present study, together with our previous studies (Sato et al. 2022b; Yoshida et al. 2022), showed that a small number of 3-s maximal eccentric contraction(s) once a day were effective in increasing muscle strength when it is performed more than 3 times per week. This suggests that even a small number of eccentric contractions performed regularly are beneficial in strengthening muscle. If this could be applied for all major muscle groups, it is possible to do the muscle strengthening exercise in a short time. This may encourage people to do more muscle strengthening exercises regularly. Resistance training focusing on eccentric contractions has been shown to produce health-promoting effects (Paschalis et al. 2011), thus it is interesting to investigate the effects of a daily small amount of eccentric contractions on health and fitness parameters in the future studies.

In conclusion, it appears that at least 3 days a week are necessary for one maximal eccentric contraction a day to increase muscle strength, and the increase is greater when it is performed 5 days a week. However, no change in muscle size occurred during the training. This suggests the importance of more frequent stimulus to the muscle in a small amount of eccentric contraction training.

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Author contributions RY, KN and MN designed the study. RY, KK, YM, SS, MT and MN collected the data, and RY, KN and MN analyzed the data, drafted 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.

Declarations

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

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 Niigata University of Health and Welfare (#18,202).

Informed consent Informed consent was obtained from each participant involved in the study.

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