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Original Research

Early Phase Adaptations in Strength, Muscle Size, and Co-activation Following Resistance Training in Untrained Women

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Abstract

International Journal of Exercise Science 19(7): 7005, 2026. The present study examined the effects of four days of training on peak torque (PT), muscle thickness (MT), and electromyographic co-activation (Co-Act). Ten untrained women (age=21.6±1.0 years) completed four days of maximal, reciprocal, concentric, isokinetic forearm extension (FE) and flexion (FF) training with six sets of 10 repetitions at $180°\cdot s^{-1}$. The subjects completed pre-training and post-training visits, which consisted of collecting FE and FF PT at $180°\cdot s^{-1}$, triceps brachii (TB) and biceps brachii (BB) MT, and FE and FF EMG Co-Act (ratio of antagonist to agonist). Separate two-way ANOVAs were used to analyze PT (Movement×Time), MT (Muscle×Time), and EMG Co-Act (Movement×Time). Individual changes from pre-training to post-training were compared to minimal difference (MD) values. For PT, a significant (p=0.040) main effect for Time indicated an increase from pre-training (19.53±5.45 N·m) to post-training (22.47±5.93 N·m). Ten and 20% of the subjects exhibited changes greater than the MD for FE and FF PT, respectively. There was no interaction (p=0.743) or main effect of Time (p=0.106) for MT. There was a decrease (p=0.011) in FF EMG Co-Act (-7.78%), whereas FE EMG Co-Act (+2.32%) did not change (p=0.598). Zero subjects exhibited changes greater than the MD for FF EMG Co-Act. The mean increases in PT were likely due to neural adaptations since there were no changes in MT. Although a mean decrease in FF EMG Co-Act suggested it may have contributed to mean increases in FF PT, none of the subjects expressed "real" changes (change values greater than the MD) in FF EMG Co-Act.

Keywords: Short-term isokinetic training, reciprocal muscle actions, electromyography, individual responses, hypertrophy

Introduction

Previous studies[1-11] have examined the effects of very short-term resistance training (two to four resistance training sessions) on the early phase adaptations in performance-based outcomes and hypertrophy. The early phase adaptations to resistance training have a variety of applications in clinical, athletic, and non-athletic populations. For example, allied health professionals (e.g., physical therapists, athletic trainers, and occupational therapists) may benefit from understanding the minimum number of sessions required for patients or athletes

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to exhibit training-induced adaptations. This may be particularly useful for those who: 1) have a limited number of covered medical visits; 2) are looking for a cost- and time-effective alternative to an invasive medical procedure; or 3) are athletes that have time constraints for returning to play.[3–6,11] In theory, training-induced increases in strength following a small number of training sessions may also help reduce the risk of re-injury, as well as increase the willingness of patients to maintain compliance with a training program.[1,4–6]

Previous studies[1–11] have reported conflicting evidence regarding the effectiveness of two to four days of isokinetic or dynamic constant external resistance (DCER) training to induce increases in performance-based outcomes, such as strength (peak torque [PT] or 1-repetition maximum), rate of velocity or acceleration development, time to PT, and mean power. The conflicting findings may be attributable to a variety of methodological differences, including the sample characteristics (e.g., sex or training status), training volume (e.g., number of sets, repetitions, load, and training sessions), type of resistance exercise (e.g., isokinetic or DCER), training velocity (e.g., 60, 180, or 300°·s^{-1}), muscle groups involved (e.g., leg or forearm muscles), and muscle actions performed (e.g., non-reciprocal concentric, concentric and eccentric, or reciprocal concentric). For example, studies by Traylor et al[9–11] have found sex differences in the early phase, training-induced increases in forearm flexion (FF) PT and mean power. Specifically, the authors[9–11] reported increases in FF PT and mean power following three days of non-reciprocal, concentric, isokinetic FF training with five sets of 10 repetitions at 60°·s^{-1} in untrained men, but not women. In contrast, Coburn et al[4] reported increases in leg extension PT in untrained women following three days of non-reciprocal, concentric, isokinetic leg extension training with four sets of 10 repetitions at either 30 or 270°·s^{-1}. Thus, there may be muscle-specific differences in the minimum number of training sessions for women to exhibit increases in PT. Moreover, Cunha et al[7] compared three days of non-reciprocal, concentric, isokinetic leg extension training to reciprocal, concentric, isokinetic leg extension and flexion training in men and found that: 1) The reciprocal group exhibited greater increases in PT at 60°·s^{-1} than the non-reciprocal group; 2) the reciprocal group increased PT at 180°·s^{-1}; and 3) the reciprocal group decreased time to PT at 60°·s^{-1}. Cunha et al[7] hypothesized that the reciprocal training group exhibited greater improvements in the performance-based outcomes because lengthening of the leg extensors with a concentric muscle action of the leg flexors has been shown[12] to enhance neural drive to the leg extensors during a subsequent contraction due to increased stimulation of group Ia afferents. To date, only Beck et al[1] have examined the effects of reciprocal, concentric, isokinetic forearm extension (FE) and FF training and reported no changes in FE or FF PT in untrained men following two days of training with six sets of 10 repetitions at 180°·s^{-1}. Thus, the minimum number of reciprocal, concentric, isokinetic FE and FF training sessions required to induce increases in FE and FF PT in men and women has yet to be determined.

Training-induced increases in strength have been primarily attributed to two factors: 1) Neural adaptations, such as increases in muscle excitation of the agonist (e.g., increased motor unit recruitment and rate coding) and/or decreases in co-activation of the antagonist; and 2) increases in muscle size (i.e., hypertrophy).[4–6,8,13–16] In general, it has been hypothesized that the early phase (i.e., after two to four training sessions) training-induced increases in strength are due to neural adaptations, whereas hypertrophy becomes a prominent factor following more training sessions (i.e., ≥7 training sessions).[4–6,8,13–16] For example, Costa et al[5] and Akima et al[13] observed increases in muscular strength following three days of concentric and eccentric DCER leg extension training and two weeks of non-reciprocal, isokinetic leg extension training, respectively, without changes in muscular size. In addition, in the absence of increased muscle size due to eccentric-induced muscle edema, Stock et al[16] examined the time course of changes in biceps brachii (BB) muscle thickness (MT) in men during four weeks of concentric-only, DCER dumbbell curl training and found that significant hypertrophy did not occur until after the seventh training session. Previous studies, however, have not examined the effects of very short-term reciprocal, concentric, isokinetic FE and FF training on muscle size in men and women.

Two general neural mechanisms for training-induced increases in strength are increases in motor unit recruitment and rate coding of the agonist.[17–19] Previous studies[4,6,20–22] have also hypothesized that decreases in co-activation (Co-Act) of the antagonist may contribute to net increases in agonist force production. For example, Coburn et al[4] and Cramer et al[6] observed training-induced increases in leg extension PT without changes in electromyographic (EMG) amplitude, which is influenced by motor unit recruitment and rate coding,[23] of the quadriceps muscles following three days of non-reciprocal, concentric, isokinetic leg extension training. Thus, the authors[4,6] hypothesized that a decrease in Co-Act from the leg flexors contributed to the increases in leg extension PT. In contrast, Costa et al[5] reported increases in biceps femoris EMG amplitude following three days of concentric and eccentric DCER leg extension training, as well as following non-reciprocal, concentric, isokinetic leg extension training. It has been suggested that training-induced increases in Co-Act from the antagonist may be beneficial for increasing joint stability.[5,24–27] Thus, the effects of training on changes in Co-Act remains unclear, and no previous studies have examined training-induced changes in FE and FF Co-Act following reciprocal, concentric, isokinetic FE and FF training in men and women.

Currently, most very short-term training studies[1–11] make inferences based on evaluating group mean responses using parametric statistical procedures. However, there has been a growing interest in analyzing individual responses to resistance training interventions, because inferences made from group mean statistical analyses can be limited by intra- and inter-individual variability in how subjects respond to training interventions.[28–30] Thus, relying solely on group mean responses can make it difficult for practitioners to determine the likelihood that an individual patient, client, or athlete will exhibit training-induced adaptions from an intervention. A variety of statistical techniques have been used to analyze individual responses, such as the use of confidence intervals, smallest worthwhile change values, and minimal difference values.[30,31] The minimal difference is calculated using the standard error of the mean from reliability analyses, and in the context of training-induced change scores (e.g., change in PT = post-training PT minus pre-training PT), the minimal difference can be interpreted as a demarcation value to determine whether an individual's change score should be considered "real".[31]

Therefore, the present study aimed to examine group mean (ANOVAs) and individual (minimal difference) responses in FE and FF PT at $180°\cdot s^{-1}$, triceps brachii (TB) and BB MT, and FE and FF Co-Act following four days of maximal, reciprocal, concentric, isokinetic FE and FF training at $180°\cdot s^{-1}$ in untrained women. Based on previous findings,[4,6,7,11,16] we hypothesized that the training would induce: 1) Group mean increases in FE and FF PT; 2) no group mean changes in TB and BB MT; and 3) group mean decreases in FE and FF Co-Act. In addition, we hypothesized that the individual responses would generally track the group mean responses: 1) The majority of the subjects would exhibit positive change values in FE and FF PT greater than the minimal difference; 2) zero or very few of the subjects would exhibit positive change values in TB and BB MT greater than the minimal difference; and 3) the majority of the subjects would exhibit negative change values in FE and FF Co-Act that are more negative than the minimal difference.

Methods

Participants

Twelve women volunteered to participate in the present study, but only 10 women (Mean ± SD: age = 21.6 ± 1.0 years; height = 168.7 ± 4.9 cm; body mass = 65.2 ± 6.8 kg) were included in the final analyses. The data of two women were excluded due to measurement issues for their EMG signals, which invalidated the Co-Act values. An a priori analysis (G*Power version 3.1.9.7, Düsseldorf, Germany) indicated that a sample size of nine subjects was required based on an alpha of 0.05, a power of 0.80, and an estimated effect size of 0.57. The estimated effect size was based on a previous study[10] that reported significant increases in PT following three days of non-reciprocal, concentric, isokinetic FF training. All subjects in this study were university students and considered to be untrained in their upper body. Untrained in the upper body was defined as not having performed upper body resistance training for more than one time per week for the past three months. The subjects were part of a larger, multiple independent and dependent variable investigation, but none of the data in the present study have been previously published. The study was approved by the University Institutional Review Board for Human Subjects (IRB Approval #: 20220421791FB) in accordance with the ethical standards set by the Declaration of Helsinki. Prior to any testing or training, every subject signed a written Informed Consent and completed a Health History Questionnaire. This research was carried out fully in accordance with the ethical standards of the *International Journal of Exercise Science*.[32]

Protocol

The present study examined the effects of four days of maximal, reciprocal, concentric, isokinetic FE and FF training at 180°·s^{-1} with the non-dominant arm on FE and FF PT at 180°·s^{-1}, TB and BB MT, and EMG Co-Act during the FE and FF PT repetitions in the non-dominant arm. The dominant arm, which was not trained or tested, was determined based on the subject's report of their preferred throwing arm (i.e., throwing arm = dominant arm). The subjects completed eight visits: Visit 1 = familiarization; Visit 2 = baseline testing; Visit 3 = pre-testing; Visits 4 to 7 = training; Visit 8 = post-testing. All eight visits were separated by 24 to 96 hours. For Visit 1, the subjects read and signed a written Informed Consent, completed a Health History Questionnaire, and were familiarized with the testing procedures. The subjects completed the testing procedures on Visit 2 and Visit 3 in an identical manner for calculating reliability statistics of the dependent variables. Regarding the order of the testing procedures, the ultrasound imaging for measuring MT was performed prior to the isokinetic testing. Then, surface EMG electrodes were placed on the TB (long head) and BB prior to the isokinetic testing for determining FE and FF EMG Co-Act. Visits 4 through 7 consisted of the subjects completing the isokinetic training protocol. The post-testing visit (Visit 8) was identical to Visit 2 and Visit 3.

Muscle thickness of the TB (long head) and BB for the non-dominant arm were assessed via separate panoramic ultrasound images (Figure 1).[33] The images were obtained using a portable brightness mode (B-mode) ultrasound-imaging device (GE Logiqe, USA) and a multi-frequency linear-array probe (12L-Rs; 5–13 MHz; 38.4 mm field-of-view). A sampling rate of 10 MHz and a gain of 58 dB were used for collecting all ultrasound images. A separate image for each muscle was collected by moving the probe along the transverse plane from the most medial to the most lateral part of the muscle while using the panoramic mode on the ultrasound-imaging device.[33] For the TB, the ultrasound probe moved along the transverse plane at 50% of the distance between the posterior crista of the acromion and olecranon. For the BB, the ultrasound probe moved along the transverse plane at 33% of the distance between the medial acromion process and antecubital fossa. These locations were in accordance with those selected for the placements of the EMG electrodes.[34] All images were taken by the same investigator while the subject was in a seated position with their non-dominant arm supported on a table. The investigator maintained minimal, consistent pressure when applying the probe to the skin to limit compression of the muscle. A generous amount of water-soluble transmission gel was applied to the skin prior to each measurement to enhance acoustic coupling and reduce near-field artifacts and friction. Muscle thickness from the panoramic ultrasound images were analyzed in ImageJ (Version 1.53t., National 130 Institutes of Health, Bethesda, MD, USA). In ImageJ, each image was scaled from pixels to centimeters using the straight-line function and a known distance (i.e., the dashed lines on the sides of the image) prior to measuring MT. After the image was scaled, the straight-line function was used to measure the MT of the TB and BB from the most deep to the most superficial connective tissue surrounding the muscle (Figure 1).[33] Muscle thickness was defined as the location with the greatest length from the most deep to the most superficial connective tissue of the muscle.

Isokinetic testing was performed with a Biodex System 4 Pro (Biodex Medical Systems, Inc. Shirley, NY, USA), and the subjects were positioned in accordance with the manufacture's guidelines for the elbow joint. Prior to testing, the subjects performed a standardized warm-up that consisted of five submaximal (~50 to 75% of their perceived max effort), reciprocal, concentric, isokinetic FE and FF repetitions at $180°\cdot s^{-1}$. After two minutes of rest, the warm-up was proceeded by three maximal, reciprocal, concentric, isokinetic FE and FF repetitions at $180°\cdot s^{-1}$. The FE and FF muscle actions were performed throughout a range of motion of approximately 135° (i.e., extension = 0° and flexion = 135°). Strong verbal encouragement was given to the subjects to encourage maximal efforts for all of the testing repetitions. The repetition with the highest torque value was denoted as PT for the analyses.

The subjects trained on the same Biodex System 4 Pro and were placed in the same position that was used for the isokinetic testing. Prior to each training session, the subjects performed the same warm-up protocol that was used for the isokinetic testing. After two minutes of rest, the subjects then performed six sets of 10 maximal, reciprocal, concentric, isokinetic FE and FF repetitions at $180°\cdot s^{-1}$. Each set was separated by two minutes of rest. Strong verbal encouragement was given to the subjects to encourage maximal efforts for all repetitions.

During each isokinetic testing visit, pre-gelled surface EMG electrodes (Ag/AgCl, Accusensor; Lynn Medical, Wixom, MI, USA) were placed in a bipolar arrangement (30-mm center-to-center) on the TB (long head) and BB of the non-dominant arm in accordance with recommendations set by the Surface Electromyography for the Non-Invasive Assessment of Muscles.[34] Prior to placing the surface electrodes, the skin was carefully shaved, abraded, and cleaned with an alcohol wipe.[34] The electrodes for the TB were placed at 50% of the distance between the posterior crista of the acromion and olecranon, and the electrodes for the BB were placed at 33% the distance between the medial acromion process and antecubital fossa. The reference electrode was placed on the spinous process of the seventh cervical spine bone (i.e., C7). The raw EMG signal was digitized using a 12-bit-analog-to-digital converter (Model MP150; Biopac Systems, Inc., Goleta, CA, USA) using a sampling rate of 2000 samples per second. The EMG signals were amplified (gain: × 1000) using differential amplifiers (EMG2-R Bionomadix, Biopac Systems, Inc. Goleta, CA, USA; bandwidth: 10 – 500 Hz) and band-pass filtered (fourth-order Butterworth) at 10 to 500 Hz. The signals were stored on a personal computer (HP Laptop Model 14-dk1013dx HP Inc., Palo Alto, CA, USA) and processed using a custom written program in LabVIEW (Version 2025

Q3, National Instruments, Austin, TX, USA). The root mean square (rms) of the middle 33% of the signal was calculated to determine the EMG amplitude for both muscles (TB and BB) during both muscle actions (FE PT and FF PT). The EMG amplitude from the TB and the EMG amplitude from the BB were normalized to the values collected during the FE PT repetition and FF PT repetition, respectively. The EMG Co-Act values were expressed as antagonist divided by agonist. Thus, the FE EMG Co-Act was calculated using the following equation:

$$\text{FE EMG Co-Act} = \left(\frac{\text{(BB EMG during FE PT / BB EMG during FF PT)}}{\text{(TB EMG during FE PT / TB EMG during FE PT)}}\right) \times 100$$

The FF EMG Co-Act was calculated using the following equation:

$$FF\ EMG\ Co\text{-}Act = \left(\frac{(TB\ EMG\ during\ FF\ PT\ /\ TB\ EMG\ during\ FE\ PT)}{(BB\ EMG\ during\ FF\ PT\ /\ BB\ EMG\ during\ FF\ PT)}\right) \times 100$$

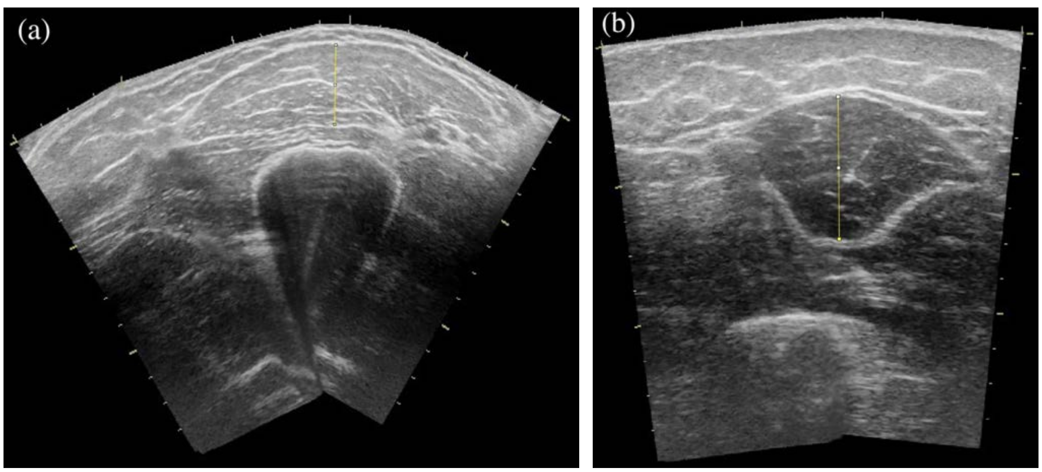

Figure 1. Panoramic ultrasound images of the biceps brachii (a) and long head of the triceps brachii (b) with the straight-line function used for measuring muscle thickness in ImajeJ.

Statistical Analysis

Reliability analyses for FE and FF PT, TB and BB MT, and FE and FF EMG Co-Act were collected for Visit 2 (baseline) versus Visit 3 (pre-testing) and included repeated measures ANOVAs to evaluate systematic error, and a 2,1 model was used to calculate intraclass correlation coefficients (ICC).[31] The ICC values were interpreted as ≤ 0.5 = poor, 0.5 – 0.75 = moderate, 0.75 – 0.90 = good, ≥ 0.90 = excellent.[35] To determine the percentage of subjects who exhibited "real" changes from pre-testing (Visit 3) to post-testing (Visit 8), minimal difference values were calculated for each dependent variable using the following equation:[31]

$$Minimal\ Difference = Standard\ Error\ of\ the\ Mean \times 1.96 \times \sqrt{2}$$

Standard error of the mean was calculated using the following equation:[31]

$$Standard\ Error\ of\ the\ Mean = SD \times \sqrt{1} \times ICC$$

Separate two-way repeated-measures ANOVAs (Movement [FE versus FF] × Time [pre-testing versus post-testing]) were used to assess changes in PT and EMG Co-Act. In addition, a separate two-way repeated measures ANOVA (Muscle [TB versus BB] × Time [pre-testing versus post-testing]) was used to assess changes in MT. Post-hoc pairwise comparisons with Bonferroni corrections were used when appropriate. Effect sizes for the interaction and main effects of the repeated measures ANOVAs were calculated using a partial eta squared (η_p^2) and interpreted as 0.01 = small, 0.06 = medium, and 0.14 = large.[36] Cohen's *d* was used for calculating the effect sizes of the post-hoc pairwise comparisons and interpreted as 0.2 = small, 0.5 = medium, and 0.8 = large.[36] An alpha of $p \leq 0.05$ was used to determine statistical significance for all of the analyses. All statistical analyses were conducted in IBM SPSS v. 29 (Armonk, NY, USA).

Results

Reliability Analyses

The test-retest (baseline versus pre-training) reliability data and minimal difference values for FE and FF PT, TB and BB MT, and FE and FF EMG Co-Act are displayed in Table 1. The ANOVAs (2,1 model) indicated no significant ($p = 0.181 – 0.876$) mean differences for any of the variables, and the ICC values ranged from 0.768 to 0.973 (Table 1).

Isokinetic Peak Torque

Absolute pre-training, post-training, and change (i.e., post-training minus pre-training) values for FE and FF PT are displayed in Table 2. The repeated measures ANOVA indicated no significant ($p = 0.494$; $\eta_p^2 = 0.054$) two-way interactions for Movement (FE versus FF) by Time (pre-training versus post-training). There was, however, a significant ($p < 0.001$; $\eta_p^2 = 0.836$) main effect for Movement collapsed across Time (FF PT > FE PT; Table 3), and a significant ($p = 0.040$; $\eta_p^2 = 0.389$) main effect for Time collapsed across Movement (pre-training < post-training; Table 4). Individual absolute change values for FE and FF PT are shown in Table 5. Twenty percent of the subjects exceeded the FF PT minimal difference value of 4.67 N·m, whereas 10% of the subjects exceeded the FE PT minimal difference value of 6.14 N·m (Table 5). All subjects who exceeded the minimal difference values for FE or FF PT exhibited increases in PT from pre-training to post-training.

Electromyographic Co-activation

Absolute pre-training, post-training, and change values for FE and FF EMG Co-Act are displayed in Table 2. The repeated measures ANOVA indicated a significant ($p = 0.031$; $\eta_p^2 = 0.421$) two-way interaction for Movement (FE versus FF) by Time (pre-training versus post-training) (Figure 2). The Bonferroni corrected post-hoc comparisons indicated that FF EMG Co-Act decreased significantly ($p = 0.011$; $d = -1.01$) from pre-training (36.18%) to post-training (28.40%) by 7.78%, but there was no significant ($p = 0.598$; $d = 0.17$) difference between pre-training (20.58%) and post-training (22.90%) for FE EMG Co-Act (Figure 2). Furthermore, FF EMG Co-Act (36.18%) was significantly ($p = 0.003$; $d = 1.25$) greater than FE EMG Co-Act (20.59%) at pre-training by 15.59%, but there was no significant ($p = 0.149$; $d = 0.50$) difference between FF EMG Co-Act (28.40%) and FE EMG Co-Act (22.90%) at post-training (Figure 2). Individual absolute change values for FE and FF EMG Co-Act are shown in Table 5. None of the subjects exceeded the FF EMG Co-Act minimal difference value of 27.02%, whereas 20% of the subjects exceeded the FE EMG Co-Act minimal difference value of 16.22% (Table 5). Notably, subject 2 exhibited an increase (35.02%) in FE EMG Co-Act from pre-training to post-training, whereas subject 5 exhibited a decrease (-16.73%) in FE EMG Co-Act (Table 5).

Muscle Thickness

Absolute pre-training, post-training, and change values for TB and BB MT are displayed in Table 2. The repeated measures ANOVA indicated no significant ($p = 0.743$; $\eta_p^2 = 0.013$) two-way interactions for Muscle (TB versus BB) by Time (pre-training versus post-training). There was a significant ($p < 0.001$; $\eta_p^2 = 0.906$) main effect for Muscle collapsed across Time (BB < TB; Table 3), but there was no significant ($p = 0.106$; $\eta_p^2 = 0.264$) main effect for Time collapsed across Muscle (Table 4). Individual absolute change values for TB and BB MT are shown in Table 5. None of the subjects exceeded the BB MT minimal difference value of 0.25 cm, whereas one subject (i.e., 10%) exceeded the TB MT minimal difference value of 0.26 cm via a positive change value of 0.36 cm (Table 5).

Table 1. Reliability data and minimal difference values for isokinetic forearm extension and flexion peak torque and electromyographic co-activation at 180°·s^{-1}, as well as for the muscle thickness of the triceps brachii and biceps brachii.

Dependent Variable	Baseline (mean ± SD)	Pre-Training (mean ± SD)	*p*	ICC	$ICC_{95\%}$	SEM	Minimal Difference
Forearm Extension							
PT (N·m)	14.61 ± 4.56	15.48 ± 4.29	0.231	0.876	0.600 – 0.967	2.21	6.14
EMG Co-Act (%)	18.04 ± 8.19	20.58 ± 9.61	0.181	0.790	0.387 – 0.942	5.85	16.22
TB MT (cm)	1.74 ± 0.18	1.77 ± 0.22	0.402	0.889	0.634 – 0.971	0.09	0.26
Forearm Flexion							
PT (N·m)	23.49 ± 7.35	23.58 ± 7.14	0.876	0.973	0.896 – 0.993	1.68	4.67
EMG Co-Act (%)	32.02 ± 13.92	36.18 ± 14.36	0.190	0.768	0.342 – 0.936	9.75	27.02
BB MT (cm)	1.23 ± 0.14	1.26 ± 0.19	0.388	0.860	0.555 – 0.963	0.09	0.25

p = probability statistic from the ANOVA (2,1 model); ICC = intraclass correlation coefficient; $ICC_{95\%}$ = 95% confidence interval of the ICC; SEM = standard error of the mean; PT = peak torque; EMG Co-Act = electromyographic co-activation; TB MT = triceps brachii muscle thickness; BB MT = biceps brachii muscle thickness. The minimal difference was calculated using the following equation:[31] MD = SEM × 1.96 × √2.

Table 2. Performance data (mean ± SD) for isokinetic forearm extension and flexion peak torque and electromyographic co-activation at 180°·s^{-1}, as well as for the muscle thickness of the triceps brachii and biceps brachii.

Dependent Variable	Pre-Training (Min – Max)	Post-Training (Min – Max)	Absolute Change (Min – Max)
Forearm Extension			
PT (N·m)	15.48 ± 4.29 (9.50 – 22.60)	17.97 ± 6.53 (10.60 – 27.50)	2.49 ± 1.90 (-3.60 – 12.90)
EMG Co-Act (%)	20.58 ± 9.61 (6.14 – 40.24)	22.90 ± 12.16 (10.35 – 51.72)	2.32 ± 13.43 (-16.73 – 35.02)
TB MT (cm)	1.77 ± 0.22 (1.49 – 2.15)	1.82 ± 0.20 (1.49 – 2.15)	0.06 ± 0.16 (-0.15 – 0.36)
Forearm Flexion			
PT (N·m)	23.58 ± 7.14 (15.50 – 33.50)	26.96 ± 6.13 (20.10 – 37.80)	3.38 ± 4.37 (-4.70 – 12.30)
EMG Co-Act (%)	36.18 ± 14.36 (13.54 – 56.88)	28.40 ± 11.82 (14.07 – 47.43)	-7.78 ± 7.66 (-17.26 – 2.29)
BB MT (cm)	1.26 ± 0.19 (0.96 – 1.63)	1.29 ± 0.18 (0.94 – 1.65)	0.04 ± 0.06 (-0.03 – 0.16)

Min – Max = range of values from minimum to maximum. Absolute Change = post-training value minus pre-training value. PT = peak torque; EMG Co-Act = electromyographic co-activation; TB MT = triceps brachii muscle thickness; BB MT = biceps brachii muscle thickness.

Table 3. The main effects for Movement or Muscle collapsed across Time (pre-training and post-training) for isokinetic peak torque and muscle thickness, respectively.

Dependent Variable	Mean ± SD
Peak Torque (N·m)	
Extension	16.73 ± 5.08
Flexion	25.27 ± 6.28
Mean Difference	-8.55 ± 3.99*
Muscle Thickness (cm)	
Triceps Brachii	1.80 ± 0.19
Biceps Brachii	1.28 ± 0.18
Mean Difference	0.52 ± 0.18*

Mean difference for peak torque = extension minus flexion. Mean difference for muscle thickness = triceps brachii minus biceps brachii.
*$p < 0.001$.

Table 4. The main effects for Time collapsed across Movement (extension and flexion) or Muscle (triceps brachii and biceps brachii) for isokinetic peak torque and muscle thickness, respectively.

Dependent Variable	Mean ± SD
Peak Torque (N·m)	
Pre-Training	19.53 ± 5.45
Post-Training	22.47 ± 5.93
Mean Difference	2.94 ± 3.88*
Muscle Thickness (cm)	
Pre-Training	1.51 ± 0.16
Post-Training	1.56 ± 0.18
Mean Difference	0.05 ± 0.09

Mean difference for peak torque and muscle thickness = post-training minus pre-training.
*$p = 0.040$.

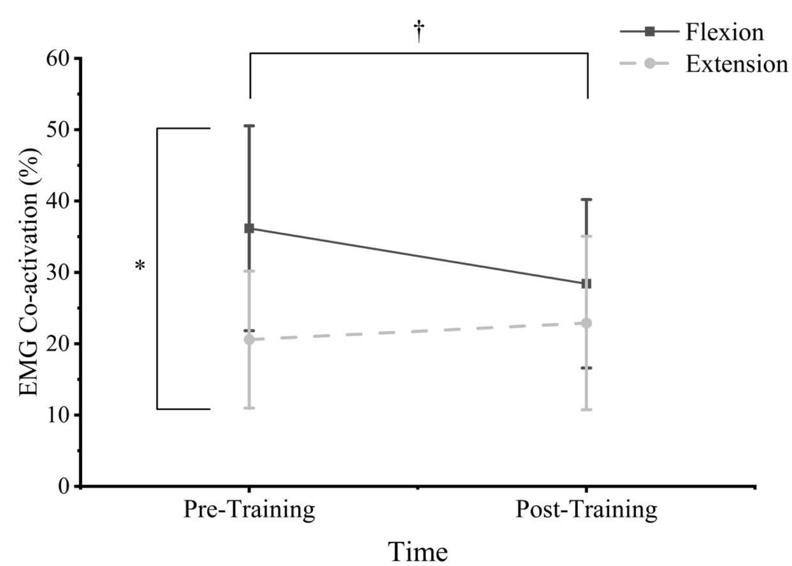

Figure 2. The Bonferroni corrected ($p \leq 0.05$ / 4 = $p \leq 0.0125$) post-hoc comparisons for the significant ($p = 0.031$) interaction for the two-way repeated-measures ANOVA (Movement [FE versus FF] × Time [pre-testing versus post-testing]) for electromyographic (EMG) co-activation. The data presented are expressed as mean and standard deviation (error bars) values.
*$p = 0.003$ (flexion > extension at pre-training).
†$p = 0.011$ (pre-training > post-training for flexion).
$p = 0.149$ (flexion = extension at post-training).
$p = 0.598$ (pre-training = post-training for extension).

Discussion

The present study aimed to examine group mean (ANOVAs) and individual (minimal difference) responses in FE and FF PT at $180°\cdot s^{-1}$, TB and BB MT, and FE and FF EMG Co-Act following four days of maximal, reciprocal, concentric, isokinetic FE and FF training at $180°\cdot s^{-1}$ in untrained women. We hypothesized that there would be group mean training-induced increases in FE and FF PT, no changes in TB and BB MT, and decreases in FE and FF EMG Co-Act. In addition, we hypothesized that the individual responses (i.e., the proportion of subjects who exceeded the minimal difference) would generally track the group mean responses for all dependent variables. The results of the ANOVAs for PT and MT supported our hypotheses as there were parallel group mean increases in FE and FF PT with no group mean changes in TB and BB MT (Table 4). Furthermore, although there was a group mean decrease in FF EMG Co-Act, there was no group mean change in FE EMG Co-Act (Figure 2). In general, the proportion of subjects who exceeded the minimal difference for BB MT (0%), TB MT (10%), and FE EMG Co-ACT (20%) tracked the group mean responses, whereas the proportion of subjects for FE PT (10%), FF PT (20%), and FF EMG Co-Act (0%) did not track the group mean responses (Table 5). Therefore, despite significant group mean responses, there was a lack of a substantial percentage of individuals who demonstrated increases in FE and FF PT greater than the minimal difference, as well as no subjects who decreased their FF EMG Co-Act greater than the minimal difference. The significant group mean responses, thus, should be considered in the context of the conflicting findings with the individual responses.

The test-retest reliability analyses indicated no significant mean difference between baseline (Visit 2) and pre-training (Visit 3) for any of the dependent variables (Table 1). The ICC values for FE PT (ICC = 0.876) and FF PT (ICC = 0.973) reflected good and excellent reliability,[35] respectively, and were higher than those reported by Neltner et al[37] for FE PT (ICC = 0.82) and FF PT (ICC = 0.63) at $180°\cdot s^{-1}$ in recreationally active women. In addition, the ICC values in the present study for FF EMG Co-Act (ICC = 0.768) and FE EMG Co-Act (ICC = 0.790), as well as for BB MT (ICC = 0.860) and TB MT (ICC = 0.889), reflected good reliability. These ICC values were lower than those reported by Miyatani et al[38] for BB MT (ICC = 0.98) and TB MT (ICC = 0.99), but similar to those of Thoirs and English[39] (BB MT = 0.84 – 0.89; TB MT = 0.84 – 0.91).

The results of the present study (Table 4) indicated that there were parallel training-induced group mean increases in FF (12.54%) and FE (13.86%) PT at $180°\cdot s^{-1}$ (Table 2) in untrained women following four days of maximal, reciprocal, concentric, isokinetic FE and FF training at $180°\cdot s^{-1}$. Beck et al,[1] however, trained the dominant arm of untrained men for two days using the same reciprocal protocol as the present study and found no training-induced changes in PT or EMG amplitude at MVIC, 60, or $180°\cdot s^{-1}$. Furthermore, the present findings were not consistent with those of Traylor et al,[9–11] who reported no changes in PT at MVIC, 60, 180, or $300°\cdot s^{-1}$ in the non-dominant arm of untrained women following three days of maximal, non-reciprocal, concentric, isokinetic FF training with five sets of 10 repetitions at $60°\cdot s^{-1}$. Unlike Traylor et al,[9–11] however, the women in the present study trained with reciprocal FE and FF muscle actions. In recreationally active men, Cunha et al[7] observed that three days of four sets of 10 repetitions at $60°\cdot s^{-1}$ of maximal, reciprocal, concentric, isokinetic leg flexion and extension training induced greater increases in PT at $60°\cdot s^{-1}$ than non-reciprocal, leg extension training. Furthermore, only the reciprocal training group exhibited training-induced increases in PT at $180°\cdot s^{-1}$.[7] Preloading an agonist, concentric, isokinetic muscle action with an antagonist, concentric, isokinetic muscle action has been shown to produce greater PT and EMG amplitude values than performing only an agonist muscle action without preloading of the leg extensors.[12] Jeon et al[12] suggested that lengthening of the leg extensors with a concentric muscle action of the leg flexors enhanced neural drive to the leg extensors during a subsequent concentric muscle action via stimulation of group Ia afferents. Moreover, when compared to previous maximal, non-reciprocal, concentric, isokinetic leg extension training studies in women, the present findings were consistent with those of Coburn et al,[4] but not Brown and Whitehurst.[2] The conflicting findings[1,2,4,7,9–11] may be due to the differences in the number of training days, as well as the number of sets and repetitions performed. For example, Coburn et al[4] reported training-induced increases in PT following three days of training with four sets of 10 repetitions, whereas Brown and Whitehurst[2] reported no changes in PT following two days of training with three sets of eight repetitions. It is possible that the present findings of training-induced increases in FE and FF isokinetic PT conflicted with previous studies[1,2,9,11] due to differences in the sex of the subjects, days of training (e.g., two versus three versus four days), training protocol (e.g., sets, repetitions, and velocity), training limb (e.g., dominant versus non-dominant), muscle groups (e.g., forearm versus leg muscles), and/or muscle actions (e.g., reciprocal versus non-reciprocal).

It has been generally accepted that very short-term training-induced increases in strength are not due to muscle hypertrophy.[4,6,8,13–16] The present findings were consistent with this hypothesis as there were no mean training-induced changes in TB MT or BB MT. DeFreitas et al[14] reported significant increases in thigh muscle cross-sectional area (CSA) in untrained men following two trainings sessions of DCER leg extensions, leg presses, and bench presses for three sets of eight to 12 repetitions to failure. The authors,[14] however, speculated that the increases in CSA within the first two weeks of training (three sessions per week) were predominately related to eccentric-induced edema and not hypertrophy because: (1) Strength did not increase until week four of training; (2) the subjects anecdotally (i.e., not measured) complained of muscle soreness during the first two weeks of training, which ceased by week three; and (3) week three was the first to exhibit CSA values that were greater than week one (i.e., the week speculated to have the highest degree of edema). To limit the confounding factor of eccentric-induced muscle edema, Stock et al[16] examined the time course of changes in BB MT in untrained men during four weeks (two sessions per week) of unilateral, concentric-only, DCER dumbbell curls and shoulder presses with five to six sets of eight to 12 repetitions to failure. The authors[16] did not observe significant increases in BB MT until the seventh training session, which suggested that hypertrophy may occur in the absence of eccentric-induced edema as early as after seven training sessions. Thus, the present findings were consistent with Stock et al[16] in that four sessions of concentric-only training were not sufficient to observe training-induced increases in BB MT in untrained women. Future studies, however, should examine the time course of changes in MT during concentric-only, reciprocal, isokinetic muscle actions to identify the earliest time point at which muscle hypertrophy is detectable.

The results of the present study indicated group mean increases in both FF PT (12.54%) and FE PT (13.86%) following four days of isokinetic training in women. For FF PT, there was also a 7.78% decrease in the group mean for FF EMG Co-Act from the TB (Figure 2), which in theory, may have influenced the net agonist torque production and, thereby, contributed to the training-induced increase in FF PT.[20–22] This was not the case, however, for FE PT as there was no training-induced changes in the group mean for FE EMG Co-Act from the BB (Figure 2). These findings suggested that there may be movement- and/or muscle-specific adaptations to very short-term isokinetic resistance training that influence Co-Act. There is conflicting evidence, however, regarding the effect of resistance training on Co-Act, and previous studies[5,20–22,24,26,27,40] have demonstrated decreases, increases, or no training-induced changes in Co-Act for various muscle groups, training protocols, and sample characteristics. Generally, studies[21,22] that have reported decreases in Co-Act have emphasized the potential contribution to increased strength, while Pucci et al[40] found no changes in Co-Act and hypothesized that Co-Act does not contribute to strength increases. It has also been hypothesized that training-induced increases in Co-Act improve joint stability.[5,24–27] Although it is unclear under what conditions decreases in Co-Act may contribute to early phase increases in strength, previous studies[17–19] have provided support for other neural adaptations as the mechanisms underlying resistance training-induced increases in strength in the absence of hypertrophy. The generic neural adaptations involve increases in motor unit recruitment and rate coding.[17–19] A number of more specific mechanisms are associated with increases in motor unit recruitment and rate coding, including increases in the peak discharge rate of motor units,[19] net excitatory input to the motor neuron pool,[17] and decreases in relative motor unit recruitment thresholds.[17] Thus, in the present study, it is unclear whether the training-induced decreases in FF Co-Act contributed to the increases in FF PT. However, it is likely that neural adaptations contributed to the early phase adaptation in FE PT and FF PT following four days of reciprocal isokinetic training, since there were no changes in TB MT or BB MT. Since the present study did not utilize techniques to directly measure motor unit behavior (e.g., EMG decomposition) or voluntary activation (e.g., interpolated twitch technique [ITT]), the precise neural mechanism that contributed to the increases in PT in the present findings are not fully understood. Costa et al[5] reported no changes in voluntary activation at 30, 50, 70, and 100% of MVIC using the ITT following short-term isokinetic and DCER training, which was consistent with Tillin et al,[27] who reported no changes in voluntary activation following four weeks of isometric training. These previous findings[5,27] indicated that increases in voluntary activation did not contribute to the early phase neural adaptations to resistance training.

Practitioners may be more interested in whether an individual patient, client, or athlete will exhibit training-induced changes in performance following a resistance training intervention compared to the mean response of a group.[29] Thus, a unique aspect of this study was the additional analyses of whether individual subjects exhibited "real" training-induced changes in PT, MT, and Co-Act based on whether their values exceeded the minimal difference from the reliability analyses.[31] For example, the sample in the present study exhibited significant mean training-induced increases in FE PT and FF PT (Table 4), but only 20% (2 out of 10) and 10% (1 out of 10) of the subjects exceeded the minimal difference for changes in FE PT and FF PT, respectively, to be considered "real" (Table 5). In addition, the sample exhibited a significant mean training-induced decrease in FF EMG Co-Act (Figure 2), but none of the subjects exhibited decreases in FF EMG Co-Act that exceeded the minimal difference (Table 5). Therefore, based on the individual analyses, the very short-term isokinetic resistance training protocol in the present study induced "real" increases in PT for only a small percentage of subjects, and it induced no "real" decreases in FF EMG Co-Act for any of the subjects. With no subjects exhibiting "real" decreases in FF EMG Co-Act, it is likely that other neural mechanisms besides a decrease in Co-Act contributed to the mean increases in PT. Moreover, perhaps a greater number of training sessions are required for more subjects to exhibit training-induced change values that exceed the minimal difference values. Thus, the present study highlighted the importance of analyzing individual responses in addition to the group mean data. Future very short-term resistance training studies aiming to evaluate early phase adaptations should include the analyses of individual responses as they may provide unique information beyond the mean responses of a group.

Table 5. Individual absolute changes (post-training value minus pre-training value) and the proportion of subjects who exceeded the minimal difference for isokinetic forearm extension and flexion peak torque and electromyographic co-activation at 180°·s^{-1}, as well as for the muscle thickness of the triceps brachii and biceps brachii.

Subject	Δ FE PT (N·m)	Δ FF PT (N·m)	Δ TB MT (cm)	Δ BB MT (cm)	Δ FE EMG Co-Act (%)	Δ FF EMG Co-Act (%)
1	2.00	4.5	-0.05	0.01	5.90	1.35
2	1.50	4.6	0.01	-0.02	35.02*	2.29
3	5.10	0.0	0.24	0.01	-2.12	-0.13
4	2.50	4.4	0.21	-0.03	6.70	-7.82
5	-1.20	-4.7	0.36*	0.12	-16.73*	-1.88
6	-3.60	5.1*	0.01	-0.01	0.34	-13.96
7	2.80	0.5	-0.01	0.02	-4.53	-17.26
8	1.80	3.8	-0.04	0.05	-5.57	-14.64
9	12.90*	12.3*	-0.02	0.16	-1.50	-16.31
10	1.10	3.3	-0.15	0.08	5.71	-9.45
Minimal Difference	6.14	4.67	0.26	0.25	16.22	27.02
Proportion of Subjects Who Exceed the Minimal Difference	1/10 (10%)	2/10 (20%)	1/10 (10%)	0/10 (0%)	2/10 (20%)	0/10 (0%)

Δ = absolute change (post-training value minus pre-training value); FE PT = forearm extension peak torque; FF PT = forearm flexion peak torque; TB MT = triceps brachii muscle thickness; BB MT = biceps brachii muscle thickness; FE EMG Co-Act = electromyographic co-activation during forearm extension; FF EMG Co-Act = electromyographic co-activation during forearm flexion.
*Value exceeds the minimal difference. The minimal difference was calculated using the following equation:[31] MD = standard error of the mean × 1.96 × √2.

The findings of the present study were limited to four days of maximal, reciprocal, concentric, isokinetic FE and FF training of the non-dominant arm at 180°·s^{-1} in untrained women. Therefore, the present findings may not reflect the responses to DCER training, which is more commonly used by recreationally active individuals and athletes, since the two resistance training modalities differ in their velocity (isokinetic = constant versus DCER = not constant) and resistance (isokinetic = not constant versus DCER = constant) profiles. Future very short-term resistance training studies should utilize various isokinetic velocities or DCER movements with other muscle actions and sample characteristics. In addition, the analyses of PT and EMG Co-Act were limited to isokinetic muscle actions at 180°·s^{-1} for the non-dominant arm. Future studies should assess PT and EMG Co-Act at MVIC and other velocities, as well for the untrained arm to examine the cross-education effect (i.e., strength gains in the untrained limb following unilateral training). Furthermore, the MT assessments were limited to the BB and the long head of the TB at a single measurement site. Future studies should analyze other FF muscles (e.g., brachialis and brachioradialis) and heads of the TB (e.g., medial and lateral) at various measurement sites (e.g., proximal, middle, and distal). In addition, the MT values from the ultrasound images were limited to the analysis of a single scan and, thus, collecting multiple scans and averaging the MT values may have improved the accuracy and sensitivity in the measurements. Moreover, the analyses of the dependent variables were only examined after completing four days of training. Thus, future studies with a similar methodology should analyze more time points following more training sessions to further examine the time-course of changes in PT, MT, and Co-Act in untrained women. Lastly, although a control group was not included in the present research design, a familiarization day was included to reduce the likelihood of subjects exhibiting learning effects (i.e., increases in PT from increased familiarity, not physiological adaptations). In addition, reliability data indicated no differences in PT for the baseline versus pre-training visits, and the use of minimal difference values allowed for the analysis of intrasubject (i.e., within-subject) responses to the training.

The findings of the present study indicated that, in untrained women, there were similar group mean increases in FE and FF PT as a result of four days of maximal, reciprocal, concentric, isokinetic FE and FF training. The lack of mean or individual training-induced changes in TB MT or BB MT suggested that the group mean increases in PT were likely the result of neural adaptations, such as increases in motor unit recruitment and rate coding, and not hypertrophy.[17–19] Furthermore, there were mean training-induced decreases in FF EMG Co-Act from the BB, but not FE EMG Co-Act from the TB. These results in combination with the mixed findings of previous studies[5,20–22,24,26,27,40] that reported decreases, increases, or no changes in Co-Act make it unclear if, in addition to other neural mechanisms, decreases in Co-Act contribute to training-induced increases in PT. Furthermore, a small percentage of individual subjects exhibited training-induced increases in FE PT (10%) and FF PT (20%) that were considered "real" (i.e., a change value greater than the minimal difference value from reliability analyses), and none of the subjects exhibited training-induced decreases in FF EMG Co-Act that were considered "real." Thus, the current findings highlighted the importance of analyzing individual responses in addition to group mean responses since the data for the individual responses indicated that only 0 to 20% of the subjects exhibited real increases in FE and FF PT or decreases in FF EMG Co-Act despite the group mean data indicating that there were significant mean changes. In addition, future very short-term studies are needed to determine the specific neural mechanisms that contribute to early phase, training-induced increases in strength, as well as to identify the earliest time point in which untrained women exhibit training-induced hypertrophy.

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