Neuromuscular Adaptations Following Antagonist Resisted Training

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Abstract

MacKenzie, SJ, Rannelli, LA, and Yurchevich, JJ. Neuromuscular Adaptations Following Antagonist Resisted Training. *J Strength Cond Res* 24(1): 156–164, 2010—The purpose was to assess a novel form of strength training, antagonist resisted training (ART), with potential use in microgravity and athletic rehabilitation settings. ART uses the force from antagonist muscles, during cocontractions, as the source of resistance for the agonists. Strength and electromyography (EMG) measurements were recorded before and after a 6-week training program during which participants trained the left arm while the right arm served as a control. Training was designed so that the elbow extensors (antagonists) served as resistance for the elbow flexors (agonists). Elbow flexor and extensor strengths were measured during maximal isometric contractions with the elbow fixed at 90 degrees. EMG was recorded from the biceps brachii and lateral head of the triceps brachii during all strength tests. EMG was also recorded from both muscles during a maximal isometric cocontraction of the elbow flexors and extensors. Elbow flexion strength increased significantly for the trained arm (5.8%) relative to the control (0.5%) ($p = 0.003$). Elbow extension strength of the trained limb also increased significantly (8.5%) relative to the control (4.5%) ($p = 0.029$). Biceps and triceps EMG, during maximum strength tests, increased significantly for the trained arm (18.5 and 18.6%) relative to the control (0.5 and −5.2%) ($p = 0.035$ and $p = 0.01$). Biceps and triceps EMG, during maximum cocontraction tests, increased significantly for the trained arm (30.1 and 61.1%) relative to the control (9.2 and 1.1%) ($p = 0.042$ and $p = 0.0005$). ART was found to increase strength and therefore could be an effective form of resistance training. Because it requires no equipment, ART may be especially applicable in microgravity environments, which have space and weight constraints.

Key Words cocontraction, strength training, biceps, EMG, elbow, microgravity

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Introduction

Most strength training methods require the application of an external force toward the distal end of a body segment to provide resistance to the contracting muscles (3,6,12, 16,17,18,21). Researchers have demonstrated that methods using neuromuscular electrical stimulation (NMES), which involve inducing an involuntary muscle contraction, do not require external resistance to bring about increases in muscle strength (15). More recently, researchers implemented a resistance training technique that involved the concentric contraction of an agonist muscle against the resistance of an antagonist muscle whose contraction was artificially induced using NMES (26,37). The results of these studies demonstrated that this artificially generated cocontraction technique was effective at producing physiological adaptations and strength gains.

This "hybrid" training exploits the fact that skeletal muscles often exist in agonist–antagonist groups that can be simultaneously activated to generate opposing torques about a joint. Researchers have suggested that agonist–antagonist groups may be controlled by a common drive (8). Their model proposes that separate "flex" and "extend" commands exist to control reciprocal actions, whereas a third command, "coactivation," controls the pure cocontraction of both the agonist and antagonist muscles (8). This notion of different controls for the different aspects of agonist–antagonist contraction states has been supported by electrophysiological evidence from other researchers (13,31).

This research suggests that if an antagonist muscle is the proposed source of resistance in a strength exercise, then NMES may not be necessary to induce its activation. In fact, it has been demonstrated that dynamic *voluntary* cocontraction of the elbow flexors and extensors is possible throughout a full range of motion (32); however, not all subjects sustained the cocontraction throughout the entire movement. Of note, the level of training, if any, the participants received in maximally performing the dynamic cocontractions was not reported (32). This is important because there is research suggesting that the level of coactivation in antagonist muscles is trainable through some form of resistive exercise (2,4,14).

Previous research suggests that voluntary dynamic cocontractions are possible without artificially stimulating either the agonist or antagonist. If the level of resistive torque provided by the antagonist is sufficient, then dynamic cocontractions could form the basis of a resistance training program. Thus, the purpose was to determine if antagonist resisted training (ART) would induce neuromuscular adaptations in an agonist–antagonist group of muscles. Specifically, the elbow flexors (agonists) and elbow extensors (antagonists) were investigated. To be clear, an ART exercise involving these muscles would require both the flexors and extensors *of the same arm* to be voluntarily activated at a high level while the forearm moved through a full range of motion. A key assumption behind ART is that the antagonist muscles (elbow extensors) can supply enough resistance to elicit a training response in the agonist muscles (elbow flexors). Therefore, a second objective was to determine if ART would improve the ability of the elbow extensors to provide resistance during a cocontraction. In other words, would the level of muscle activity generated during a maximal cocontraction be increased through training? Measurements of electromyography (EMG) and maximum isometric force were used to quantify neuromuscular adaptations to the training technique. It was hypothesized that, through ART exercises, elbow flexor and extensor strength would increase. A second hypothesis was that the ability of the elbow extensors to provide resistance during a cocontraction, as measured with EMG, would also increase.

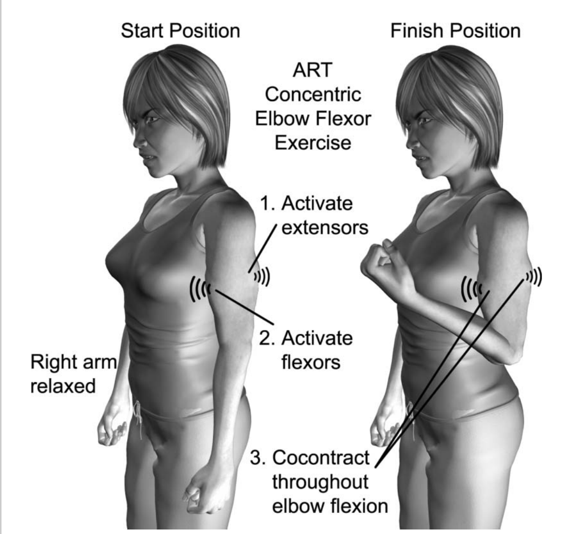

Figure 1. Sequential steps taken during the antagonist resisted training (ART) concentric elbow flexor exercise. Both the elbow flexors and extensors of the left arm were highly activated throughout the full range of motion. The torque generated by the elbow flexors was slightly greater than that of the extensors, which permitted elbow flexion to occur.

Methods

Experimental Approach to the Problem

A 6-week training program, which focused exclusively on the left arm so the right arm could be used as a control, required subjects to attend 3 training sessions per week. There were 2 independent variables, each with 2 levels: training (control, trained) and time (pre, post). The effect of the independent variables on 2 dependent variables (strength, EMG) was assessed. EMG was measured under 2 conditions: during isometric strength tests and during maximal isometric cocontractions. This design permitted the evaluation of ART as a strength training method, which was the first hypothesis, through comparison of strength changes in the control and trained limb. Initial strength gains, as a result of resistance training, are a result of neuronal adaptations (28). Therefore, comparison of EMG changes in the control and trained limb, recorded during the strength testing, further tested the hypothesis of neuromuscular adaptation as a result of ART. The second hypothesis that maximal cocontraction intensity will increase following ART was tested by comparing changes in maximal cocontraction EMG in the control and trained limb.

Subjects

Twenty-three right-handed females ranging in age from 18 to 21 years old and enrolled at St. Francis Xavier University participated in the study. All subjects reported having little to no weight training experience, with no training in the 6 months preceding the study. The height and weight of each participant were not measured. Subjects attended an information session where they were educated on testing and

Table 1. Number of sets (repetitions) performed during the training sessions. Three sessions were completed each week. Participants rested 2 minutes between each set.

Exercise	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Concentric	2 (12)	2 (12)	2 (12)	3 (12)	3 (12)	3 (12)
Eccentric	2 (12)	2 (12)	2 (12)	5 (6)	4 (6)	3 (6)
Combination	2 (8)	3 (8)	3 (9)	3 (6)	3 (6)	3 (6)
Total reps	54	72	75	84	78	72

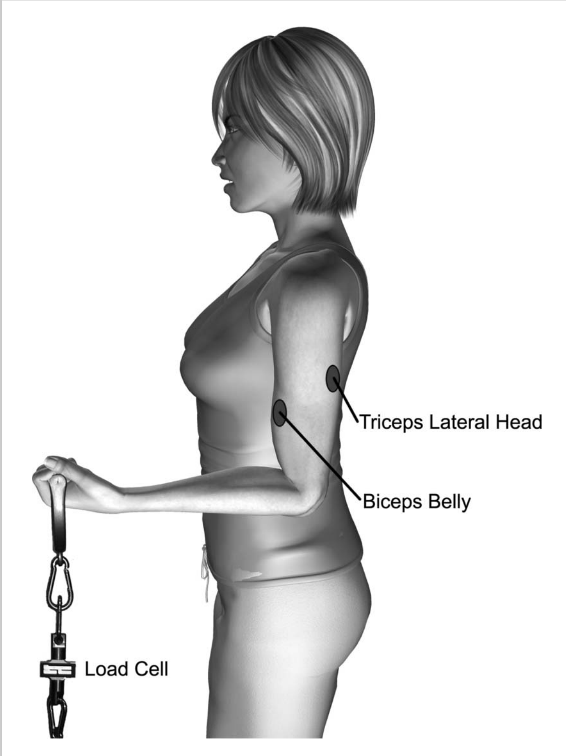

Figure 2. Set-up used for determining the maximum isometric strength of the elbow flexors. Force data were collected via a load cell, which was serially linked in an adjustable chain firmly fastened to the floor. Surface electromyography (EMG) was collected from the belly of the biceps brachii and lateral head of the triceps brachii.

training procedures prior to signing an informed consent document approved by the Institutional Review Board of the university.

Procedures

Training Protocol. Concentric, eccentric, and concentric–eccentric combination movements were incorporated as 3 variations of the ART technique. The following describes actions of the left arm only. The right arm remained relaxed at the side of the body during all exercises. During the concentric contractions, subjects would begin the movement in full elbow extension and with the elbow extensors (antagonists) activated (Figure 1). This was followed by activation of the elbow flexors (agonists). To create the *dynamic* cocontraction, the elbow flexors were activated at a level great enough to overcome the torque produced by the extensors. The repetition was completed once the elbow had moved through its entire range of motion. Subjects were instructed and monitored to ensure the motion lasted approximately 4 seconds. Similarly, eccentric contractions began with the elbow in full flexion and with the elbow flexors activated. The elbow extensors were then sufficiently activated to generate a slightly larger torque in comparison to that produced by the flexors. Again, the dynamic cocontraction lasted approximately 4 seconds as the elbow moved into full extension. The combination contraction was simply a concentric contraction immediately followed by an eccentric contraction with the whole movement lasting approximately 8 seconds. In accordance with the progressive overload principle of strength training, the number of repetitions was varied from week to week to manipulate the volume and intensity (Table 1). Participants rested for 2 minutes between each set of exercises throughout the training period. It was assumed that, over the course of the study, each subject developed the ability to cocontract the flexors and extensors, and as this task was learned, the intensity of cocontraction increased. All training sessions occurred during the months of October and November.

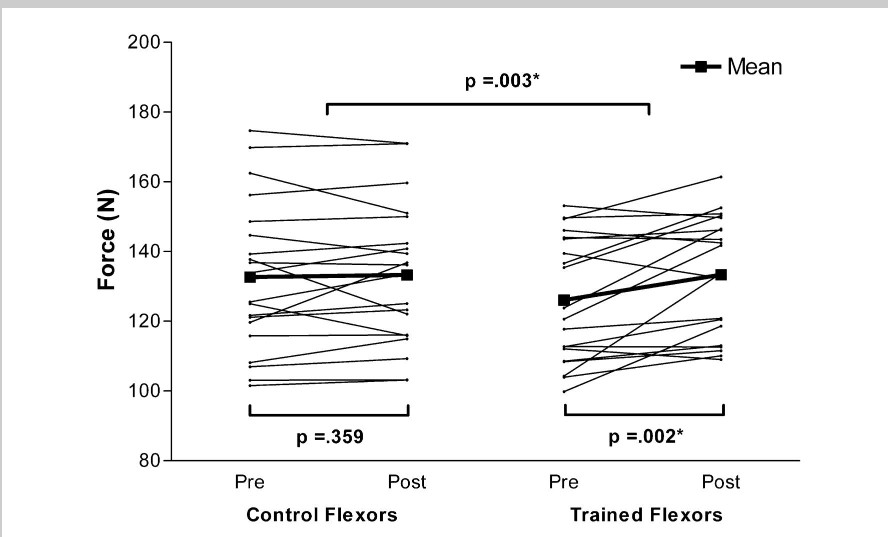

Figure 3. Maximum isometric strength of the elbow flexors for both arms before and after training. Each participant's pre-test score is connected to their post-test score with a line. Upper *p*-value indicates the significance for the time by training interaction. Lower *p*-values indicate the significance of the difference from pre- to post-test. *Statistical significance ($n = 20$).

Isometric Strength Data. Elbow flexion strength was measured with the subject standing upright, elbow flexed at 90 degrees, and forearm supinated (Figure 2). While maintaining this posture, the subject performed maximal isometric elbow flexion for 5 seconds against a stirrup-shaped handle grasped in the hand. The handle was firmly bolted to the floor with an adjustable chain, which was fitted with a load cell (MLP-300, Transducer Technology, Temecula, California, USA) to measure the force exerted by the subject. Elbow extension strength testing was similar with 2 exceptions: (a) the handle-chain system was hung from a rigid overhead beam, and (b) force was applied downward with the forearm in pronation.

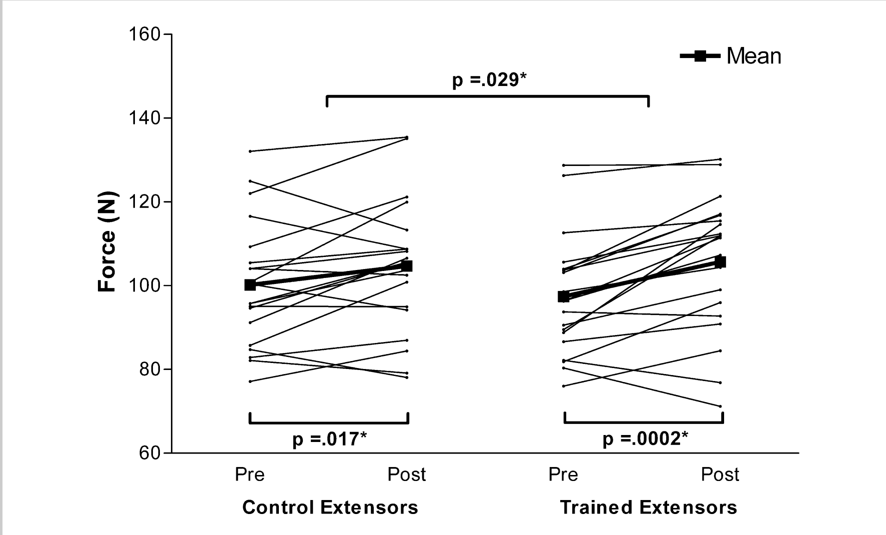

Figure 4. Maximum isometric strength of the elbow extensors for both arms before and after training. Each participant's pre-test score is connected to their post-test score with a line. Upper *p*-value indicates the significance for the time by training interaction. Lower *p*-values indicate the significance of the difference from pre- to post-test. *Statistical significance ($n = 20$).

Force data, collected at 100 Hz by the load cell, were passed through a 12-bit AtoD converter (Type 9243, A-Tech Instruments Ltd., Toronto, Canada) before being recorded on a computer. Data were imported into a custom-designed Matlab (Mathworks Inc., Natick, Massachusetts, USA) program to determine the strength scores. Force data were passed through a second-order zero-lag low-pass Butterworth filter with a cut-off frequency of 6 Hz. Strength scores were calculated by averaging the highest 100 discrete bits of digital force data. Force values were digitally stored every 0.01 seconds, so this represented the best noncontiguous second of force application by the subject. Typically, subjects generated their peak force approximately 2 seconds from the start of the contraction, and the highest 100 force values clustered closely to this time point.

Electromyography Data. EMG data were obtained, during all strength tests previously described, from 2 Delsys DE-2.3 single differential surface EMG electrodes (silver, 1-mm diameter, 10-mm interelectrode distance). One electrode was placed on the belly of the biceps brachii approximately midway between the glenohumeral joint and the antecubital space. The second electrode was placed over the lateral head of the triceps brachii (Figure 2) (4,14). Indelible ink was used to mark the location and position of the electrodes during the pre-test and to re-mark throughout the training protocol to ensure consistent placement at post-test. The reference electrode was placed over the lateral malleolus of the left ankle. EMG data were also collected under an additional cocontraction condition. While in the flexor strength testing posture (without grasping the handle), subjects were instructed to

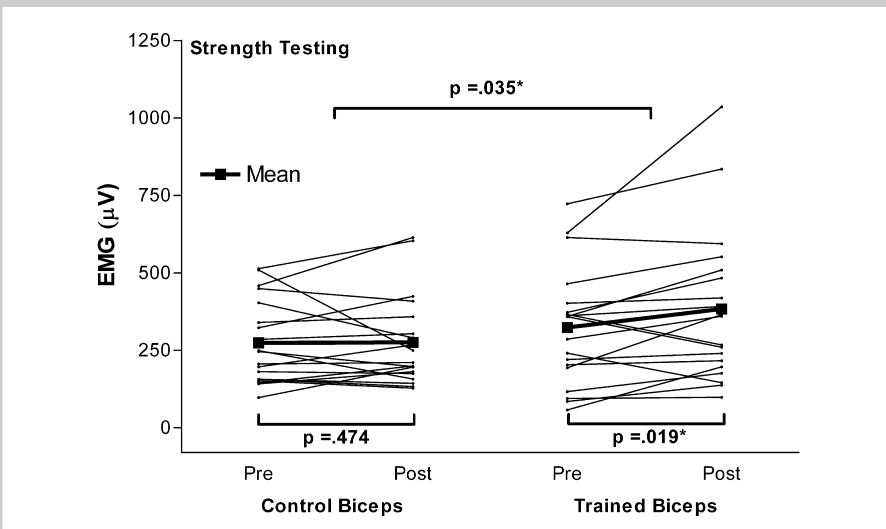

Figure 5. Root-mean-square electromyography (RMS EMG) of the biceps brachii during the strength testing for both arms before and after training. Each participant's pre-test score is connected to their post-test score with a line. Upper *p*-value indicates the significance for the time by training interaction. Lower *p*-values indicate the significance of the difference from pre- to post-test. *Statistical significance ($n = 19$).

maximally contract both the elbow flexors and extensors simultaneously. However, the 90-degree elbow angle was maintained throughout the cocontraction to reduce the likelihood of the electrodes recording activity from a different section of the underlying muscle. This condition was included to determine if the magnitude of muscular activity generated during a cocontraction improved after training.

The raw EMG data were passed through a second-order band-pass Butterworth filter with cut-off frequencies set at 20 Hz and 500 Hz (7). The filtered EMG signal was used to calculate the root-mean-square (RMS) amplitude of the EMG activity (1). Peak RMS values were then determined and used as the subjects' EMG score. All EMG data conditioning was accomplished in a custom-designed Matlab (Mathworks Inc.) program. For flexion strength tests, only biceps EMG were analyzed, and during extension strength tests, only triceps EMG data were analyzed. During the cocontraction condition, EMG data were analyzed from both muscles.

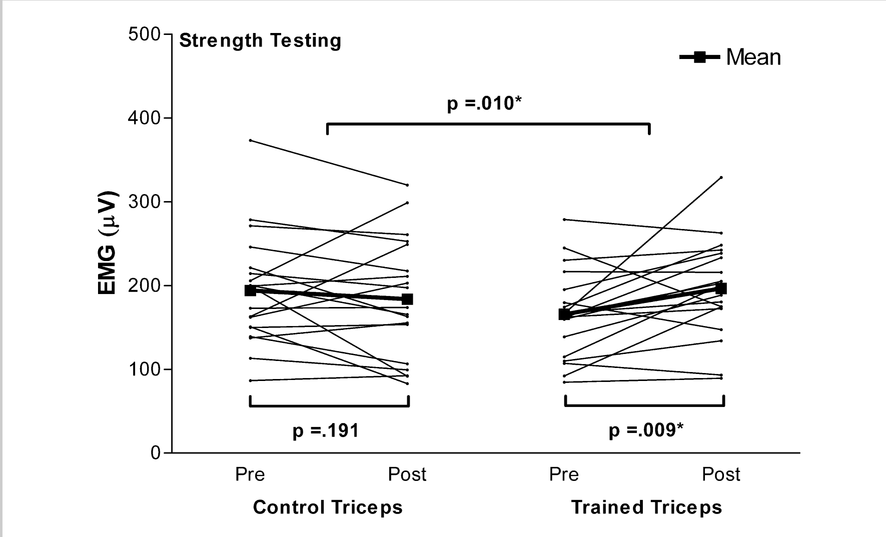

Figure 6. Root-mean-square electromyography (RMS EMG) of the triceps brachii lateral head during the strength testing for both arms before and after training. Each participant's pre-test score is connected to their post-test score with a line. Upper *p*-value indicates the significance for the time by training interaction. Lower *p*-values indicate the significance of the difference from pre- to post-test. *Statistical significance ($n = 19$).

Statistical Analyses

The first hypothesis was that, through ART exercises, elbow flexor and extensor strength would increase. This was evaluated by determining if the trained limb demonstrated greater increases with the strength tests, and the associated EMG scores, in comparison with the control limb. Statistically this was accomplished by performing a test for the interaction effect of the 2 independent variables (time × training) on these strength and EMG scores. The interaction was statistically assessed by performing a 1-tailed paired *t*-test on the change scores (post–pre) for each limb. Used in this manner, a paired *t*-test accomplishes the same goal as the interaction term in repeated-measures analysis of variance. A visual assessment can be made by comparing the difference in the slopes of the thick lines between the control and trained limbs in Figures 3–8. The second hypothesis was that the level of muscle activity generated during a maximal cocontraction would be increased through ART exercises. This was evaluated by determining if the

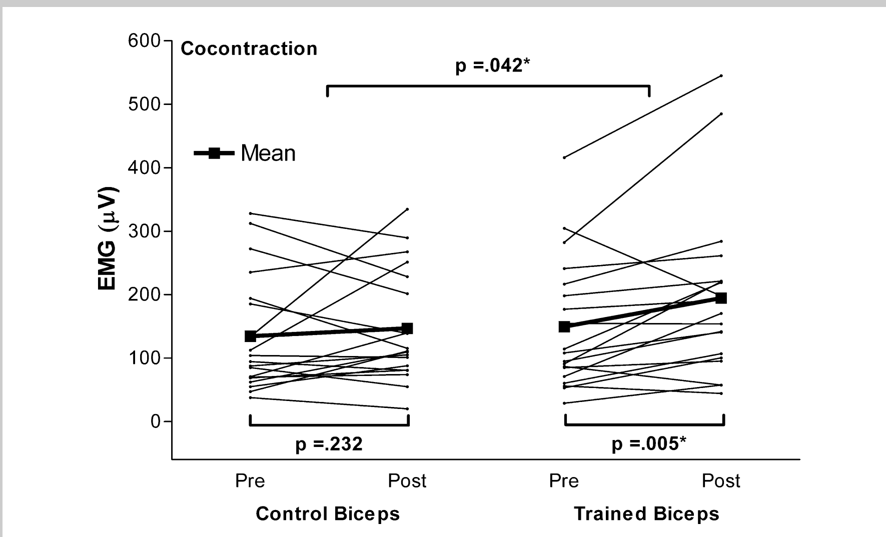

Figure 7. Root-mean-square electromyography (RMS EMG) of the biceps brachii during the maximal cocontraction for both arms before and after training. Each participant's pre-test score is connected to their post-test score with a line. Upper *p*-value indicates the significance for the time by training interaction. Lower *p*-values indicate the significance of the difference from pre- to post-test. *Statistical significance ($n = 19$).

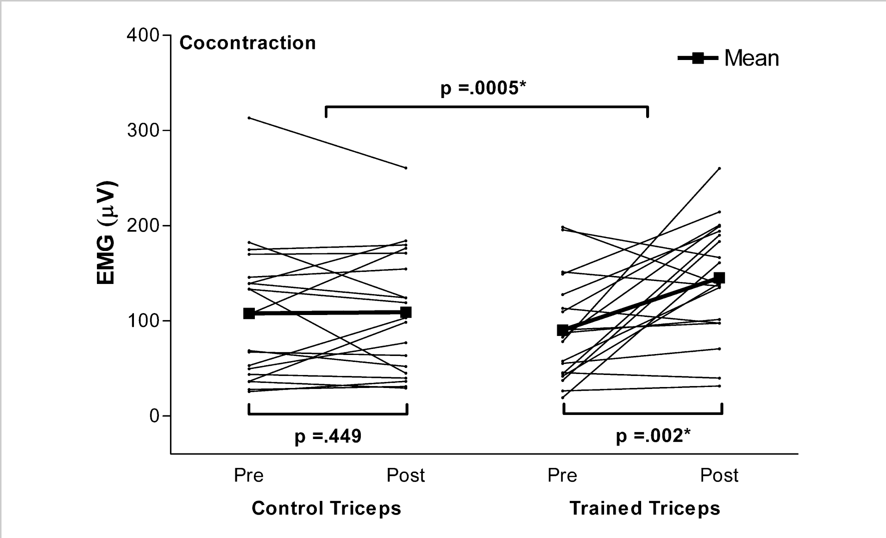

Figure 8. Root-mean-square electromyography (RMS EMG) of the triceps brachii lateral head during the maximal cocontraction for both arms before and after training. Each participant's pre-test score is connected to their post-test score with a line. Upper *p*-value indicates the significance for the time by training interaction. Lower *p*-values indicate the significance of the difference from pre- to post-test. *Statistical significance ($n = 19$).

trained limb demonstrated greater increases in EMG scores during the cocontraction tests in comparison with the control limb. The same statistical methods were used as per the first hypothesis. For each interaction test, statistical significance was set at $p \leq 0.05$. Within each limb pre- and post-test scores, for all dependent measures, were compared using 1-tailed paired *t*-tests. These tests were conducted because the interaction test only indicates the improvement of 1 limb relative to the other. The Holm-Sidak step-down multiple comparison procedure was used to assure the probability of a Type I error was maintained at $\alpha = 0.05$ (24). Two trials of each strength and cocontraction test were performed, but only the best trial for each condition was selected for the previously mentioned statistical analyses. Repeating each test permitted intraclass correlation coefficients (ICC) to be calculated for each strength and EMG measurement. The average ICC for the strength measurements was 0.94, whereas the average ICC for the EMG measurements was 0.95.

Results

Subjects

Twenty subjects completed the 6 weeks of training with 3 subjects withdrawing as a result of personal time commitments. A single participant had spuriously high EMG activity in the trained arm during the post-test; therefore, their data were removed from all statistical EMG analyses. The participant's high EMG scores were considered extreme outliers (35).

Isometric Strength

Elbow flexion strength of the trained limb increased significantly (5.8%) after 6 weeks of ART relative to the control limb (0.5%), $t(19) = 3.04$, $p = 0.003$ (Figure 3, Table 2). Similarly, elbow extension strength of the trained limb increased significantly (8.5%) relative to the control limb (4.5%), $t(19) = 2.02$, $p = 0.029$ (Figure 4). Of interest, the paired sample *t*-test on the control limb extension strength pre- and post-test scores revealed that the 4.5% improvement was significant, $t(19) = 2.28$, $p = 0.017$.

Electromyography

The EMG activity recorded during the strength testing against external resistance revealed similar findings to the strength scores. EMG of the trained biceps increased

Table 2. Mean (*SD*) strength and electromyography (EMG) scores. Flexor EMG is for the biceps and extensor EMG is for the lateral head of the triceps.

Muscle group	Training condition	Strength test (*n*) Pre	Strength test (*n*) Post	EMG: Strength test (μV) Pre	EMG: Strength test (μV) Post	EMG: Cocontraction (μV) Pre	EMG: Cocontraction (μV) Post
Flexors	Trained	126 (18)	133 (17)	324 (189)	383 (245)	150 (104)	195 (133)
	Control	133 (22)	133 (21)	275 (135)	276 (146)	135 (92)	147 (88)
Extensors	Trained	97 (14)	106 (16)	166 (52)	197 (58)	90 (54)	145 (61)
	Control	100 (15)	105 (16)	194 (67)	184 (71)	108 (74)	109 (66)

significantly (18.5%) relative to the control biceps (0.5%), t(18) = 1.92, p = 0.035 (Figure 5). Trained triceps EMG activity also showed a significant increase (18.6%) relative to the change in the control arm (−5.2%), t(18) = 2.55, p = 0.01 (Figure 6). The EMG activity collected during the cocontraction condition indicated the degree to which the ability to maximally cocontract could be improved. EMG of the trained biceps, generated during the cocontraction condition, showed a significant increase (30.1%), relative to the change in the control arm (9.2%), t(18) = 1.83, p = 0.042 (Figure 7). During the same cocontraction condition, the EMG activity of trained triceps increased significantly (61.1%) relative to the control triceps (1.1%), t(18) = 3.94, p = 0.0005 (Figure 8).

Discussion

Our findings demonstrate that ART can be an effective form of strength training. The maximum isometric strength of both the flexors and extensors of the trained arm improved significantly. These improvements were supported by significant increases in both biceps and triceps EMG activity of the trained arm. The 5.8% (7.3 N) strength increase and the 18.5% EMG increase in the trained flexor muscles are comparable to the results found in similar-length traditional strength training studies. A 6-week study (27) reported a strength gain in the elbow flexor muscles of 7.4% with an associated 31% increase in EMG activity. Other researchers (34) reported a strength increase of 6.3 N following an 8-week period using low-velocity weight-resisted training of the elbow flexors. Another study (29) conducted on elbow flexor training demonstrated an 8.8 N increase in bicep strength after subjects completed 4 weeks of training with weights equivalent to 90% of their 1 repetition maximum.

Adaptations occurred in both flexor and extensor muscles of the trained arm; however, it appears that the extensor muscles improved to a slightly greater extent. One possible explanation is the difference in maximal isometric strength between the flexors and extensors, of the trained arm, prior to training. The pre-test strength data revealed that on average the flexors generated strength scores that were 29 N greater than the extensors (Table 2). Because of this initial difference, cocontraction of the extensor muscles would not stimulate the opposing flexor muscles as much as cocontraction of the flexor muscles would stimulate the opposing extensor muscles. Therefore, the extensors would experience greater strength adaptations. Theoretically, the rate of extensor strength increase would eventually match that of flexors as the extensors increased in strength. Consequently, as the strength of the extensors increased, their ability to sufficiently stimulate the flexors to induce adaptations would also increase.

With respect to the ART technique, the ability to sufficiently activate the antagonists during a cocontraction is perhaps more important than the maximum strength of that muscle group. An inherent assumption of the ART technique is that the resistance provided by the antagonists will be sufficient to elicit a training response in the agonists. Without the use of highly invasive methods, it is not possible to directly measure the amount of force generated by the antagonists during a cocontraction. However, both muscular force production and EMG magnitude depend on the firing rate of each motor unit and the number of motor units recruited (9). The results indicate significant increases in the EMG amplitude during cocontraction of the trained arm extensors (61.1%) and flexors (30.1%) following training, whereas no significant improvements were evident in the control arm. The increase in EMG amplitude is indicative of an increase in the force production of the extensor muscles. This finding is important because it suggests that the intensity of a cocontraction can be improved through training, thus supporting the second hypothesis.

Certain aspects of the results may seem ambiguous. For example, the strength of the control arm extensors improved significantly following training without an associated increase in triceps EMG of the control arm. Although this result is somewhat surprising, it is not untenable. There are 3 heads of the triceps complex, and EMG was only collected from a selection of fibers belonging only to the lateral head. Although it has been suggested that the level of activity measured in 1 head is indicative of the level of activation in the other 2 (23,33), evidence suggests that the medial head is the primary contributor to elbow extension (36). Further, there are also numerous factors that confound the complex relationship between EMG activity and the actual force generated by a muscle (7).

The thought behind selecting right-handed subjects for an exclusively left-arm strength training program was to decrease the level of cross education from trained to untrained arm. It has been suggested that the effects of cross education are greatest when the dominant arm is trained (11). However, the significant improvement in strength (4.5%) of the extensors of the control arm suggests that a certain level of cross education occurred. Similarly, cross education from left to right limb during a left quadriceps training program has been previously reported (19). The findings of the present research are supported by data suggesting that the level of cross education may be related to the degree of unfamiliarity of a task (10). With the lack of weight training experience present among the subjects in this study, in addition to the novelty of sustained cocontraction throughout a range of motion, it is assumed that the task was quite unfamiliar. Also contributing to this cross education may be the strong neural involvement of the task. The idea that cross education has a neural basis has become well-established over the years (20). It seems reasonable to suggest, therefore, that cross education would occur during cocontraction resistance training because the task involves a high level of neurological control. Additionally, as a result of this high neurological involvement, the idea that the cross education from left limb to right, which is typically small, becomes more reasonable.

Practical Applications

This study is the first step in determining if ART could be an effective form of exercise in microgravity environments where individuals suffer from decreases in muscle mass and bone mineral density. Theoretically, ART is well-suited for individuals spending time in space because it does not require equipment and can be performed in the absence of gravity. The forces about the joint during ART would theoretically provide bone mineral density benefits. In this particular case, both the biceps and triceps brachii are pulling the distal end of the humerus and the proximal end of the ulna together, resulting in an increased contact force between the 2. Increased joint reaction forces, as are produced during ART, have been shown to improve or maintain bone mineral density (22). It was demonstrated that a larger magnitude of joint forces served as a more efficient countermeasure to bone density reduction than loading cycles (39). The simple implementation of ART into an individual's rehabilitation program also may help offset the bone mineral density decreases associated with other chronic non–weight-bearing situations. This type of exercise also has potential for athletes attempting to maintain muscular strength following an injury to a distal joint such as the wrist, which prevents an application of force through the hand.

A few other characteristics make ART an interesting type of resistance exercise. Agonist–antagonist muscle imbalances are often indicated as a contributor to musculoskeletal disorders (5,25,30,38,40). As described previously in this article, the very nature of ART will lead to agonist–antagonist muscle groups attaining more similar maximal strength values. There is also no theoretical upper limit to the gains in strength that can be obtained. As the strength of the agonists increase, so will the strength of the antagonists. A similar principle is also apparent when considering a single workout session. Because of the onset of muscle fatigue, several methods of resistance training require individuals to decrease the weight being lifted (intensity) to maintain the desired number of repetitions. With ART, both the agonists and antagonists should fatigue at similar rates; therefore, there is an inherent adjustment in the intensity of the exercise. Theoretically, ART can be used with any agonist–antagonist group of muscles. The elbow model was used as an initial starting point because of the relative ease of isolating the joint and muscle groups to test for strength increases. The authors believe that the muscles that produce flexion and extension of the trunk, as an example, are also well suited for use with ART.

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