Strength training the free limb attenuates strength loss during unilateral immobilization

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Farthing JP, Krentz JR, Magnus CR. Strength training the free limb attenuates strength loss during unilateral immobilization. J Appl Physiol 106: 830–836, 2009. First published January 15, 2009; doi:10.1152/japplphysiol.91331.2008.—The objective was to determine if strength training the free limb during a 3-wk period of unilateral immobilization attenuates strength loss in the immobilized limb through cross-education. Thirty right-handed participants were assigned to three groups. One group (n = 10) wore a cast and trained the free arm (Cast-Train). A second group (n = 10) wore a cast and did not train (Cast). A third group (n = 10) received no treatment (control). Casts were applied to the nondominant (left) wrist and hand by a physician. Strength training was maximal isometric ulnar deviation (right hand) 5 days/wk. Peak torque (dynamometer), electromyography (EMG), and muscle thickness (ultrasound) were assessed in both arms before and after the intervention. Cast-Train improved right arm strength [14.3 (SD 5.0) to 17.7 (SD 4.8) N·m; P < 0.05] with no significant muscle hypertrophy [3.73 (SD 0.43) to 3.84 (SD 0.68) cm; P = 0.09]. The immobilized arm of Cast-Train did not change in strength [13.9 (SD 4.3) to 14.2 (SD 4.6) N·m] or muscle thickness [3.61 (SD 0.51) to 3.57 (SD 0.43) cm]. The immobilized arm of Cast decreased in strength [12.2 (SD 3.8) to 10.4 (SD 2.5) N·m; P < 0.05] and muscle thickness [3.47 (SD 0.59) to 3.32 (SD 0.55) cm; P < 0.05]. Control showed no changes in the right arm [strength: 15.3 (SD 6.1) to 14.3 (SD 5.8) N·m; muscle thickness: 3.57 (SD 0.68) to 3.52 (SD 0.75) cm] or left arm [strength: 14.5 (SD 5.3) to 13.7 (SD 6.1) N·m; muscle thickness: 3.55 (SD 0.77) to 3.51 (SD 0.70) cm]. Agonist muscle activation remained unchanged after the intervention for both arms [right: 302 (SD 188) to 314 (SD 176) μV; left: 261 (SD 139) to 288 (SD 151) μV] with no group differences. Strength training of the free limb attenuated strength loss in the immobilized limb during unilateral immobilization. Strength training may have prevented muscle atrophy in the immobilized limb.

limb unloading; disuse; cross-education; muscle atrophy; wrist strength

MATERIALS AND METHODS

Subjects. A convenience sample of 30 participants (8 males and 22 females) from the University of Saskatchewan and surrounding comm...
munity took part in the study. The study was approved by the University of Saskatchewan biomedical review board for research in human subjects, and all subjects gave their written informed consent before data collection. All participants were strongly right-handed, had little prior resistance training experience in the previous year, and no recent history of unilateral upper limb injuries. Handedness was determined using a 10-item version of the Waterloo Handedness Questionnaire (WHQ), the same as previous studies in our laboratory (12, 13). Scores on the questionnaire can range from −20 to +20, where negative scores indicate left-handedness and positive scores indicate right-handedness. Right-handed subjects were chosen to replicate the substantial amount of cross-education (39–47%) found previously after dominant hand training in right-handed subjects (12, 13). Subject descriptive statistics are shown in Table 1.

**Experimental design.** The study employed a between-within mixed design. Dependent measures of isometric maximal strength, muscle thickness, and electromyography (EMG) were completed for both the right and left arms of all subjects before and after a 3-wk intervention period. Participants were split up into the three experimental groups. The first group (n = 10; 7 female, 3 male) received unilateral immobilization (nondominant forearm cast) and concurrently trained the free arm (Cast-Train group). The second group (n = 10; 8 female, 2 male) received unilateral immobilization (nondominant forearm cast) and did not train (Cast group). The third group (n = 10; 7 female, 3 male) received no intervention (control group). Once the casts were removed at the end of the 21-day intervention, the time intervals between the muscle thickness and strength measures were controlled as strictly as possible. Participants were provided a chance to wash their arm and completed muscle thickness measures within 20 min. Strength measures followed and were completed within ~40 min after cast removal. The average time lapse [mean (SD) in min] between the cast removal and strength testing was not significantly different between the Cast-Train [37 min (SD 13)] and Cast [44 min (SD 23)] intervention groups (P = 0.424).

**Muscle thickness.** Muscle thickness was measured using B-Mode ultrasound (Aloka SSD-500, Tokyo, Japan) and was completed on both the right and left posterior medial forearm (flexor carpi ulnaris and flexor digitorum superficialis) before and after the intervention. A stringent and reliable method for accurate muscle thickness measurement was adhered to (11, 12). The landmark for the center of the ultrasound probe was placed on the medial aspect of the forearm (bulk of the muscle), one-fourth of the distance down from the olecranon process to the distal head of the ulna. A stringent landmarking method using overhead transparency film was employed to ensure identical locations were measured before and after the intervention (11). Muscle thickness was assessed before any strength assessment, and the right arm was always measured first to standardize the timing of the procedure for postimmobilization measurements. The coefficient of variation (CV) for the muscle ultrasound procedure for the medial forearm muscles is 1.4–1.5% (12).

**Table 1. Subject descriptive statistics for each experimental group**

<table>
<thead>
<tr>
<th></th>
<th>Cast-Train (n = 10)</th>
<th>Cast (n = 10)</th>
<th>Control (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height, cm</td>
<td>171.6 (9.5)</td>
<td>169.7 (8.8)</td>
<td>169.9 (9.6)</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>72.5 (12.0)</td>
<td>72.5 (24.4)</td>
<td>68.5 (15.6)</td>
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<td>Age, yr</td>
<td>20.9 (2.4)</td>
<td>22.2 (2.8)</td>
<td>25.4 (3.0)</td>
</tr>
<tr>
<td>Training experience, mo</td>
<td>4.7 (4.4)</td>
<td>2.5 (3.9)</td>
<td>4.6 (4.3)</td>
</tr>
<tr>
<td>Handedness score, WHQ</td>
<td>+16.3 (3.3)</td>
<td>+15.7 (4.2)</td>
<td>+17.4 (2.6)</td>
</tr>
</tbody>
</table>

Values are means (SD). Cast-Train group received unilateral immobilization (nondominant forearm cast) and concurrently trained the free arm. Cast group received unilateral immobilization (nondominant forearm cast) and did not train. Control group received no intervention. WHQ, Waterloo Handedness Questionnaire. *Age in years was significantly different from the other 2 groups.

**Strength.** Isometric ulnar deviation peak torque was assessed on a Humac NORM isokinetic dynamometer (Humac NORM, Computer Sports Medicine, Stoughton, MA) before and after the intervention for both the right and left arm and was done in the supine position to resemble previous experiments in our laboratory (12, 13). The highest peak torque achieved in four attempts was used for comparison. Each maximal attempt was 3 s long and was separated by 1 min of rest. The order of strength tests (right or left first) was randomly allocated for each participant and kept consistent before and after the intervention. Participants were instructed that optimal performance of the ulnar deviation strength task was achieved by combining ulnar deviation of the wrist and a handgrip contraction (a weak grasp of the handle would result in weak wrist deviation torque). This strength task was employed because it is highly effective for eliciting cross-education of strength (12, 13). To minimize the effect of learning during testing, all participants were familiarized with the lab equipment before maximal strength testing by performing two or three low-intensity contractions on the dynamometer.

**Electromyography.** Maximal isometric muscle activation was assessed using EMG (Bagnoli-4, Delsys, Boston, MA) similar to previous experiments in our laboratory (12, 13). Raw EMG signal was collected for the right and left arm during each of the four repetitions on the isokinetic dynamometer for both the primary agonist (flexor carpi ulnaris) and the primary antagonist (extensor carpi radialis). Using the accompanying software (EMGworks, version 3.1), raw data (in V) were later converted to mean absolute value (MAV) to examine changes in signal amplitude, and median frequency (MDF) to examine changes in frequency of the signal. MAV processing was used as the maximum likelihood estimator of the EMG amplitude. MAV processing generates comparable amplitude estimates to root mean square processing but often produces a higher signal-to-noise ratio (5). In the EMGworks software, MAV is measured as a function of time and is calculated using a moving window. The MAV was calculated using a window length of 0.125 s of data. MDF involves first calculating a fast Fourier transform (FFT) on the raw data within a specified window (1 s) and then determining the power density spectrum (PDS) by squaring the FFT. The MDF is the frequency at which the PDS is divided in two sections with equal power. A reference electrode (common ground) was applied to the kneecap with a single conductor. The EMG main amplifier unit included single differential electrodes with a bandwidth of 20 ± 5 to 450 ± 50 Hz, a 12 dB/octave cut-off slope, and a maximum output voltage frequency range ± 5 V. The overall amplification or gain per channel was 1,000. The system noise was < 1.2 μV (rms) for the specified bandwidth. The electrodes were two silver bars (10 mm × 1 mm diameter) spaced 10 mm apart, with a Common Mode Rejection Ratio (CMRR) of 92 dB. A stringent method for landmarking the electrodes was utilized to ensure accurate placement of the electrodes for each testing occasion (12). The skin surface was shaved and cleaned adequately before placing the electrodes. Resting muscle signals were checked for noise, and where appropriate, the skin was cleaned and shaved again, and the electrodes were repositioned. The quality of the skin contact was checked during low-level muscle contractions.

**Imobilization.** Standard circular casts were used to effectively immobilize the nondominant (left) wrist, thumb, and hand for 21 days. All casts were fiberglass and placed by the same licensed physician to fit like a typical wrist fracture cast. To minimize discomfort for the participants, the forearm was fitted with a cloth sleeve and then wrapped with thin foam padding. Each cast was carefully positioned with the wrist in neutral position and slightly extended (as recommended by the physician for comfort). The casts extended from the proximal interphalangeal joints of the fingers to approximately two-thirds of the distance up the forearm. The thumb digit was in neutral position and wrapped separate from the rest of the fingers and was completely restricted. The casts allowed for some movement of the last two joints of each finger (distal and proximal interphalangeal joints), but participants were instructed to avoid lifting or holding.
heavy items with the ends of the fingers. Although there was some small variation in the placement of each cast, complete immobilization of the wrist was ensured so that grasping with the thumb and fingers, wrist deviation, and wrist flexion/extension were not possible.

Strength training. Strength training was isometric ulnar deviation of the right wrist for 5 days/wk for 3 wk. The training program was completed on the Humac NORM dynamometer in the same fashion as for testing and was supervised at all times. The program was progressive in nature, beginning with three sets of eight repetitions and increasing in volume by one additional set each training day, up to a maximum training volume of six sets of eight repetitions. The isometric repetitions were 3 s long and were cadenced using the Humac dynamometer software. Participants were permitted to view their real-time peak torque during training and were given verbal encouragement. The program consisted of 15 training sessions in total. Participants had to complete a minimum of 12 of 15 sessions in the 3-wk period to qualify for posttesting. Isometric ulnar deviation training of the right wrist has proven very effective in our laboratory for inducing muscle hypertrophy, strength, and cross-education (12, 13).

Data analysis. Strength and muscle thickness data were analyzed together using a between-within group (Cast-Train, Cast, control) × arm (left, right) × time (Pre, Post) multivariate factorial ANOVA with two dependent measures (strength, muscle thickness). Univariate analysis for each dependent measure (strength and/or muscle thickness) followed if a significant multivariate effect was found. EMG was analyzed separately because of an additional factor in the design. EMG data were analyzed using a between-within three-group (Cast-Train, Cast, control) × arm (left, right) × time (Pre, Post) multivariate factorial ANOVA with two dependent measures (MAV, MDF). Univariate analysis for each dependent measure (MAV and/or MDF) followed if a significant multivariate effect was detected. If significant main effects or interactions were detected, simple main effects analysis followed using one-way ANOVA and Tukey’s post hoc test, or dependent t-tests where appropriate. Significance was accepted at $P < 0.05$. All analyses were performed using SPSS version 15.0.

RESULTS

Strength and muscle thickness. As might be expected with 30 strongly right-handed participants, the right arm was significantly stronger ($P < 0.05$) and had greater muscle thickness than the left arm ($P < 0.05$) at baseline. There were no significant differences between the three experimental groups at baseline for any of the dependent measures. Subjects in the Cast-Train group completed an average of 13.8 (SD 1.4) training sessions (of a possible 15) during the 3-wk intervention. There was a significant group × arm × time multivariate interaction for strength and muscle thickness ($P < 0.05$). Univariate ANOVA for strength revealed a significant group × arm × time interaction ($P < 0.05$). Simple main effects analysis of the interaction revealed that there was a significant increase in strength of the trained arm of the Cast-Train group (23.8%; $P < 0.05$), and a significant decrease in strength of the casted arm of the Cast group (−14.7%; $P < 0.05$). There were no other significant changes in strength over time among the groups. Particularly relevant to the hypotheses of the study, there was no significant change in strength of the casted arm of the Cast-Train group. The change in strength over time for each group is displayed in Fig. 1.

Univariate ANOVA for muscle thickness revealed a significant group × time interaction ($P < 0.05$), and a significant arm main effect ($P < 0.01$). Simple main effects analysis revealed that the immobilized arm of the Cast group significantly decreased in muscle thickness after the intervention (−4.3%; $P < 0.05$). There were no other significant changes in muscle thickness after the intervention. The change in muscle thickness over time for each group is displayed in Fig. 2.

Muscle activation. For the EMG data, the multivariate ANOVA for MAV and MDF variables revealed a significant main effect of muscle ($P < 0.01$). There were no other significant multivariate main effects or interactions. The univariate main effect of muscle for MAV was significant ($P < 0.001$), indicating that the agonist muscle [0.291 mV (SD 0.085)] showed a significantly higher amplitude of activation compared with the antagonist muscle [0.122 mV (SD 0.025)], pooled across all other factors (i.e., group, arm, time). The univariate main effect of time for MAV narrowly reached significance ($P = 0.048$), indicating that the amplitude of activation increased significantly after the intervention [0.201 (SD 0.047) to 0.212 mV (SD 0.047)] pooled across all other factors (i.e., group, arm, muscle). Muscle activation amplitude data (MAV) are presented in Fig. 3. The univariate main effect of muscle for MDF is presented in Fig. 4. The univariate main effect of muscle for MDF approached significance ($P = 0.058$). Muscle activation MDF data are presented in Fig. 4.

![Fig. 1. Cast-Train group received unilateral immobilization (nondominant forearm cast) and concurrently trained the free arm. Cast group received unilateral immobilization (nondominant forearm cast) and did not train. Control group received no intervention. Pre and Post refer to before and after 3-wk intervention period. A: change in strength over time for the right arm. Note that the right arm of the Cast-Train group was trained. *Significant increase in strength for the right (trained) arm of the Cast-Train group ($P < 0.01$). There were no significant changes in strength for the right arm of the other 2 groups. B: change in strength over time for the left arm. Note that the left arm of the Cast-Train group and the Cast group was immobilized with a cast. *Significant decrease in strength for the left (casted) arm of the Cast group ($P < 0.05$). There were no significant changes in strength for the left arm of the other 2 groups. All values are means ± SE in N·m.](http://jap.physiology.org/DownloadedFrom)
DISCUSSION

The major finding of this study is that strength training of the free limb attenuated the loss in strength during a 3-wk period of unilateral immobilization. Strength was improved substantially in the trained right arm (23.8%) of the Cast-Train group, while there was no significant change in strength in the opposite casted arm (2.2%). For the Cast group, there was a significant decrease in strength of the casted arm (14.7%).

These results provide support for the hypothesis that cross-education would be beneficial for attenuating the strength loss observed during unilateral immobilization. We propose that the cross-education effect observed in this experiment was a maintenance effect, whereby unilateral strength training prevented the decrease in strength that was expected in the opposite immobilized limb (Fig. 1). To our knowledge, this represents the first attempt to apply cross-education using a model of unilateral injury (i.e., unilateral immobilization of a healthy limb) with a controlled study design.

The decrease in strength (−14.7%) and muscle size (−4.3%) after unilateral immobilization in this experiment is reasonably consistent with other immobilization or unloading studies targeting hand and arm muscles (21, 25, 27, 28, 30, 32). The magnitude of muscle size decrease in these previous studies ranges from about 1–10% after 3–4 wk and is not always statistically significant. The magnitude of strength loss is larger, ranging from about 10 to 24% after 3–4 wk. The most similar immobilization protocols to our experiment can be found in Kitahara et al. (21) and Matsumura et al. (27), who also prescribed 21 days of nondominant forearm cast immobilization. However, both studies reported significant reductions in strength with no change in muscle morphology. Lundbye-Jensen and Nielsen (25) also used wrist and hand casts and found a 24% reduction in strength after 1 wk of immobilization, but no measures of muscle size were reported. In general, our findings are consistent with previous work that has prescribed immobilization or unloading protocols for the non-dominant upper limb.

An intriguing finding of this experiment is that there was no significant change in muscle size (−1.1%) of the casted arm of the Cast-Train group, whereas there was a significant decrease in muscle size (−4.3%) of the casted arm of the Cast group (Fig. 2). Note that the magnitude of change for the casted arm of the Cast group is threefold larger than the CV for the muscle ultrasound procedure (1.4–1.5%). This suggests that muscle atrophy was somehow prevented or delayed for the group that received unilateral strength training during immobilization. The mechanism responsible for the maintenance of muscle size is unclear. It is well known that unilateral training enhances the motor pathways associated with the untrained contralateral limb and that this leads to strength gain (i.e., cross-education) that is not associated with changes in muscle size (4, 12, 13).
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However, when the untrained contralateral limb is immobilized as in the present study, unilateral training might have provided enough of a stimulus to the contralateral motor system to prevent muscle atrophy. A recent animal study suggests this might not be the case. Adams et al. (1) found that daily unilateral resistance exercise induced by muscle stimulation was effective for limiting muscle atrophy in the trained suspended limb but not the contralateral suspended limb. Unfortunately, the muscle weights were compared with a group of control animals that received no treatment, so whether unilateral training would have attenuated muscle atrophy compared with a hindlimb suspension group that did not receive unilateral training remains uncertain.

One possible explanation for the reduced muscle atrophy in our study is that the muscles of the immobilized forearm were marginally activated during unilateral training. There is evidence in the literature that activation of one joint or limb results in low level activation of the contralateral homologous muscles (39, 40). Several cross-education studies report some activation of the untrained homologous muscles during training, but it is typically very small and is unlikely to contribute significantly to the magnitude of cross-education that is observed (9, 12, 16, 20). Although this low level activation does not lead to significant muscle hypertrophy, it might be enough to prevent or slow down muscle atrophy during a period of immobilization. To limit the possibility that activation of the casted limb during training was a factor in this experiment, we carefully monitored the participants in the Cast-Train group during all training sessions. They were required to relax the casted arm by resting it across the stomach or waist area and avoid movement while contracting the right arm. In addition, the forearm cast prevented any radial-ulnar deviation, or flexion-extension movement of the wrist joint, to limit the activation of the forearm muscles that are primarily involved in ulnar deviation. Unfortunately, relaxing the casted arm does not eliminate the possibility that a small amount of activation was present in the casted arm during training. Follow-up studies are necessary to determine whether muscle activation of the immobilized limb during unilateral training of the free limb contributes to the maintenance of muscle size and strength. Unilateral strength training might be associated with small peripheral muscular adaptations that contribute to a small degree to the cross-education effect (4). If present at all, these adaptations alone are unlikely to generate a significant increase in strength (i.e., cross-education), but they might play a role in preventing or delaying strength loss in an immobilized muscle. In addition to measuring the activation in the casted arm during training, another strategy could be to include a group of participants who wear a cast and perform low-volume isometric contractions with the casted arm, similar to the protocol of Matsumura et al. (27). Regardless of the mechanism, in this study unilateral training of the free limb was associated with a significant benefit for the immobilized limb.

We hoped to gain some insight into the possible sites of neural adaptation associated with unilateral strength training and immobilization by comparing the amplitude and frequency of activation of the agonist and antagonist muscles. Muscle activation amplitude and frequency remained unchanged following the intervention for each of the groups (Figs. 3 and 4), and there were no significant interaction effects. The only significant results were that the agonist muscle had greater activation than the antagonist muscle (pooled across all other factors), and muscle activation amplitude increased marginally after the intervention (pooled across all other factors). For both arms of the control group, the free (right) arm of the Cast group, and the casted arm of the Cast-Train group, changes in muscle activation might not have been expected since there were no significant changes in strength or muscle size. However, changes in muscle activation for the trained arm of the Cast-Train group and the casted arm of the Cast group might have been expected to coincide with the respective changes in strength (Fig. 1). Several studies have reported increased EMG activation amplitude of the trained limb after unilateral training (16, 17, 29, 34), including our two previous studies with unilateral ulnar deviation training (12, 13). However, these studies had training durations of 6 wk or more compared with only 3 wk in the present experiment. Muscle activation might remain unchanged with brief training periods of 3 wk or less, despite improvements in strength. Carolan and Cafarelli (3) found that knee extension strength was improved in both limbs as early as 2 wk into training, but muscle activation of the agonist muscle was unaltered. In contrast, a more recent study by Griffin and Cafarelli (15) reported significant increases in EMG activation and strength after 2 wk of training.

Consistent with our findings, there are at least two studies where immobilization of a healthy limb has resulted in significant strength decreases without corresponding changes to muscle activation parameters (2, 37). However, the majority of studies report a decrease in muscle activation after immobilization (14, 18, 25, 30, 32). One possibility is that the neural
mechanisms responsible for the strength changes observed in the present experiment reside in higher-order or supraspinal locations such as the corticospinal tract or motor cortex, which would be consistent with two recent cross-education studies (12, 23) and with at least one immobilization study (10). The dissociation between the changes in strength, muscle size, and muscle activation observed in the trained arm of the Cast-Train group provides further support for the contribution of a higher order neural mechanism. The large increase in strength in the trained right arm (23.8%; Fig. 1) was accompanied by a small nonsignificant change in muscle size (3%; Fig. 2). Given that there was no significant change in peripheral muscle activation or muscle size to accompany the increase in strength, it is likely that spinal or higher-order neural mechanisms were at least partly responsible for the large strength increase observed in the trained limb (12, 23).

While we are confident that unilateral strength training provided a benefit for the immobilized limb during the intervention, it is unclear what the exact benefit would be during recovery from injury in a clinical setting. One important consideration is that the maintenance of strength in the immobilized limb might be relevant for the prevention of injury recurrence. Although our findings have clinical implications, we caution against the direct application of our study to a clinical setting where unilateral immobilization is part of recovery from an actual injury. Stevens et al. (35) measured the recovery of strength, muscle cross-sectional area (CSA), and muscle activation after a long period (7 wk) of cast immobilization associated with ankle injury by contrasting measures with the uninjured limb during 10 wk of rehabilitation. The long duration of immobilization and the presence of injury were associated with much larger deficits in strength (~75%), muscle CSA (~26%) and muscle activation (~42%) immediately postimmobilization than is typically reported in immobilization studies where the limb is previously healthy. We have shown that unilateral strength training can preserve strength in a previously healthy immobilized limb through the cross-education effect. However, the precise benefit of unilateral strength training during prolonged immobilization of an injured limb is still uncertain.

The purpose of this study was to determine if unilateral strength training of the free limb would attenuate the strength loss observed during a period of unilateral immobilization through the cross-education effect. The results suggest that unilateral strength training provides a significant benefit for the immobilized limb. The mechanisms responsible for this effect remain unclear, and subsequent experiments are necessary to examine the role of spinal cord and higher-order neural mechanisms. In addition, there is a need to examine the potential link between unilateral strength training and the maintenance of muscle size during unilateral immobilization. These results have implications for recovery from unilateral injury that requires immobilization of a joint or joints, where unilateral strength training might limit the amount of strength loss that is normally acquired during disuse.

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