Effects of cross-education on the muscle after a period of unilateral limb immobilization using a shoulder sling and swathe

Charlene R. A. Magnus, Trevor S. Barss, Joel L. Lanovaz, and Jonathan P. Farthing

College of Kinesiology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

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Magnus CR, Barss TS, Lanovaz JL, Farthing JP. Effects of cross-education on the muscle after a period of unilateral limb immobilization using a shoulder sling and swathe. J Appl Physiol 109: 1887–1894, 2010. First published October 21, 2010; doi:10.1152/japplphysiol.00597.2010.—The purpose of this study was to apply cross-education during 4 wk of unilateral limb immobilization using a shoulder sling and swathe to investigate the effects on muscle strength, muscle size, and muscle activation. Twenty-five right-handed participants were assigned to one of three groups as follows: the Immob + Train group wore a sling and swathe and strength trained (n = 8), the Immob group wore a sling and swathe and did not strength train (n = 8), and the Control group received no treatment (n = 9). Immobilization was applied to the nondominant (left) arm. Strength training consisted of maximal isometric elbow flexion and extension of the dominant (right) arm 3 days/wk. Torque (dynamometer), muscle thickness (ultrasound), maximal voluntary activation (interpolated twitch), and electromyography (EMG) were measured. The change in right biceps and triceps brachii muscle thickness [7.0 ± 1.9 and 7.1 ± 2.2% (SE), respectively] was greater for Immob + Train than Immob (0.4 ± 1.2 and −1.9 ± 1.7%, respectively) and Control (0.8 ± 0.5 and 0.0 ± 1.1%, P < 0.05). Left biceps and triceps brachii muscle thickness for Immob + Train (2.2 ± 0.7 and 3.4 ± 2.1%, respectively) was significantly different from Immob (−2.8 ± 1.1 and −5.2 ± 2.7%, respectively, P < 0.05). Right elbow flexion strength for Immob + Train (18.9 ± 5.5%) was significantly different from Immob (−1.6 ± 4.0%, P < 0.05). Right and left elbow extension strength for Immob + Train (68.1 ± 25.9 and 32.2 ± 9.0%, respectively) was significantly different from the respective limb of Immob (1.3 ± 7.7 and −6.1 ± 7.8%) and Control (4.7 ± 4.7 and −0.2 ± 4.5%, P < 0.05). Immobilization in a sling and swathe decreased strength and muscle size but had no effect on maximal voluntary activation or EMG. The cross-education effect on the immobilized limb was greater after elbow extension training. This study suggests that strength training the nonimmobilized limb benefits the immobilized limb for muscle size and strength.

Evidence is mixed as to whether short-duration immobilization leads to a decrease in muscle size. Decreases in muscle size of 4.0% after 4 wk of immobilization (27), 7.7% after 3 wk of immobilization (25), and 11.8% after 10 days immobilization (31) have been shown. Conversely, other studies have found no change in muscle size after 2 wk (7) and 3 wk (21) of immobilization.

It is important to discover new ways of minimizing changes in the muscle for quicker recovery from any injury. One way of minimizing this decline may be application of cross-education to a period of disuse. Cross-education of strength is defined as the increase in strength of the untrained contralateral limb after unilateral training of the opposite homologous limb (6, 10). The exact mechanisms of cross-education are not known; however, the current literature suggests that the mechanisms are neural (6, 12, 24). In cross-education, the increase in strength of the untrained limb is thought to be related to the gain in magnitude of the trained limb and is, on average, 52% of the strength gain observed in the trained muscle (6). Greater transfer to the untrained limb has been demonstrated in more novel or unfamiliar tasks (10). The cross-education effect has been consistently shown after unilateral training in healthy individuals; however, less is known about the effect of cross-education in a disuse setting.

Farthing et al. (12) recently conducted a study that applied cross-education to a healthy immobilized limb. The study showed that strength training the free limb via ulnar deviation attenuated the loss in muscle strength and size of the immobilized limb during a 3-wk period of unilateral forearm casting. This study suggests that strength training the free limb provides a maintenance effect for the immobilized limb; however, only the primary agonist muscle was investigated, and only one exercise for strength training was used. In a clinical setting, it is unlikely that one exercise would be used for rehabilitation from an injury; therefore, it is difficult to generalize these results. More evidence is needed to determine whether cross-education can be used in a clinical setting and whether it can be applied to different types of immobilization.

The purpose of the present study was to apply cross-education during 4 wk of unilateral limb immobilization to investigate the effects on muscle strength, muscle size, and muscle activation. The novel aspect of this study was use of a sling-and-swathe unilateral unloading model with and without concurrent unilateral training of the elbow flexors and extensors. To our knowledge, this is the first cross-education study to investigate the effects on the contralateral limb with two different, opposing strength-training exercises (i.e., elbow flexion and elbow extension). The sling-and-swathe unloading model is clinically relevant, as many shoulder injuries result in slingling. The sling-and-swathe model also enabled examination of the effect of immobilization on flexor and extensor

IMMobilization or UNloading of a limb can have many effects on muscle. Immobilization places the limb in a passive state (35), generates modifications in contractility (8), and decreases electromyographic (EMG) activity (7, 27) and maximal voluntary muscle activation (8, 17, 32).

Significant decreases in muscle strength have been shown in the affected limb following immobilization (7, 17, 20, 25, 27). Strength has been shown to decrease up to 60% after 5–6 wk of immobilization following injury (14, 33). The majority of muscle strength is lost within the first 2 wk of disuse (32), suggesting that this early decline in strength is neural (7).

Address for reprint requests and other correspondence: J. P. Farthing, College of Kinesiology, Univ. of Saskatchewan, 87 Campus Dr., Saskatoon, SK S7N 5B2, Canada (e-mail: jon.farthing@usask.ca).

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mores, while allowing convenient access to the target muscles during the intervention. The present study also investigated muscle activation in the immobilized limb during strength-training sessions of the training limb. This study may help shed light on new approaches to rehabilitation after unilateral injury, whereby strength training the nonaffected limb may have beneficial effects on the affected limb (e.g., during recovery from shoulder surgery, where a sling-and-swatche unloading protocol is commonly used).

MATERIALS AND METHODS

Subjects. Twenty-five healthy men and women from the University of Saskatchewan participated in the study. Prior to commencement, all participants signed informed written consent approved by the Biomedical Ethics Review Board at the University of Saskatchewan. Participants were right-handed according to the Waterloo Handedness Questionnaire (WHQ). The 10-item version of the WHQ is scored positive scores indicate right-handedness. Right-handed participants were chosen to ensure consistency with previous cross-education studies conducted in our laboratory (5, 9, 10, 23). The biceps and triceps brachii were assessed with an overhead transparency film to demonstrate to be valid and reliable on previous occasions in our laboratory.

Age, yr

20.9 (3.2) 20.3 (1.8) 24.9 (5.1)

Resistence-training experience, mo

2.8 (4.0) 2.0 (3.9) 5.4 (5.2)

WHQ score

+14.1 (3.6) +15.4 (5.0) +16.2 (3.3)

Time in sling

days

26.0 (2.7) 27.8 (2.3) 13.4 (1.4) 12.6 (0.9)

h/day

13.4 (1.4) 12.6 (0.9)

Values are means (SD). Immob + Train, nondominant (left) limb immobilization (sling and swathe) and concurrent strength training; Immob, nondominant (left) limb immobilization (sling and swathe) without strength training; Control, no intervention. WHQ, Waterloo Handedness Questionnaire. *Significantly different from Control (P < 0.05).

Elbow flexion was tested; then elbow extension was tested in the same arm. The arm tested first (right or left) was random, with the order kept consistent for all testing sessions. The participants were in a seated position with the chair back angle at 60° and were instructed to keep the opposite arm on their lap. For elbow flexion and extension contractions, a plastic molded wrist brace was worn to limit synergistic activity of the forearm muscles by eliminating the need for participants to grasp a handle to execute elbow flexion or extension. For elbow flexion contractions, the forearm/wrist of the participant was strapped to a firmly padded arm attachment that was fastened to the dynamometer handle, and the subject pulled on the apparatus to perform the contraction (Fig. 1). The elbow extension contractions were similarly conducted, but with the hand in neutral position and the ulnar aspect of the wrist strapped to the padded arm attachment, where the subject pushed on the apparatus to perform the contraction. Verbal encouragement was given for all testing sessions. At posttesting, strength was assessed 59.3 (SD 15.4) min (average of Immob + Train and Immob) after removal of the sling and swathe.

All strength-training sessions were performed in the laboratory on the Humac Norm dynamometer using the free (right) arm in the Immob + Train group only. The training set-up was the same as the testing set-up, with all training sessions completed under supervision. Strength training consisted of isometric elbow flexion and extension training three times per week for 4 wk using a progressive protocol. Subjects began with three sets of eight elbow flexion contractions and three sets of eight elbow extension contractions and progressed each training day by one set until full volume of six sets of eight contractions. During the last two training sessions, the volume was reduced to three sets to serve as a taper. The training intensity was maximal effort on each repetition, with contractions held for 3 s alternated with 3 s of rest. There was 1 min of rest between each set. Participants were permitted to view their real-time torque and were given verbal encouragement throughout the training.

Muscle thickness. Muscle thickness was measured using B-mode ultrasound (model SSD-500, Aloka, Tokyo, Japan), which has been demonstrated to be valid and reliable on previous occasions in our laboratory (5, 9, 10, 23). The biceps and triceps brachii were assessed prior to any strength testing. Both arms were measured with a stringent landmarking method using an overhead transparency film to ensure identical locations at all testing time points (9). Biceps and
triceps brachii muscle thickness was measured on the bulk of the muscle when it was in a lengthened position. The ultrasound probe was placed at the center of the muscle bulk. The right arm was always measured first to ensure standardized timing of the procedure. At each testing point, four measurements were taken on each arm, with the average of the two closest measures used as the thickness value. Additional measurements were taken in the event that any two of the four measurements were not within 1 mm to ensure precision.

**Interpolated twitch.** A constant-current high-voltage stimulator (model D37AH, Digitimer) was used to activate the elbow flexors and extensors. Self-adhesive electrodes, with the cathode placed over the proximal muscle belly of the biceps and triceps brachii and the anode placed over the distal tendon of the biceps and triceps brachii, were used (Fig. 1). Two doublet pulses (at 100 Hz, 50-μs pulse duration) were applied during and ~5 s after the maximal voluntary contraction. The doublets were manually triggered at the peak of the maximal voluntary contraction. The activation levels were calculated as follows: [1 − superimposed twitch torque magnitude + control twitch torque magnitude] × 100 (1, 15, 28). The average of four maximal voluntary repetitions was used to calculate the percent activation. Control twitches were elicited by stimulation of the muscle in its resting state. Torque from the dynamometer was recorded during the superimposed maximal voluntary contractions and the control twitches.

The magnitude of electrical current applied to the muscle during twitch interpolation ranged from 100 to 400 mA, depending on the subject. Beginning with a very small 50-mA current, stimulus intensity was progressively increased in small increments. The appropriate level of stimulation was determined when no further increase in twitch torque response to stimulation was observed or when the subject reached maximal intensity deemed tolerable. Once the appropriate current intensity was identified, the stimulus intensity was used for the superimposed twitch during maximal voluntary contractions and the subsequent control twitch. This was completed on the biceps and triceps brachii.

**EMG.** Maximal isometric muscle activation was assessed using EMG (Bagnoli-4, Delsys, Boston, MA) for elbow flexion and extension. The raw EMG signal was recorded for each of the four contractions on the isokinetic dynamometer for the biceps and triceps brachii during elbow flexion and extension. The biceps and triceps brachii electrodes were placed on the bulk of the muscle when the muscle was in a flexed position and were located between the anode and cathode of the interpolated twitch electrodes according to the methods of Klein et al. (22) (Fig. 1). A reference electrode was placed on the knee cap to serve as a common ground for the EMG signal. Landmarking measurements were recorded after the first testing session to ensure correct placement at each testing time point. Before positioning of the electrodes, the skin was shaved and the area was cleaned with alcohol to reduce skin impedance values. Resting muscle signals were tested to limit signal noise, and, where appropriate, electrodes were repositioned and the skin was resheathed and cleaned to yield a clear signal.

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 of ±5 V. The overall amplification or gain per channel was 1,000 for the biceps and triceps brachii muscles. The system noise was <1.2 μV (root mean square). The electrodes were two silver bars (10 mm × 1 mm diameter) that were spaced 10 mm apart and had a common mode rejection ratio of 92 dB.

Additional muscle activation measurements were recorded in the training (Immob + Train) group only once per week to monitor the amount of activation in the immobilized arm during strength training. The amplification or gain per channel was 1,000 for the training arm and 10,000 for the immobilized arm. During elbow flexion training, EMG electrodes were placed on the bulk of the biceps brachii muscles in trained and untrained arms. The same technique was used for elbow extension, with electrodes placed on trained and untrained triceps brachii muscles during training sessions. Muscle activation was recorded during the first and last sets of the training session.

Raw EMG signals (in V) were converted to mean absolute value (MAV) using MATLAB (version 7.3.0). MAV was used to obtain an estimate of the amplitude of the signal. It is measured as a function of time and was calculated using a defined window. A 0.5-s epoch immediately prior to the interpolated twitch was used to calculate the MAV. During the testing sessions, the average MAV from the four repetitions was used for comparison. During the weekly EMG measurements, the average MAV of the eight repetitions was used. Postintervention MAV scores were normalized to the preintervention scores to account for baseline differences between groups.

**Data acquisition.** Custom software in LabVIEW (version 8.6) was used to obtain interpolated twitch, torque, and EMG (2 channels) data simultaneously. All channels were acquired at a sampling rate of 1,000 Hz. An analog-to-digital converter (model PCI-6034E, National Instruments, Austin, TX) was used to convert the analog signals from each device to digital signals displayed in LabVIEW.

**Imobilization.** Four weeks of unloading was achieved using a sling and swathe on the nondonimand (left) arm. Previous sling protocols by Parcell et al. (27) and Miles et al. (25) effectively decreased cross-sectional area and strength after 4 and 3 wk, respectively. The sling suspended the elbow in a flexed position (elbow at ~90°), and the swathe held the arm against the torso. The sling was fitted for all participants to ensure that the arm was at a 90° angle. The sling unloaded the elbow flexor and extensor muscles, and the swathe prevents the shoulder muscles from supporting the arm and limits shoulder movement. The sling and swathe were worn during the waking hours to immobilize the arm. Participants removed the sling and swathe for sleeping and bathing and were required to record the number of hours (≥12–14 h/day) the sling was worn. If they removed the sling for any other reason, the reason for removal, duration of removal, and day and time of removal were recorded. Use of the immobilized arm for any type of work (i.e., lifting, pushing, or pulling) and any type of stability/holding was prohibited.

**Data analysis.** Percent change was used to analyze strength and muscle thickness data to control for variability between subjects. Percent change was calculated by subtracting the posttraining score from the pretraining score, dividing by the pretraining score, and multiplying by 100. Strength was analyzed using a one-way independent-measures ANOVA (group). Separate analyses were conducted for the right and left arm for each task (elbow flexion and extension). Separate analyses were conducted, because the combined effect of the arms (main effect of “arm”) was not of interest to the researchers. Muscle thickness was analyzed using a one-way independent-measures ANOVA (group). Separate analyses were conducted for the right and left arm for each muscle (biceps and triceps brachii). The interpolated twitch percent activation levels were analyzed separately using a between-within group (Immob + Train, Immob, Control) × time (pre, post) factorial ANOVA and separate analyses for the right and left arm for each muscle (biceps and triceps brachii). For agonist EMG, MAV was normalized to the preintervention scores because of baseline differences between groups. The normalized agonist MAV scores were analyzed using a one-way ANOVA (group), with separate analyses for the right and left arm for each task (elbow flexion and extension). For antagonist EMG, a between-within group (Immob + Train, Immob, Control) × time (pre, post) factorial ANOVA, with separate analyses for the right and left arm for each task (elbow flexion and extension), was used. If significant main effects or interactions were detected, simple main effects analysis continued using one-way ANOVA and Tukey’s post hoc tests or multiple comparisons, with adjustment where appropriate. Significance was accepted at P < 0.05. All analyses were performed using SPSS version 17.0.
RESULTS

Muscle thickness. There were no significant differences at baseline for absolute muscle thickness between the groups for the right or left arm. Univariate ANOVA for percent change in muscle thickness showed a significant main effect of group for the biceps and triceps brachii for right and left arms (P < 0.05). Post hoc analyses of the right biceps brachii revealed a significant difference between the Immob + Train group [7.0 ± 1.9% (SE)] and the Immob (0.4 ± 1.2%) and Control (0.8 ± 0.5%) groups (P < 0.05). Muscle thickness of the left biceps brachii for the Immob + Train group (2.2 ± 0.7%) was significantly different from the Immob group (−2.8 ± 1.1%, P < 0.05). Muscle thickness of the right triceps brachii for the Immob + Train group (7.1 ± 2.2%) was significantly different from the Immob (−1.9 ± 1.7%) and Control (0.0 ± 1.1%) groups, and muscle thickness of the left triceps brachii for the Immob + Train group (3.4 ± 2.1%) was significantly different from the Immob group (−5.2 ± 2.7%, P < 0.05). Percent change muscle thickness data are presented in Fig. 2.

Strength. Subjects in the Immob + Train group performed an average of 11.9 (SD 2.3) training sessions during the 4-wk immobilization period. There were no significant differences in absolute strength values between the groups for the right or left arm at baseline. Univariate ANOVA for percent change in strength showed a significant main effect of group in right elbow flexion and right and left elbow extension (P < 0.05). Post hoc analysis for right elbow flexion showed that the Immob + Train group (18.9 ± 5.5%) was significantly different from the Immob group (−1.6 ± 4.0%, P < 0.05). Right elbow extension strength for the Immob + Train group (68.1 ± 25.9%) was significantly different from the Immob (1.3 ± 7.7%) and Control (4.7 ± 4.7%) groups (P < 0.05). Left elbow extension for the Immob + Train group (32.2 ± 9.0%) was significantly different from the Immob (−6.1 ± 7.8%) and Control (−0.2 ± 4.5%) groups (P < 0.05). ANOVA for left elbow flexion was not significant. Percent change strength data are presented in Fig. 3.

Percent activation via interpolated twitch. Univariate ANOVA revealed a time main effect for elbow flexion in the right biceps brachii for all groups pooled (P < 0.05). Post hoc analyses showed no significant differences between groups. No other significant differences for percent activation were detected. Percent activation data are presented in Table 2.

EMG. ANOVA for agonist MAV activation (normalized to preintervention scores) revealed a significant main effect of group for right elbow extension. Post hoc analysis showed a significant difference between the Immob + Train [1.392 (SD 0.625)] and Control [0.872 (SD 0.211)] groups (P < 0.05).
There were no other significant differences for agonist MAV activation in elbow flexion or extension. Agonist MAV activation is presented in Table 3. No significant differences were found for antagonist MAV activation ($P > 0.05$). The magnitude of antagonist muscle activation was minimal for all subjects. Antagonist activation is presented in Table 4. For the weekly EMG (conducted in the Immob + Train group only), the immobilized biceps brachii was activated at a level of 3.1% (SD 0.9) of the training biceps brachii during strength training, and the immobilized triceps brachii was activated 6.1% (SD 2.0) of the training triceps brachii during strength training (pooled across the 4-wk intervention).

**DISCUSSION**

The main finding of the present study was that strength training the nonimmobilized limb provided a beneficial effect for muscle thickness and strength in the immobilized limb after 4 wk of wearing a sling and swathe. The cross-education effect was much more pronounced with elbow extension than elbow flexion training. The present study also found that the immobilization had no effect on maximal voluntary activation or amplitude of muscle activation (MAV) and that there were minimal levels of activation in the immobilized limb during unilateral strength training of the right limb.

An interesting finding in the present study is a significant difference between the Immob + Train and Immob groups for muscle thickness in the immobilized biceps and triceps brachii. The immobilized biceps and triceps brachii in the Immob + Train group showed positive changes in muscle thickness (2.2% in biceps brachii and 3.4% in triceps brachii, not significantly different from Control), whereas the Immob group showed negative changes in muscle thickness ($-2.8\%$ in biceps brachii and $-5.2\%$ in triceps brachii, not significantly different from Control; Fig. 2). This suggests that loss of muscle size may have been attenuated for the Immob + Train group in both muscles. However, it is difficult to draw conclusions from these findings, since the changes were not significantly different from the Control group. A previous study in our laboratory showed a maintenance effect in the immobilized limb with use of a forearm casting protocol (12). The mechanism for the prevention of muscle size loss is not known; however, Farthing et al. (12) suggest that unilateral strength training of the nonimmobilized limb may have provided a large enough stimulus to the motor system to prevent muscle atrophy in the immobilized limb. Loss of muscle size may have also been prevented by motor unit activation in the immobilized arm during unilateral strength training of the free arm (12). We were able to better test this theory with the sling-and-swathe protocol than with casting protocols, which limit convenient access of the target muscles. The sling and swathe were removable; therefore, during the strength-training sessions, motor unit activation of the immobilized arm was monitored via EMG to determine the level of activation. Results showed minimal activation in the immobilized arm during strength training. The immobilized arm was activated 4.6% (average of biceps and triceps brachii) of the training arm during strength-training contractions. Other cross-education studies showed small amounts of activation in the nontraining limb during strength training (10, 19); however, the amount of activation was so small that it was unlikely to provide enough of a stimulus to maintain muscle size (12). In fact, the level of associated activation we report here is probably less than what might have occurred while the sling and swathe were removed (i.e., during sleep or bathing), and since these activities were permitted for the Immob group as well, it might have resulted in maintenance of muscle size, rather than the demonstrated decline in muscle size (Fig. 2).

A fascinating result of the present study is that strength training the nonimmobilized arm produced a significant increase in strength in the immobilized arm for elbow extension (32.2%) in subjects after 4 wk of wearing the sling and swathe.

**Table 2. Percent activation via interpolated twitch**

<table>
<thead>
<tr>
<th></th>
<th>Elbow Flexion (Biceps Brachii)</th>
<th>Elbow Extension (Triceps Brachii)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Pre</td>
<td>81.8 (8.4)</td>
<td>94.5 (5.4)*</td>
</tr>
<tr>
<td>Post</td>
<td>92.2 (4.7)</td>
<td>94.3 (4.5)</td>
</tr>
<tr>
<td>Immob + Train</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>91.7 (6.4)</td>
<td>941.5 (5.6)</td>
</tr>
<tr>
<td>Immob</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>91.1 (5.0)</td>
<td>93.5 (6.9)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>94.0 (4.6)</td>
<td>90.4 (9.1)</td>
</tr>
</tbody>
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Values [means (SD)] are normalized to preintervention scores. *Significantly different from Control ($P < 0.05$).

**Table 3. Agonist activation via EMG**

<table>
<thead>
<tr>
<th></th>
<th>Elbow Flexion (Biceps Brachii)</th>
<th>Elbow Extension (Triceps Brachii)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Immob + Train</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Train</td>
<td>1.053 (0.321)</td>
<td>0.912 (0.276)</td>
</tr>
<tr>
<td>Immob</td>
<td>0.988 (0.290)</td>
<td>0.994 (0.329)</td>
</tr>
<tr>
<td>Control</td>
<td>1.133 (0.308)</td>
<td>1.025 (0.332)</td>
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</table>

**Table 4. Antagonist activation via EMG**

<table>
<thead>
<tr>
<th></th>
<th>Elbow flexion (triceps brachii)</th>
<th>Elbow extension (biceps brachii)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Immob + Train</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Train</td>
<td>0.043 (0.045)</td>
<td>0.030 (0.010)</td>
</tr>
<tr>
<td>Immob</td>
<td>0.031 (0.017)</td>
<td>0.027 (0.017)</td>
</tr>
<tr>
<td>Control</td>
<td>0.024 (0.007)</td>
<td>0.029 (0.010)</td>
</tr>
</tbody>
</table>

**Values [means (SD)] are mV. No significant differences were found.**
This increase in strength is consistent with the magnitude of cross-education that would be expected without an immobilization intervention. Conversely, strength in the Immob group (no strength training) declined in strength by 6.1% in the immobilized arm (Fig. 3), although not significantly different from the Control group. To our knowledge, this prominent increase in strength after a period of immobilization has not been previously demonstrated. Farthing et al. (12) found that strength was maintained, but not enhanced, in the immobilized arm after application of cross-education using a 3-wk casting protocol. This large increase in strength in the immobilized arm may be due to alterations in muscle recruitment that may not be associated with the target muscles. Agonist and antagonist activation in the Immob + Train group was not significantly different from that in the Immob or Control group (Tables 3 and 4) and, therefore, cannot account for the large increase in strength. Activation of the homologous agonist muscle in the immobilized limb during strength-training sessions was monitored; however, minimal activation was detected. It is possible that activation of other muscles not monitored in the immobilized limb contributed to the large increase in strength. The Immob + Train group may not have been able to better activate the target muscles (no change in percent activation or EMG); however, they may have been better to coordinate or stabilize the joint. This may be due to inclusion of flexion and extension exercises in the strength-training program. No other cross-education study has used two opposing exercises for strength training; therefore, the effect of the two exercises across the joint could have contributed to the large increase in strength for elbow extension.

Although the present study did not investigate neural mechanisms in the brain, it has been suggested that cross-education may be due to changes in motor learning. These changes may include plasticity in the brain, particularly in the primary motor cortex, premotor cortex, or supplementary motor area (13). It has been shown that unilateral strength training of the trained limb produced changes in brain activation in both hemispheres and that the untrained limb showed increased activation in the contralateral sensorimotor cortex and ipsilateral temporal lobe, suggesting that changes in the brain are being shared between hemispheres (11). In the present study, evidence of motor learning may be 1) the high level of cross-education, despite 4 wk of immobilization of the untrained limb, and 2) no change in muscle activation. Spinal mechanisms may also play a role in cross-education; however, it has been shown that, after an increase in strength in trained and untrained limbs, increased spinal excitability was found only in the trained limb (24). Lagerquist et al. (24) suggested that supraspinal mechanisms contributed to the increase in strength in the untrained limb. More research into the mechanisms of cross-education is needed for a better understanding of these effects.

It was puzzling that a decrease in elbow flexion strength was not found in the immobilized arm of the Immob group (Fig. 3). Previous research has shown decreases in strength following immobilization (25, 27). This questions whether the immobilization protocol had an effect; however, we did find a decrease in elbow extension strength (−6.1%, which is signficantly different from Immob + Train, but not Control) and a decrease in muscle size for the biceps (−2.8%) and triceps (−5.2%) brachii (significantly different from Immob + Train, but not Control). Reasons for this finding may be as follows: 1) the 4-wk intervention period was not long enough to induce decreases in strength or 2) the subjects were not as compliant as they reported in the daily immobilization logs. Elbow flexion strength was actually higher (4.0%) for the Immob group after the intervention, but this was not significantly different from either of the other two groups, so it likely represents no change. The Control group also showed an increase in strength (5.5%), which may indicate that the participants learned how to better execute the elbow flexion task from pre- to posttesting.

It was hypothesized that the Immob + Train group would maintain elbow flexion strength in the immobilized arm, therefore demonstrating the cross-education effect to an immobilized limb. As stated above, all three groups increased left arm strength slightly, but no significant differences between groups were found (Fig. 3). The nonsignificant finding of cross-education for elbow flexion was possibly due to the smaller gain in magnitude in the training arm for elbow flexion. The Immob + Train group increased strength in the training arm by 18.9% compared with a 68.1% increase for elbow extension. On average, cross-education is 52% of the strength gained in the trained muscle (6). The strength gain from the trained to untrained muscle was ~47% for elbow extension and 41% for elbow flexion. The untrained arm strength gain relative to the trained muscle in elbow extension and flexion was similar (47% and 41%, respectively); however, with the smaller increase in trained arm strength for elbow flexion, in combination with an increasing trend for strength in the Immob and Control groups, no significant cross-education effect was shown.

The lack of cross-education for elbow flexion may have also been due to the task itself. Cross-education has been shown to have a greater effect in more unfamiliar tasks (10, 13). The elbow flexion task was quite simplistic and easy to execute with consistency. It required the participants to pull toward themselves with the hand supinated. The elbow extension task was less familiar: it required the participants to push away from themselves with the hand internally rotated from the supinated position 90°. More complex strength tasks require coordination and recruitment of multiple muscle groups; therefore, greater motor learning adaptations in response to strength training are evident (13). However, in the present study, the Control group showed no significant increase in strength for either strength task, suggesting that the strength-training intervention was responsible for any motor learning adaptation that contributed to the cross-education effect.

The immobilization unloading protocol using the sling and swathe had a greater effect on muscle thickness than on strength (Figs. 2 and 3). It was previously shown that the position in which the muscle is placed may influence changes in muscle morphology (3, 16, 18, 30). When muscles are fixed in a shortened or neutral position, they will likely atrophy; however, when muscles are fixed at a lengthened position beyond neutral, muscle atrophy may be attenuated or prevented, and, in some cases, muscle hypertrophy can occur (16, 18, 30). The present study found that, in the Immob group, the biceps and triceps brachii decreased muscle size by 2.8% and 5.2%, respectively (not significantly different from Control; Fig. 2). The reason for the greater decline in muscle thickness in the triceps than biceps brachii is not known. The placement of the elbow joint at 90° elbow flexion may not have been...
sufficient to maintain muscle size. A further decrease in the elbow flexion angle may have led to different results.

The changes in the muscle for the Immob group are consistent with changes reported in other research studies using immobilized healthy limbs. Significant decreases in elbow flexor volume (7.7%) and elbow flexion strength (25), as well as significant decreases in triceps brachii cross-sectional area (4%) and elbow extension strength (12%) (27), have been found after arm sling unloading. Both of these studies, along with the present study, allowed participants to remove the sling during sleeping and bathing. A 4-wk casting study on the elbow joint found that the elbow flexors significantly decreased cross-sectional area (11.2%) but showed a nonsignificant decline in force, whereas the elbow extensors showed nonsignificant declines in cross-sectional area and maximal voluntary force (35). More research is needed to understand the effects of immobilization protocols on different muscle groups in the upper limb.

The present study also examined changes in maximal voluntary muscle activation following immobilization. A significant time main effect for right elbow flexion was found in all groups pooled; however, no other significant changes were detected (Table 2). These results indicate that the immobilization protocol had no effect on the ability of the muscles to maximally activate. Gondin et al. (17) found a 6% decrease in maximal voluntary activation after ankle immobilization. Similarly, other studies have found that immobilization decreased the ability to maximally activate the muscles (2, 7, 31). However, these studies were conducted on injured participants; therefore, the effects of the injury undoubtedly hindered the ability to maximally contract. A study using cross-education alone (i.e., training without immobilization) found no change in maximal voluntary activation in the nontraining limb (34). From this observation, if a decrease in activation was present (i.e., after an injury), it may be speculated that there would not be a maintenance effect for muscle activation in the immobilized limb after cross-education training. However, the cross-education effect may still be beneficial for an injured limb compared with no contralateral training. This is an important question for future work.

A limitation to the method of using interpolated twitch to predict percent activation is that when inexperienced participants are used, the expectation of a stimulus during a maximal contraction may significantly reduce strength and percent activation (4). This may have influenced the present study, where the force and percent activation levels recorded may actually be lower than if there was no anticipated stimulus during the maximal contraction. However, since all participants in the present study were inexperienced, it would be expected that all groups would show a similar response to the stimulus.

The present study also investigated changes in EMG activity and found, for normalized agonist MAV activity, a significant difference for right elbow extension between the Immob + Train and the Control group (Table 3). This difference reflects the increase in muscle activation after strength training the right arm of the Immob + Train group, which is consistent with previous strength-training studies (19, 26, 29). There were no other significant differences for activation amplitude in agonist or antagonist muscles. Wearing the sling and swathe for 4 wk appeared to have no effect on the electrical activity of the immobilized muscles. Farthing et al. (12) also found no change in MAV activity after 3 wk of forearm casting. Yue et al. (35) studied changes in EMG in the biceps and triceps brachii after elbow immobilization and found a decrease in biceps brachii activation after 4 wk; however, the effects on the triceps brachii were not reported. Other studies have found decreases in the amplitude of the EMG signal after immobilization (7, 27), making results inconsistent as to whether or not short-term immobilization leads to reductions in muscle activation. The difference in the studies may be due to different types and durations of immobilization, as well as the muscles being immobilized.

Another limitation of the present study is that we could not be absolutely sure how compliant the participants were in wearing the sling and swathe. Subjects were instructed to wear the sling and swathe for ≥12–14 h/day and record in daily journals any time it was removed. From the daily journals, the sling and swathe were removed for activities such as bathing, sleeping, and driving and were worn for an average of 13.0 h/day (Immob + Train and Immob averaged; Table 1). An improved model to ensure compliance may be use of an elbow cast; however, we were interested in the effects of the sling and swathe because of its wide use in clinical practice after upper limb injuries (i.e., shoulder surgery). We were also interested in conveniently monitoring muscle activation of the immobilized arm during strength training of the free arm, which required access to the target muscles.

The purpose of the present study was to apply cross-education during 4 wk of unilateral limb immobilization using a shoulder sling and swathe to investigate the effects on muscle strength, muscle size, and muscle activation. The results suggest that strength training the nonimmobilized limb provided a benefit to the immobilized limb in healthy participants. These findings have the potential for application to real injuries where strength training of the healthy limb may have a beneficial effect on the injured limb. The extent of the benefits in an injured population are not known; therefore, these results should be taken with caution when considering real injuries. This study is unique, in that it is the first cross-education study to investigate the effects on the contralateral limb with two opposing strength-training exercises. Another novel aspect of this study is that we were able to monitor muscle activation in the immobilized limb during unilateral strength training of the free limb. The amount of activation in the immobilized limb was minimal and, therefore, was not likely to be a mechanism of the cross-education effect in this context. In conclusion, cross-education seems to be beneficial for preventing the harmful effects of unilateral limb immobilization in healthy participants; however, more research is needed to further investigate the effects in a clinical population.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.
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