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Training with unilateral resistance exercise increases contralateral strength

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It is widely believed that unilateral strength training increases strength in the homologous muscle group of the contralateral limb (for reviews, see Refs. 6, 20, 31). Recently, a meta-analysis of randomized studies concluded that unilateral training produces a small but statistically significant effect on the strength of the homologous muscles on the contralateral side (an increase of 8% of initial strength of the untrained limb) (20). This review pooled data from 13 studies in an attempt to overcome the problem of underpowered individual studies. Although the review only considered studies that were randomly controlled, the conclusion in this review (20) is weakened because its conclusions were based on data pooled from studies that were heterogenous with respect to the training method, the muscle group trained, and the training duration (20). Another limitation in most unilateral training studies is that there has been no control for the potential influence of the training environment on contralateral strength. Control subjects are typically not exposed to other subjects training because they typically do not attend training sessions. Exposure to others performing a motor task can affect performance of the observer (11), so it is important to control for this influence when determining the effect of unilateral training on contralateral strength.

Although there is no consensus on the mechanism that produces contralateral strength adaptations, it has been suggested that the magnitude of strength gained on the contralateral side is related to the strength gain on the trained side (31). A review by Zhou (31) explored this premise by examining results of previous studies, but the relationship between strength gain on the trained and untrained sides has not been assessed in an individual study. Given that training speed (7, 24) and the volume of training (26) are believed to influence the magnitude of strength adaptations on the trained limb, it is possible that these parameters could also affect adaptations of contralateral strength.

This study aimed to determine the effect of unilateral resistance training on the strength of the untrained limb. It was designed to overcome limitations of previous studies, including inadequate sample size, inappropriate statistical analysis, and failure of control subjects to attend training sessions. A second aim was to determine whether the number of training sets and contraction speed of unilateral progressive resistance exercise affects contralateral strength. Lastly, we sought to determine whether contralateral increases in strength scaled with ipsilateral strength gains.

**METHODS**

**Subjects**

One hundred fifteen untrained and apparently healthy subjects (21 men and 94 women) with a mean age of 20.6 yr (SD 6.1) [mean height of 168.1 cm (SD 9.1) and weight of 64.2 kg (SD 11.6)] participated in the study. Subjects had no known musculoskeletal or neurological impairment that might affect performance of the upper limb, and their responses to a standardized questionnaire (3) suggested that they could safely participate in physical activity. Subjects had not been involved in regular strength training for the upper limbs in the 6 mo before commencement of the study. Strength was measured bilaterally, and details of the contralateral increase in strength have been reported (21). Written, informed consent was obtained from all participants before commencement of the study, which had been approved by the local Human Research Ethics Committee.

**Measurements**

After a warm-up, strength of the elbow flexor muscles was measured on the right and left arms of all subjects using a one-repetition maximum (RM) test. High reliability of RM testing for the elbow flexors (coefficients > 0.90) have been reported previously (5, 25). Subjects were seated holding a loaded bar with the test arm resting on
a bench, starting from full elbow extension and supination. The nonatest arm remained relaxed behind the back. Instructions were given to ensure correct technique and to minimize compensatory movements that may assist in performing the lift. The following strategies were adopted to try to ensure maximal efforts. Subjects were reminded to perform with maximal effort on each lift, were loudly exhorted by the researcher, were able to discount an attempt if he/she believed it was submaximal, and were informed that a prize would be awarded to the strongest person (factored for gender, weight, and height) (8). The testing procedure was repeated to determine a 1 RM to the nearest 0.25 kg. A 2- to 3-min rest interval was given between each effort.

Skinfold thickness over the biceps site was measured in a standardized way with Harpenden calipers (23). Upper arm circumference was measured with the shoulder flexed to ~90°, at a point where circumference was greatest. The subject clenched the fist and attempted to maximally tense the elbow flexors while maintaining the forearm at ~45° to the upper arm (23). This task requires cocontraction of the elbow extensors.)

After baseline measurements, subjects were randomly allocated to one of five equally sized groups: control, training with three sets at high speed, training with three sets at low speed, training with one set at high speed, or training with one set at low speed. The training arm was also randomly assigned for all training and control subjects.

Training Procedures

Subjects in both the training and control groups attended 18 training sessions over a 6- to 7-wk period. Where training was missed, subjects were encouraged to make up the session to ensure that all subjects completed the same total number of sessions. Just over one-half of all subjects required a training session to be rescheduled. All training sessions were supervised by a physical therapist.

Training groups. After a light warm-up, subjects performed unilateral elbow flexion contractions to failure (i.e., until they could no longer complete a lift) with an estimated 6- to 8-RM load (~80% 1 RM). When greater than eight lifts could be performed in a training set, the training load was increased by the researchers for the subsequent training session. Average training speed for subjects assigned to high-speed training (1-s concentric and 1-s eccentric phase) was ~140°/s and for low-speed training (3-s concentric and 3-s eccentric phase) was ~50°/s. Cadence was set by a tape recording that also instructed subjects to keep the nontraining arm relaxed and controlled the duration of the rest interval between sets (2-min maximum).

Control group. Control subjects attended the same gymnasium at the same times as training subjects. Control subjects sat with the assigned training arm resting on the bench but did not lift a weight. They also listened to a tape recording, which instructed them to keep both arms relaxed for 4 min (the average time taken in the other groups).

After the training period, elbow flexor strength, skinfold thickness, and arm circumference were remeasured for both limbs as previously described. This testing was performed between 2 and 7 days after training was completed.

Data Analysis

Data for the untrained arm were analyzed with factorial analysis of covariance using a linear regression approach. The purpose of this analysis was to determine the effect of number of sets and speed of contraction on outcomes for the untrained arm. The regression model was:

\[
\text{outcome} = a + b(\text{initial value}) + c(\text{trained}) + d(\text{sets}) + e(\text{speed}) + f(\text{sets} \times \text{speed})
\]

where outcome is the final measure of strength, arm girth, or biceps skinfold thickness; initial value is the initial measure of strength, arm girth, or biceps skinfold thickness; trained indicates whether the subject trained (dummy coded as 0 or 1 for control and trained subjects, respectively); sets indicates whether the subject trained with one or three sets (dummy coded as 1 for subjects who trained with 3 sets and 0 for all other subjects); speed indicates whether the subject trained at high or low speeds (dummy coded as 1 for subjects who trained fast and 0 for all other subjects); and \(a, b, c, d, e,\) and \(f\) are the coefficients that describe the magnitude of each of these effects.

Outcome data were analyzed by intention to treat (14). Thus outcome measures were obtained for all subjects, and data were analyzed according to the groups to which subjects were randomized, regardless of compliance with the training protocol. Significance for all statistical analysis was set at \(P < 0.05\).

RESULTS

Of the 115 subjects, two discontinued participation following randomization but before commencement of training (1 in the control group, and 1 in the 3 sets low-speed training group) because they did not wish to adhere to training protocols. One subject in the one-set low-speed training group completed only 4 wk of training (12 sessions) because she developed neck pain, and one other subject, who completed all training requirements, admitted to having trained the contralateral arm outside the research gymnasium despite being aware of the study requirements not to do so. Thus a total of 111 subjects completed the study according to the training protocol (\(n = 22\) control group, \(n = 22\) training with 3 sets at high speed, \(n = 23\) training with 3 sets at low speed, \(n = 22\) training with 1 set at high speed, and \(n = 22\) training with 1 set at low speed). However, in keeping with the intention to treat principle, outcome data are reported for all 115 subjects.

For the trained arm, one set of slow exercise increased initial strength by 25% [mean increase of 1.38 kg; 95% confidence interval (CI): 0.75–2.02 kg; \(P < 0.001\)], and three sets produced a greater effect and increased initial strength by 48% (additional mean effect of 1.28 kg; 95% CI: 0.65–1.92 kg; \(P < 0.001\)). Training at the higher speed resulted in an 11% greater strength if subjects performed only one set of exercise at the slower speed (mean increase of 0.07 kg; 95% CI: 0.00–0.14 kg; \(P = 0.06\)). When three sets of exercise were performed, there was a significant increase in contralateral strength compared with one set (additional mean effect of 0.41 kg; 95% CI: 0.06–0.75 kg; \(P = 0.02\)). This was equivalent to a 7% increase in strength (% of pooled initial strength).

The effect of training speed on contralateral strength was not statistically significant, but there was a tendency for training at the higher speed to have a greater effect on strength of the contralateral limb than training at the lower speed (additional mean effect of 0.31 kg, or ~5% of initial strength; 95% CI: ~0.03–0.66 kg; \(P = 0.08\)). There was no interaction between training speed and number of sets (additional mean effect of ~0.41 kg; 95% CI: ~0.90–0.07; \(P = 0.10\)). Unilateral training had no effect on the girth or skinfold thickness of the untrained arm.
The relationship between ipsilateral and contralateral strength gains for trained subjects is shown in Fig. 2. The regression was contralateral strength increase (\%) / ipsilateral strength increase (\%) = 0.54 (\% ipsilateral strength increase) / 7.0; \( r = 0.532; P < 0.001 \). This indicates that there is a highly significant relationship between the magnitude of strength gained for the trained and untrained limbs.

**DISCUSSION**

This study investigated the contralateral effects of ipsilateral strength training using a rigorous design. There was true random allocation of a moderately large sample of subjects to exercise and control groups, subjects in the control group attended the training facility but did not train, and estimates of the effects of training on contralateral homologous muscles were based on analysis by intention to treat of contrasts between trained subjects and untrained controls.

In the present study, 6 wk of training with three sets of dynamic resistance exercise produced a mean increase in contralateral strength of 7\% (95\% CI: 1–13\%) in subjects without recent history of training. This effect is similar to that derived from a recent meta-analysis (mean of 8\%; 95\% CI: 4–12\%) (20) and to the effect reported by Shaver (27), who also trained elbow flexors dynamically using three sets (mean increase of 9\%; 95\% CI: 4–14\%). In the present study, although there was a significant increase in mean contralateral strength, 10 subjects from the sample showed decreased contralateral strength at follow up (Fig. 2). Interestingly, for most of these 10 subjects, increases in strength on the trained side were relatively small compared with the majority of the sample (Fig. 2).

In a recent review, Zhou (31) suggested that contralateral strength gains were related to the magnitude of strength gained in the trained limb. This hypothesis is supported by our data, which show that the relationship between strength gains on the trained and untrained limb is highly significant. There was a nonsignificant trend for training at higher speeds to produce a greater contralateral effect than training at lower speeds (\( P = 0.08 \)). In the present study, the effect of training at higher speeds on contralateral strength was significant (\( P = 0.04 \)).

| Table 1. Pre- and posttraining measures of strength, girth, and biceps skinfold for the contralateral arm of control and trained subjects |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|
|                                | Control (n = 23) | One Set, High Speed (n = 23) | One Set, Low Speed (n = 23) | Three Sets, High Speed (n = 23) | Three Sets, Low Speed (n = 23) |
|                                | Pretraining | Posttraining | Pretraining | Posttraining | Pretraining | Posttraining | Pretraining | Posttraining | Pretraining | Posttraining |
| 1 RM, kg                       | 6.0 (2.2)    | 6.2 (2.5)    | 6.2 (4.7)   | 6.7 (5.0)    | 5.3 (2.0)   | 5.5 (2.0)    | 5.5 (2.2)   | 6.0 (2.3)    | 5.5 (2.7)   | 5.6 (2.0)    |
| Girth, cm                      | 29.2 (3.0)   | 29.7 (2.8)   | 29.4 (4.6)  | 29.4 (4.2)   | 28.8 (2.9)  | 29.2 (2.9)   | 29.0 (3.2)  | 29.3 (3.2)   | 28.9 (3.2)  | 29.7 (3.2)   |
| Skinfold, mm                   | 8.4 (4.3)    | 8.1 (3.2)    | 7.7 (3.8)   | 7.2 (3.3)    | 8.2 (2.7)   | 8.2 (2.3)    | 7.8 (3.4)   | 7.5 (3.0)    | 7.4 (4.0)   | 7.8 (3.9)    |

Data are means (SD). RM, repetition maximum.
speeds on strength of the trained arm was 11% greater than the effect of training at lower speeds (and 36% greater than for controls) (21). The trend seen in favor of training at higher speeds on contralateral strength increases may be related to the greater magnitude of strength gained in the trained arm when training at faster speeds (21).

There were no changes in the circumference of the untrained arm. Although the arm circumference measure used here may not be as sensitive to small changes in muscle size as other measures, such as those made with ultrasound (28), it is unlikely that the contralateral increases in strength resulted from muscle hypertrophy. Several studies, using a range of methods, have shown that increases in contralateral strength with unilateral training are not accompanied by contralateral increases in muscle anatomical cross-sectional area or muscle fiber cross-sectional area [measured with ultrasound (7), computer tomography scan (10), magnetic resonance imaging (17, 22), or biopsy (18)]. However, the ability of these methods to detect changes in cross-sectional area of a few percent is unknown.

In the absence of increased muscle cross-sectional area, improved voluntary activation via motor unit recruitment and increase in firing rate through central neural mechanisms may be responsible for the contralateral effect of unilateral strength training. With isometric elbow flexion contractions, maximal voluntary activation of the biceps brachii and brachialis measured with twitch interpolation using nerve stimulation is usually nearly 100% (2, 9). These levels of voluntary activation are characteristic for individual subjects (1), and the level of activation does not improve with training (13). However, it has been demonstrated that activation of brachioradialis is suboptimal for force production (2), and following elbow flexor training it is possible that strength gains may in part be attributed to increased drive to this muscle (13). If voluntary activation for elbow flexion is suboptimal pretraining, strength increases on the trained side may in part be due to increased ability to recruit motor units and to make unfused units fire faster. Unilateral voluntary movements have been shown to have contralateral effects at a cortical level (16) and activate both the contralateral and ipsilateral sensorimotor cortex (e.g., Refs. 16, 19). This may induce a learning effect for activation of the contralateral side following unilateral resistance training (12, 29, 30) and result in strength increases in the untrained limb. There may also be neural changes at other levels involving spinal (15, 16) and supraspinal premotor networks (4).

In summary, three sets of progressive dynamic resistance exercise produce small contralateral increases in strength, and these are graded according to the ipsilateral strength increases. There is a trend toward greater contralateral training effects when the training load is lifted quickly. It has not been established whether this small increase in contralateral strength occurring with unilateral training is functionally important.

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