Contralateral effects of unilateral resistance training: a meta-analysis

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Munn, J., R. D. Herbert, and S. C. Gandevia. Contralateral effects of unilateral resistance training: a meta-analysis. J Appl Physiol 96: 1861–1866, 2004; 10.1152/japplphysiol.00541.2003.—It is often claimed that strength training of one limb increases the strength of the contralateral limb, but this has not been demonstrated consistently, particularly in well-controlled studies. The aim was to quantitatively combine the results of other studies on the effects of unilateral training on contralateral strength in humans to provide an answer to this physiological question. We analyzed all randomized controlled studies of voluntary unilateral resistance training that used training intensities of at least 50% of maximal voluntary strength for a minimum of 2 wk. Studies were identified by computerized and hand searches of the literature. Data on changes in strength of contralateral and control limbs were extracted and statistically pooled in a meta-analysis. This approach allows conclusions to be based on a statistically meaningful sample size, which might be difficult to achieve in other ways. Seventeen studies met the inclusion criteria, and 13 provided enough data for statistical pooling. The contralateral effects of strength training reported in individual studies varied from −2.7 to 21.6% of initial strength. The pooled estimate of the effect of unilateral resistance training on the maximal voluntary strength of the contralateral limb was 7.8% (95% confidence interval: 4.1–11.6%). This was 35.1% (95% confidence interval: 20.9–49.3%) of the effect on the trained limb. Pooling of all available data shows that unilateral strength training produces modest increases in contralateral strength, strength; muscle; exercise

It is often claimed that strength training of one limb produces increased strength of the contralateral homologous muscle group. This phenomenon was first observed over a century ago (35). Subsequently, the finding has been replicated in many studies (e.g., Refs. 6, 8, 18, 22, 26, 36). However, many who have investigated this phenomenon failed to see such an effect (e.g., Refs. 14, 15, 24, 32).

A serious problem with many of the studies that have shown contralateral strength gains is that they compare strength increases in trained and untrained limbs of subjects undergoing training. With this design, the apparent contralateral increases in strength may be due to familiarity with test procedures. Repeated exposure to muscle testing can improve performance as subjects become habituated to the test (17). A better way to assess the contralateral effects of training is to randomize subjects into two groups (one that trains and one that does not) and then compare strength increases in the contralateral limb of trained subjects with strength increases in untrained subjects. Randomization eliminates potential allocation bias, which may cause systematic differences between groups (1). Relatively few studies have used this design, and most have failed to demonstrate a significant difference between groups (e.g., Refs. 15, 32). This may be because there is no contralateral effect or because the sample size in these studies is inadequate.

The typical sample size in controlled studies of the contralateral effects of training is ~10 subjects in each group (e.g., Refs. 6, 28, 32, 44), which provides very low statistical power [e.g., in studies with 10 subjects/group, the power to detect an 8% increase in contralateral strength in the presence of a standard deviation (SD) of 24% (estimated from previous studies included in this meta-analysis) and α = 0.05 is 11%].

One way to overcome the problem of small sample size is to pool the findings of appropriately controlled studies in a meta-analysis (10). Because meta-analysis effectively increases overall sample size, it can provide a more precise estimate of the contralateral training effect of unilateral resistance training.

The primary objective of this study was to evaluate the effect of unilateral training on the strength of the untrained limb. A systematic review was conducted to minimize the potential for bias (10). The findings of properly controlled studies were statistically combined in a meta-analysis (12) to determine a precise estimate of the effect of unilateral training on the untrained limb.

METHODS

Identification and selection of studies. An electronic search was performed on the bibliographic databases of MEDLINE (1966 to March 2002), CINAHL (1982 to March 2002), EMBASE (1988 to March 2002), SPORTDiscus (1949 to March 2002), and AUSPORT (1989 to March 2002). They were searched using a combination of keywords and/or MeSH headings related to strength measures, resistance training, and the contralateral limb. Reference lists of retrieved articles were inspected, and the personal files of the authors were also checked. Because translations were unavailable, papers not written in English were not considered in this review. This is unlikely to have significantly affected the number of relevant studies identified. For example, an electronic search of MEDLINE (1996 to present) using the strategy outlined above identified 193 papers. When papers not in English were accepted in the search, only a further seven papers were identified (6 in German and 1 in Chinese), and from their English abstract or title it was determined that these were not relevant to the analysis.

Criteria for eligibility. Only studies that clearly randomly allocated subjects to trained and untrained groups were included in the study because randomization controls for allocation bias (1, 2, 16). Other studies (those with no control group or with nonrandomized control subjects) were not considered because of the potential for bias.

All retrieved studies were screened and included if resistance training used at least 50% of maximal voluntary strength [because it is thought that training at and above this intensity results in strength increases (3)], subjects had no pathology that could affect voluntary

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activation (e.g., previous history of stroke), and training involved only one limb and no other interventions were performed. Training had to be performed for a minimum of 2 wk, and strength had to be evaluated in the untrained limb through measures of recorded maximum load, or force or torque exerted against a dynamometer during maximal voluntary contraction.

Assessment of selection criteria and outcomes. Most statistical models for meta-analysis permit the use of only one outcome from each study. When studies reported more than one outcome, a simple algorithm was used to determine which outcome was analyzed. Data for the strength measure most homologous to the type of resistance training were preferred. For example, if training was isometric, and both isometric and isokinetic strength measures were recorded, the homologous measure (in this example, isometric strength) was preferred. If more than one muscle group was trained, data from the group with the highest training intensity were preferred. If more than one muscle group was trained, data for knee extensor muscles were preferred. Where the experimental design involved random assignment of subjects to more than one training group, data from the group with the highest training intensity were preferred, and data for the concentric training group were preferred over data for the eccentric training group.

Analysis of data. Measures of the size of the contralateral effect of training were extracted from each study. Raw data (means and SD) were extracted or calculated from standard errors, 95% confidence intervals (CI), P values, r values, or F values. In studies that reported SDs of strength before and after training, the SD of the change in strength was estimated by assuming a correlation of 0.5 between measures taken before and after training. This is probably a conservative estimate. The size of the contralateral effect of training is given by the difference between the mean change in strength of untrained contralateral limbs of subjects in the trained and untrained groups.

The method for pooling data across studies is to express the size of the contralateral effect of training as a percentage of the initial strength before training. Both the numerator and denominator in the estimates of percent increase in strength are variables, so it was necessary to calculate the variance of the estimates of percent increases in strength using the following approximation (4)

$$\text{var}\left(\frac{\Delta}{\text{init}}\right) = \text{var}\Delta + \text{var(\text{init})} \times \frac{\Delta^2}{\text{init}^2} - 2 \times \frac{\Delta \times \text{cov(\Delta init)}}{\text{init}^2}$$

where $\Delta$ is the size of the contralateral effect of training, var indicates a variance, init is initial strength, a horizontal bar above a variable indicates its mean, and cov indicates a covariance. This approximation is reasonable if the SD of the denominator variable is small relative to its mean, as is the case with the present data. The covariance of initial strength and change in strength was estimated by assuming that the correlation between initial and final strength was 0.5. Pooling of data across studies (meta-analysis) was carried out using a random-effects model (12). Statistical power calculations were based on the ability to detect an 8% increase in strength.

RESULTS

Identification and selection of studies. A total of 81 studies spanning the period of 1894–2002 were identified, of which 22 studies randomized subjects to training or control groups. Seventeen of the 22 studies met the selection criteria for the primary analysis. Five studies were excluded because training intensities were <50% of MVC (2 studies), description of the training protocol was inadequate (2 studies), or the strength of the untrained limb was not reported (1 study).

In the studies that underwent further analysis, training involved the knee extensor muscles (9 studies), elbow flexor muscles (5 studies), ankle muscles (2 studies), and abductor digiti minimi (1 study). Two of the included studies did not use the corresponding limb in the control group for comparison with the untrained limb in the training group (15, 28). In one study, the right limb of the control group was used (because there was not a statistically significant between-limb difference in the control group) (15), and in the other study data for both control limbs were combined (28). This is unlikely to affect the results of the analysis because the purpose of including control limb data is to account for the potential effect on strength of repeated exposure to the testing procedure, and both limbs in the control groups of these studies were exposed equally (15, 28). Training periods ranged from 4 to 12 wk, with most studies training subjects for 6 wk (8 studies). Ten of the studies used only male subjects, and three studies used only female subjects. The remaining studies used both genders in their study samples. All studies used healthy and mostly young individuals (Table 1).

Individual studies. Thirteen studies provided an estimate of the effect of contralateral training. Details of these studies are provided in Table 1. Estimates of the contralateral effect varied from −2.7 to 21.6%. The remaining 4 studies of the 17 that met the selection criteria (5, 21, 39, 41) did not provide sufficient data to be included in the meta-analysis.

Most studies with appropriate controls did not report whether strength changes in the untrained limb of trained subjects differed significantly from strength changes in the untrained limb of control subjects. The strength increase in the untrained limb of trained subjects was reported as significantly different ($P < 0.05$) from controls in only one of three studies that performed this comparison (36). When we analyzed the raw data reported in all studies individually, we found that this difference was statistically significant in only 2 of 13 studies (22, 36).

Pooled analysis. The pooled estimate of the effect of contralateral training from 13 studies (309 subjects) was an increase in muscle strength of 7.8% (95% CI: 4.1–11.6%; $P < 0.0001$; Fig. 1). The effect of training on the trained limb was an increase in muscle strength of 20.5% (95% CI: 16.0–25.1%; $P < 0.0001$, Fig. 2). When the strength increase of the contralateral limb was expressed as a proportion of the strength increase in the trained limb, the effect was 35.1% (95% CI: 20.9–49.3%).

A post hoc analysis was performed to determine whether the type of training (isometric or dynamic) influenced the contralateral effect of training. A pooled analysis of seven studies (101 subjects) of isometric training revealed that the effect of isometric training on the strength of the untrained limb was 4.0% (95% CI: −1.7–9.7%; $P = 0.08$). A pooled analysis of five studies (188 subjects) revealed that dynamic training increased strength of the untrained limb by 9.8% (95% CI: 3.9–15.7%; $P < 0.01$). The size of the effects for isometric and dynamic training were compared, and this difference was not significant ($P = 0.17$).

Comparisons of the effect of upper limb training and lower limb training were also performed post hoc. A pooled analysis of five studies (179 subjects) showed the effect of ipsilateral training on the untrained upper limb to be a 3.8% (95% CI: −2.2–9.8%; $P = 0.22$) increase in strength, and for the lower limb a pooled analysis of eight studies (130 subjects) showed an effect of 10.4% (95% CI: 3.5–17.3%; $P < 0.01$). The effect size for upper and lower limb training was not significantly different ($P = 0.16$).
CONTRALATERAL EFFECTS OF RESISTANCE TRAINING

Table 1. Details of trials included in the meta-analysis of contralateral effects of unilateral resistance training

<table>
<thead>
<tr>
<th>Reference</th>
<th>Subjects</th>
<th>Muscle Group</th>
<th>Intervention Considered in Meta-analysis</th>
<th>Outcome Measure Used in Meta-analysis</th>
<th>*Contralateral Effect of Training (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Komi et al. (30)</td>
<td>2 female sets and 4 male sets of healthy monozygous twins (6 control subjects, 6 experimental subjects)</td>
<td>Knee extensors</td>
<td>Isometric: 5 reps × 3- to 5-s MVC (weeks 1 and 2) then reps increased by 1 every 2nd week 4×/wk × 12 wk</td>
<td>Isometric knee extension</td>
<td>12.1(−24 to 48.3)</td>
</tr>
<tr>
<td>Carolan and Cafarelli (7)</td>
<td>20 sedentary males (10 control subjects, 10 experimental subjects) Age (mean ± SD): 21.8±0.8 yr</td>
<td>Knee extensors</td>
<td>Isometric: 30 reps × 3- to 4-s MVC 3×/wk × 8 wk</td>
<td>Isometric knee extension</td>
<td>21.6(−2.9 to 46.2)</td>
</tr>
<tr>
<td>Garfinkel and Cafarelli (15)</td>
<td>15 sedentary females (7 control subjects, 8 experimental subjects) Age (mean ± SD): 21.9±2.7 yr</td>
<td>Knee extensors</td>
<td>Isometric: 3 reps × 10 × 3 to 5-s MVC 3×/wk × 8 wk</td>
<td>Isometric knee extension</td>
<td>3.1(−10.2 to 16.4)</td>
</tr>
<tr>
<td>Kannus et al. (28)</td>
<td>10 males, 10 females moderately active and healthy (10 control subjects, 10 experimental subjects) Age range: 23–40 yr</td>
<td>Knee extensors and flexors</td>
<td>Isometric: 5 reps × 10-s MVC at 60° knee extension + 5 reps × 10-s MVC at 30° knee extension + isokinetic (concentric): 10 MVC × 5 sets at 240° + 5 MVC × 5 sets at 60° + 25 MVC × 5 sets at 240° 3×/wk × 7 wk</td>
<td>Isometric knee extension</td>
<td>13.3(−3.6 to 30.3)</td>
</tr>
<tr>
<td>Hortobagyi et al. (22)</td>
<td>14 sedentary males [6 control subjects, 8 experimental subjects (concentric training group)] Age (mean ± SD): 21.3±1.9 yr</td>
<td>Knee extensors</td>
<td>Isokinetic (concentric): 8–12 reps MVC × 4–6 sets (periodization principle) 4×/ wk × 12 wk</td>
<td>Isokinetic (concentric) knee extension</td>
<td>20.9(12–29.8)</td>
</tr>
<tr>
<td>Evetovich et al. (11)</td>
<td>20 males (9 control subjects, 11 experimental subjects) Age (mean ± SD): 22.2±2.8 yr</td>
<td>Knee extensors</td>
<td>Isokinetic (concentric): 6–8 reps MVC × 3–6 sets (periodization principle) 3×/ wk × 12 wk</td>
<td>Isokinetic (concentric) knee extension</td>
<td>3.9(−0.3 to 8.0)</td>
</tr>
<tr>
<td>Hortobagyi et al. (23)</td>
<td>14 sedentary females [6 control subjects, 8 experimental subjects (voluntary eccentric training group)] Age (mean ± SD): 24.8±4.5 yr</td>
<td>Knee extensors</td>
<td>Isokinetic (eccentric): 4–6 sets × 6–8 reps (periodization principle) 4×/wk × 6 wk</td>
<td>Isokinetic (eccentric) knee extension</td>
<td>19.0(−6.8 to 44.8)</td>
</tr>
<tr>
<td>Meyers (32)</td>
<td>19 healthy active males [9 control subjects, 10 experimental subjects (high intensity training group)] Age: “junior” university students</td>
<td>Elbow flexors</td>
<td>Isometric: 20 reps × 6-s MVC at 10° elbow flexion 3×/ wk × 6 wk</td>
<td>Isometric elbow flexion</td>
<td>−2.7(−15 to 9.5)</td>
</tr>
<tr>
<td>Khouw and Herbert (29)</td>
<td>33 females and 18 males† Age range: 18–35 yr</td>
<td>Elbow flexors</td>
<td>Isometric: 6 reps × 10 s at elbow angle of 140° 3×/ wk × 6 wk</td>
<td>Isometric elbow flexion</td>
<td>4.0(−6.7 to 14.7)</td>
</tr>
<tr>
<td>Shaver (37)</td>
<td>40 healthy males (20 control subjects, 20 experimental subjects) Age range: 18–20 yr</td>
<td>Elbow flexors</td>
<td>Dynamic: 1 set × 10 reps at 50% of 10 RM + 1 set × 10 reps at 75% of 10 RM + 10 RM × 1 set (progressive) 3×/wk × 6 wk</td>
<td>Isometric elbow flexion</td>
<td>6.5(−3.2 to 16.2)</td>
</tr>
<tr>
<td>Shaver (36)</td>
<td>100 healthy males (20 control subjects, 80 experimental subjects) Age range: 18–22 yr</td>
<td>Elbow flexors</td>
<td>Dynamic: 10 reps × 1 set at 50% of 10 RM + 10 reps × 1 set at 75% of 10 RM + 10 RM × 1 set (progressive) 3×/wk × 6 wk</td>
<td>Isometric elbow flexion</td>
<td>9.0(4.4–13.6)</td>
</tr>
<tr>
<td>Yue and Cole (44)</td>
<td>20 healthy subjects (10 control subjects, 10 experimental subjects) Age range: 21–29 yr</td>
<td>5th digit abductors (finger)</td>
<td>Isometric: 15 reps × 10-s MVC 5×/wk × 4 wk</td>
<td>Isometric abduction 5th digit</td>
<td>12.1(−11.7 to 35.9)</td>
</tr>
<tr>
<td>Shima et al. (38)</td>
<td>15 healthy active males (6 control subjects, 9 experimental subjects) Age (mean ± SD): 26.2±4.6 yr</td>
<td>Ankle plantarflexors</td>
<td>Dynamic: (single leg calf raises and plantarflexion against foot plate) 10–12 reps × 3 sets at (70–75% of 1 RM) for each exercise 4×/wk × 6 wk</td>
<td>Isometric plantarflexion</td>
<td>4.0(−9.8 to 17.8)</td>
</tr>
</tbody>
</table>

reps, Repetitions; MVC, maximum voluntary contraction; RM, repetition maximum; CI, confidence interval. *The contralateral effect of training is given by the difference in mean change in strength of untrained contralateral limbs in the training group and untrained limbs of untrained controls (see METHODS). †Subjects randomly allocated to training intensities between 0 and 100%. In Ref. 29, effects and variances for experimental and control conditions were obtained from linear regression. Numbers given after authors’ names are reference numbers.
Fig. 1. Effect of unilateral resistance training on the strength of the contralateral limb.

Fig. 2. Effect of unilateral resistance training on the strength of the ipsilateral limb.
DISCUSSION

This meta-analysis provides a precise estimate of the contralateral effect of strength training based on a statistically meaningful sample size, which may be difficult to achieve in individual physiological studies. Pooling of data shows that unilateral resistance training produces moderate increases in contralateral strength in young, healthy individuals. The effect of unilateral training is to increase contralateral strength by 7.8% of the initial strength of the contralateral limb, which corresponds to 35% of the effect on the ipsilateral side.

Previous research on the effect of contralateral training is potentially misleading because many studies are underpowered and most do not perform between-group comparisons. Of the 13 studies analyzed here, statistical power of individual studies to detect an 8% increase in strength ranged from 1 to 96%, with only two studies (11, 36) achieving a statistical power of 80%. Nine studies claimed a significant contralateral effect on the basis of significant pre to post strength gains in the untrained limb (7, 11, 22, 23, 28, 30, 37, 38, 44). When we compared strength changes between the untrained limbs in the training group with the equivalent limb in the control group using data from these individual studies, only one demonstrated a statistically significant contralateral training effect (22). For studies to have adequate statistical power to detect a contralateral training effect of 8% in the presence of large SDs similar to those in the studies included in this analysis, subject numbers in excess of 280 would be required.

Another limitation of studies included in this meta-analysis is that measurement protocols used to record strength did not appear to fulfill many of the criteria identified by Gandevia (13) for optimal measurement of maximal voluntary strength. These criteria relate to practice, feedback, standardized verbal encouragement, rewards with repeated testing, and elimination of subject-perceived submaximal efforts, and they aim to promote true maximal voluntary efforts (13). At best, only half of the recommended criteria was fulfilled (7, 29, 44), with most of the 13 studies eligible for inclusion in this analysis only meeting one or two of the six criteria. It is possible that measurements of strength may have been submaximal in some studies, which could affect the size of the contralateral training effect.

There is no evidence that the contralateral effect of training is dependent on whether training is isometric or dynamic or on whether upper or lower limb muscles are trained. There were no significant differences between pooled estimates of effects of these training types. However, these analyses were underpowered (not achieving a statistical power of 80%); therefore, an influence of training type on the effect of contralateral training cannot be confidently excluded.

Although it is clear that unilateral training has a contralateral effect, the mechanisms behind this effect remain unclear. It has been established that contralateral strength gains do not result from changes in muscle morphology (25). There is no consensus on other proposed mechanisms. Central neural mechanisms involving excitation of the relevant part of the cortex during voluntary contraction of the trained limb are thought to produce contralateral facilitation (9, 18, 42, 43). In support of this mechanism, Kristeva et al. (31) showed that unilateral voluntary movements also involve activity in the contralateral motor cortex. Other support for a contribution of cortical mechanisms to the contralateral training effect comes from the observation that unilateral imagined training increases strength on the contralateral side (44), at least for intrinsic hand muscles. These muscles may have lower maximal voluntary activation than other muscles, and this makes them especially susceptible to central factors that increase activation (19). Because contralateral effects occur with nonvoluntary muscle training using electrical stimulation, spinal mechanisms may also have a role (23, 33).

Apart from central and spinal neural mechanisms, effects of unilateral training on postural stabilization are thought to influence contralateral effects. Hellebrandt et al. (18) suggested that the contralateral limb contracts during unilateral training to assist in stabilization, and thus the untrained limb is not “unexercised.” However, the design of training interventions in most contemporary studies minimizes activity in the untrained limb. It is also thought that unilateral training places widespread bilateral demands on postural stabilizing muscles and the benefits of this associated training will also be available to the contralateral side (11, 18, 27, 34), but this is possibly less likely for smaller muscle groups such as the elbow flexors.

Of the studies used in our analysis, Yue and Cole (44) controlled for the potential effect of humoral factors on unilateral training. If humoral mechanisms contribute to contralateral strength increases associated with unilateral training, increased strength should not only be seen in the homologous untrained muscle group but generalized to all muscle groups. However, Yue and Cole (44) found no increase in strength of the great toe extensors despite significant strength gains in finger abduction of the untrained hand after unilateral training (44). This discounts humoral factors as a potential mechanism for any contralateral effect of training.

This is the first systematic analysis of all the data on changes in contralateral strength produced by muscle testing. Conclusions from this analysis provide insight into the contralateral effect of training because they are based on a statistically meaningful sample size that would otherwise be difficult to achieve. Pooling of data showed that unilateral training increased contralateral strength by 7.8% of initial strength (95% CI: 4.1–11.6%) in healthy individuals, which is 35% of the effect on the ipsilateral limb. It is concluded that voluntary unilateral training produces modest increases in contralateral strength.

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