Muscle quality. II. Effects of strength training in 65- to 75-yr-old men and women

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Tracy, B. L., F. M. Ivey, D. Hurlbut, G. F. Martel, J. T. Lemmer, E. L. Siegel, E. J. Metter, J. L. Fozard, J. L. Fleg, and B. F. Hurley. Muscle quality. II. Effects of strength training in 65- to 75-yr-old men and women. J. Appl. Physiol. 86(1): 195–201, 1999.—To determine the effects of strength training (ST) on muscle quality (MQ), strength/muscle volume of the trained muscle group, 12 healthy older men (69 ± 3 yr, range 65–75 yr) and 11 healthy older women (68 ± 3 yr, range 65–73 yr) were studied before and after a unilateral leg ST program. After a warm-up set, four sets of heavy-resistance knee extensor ST exercise were performed 3 days/wk for 9 wk on the Keiser K-300 leg extension machine. The men exhibited greater absolute increases in the knee extension one-repetition maximum (1-RM) strength test (75 ± 2 and 94 ± 3 kg before and after training, respectively) and in quadriceps muscle volume measured by magnetic resonance imaging (1,753 ± 44 and 1,955 ± 43 cm3) than the women (42 ± 2 and 55 ± 3 kg for the 1-RM test and 1,125 ± 53 vs. 1,261 ± 65 cm3 for quadriceps muscle volume before and after training, respectively, in women; both P < 0.05). However, percent increases were similar for men and women in the 1-RM test (27 and 29% for men and women, respectively), muscle volume (12% for both), and MQ (14 and 16% for men and women, respectively). Significant increases in MQ were observed in both groups in the trained leg (both P < 0.05) and in the 1-RM test for the untrained leg (both P < 0.05), but no significant differences were observed between groups, suggesting neuromuscular adaptations in both gender groups. Thus, although older men appear to have a greater capacity for absolute strength and muscle mass gains than older women in response to ST, the relative contribution of neuromuscular and hypertrophic factors to the increase in strength appears to be similar between genders.

The decline in muscle strength and muscle mass (MM) with age (sarcopenia) is well documented (16, 21, 22) and is associated with a deterioration of health status and functional abilities (1, 14). Strength training (ST) is thought to be an effective intervention against sarcopenia, because it increases muscle strength and MM in the elderly (6–8, 11, 13, 32). MM and neuromuscular factors contribute to losses in strength with age (16, 21) and gain in strength with ST (10–12), but whether the relative contribution of each is affected by gender in the elderly is unclear. Expressing strength per unit of the trained MM [muscle quality (MQ)], also known as specific tension, provides an estimate of the contribution of muscle hypertrophy and neuromuscular factors to changes in strength (3, 24, 25). This issue may be more important for older than for younger individuals, because losses in MQ may be more related to functional disabilities in the elderly, and older women tend to suffer greater disabilities than older men (17). ST improves MQ similarly in young men and women (5, 15, 27), but whether there are gender differences in MQ responses to ST in older individuals is not well understood (11, 33).

Measurement of the total volume of the entire trained musculature to determine MQ response to ST in older men and women has not been reported previously. This is an important methodological consideration for assessment of MQ, because previous estimates of hypertrophy based on a single cross-sectional image (6–8, 11–13) may not be representative of hypertrophy at other locations along the length of the muscle (9, 26, 29).

Therefore, the purpose of this study was to compare MQ responses to a unilateral quadriceps ST program between older men and older women with use of the entire trained musculature (quadriceps) to quantify the hypertrophic response to training. To accomplish this purpose, strength, quadriceps muscle volume, and MQ (quadriceps strength/quadriceps muscle volume) were determined before and after ST in the trained and untrained quadriceps.

METHODS

Subjects. Twelve older men (65–75 yr) and 11 older women (65–73 yr) volunteered to participate in the ST program. Subjects were screened by a physician, who performed a medical history, physical examination, and maximal graded exercise test. All subjects were nonsmokers, free of significant cardiovascular, metabolic, or musculoskeletal disorders, and not currently taking antihypertensive, cardiovascular, or metabolic medications. Only sedentary individuals who had not exercised regularly during the past 6 mo were allowed to participate. Before participation, the purpose and procedures of the study were explained in detail and the subjects gave their written informed consent. The procedures used in this study were approved by the Human Subjects Institutional Review Boards of the University of Maryland, the Baltimore Veterans Affairs Medical Center, and the Johns Hopkins Bayview Medical Center (Baltimore, MD).

Body composition assessment. Total body nonosseous fat-free mass (FFM) and fat mass were estimated by the use of a
Lunar DPXL dual-energy X-ray absorptiometer, as previously described (32). Subjects were instructed to not eat or drink after midnight before their morning scan. A calibration standard was scanned daily, and measurement accuracy was ensured by scanning a water/oil phantom of known proportions (41% fat) monthly. The coefficient of variation of repeated measurements was <1.0%.

Strength tests. The one-repetition maximum (1-RM) strength test, isometric force production, and isokinetic peak torque were assessed in the knee extensors before and after training. Three low-resistance training sessions were conducted before 1-RM strength testing so that subjects would be familiar with the equipment and proper exercise techniques. In addition, this familiarization procedure helps control for large initial gains in strength due to motor learning and may help prevent injuries. After the three familiarization training sessions and before the regular training sessions began, knee extensor strength of both legs was assessed on the training apparatus (Keiser K-300 knee extension machine) by use of the 1-RM strength test. Subjects were positioned on the knee extension machine with a pelvis strap in place. After a few warm-up repetitions, a resistance was chosen that was thought to be slightly below the 1-RM value, and the subject performed one repetition of the knee extension exercise. After ~60 s of rest, another attempt was made against a higher resistance. Thereafter, the increases in resistance were adjusted so as to minimize the total number of trials required before the true 1-RM value was obtained, i.e., the highest resistance at which one repetition can be successfully completed. Approximately the same number of trials (5–7 for each) was used before and after training. The same investigator measured 1-RM strength before and after training using the same levels of vocal encouragement. All testing procedures were standardized on the basis of specific seat adjustments and body position during testing. To determine the initial resistance for the first regular training session, the heaviest resistance (kg) that could be performed exactly five times (5 RM) was also measured. The procedure for testing was the same as for the 1-RM test. Variations in strength values from test-retest measurements on Keiser K-300 knee extension machines are <5% (13).

To assess training effects on nonspecific strength tests, quadriceps muscle strength was assessed twice before training on separate days ~5 days apart and once after training with use of an isokinetic dynamometer (Kinetic Communicator model 125-E, Chattecx, Chattanooga, TN; Kin-Com). Results revealed a slight nonsignificant reduction during the second baseline testing in knee extension peak torque at 0.52 rad/s (127 ± 40 vs. 119 ± 31 N·m). Test-retest reliability was assessed by repeated measurements of three subjects (r = 0.88). The dynamometer was externally calibrated for force before each test by hanging a known weight on the load cell. In addition, the same investigator used a consistent testing protocol to perform the strength tests before and after training for each subject.

A 3-min warm-up on a bicycle ergometer and light stretching of the quadriceps and hamstrings preceded each Kin-Com strength test. Thigh, pelvis, and chest straps were used to provide stabilization and to minimize involvement of muscle groups other than the quadriceps. The rotation axis of the knee was aligned with the rotation axis of the dynamometer. After a goniometer-measured reference angle was set, joint range of motion was established from 1.75 to 2.88 rad (3.14 rad = full extension). The gravity correction option on the Kin-Com software was used to correct torque values for gravitational effects. The shank was weighed at a joint angle of 2.62 rad rather than 3.14 rad (straight-legged position) to avoid the contribution of hamstring passive tension to the gravity correction value. Threshold forces required for initiation of dynamometer arm movement were kept constant before and after training. In addition, the minimum force setting (force required for smooth dynamometer arm movement) and the acceleration/deceleration settings remained the same before and after training.

Peak torque production (N·m) was measured in both legs at 0.52 and 3.14 rad/s in concentric mode. Three submaximal practice efforts were performed followed by three maximal efforts with loud vocal encouragement, with >30 s of rest allowed between each trial. The same level of vocal encouragement was used for all tests. The highest peak value of the three maximal efforts was recorded as peak torque for each speed. The mean peak torque between the two pretraining testing days was calculated and recorded as the pretraining maximal strength value.

Maximal voluntary isometric force production (N) was assessed at knee angles of 1.75 and 1.92 rad (3.14 rad = straight leg). Two series of isometric efforts were performed with 10 s of rest between trials. One minute of rest was allowed before the second series of contractions. The highest peak force at each angle was taken as the maximal isometric strength value. In all tests the isometric testing was performed immediately after the series of dynamic assessments.

ST program. The ST program consisted of three training sessions per week of unilateral (1-legged) training of the knee extensors of the dominant leg for ~9 wk. Training was performed on a Keiser K-300 knee extension machine, which allows the subject to change the resistance easily without interrupting the cadence of the exercise. The untrained control leg performed no muscular contractions during training. Relaxation of the untrained leg during the training sessions was ensured by having the subject rest his/her leg in front of the pad on the exercise machine and was verified by investigator observation.

Subjects performed a 3-min warm-up on a bicycle ergometer followed by supervised stretching of the knee extensor and flexor muscle groups. The training consisted of five sets of knee extension exercise designed to include a combination of heavy-resistance and high-volume exercise. Before the regular training sessions, subjects underwent three familiarization sessions, during which they completed a typical training session with little or no resistance. The concentric and eccentric phases were performed in ~1 and 2 s, respectively. The first set was considered warm-up and consisted of five repetitions at 50% of the 1-RM strength value. The second set consisted of five repetitions at the current 5-RM value. This value was increased continually throughout the training program to reflect increases in strength levels. The third set consisted of 10 repetitions, with the first four or five repetitions at the current 5-RM value; then the resistance was lowered just enough to complete one or two more repetitions before muscular fatigue. This process was repeated until a total of 10 repetitions were completed. This same procedure was used in the fourth and fifth sets, but the total number of repetitions was increased. The fourth set consisted of five repetitions at the 5-RM resistance followed by 10 more repetitions as described for the 10-repetition set. The fifth set consisted of five repetitions at the 5-RM resistance followed by 15 more repetitions as in the other sets. This procedure allowed subjects to use near-maximal effort on every repetition. The second, third, fourth, and fifth sets were preceded by rest periods lasting ~30, 90, 150, and 180 s, respectively. Every subject was well supervised by a qualified exercise specialist throughout the training program. This helped
achieve a compliance rate (i.e., percent attendance for all training sessions) of >96.2%.

Magnetic resonance imaging. The thighs of each subject were scanned via magnetic resonance imaging (MRI) before and after training. A Picker Edge 1.5-T MRI scanner was used to obtain a series of axial slices from the superior border of the patella to the anterior superior iliac spine encompassing the entire quadriceps femoris muscle group. The images were produced using 9-mm-thick (1-mm gap), T1-weighted axial scans with an echo time of 14 ms and a relaxation time of 700 ms. Subjects were instructed not to drink or eat after midnight before the scans, which were performed between 8 and 10 AM. The scan files were stored on magnetic disk for subsequent analysis on a personal computer. The MRI scanner calibration was checked daily and adjusted if needed. The scan files were imported into NIH Image version 1.61 for analysis.

For each axial slice the cross-sectional area (CSA, cm²) of the quadriceps muscle group was manually outlined as a region of interest. The quadriceps CSA was outlined in every axial image from the superior border of the patella proximal to a point where the quadriceps muscle group is no longer reliably distinguishable from the adductor and hip flexor groups. The same number of slices proximal from the patella was measured for a particular subject before and after training to ensure within-subject measurement replication. The sartorius muscle was not included in the CSA, because it does not contribute to knee extension. The same investigator, blinded to subject identification and time point, performed the pre- and posttraining analyses. Repeat measurement by the same investigator of 300 different cross sections from different areas of the muscle yielded an average coefficient of variation of 0.78%. Reliability of total quadriceps volume measurement, assessed by repeat measurement of the same set of axial scans on different days by the same investigator, yielded a 3.5% difference between measurements. In addition, validity of volume determination was assessed by scanning and analysis of a lean beef phantom with dimensions approximating the knee extensor group. The volume of the beef phantom as measured via water displacement measurement. Repeat MRI volume measurement of the beef specimen yielded a 0.12% difference between measurements.

Muscle volume and MQ calculation. The CSA of each axial slice was multiplied by the distance between slices (1 cm) and summed across slices. This value represents quadriceps muscle volume (cm³). Isometric and 1-RM strength values (N and kg, respectively) were divided by muscle volume values before and after training to determine strength per unit muscle volume (MQ). MQ was not reported when using isokinetic peak torque values because of the lack of testing specificity, but isokinetic peak torque was used for strength assessment to determine the extent to which strength gains carried over to movements not specific to training.

Statistical analysis. A repeated-measures multivariate ANOVA model was employed to assess training-related effects, gender-based interactions, and between-leg interactions using SPSS version 7.5. The between-subject factor was gender group (male and female) and the within-subject factors were leg (trained and untrained) and time (before training and after training). The dependent variables included isokinetic, isometric, and 1-RM strength values, muscle volume, and MQ. Specific comparisons or interactions were assessed using preplanned, syntax-based contrasts. When the multivariate significance level was reached, the individual univariate test results were used for each dependent variable. In assessing reliability or validity of measurement techniques, the coefficient of variation or paired t-test was employed, where appropriate. Values are means ± SE. Statistical significance was set at P < 0.05.

RESULTS
Subject characteristics. At baseline the men were significantly taller and heavier with lower percent fat and greater nonosseous FFM than the women (all P < 0.05). There was no significant difference in ages between the two groups. The older men, but not the women, displayed a small, but significant increase in body mass after training (P < 0.05). There were no significant changes in percent fat or FFM in either gender group during the 9-wk training period (Table 1).

1-RM strength. The ST program resulted in significant increases in 1-RM strength in the trained legs of both groups (P < 0.01; Table 2). Although the absolute increase in 1-RM strength of the trained leg was significantly larger for men than for women (P < 0.05), the gender group difference was not significant. Treatment was effective at increasing 1-RM strength in both men and women.

Table 1. Physical characteristics before and after training

<table>
<thead>
<tr>
<th></th>
<th>Men (n = 12) Before training</th>
<th>Men (n = 12) After training</th>
<th>Women (n = 11) Before training</th>
<th>Women (n = 11) After training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>69 ± 1</td>
<td>68 ± 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height, cm</td>
<td>174.2 ± 1.2</td>
<td>160.5 ± 2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>81.7 ± 2.3</td>
<td>82.5 ± 2.3 *</td>
<td>69.5 ± 2.5</td>
<td>69.3 ± 2.5</td>
</tr>
<tr>
<td>%Fat</td>
<td>28.3 ± 1.4</td>
<td>28.3 ± 1.3</td>
<td>38.8 ± 1.8</td>
<td>38.1 ± 1.9</td>
</tr>
<tr>
<td>FFM, kg</td>
<td>53.75 ± 1.0</td>
<td>54.18 ± 1.0</td>
<td>39.1 ± 1.0</td>
<td>39.6 ± 1.1</td>
</tr>
</tbody>
</table>

Values are means ± SE. FFM, fat-free mass. *Significantly different from before training (P < 0.05).

Table 2. 1-RM, isometric, and isokinetic strength values before and after training in trained and untrained leg

<table>
<thead>
<tr>
<th></th>
<th>Men (n = 12) Before training</th>
<th>Men (n = 12) After training</th>
<th>Women (n = 11) Before training</th>
<th>Women (n = 11) After training</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 RM, kg</td>
<td>75 ± 2</td>
<td>94 ± 3 *‡</td>
<td>42 ± 2</td>
<td>55 ± 3 *‡</td>
</tr>
<tr>
<td>Isometric force, N</td>
<td>473 ± 24</td>
<td>527 ± 25 *</td>
<td>301 ± 19</td>
<td>321 ± 20</td>
</tr>
<tr>
<td>Isokinetic peak torque, N·m</td>
<td>0.52 rad/s</td>
<td>153 ± 4</td>
<td>90 ± 4</td>
<td>97 ± 6</td>
</tr>
<tr>
<td></td>
<td>1.14 rad/s</td>
<td>103 ± 3</td>
<td>58 ± 4</td>
<td>64 ± 4</td>
</tr>
<tr>
<td>Untrained leg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 RM, kg</td>
<td>76 ± 3</td>
<td>83 ± 3 *‡</td>
<td>42 ± 3</td>
<td>46 ± 3 *‡</td>
</tr>
<tr>
<td>Isometric force, N</td>
<td>498 ± 26</td>
<td>514 ± 31</td>
<td>313 ± 22</td>
<td>338 ± 22</td>
</tr>
<tr>
<td>Isokinetic peak torque, N·m</td>
<td>0.52 rad/s</td>
<td>150 ± 7</td>
<td>86 ± 5</td>
<td>92 ± 6</td>
</tr>
<tr>
<td></td>
<td>3.14 rad/s</td>
<td>105 ± 4</td>
<td>59 ± 3</td>
<td>58 ± 3</td>
</tr>
</tbody>
</table>

Values are means ± SE. 1 RM, 1 repetition maximum. Isometric force was measured at an angle of 1.75 rad of knee extension. *Significantly different from before training (P < 0.05). †Significant gender-by-time interaction within trained leg (P < 0.05). ‡Significant leg-by-time interaction within gender group (P < 0.06).
the percent or relative change in strength was similar for men and women (27 ± 6 and 29 ± 6%, respectively).

The untrained legs also demonstrated significant, but smaller, increases in 1-RM strength after the training program for men and women (P < 0.01 and P < 0.05, respectively; Table 2). The relative magnitude of response in the untrained leg was again similar for men and women (10 ± 3 and 12 ± 4%, respectively). The increases in 1-RM strength were significantly greater in the trained than in the untrained leg for men and women (P < 0.01).

Isometric strength. The trained knee extensors of older men exhibited a 13 ± 6% increase (P < 0.01) in isometric peak force at 1.75 rad (100°) of knee flexion, whereas the women demonstrated a 7 ± 3% increase that did not reach statistical significance (Table 2). Nevertheless, the absolute changes in isometric peak force in the trained leg of the men were not significantly different from those of the women.

There were no significant changes in isometric peak force in the untrained knee extensors after training in men or women (Table 2). However, the trend toward higher values in both groups prevented the trained leg from exhibiting significantly greater increases than the untrained leg, although it approached significance in the men (P = 0.06).

Isokinetic strength. There was a significant increase in knee extensor peak torque at 0.52 rad/s in the trained legs of men (P < 0.05) but not in women (P = 0.09). This increase in the trained leg was not significantly different from that of the untrained leg for men or women (Table 2). The changes in the untrained leg, however, did not reach significance in either gender group. At the faster velocity (3.14 rad/s) there was no significant effect of training in either leg of men or women. No significant interactions were found between legs or genders.

Muscle volume. The training program resulted in a 12% increase (P < 0.01) in quadriceps muscle volume in the trained legs of both genders (Table 3, Fig. 1). Despite having the same percent increases as the women, the men demonstrated significantly greater absolute increases (P < 0.05) in muscle volume than the women. The largest gains in muscle hypertrophy throughout the length of the quadriceps appear to be in the midthigh region for men and women (Fig. 1). There was a small (2 ± 1%) but statistically significant increase (P < 0.05) in muscle volume in the untrained quadriceps muscles of men (Table 3), which was within the error of the measurement technique. The women exhibited no significant change in muscle volume in the untrained limb. The training program increased the volume of the trained leg to a greater extent than the untrained leg in both genders.

MQ. When MQ was expressed as 1-RM per unit of muscle volume (kg/cm³), there were significant increases (P < 0.01) in the trained leg of men and women
(14 ± 4 and 16 ± 4%, respectively) after training (Table 3), but there was no significant difference between genders. The untrained knee extensors of men and women also exhibited a significant improvement in MQ when 1-RM values were used (Table 3). As in the trained limb, there were no significant differences in the increases in 1-RM MQ of the untrained leg between men and women (8 ± 3 and 10 ± 3%, respectively). Training increased the 1-RM MQ of the trained leg significantly more than the untrained leg in men (P < 0.05), whereas in women this difference between legs did not quite reach statistical significance (P = 0.06; Table 3).

In contrast, when MQ values were expressed as peak isometric force per unit muscle volume (N/cm³), no significant training-induced changes were found in the trained or untrained leg of either gender group (Table 3). However, the significant leg-by-time interaction in women shown in Table 3 shows a different response to training, but the difference is not likely to be meaningful since neither leg changed significantly.

**DISCUSSION**

To our knowledge, this is the first study to report increases in MQ as assessed by the total volume of the trained musculature after short-term ST in older men and women. The training program resulted in greater absolute increases in 1-RM strength and muscle volume in men than in women. However, men and women increased MQ similarly when the 1-RM test was used to assess strength, suggesting that, in addition to muscle hypertrophy, the observed strength increases involve neuromuscular adaptations (3, 10, 12, 24, 25).

Several previous investigations have reported greater relative increases in strength than in muscle size after ST in older subjects (2, 6–8, 11, 12, 29, 32, 33). Only a few of these studies, however, have reported MQ (or specific tension) values before and after training. Welle et al. (33) studied the effect of ST on MQ (3-RM strength/muscle CSA) in young and older subjects. Their older subjects exhibited a 32% increase in MQ of the knee extensors, which was not significantly different from the increase in their young subjects. Although they included men and women, a gender comparison was not performed. Thus our results extend their findings by directly comparing the magnitude of MQ increase between older men and women and observing no gender differences in response to ST.

Our gender and MQ findings would appear to be in agreement with those of Häkkinen and Häkkinen (11), who also found similar MQ improvements in older men and women in response to ST. However, they assessed muscle strength with an isometric test, whereas our results indicate no significant improvement in MQ in either gender when isometric strength is assessed. Thus our findings differ from those of Häkkinen and Häkkinen and, on the basis of the notion that increases in MQ represent neuromuscular effects (3, 24, 25), extend their findings by suggesting that neuromuscular adaptations may play a greater role in explaining strength gains when training-specific strength tests are used. This is likely to be most important during early stages of training, when neural adaptations result in rapid strength improvements (25). We tried to minimize this effect by having subjects perform several low-resistance practice (familiarization) training sessions before strength testing.

Previous investigations using only young subjects suggest that men and women display equivalent increases in MQ in response to ST (3, 5). A cross-sectional comparison in young subjects by Castro et al. (3) suggested that the higher MQ values observed in strength-trained than in untrained subjects are not different between genders. Likewise, Cureton et al. (5) measured similar increases in MQ for young men and women after 16 wk of ST, which suggests that the relative contributions of hypertrophy and neural factors are similar between genders at a young age. We originally hypothesized that older men might improve their MQ to a greater extent than older women as a result of ST because of the greater age-related decline in MQ reported for men than for women (34, 35). However, our group recently observed no gender differences in age-associated losses in MQ (22). This led us to hypothesize that men and women should respond similarly to ST. Thus our finding of similar responses to ST between genders did not support our original hypothesis but did support our revised hypothesis based on our most recent finding and those from studies using young men and women (3, 5). This finding suggests no gender difference in the magnitude of neuromuscular adaptation to ST (3, 24, 25). In support of this implication, Häkkinen and Häkkinen (11) reported no gender differences in older subjects for the increase in maximum integrated electromyogram in response to ST. The specific neuromuscular mechanisms responsible for ST-induced increases in MQ are unknown; however, increases in motor unit recruitment or discharge rate, increased activation of synergistic muscles, and decreased activation of antagonist muscles (12) are possible explanations (25, 30). Alterations in muscle architecture could also affect changes in MQ with ST (18, 19). Kawakami et al. (18) reported greater pennation angles in subjects with hypertrophied muscles than in those with normal muscles. Increases in muscle fascicle angles have also been reported as a result of ST (19). However, this effect was thought to decrease MQ by reducing the muscle's capacity for producing force.

Direct measurement of the entire volume of the trained musculature, although labor intensive, provides a better representation of muscle hypertrophy of the trained musculature than the more commonly employed single-slice CSA. Muscle area determined from the single-slice method may not be representative of changes that occur at other points along the length of the muscle (9, 26, 29). Indeed, the results of the present investigation shown in Fig. 1 indicate that ST-induced muscle hypertrophy is greatest in the region of largest CSA (midthigh), and the increases in CSA become progressively smaller toward the proximal and distal regions of the quadriceps in men (Fig. 1A) and women (Fig. 1B). Therefore, the single-slice method may over-
estimate MQ changes from regions of the trained muscle group outside the midhigh region and may be prone to error (29). Nonetheless, studies using the single-slice method have reported changes in quadriceps CSA of 3–15% in response to ST of varying duration (6–8, 20, 23, 29, 33). The studies reporting relative increases in CSA of similar magnitude to those in the present study employed training of longer duration than the present study or used very elderly, frail subjects with extremely low baseline muscle size and strength levels who would be expected to display larger percent increases in muscle CSA (6, 8). Roman et al. (29) and Keen et al. (20) also measured total muscle volume before and after training but used younger subjects and reported a 14 and a 7% increase, respectively. However, they also employed longer training periods and assessed much smaller muscle groups, which tend to inflate percent increases due to smaller initial values. Therefore, the 12% increase in muscle volume observed in our nonfrail subjects is relatively large, given the short duration of training and the large muscle group assessed. This magnitude of hypertrophy may be partially due to the heavy-resistance, high-volume nature of our short-term ST program.

Although Häkkinen and co-workers (11, 12) also reported percent increases in muscle CSA between men and women in response to ST, they did not report a comparison of absolute changes, as in the present study. Nevertheless, their mean absolute increase in CSA was slightly greater for men than for women (5.5 vs. 3.4 cm²) in their first study (11) but greater for women in their second study (1.9 and 0.9 cm² for women and men, respectively) (12). In contrast to our finding of a gender difference in the increase in muscle volume, Cureton et al. (5) observed no differences between men and women for absolute or relative increases in elbow flexor CSA in response to ST. Their study, however, employed young subjects and a much longer training program than was used in the present study. O’Hagan et al. (28) also observed no differences between young men and women for the relative or absolute hypertrophic response to heavy-resistance ST. In addition, Staron et al. (31) found no significant hypertrophy of muscle fibers in young men or women after 8 wk of quadriceps ST, but there was no measurement of whole muscle hypertrophy. Finally, McCartney et al. (23) found no gender differences in muscle hypertrophy after the first 10 mo of moderate ST in older men and women, but additional training resulted in a trend toward a greater absolute change in CSA for men than for women (P = 0.068). However, none of these previous studies assessed the volume of the entire trained musculature.

The increases in 1-RM strength of the trained knee extensors in this study are lower than those reported by some investigators who used older subjects. For example, Frontera et al. (8) observed much larger increases (107%) in 1-RM values for the knee extensors after 12 wk of bilateral ST in older subjects. Increases in leg strength of 174% were documented by Fiatarone et al. (6) after only 8 wk of training. However, the large relative increase in strength may be explained by the low baseline strength values of their very elderly subjects (6). In another study, women similar in age to our subjects displayed a 93% increase in 1-RM strength after 12 wk of ST (4). The absence of familiarization sessions to control for motor learning effects (4, 6, 22) may also explain at least some of the difference in relative increases in our study. In the present study we attempted to control for the large initial gains in strength due to becoming accustomed to the movement (motor learning) by having subjects undergo three training sessions with little or no resistance before baseline 1-RM testing. Although this tends to reduce the magnitude of relative changes in 1-RM values, we believe it is a better indicator of the actual effects of ST on the strength of the muscle group involved in training. Furthermore, it may explain the smaller 1-RM increases in the present study than in some of the other studies. The shorter length of our training program than some other studies (4, 8) may also contribute to this difference.

Our finding of significant changes in 1-RM strength in the untrained leg (cross education) indicates an adaptation at some level of the nervous system that allows an untrained muscle to produce more force. However, an effect from circulating paracrine factors cannot be excluded. Therefore, the specific adaptations responsible for the strength increase in the contralateral leg are not known. There was no difference in the cross-education effect between men and women, as evidenced by equivalent changes between genders in 1-RM strength and 1-RM MQ of the contralateral untrained knee extensors. To our knowledge, this is the first report of a direct gender comparison of strength changes in an untrained contralateral muscle group. Thus older men and women appear to possess equivalent potential for the transfer of ST-induced neural adaptations to an untrained limb.

In summary, older men exhibit greater absolute increases in muscle volume and 1-RM strength gains than similarly aged women in response to 9 wk of ST. There is no gender difference, however, in the MQ response to ST. Older men and women exhibit MQ increases in trained and untrained contralateral limbs, suggesting equivalent contribution of neural adaptations between genders.

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