Effects of Strength Training and Detraining on Muscle Quality: Age and Gender Comparisons

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Maximal force production per unit of muscle mass (muscle quality, or MQ) has been used to describe the relative contribution of non-muscle-mass components to the changes in strength with age and strength training (ST). To compare the influence of age and gender on MQ response to ST and detraining, 11 young men (20–30 years), nine young women (20–30 years), 11 older men (65–75 years), and 11 older women (65–75 years), were assessed for quadriceps MQ at baseline, after 9 weeks of ST, and after 31 weeks of detraining. MQ was calculated by dividing quadriceps one repetition maximum (1RM) strength by quadriceps muscle volume determined by magnetic resonance imaging. All groups demonstrated significant increases in 1RM strength and muscle volume after training (all \( p < .05 \)). All groups also increased their MQ with training (all \( p < .01 \)), but the gain in MQ was significantly greater in young women than in the other three groups (\( p < .05 \)). After 31 weeks of detraining, MQ values remained significantly elevated above baseline levels in all groups (\( p < .05 \)), except the older women. These results indicate that factors other than muscle mass contribute to strength gains with ST in young and older men and women, but those other factors may account for a higher portion of the strength gains in young women. These factors continue to maintain strength levels above baseline for up to 31 weeks after cessation of training in young men and women, and in older men.

Losses in muscular strength with age are thought to be secondary to declines in muscle mass (1,2), neuromuscular function (1,2), and mechanical and contractile properties of muscle (3). In addition, changes in architectural components such as increases in connective tissue (4) and decreases in muscle fiber pennation angles are associated with aging, and therefore likely contribute to strength loss with age. Many of these non-muscle-mass components of strength loss are reversed with strength training (ST) (5–7). Thus, although muscle mass is an important determinant of strength loss with age and strength gain with ST, it is clearly not the only factor involved. Alterations in the neuromuscular, mechanical, contractile, and architectural components can affect the quality of skeletal muscle. The importance of studying muscle quality (MQ) with age was emphasized by a panel of experts at the 1996 National Institute on Aging workshop “Sarcopenia and Physical Performance in Old Age,” during which it was concluded that there is a need for “more comprehensive evaluations of muscle quality using noninvasive methods” (8). In this regard, we recently reported age-related losses in MQ (9), and gains in MQ with ST (10) in older men and women. However, we are aware of only one investigation that has attempted to study the effects of age on the MQ response to ST (11). Furthermore, no previous study has reported age and gender comparisons of the MQ response to the same ST and detraining program. Although the effects of ST on MQ have previously been studied (11–14), the measurement of the total volume of the entire trained musculature to determine MQ responses had not been utilized prior to our recent report (10). This is an important methodological consideration for the assessment of MQ because previous estimates of hypertrophy based on a single cross-sectional image (12,15–18) may not be representative of hypertrophy at other locations along the length of the muscle (14,19,20).

Regardless of methodology, we are unaware of any reports that have assessed MQ changes following the cessation of a training stimulus (detraining). Exploring the question of whether age or gender affect the rate at which MQ adaptations are lost after detraining addresses the important issue of how a decline in muscular activity contributes to the age-related loss of MQ.

Hence, the purpose of this study was to make direct age and gender comparisons of the MQ response to ST and detraining, using identical protocols for all groups. This information will help to clarify the extent to which factors other than muscle mass influence strength gains and losses in young and older men and women.

Methods

Subjects

Eleven young men (20–30 years), nine young women (20–30 years), 11 older men (65–75 years), and 11 older women (65–75 years) volunteered to participate in a 9-week unilateral ST program followed by a 31-week detraining
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 were not currently taking antihypertensive, cardiovascular, or medicinal medications. Only sedentary persons who had not exercised regularly during the past 6 months prior to the study were allowed to participate. Prior to 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, College Park, the Baltimore Veterans Affairs Medical Center, and the Johns Hopkins Bayview Medical Center in Baltimore.

Body Composition Assessment
Total body nonosseus fat-free mass (FFM) and fat mass were estimated with a Lunar DPX-L dual energy x-ray absorptiometer (Lunar Corporation, Madison, WI) as described previously (22). Subjects were instructed not to eat or drink anything 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 properties (41% fat) monthly. The coefficient of variation of repeated measurements was less than 1.0%.

Strength Tests
The one repetition maximum (1RM) strength test was assessed in the knee extensors before and after training and detraining. Three low-resistance training sessions were conducted prior to the 1RM strength testing, so that subjects would be familiar with the equipment and proper exercise techniques. In addition, this familiarization procedure helps to control for the large initial gains in strength that are due to motor learning and may help to prevent injuries. After three familiarization training sessions and before the regular training sessions began, the knee extensor strength of both legs was assessed on the training apparatus (Keiser K-300 Knee Extension, Keiser Sport/Health Equipment, Fresno, CA) using the 1RM strength test. Subjects were positioned on the knee extensor 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 1RM value, and the subject performed one repetition of the knee extension exercise. After ~60 seconds 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 1RM value was obtained, i.e., the highest resistance at which one repetition can be successfully completed. Approximately the same number of trials were used before and after training. The same investigator measured 1RM strength before and after training, using the same levels of vocal encouragement. All testing procedures were standardized based on specific seat adjustments and body position during testing. As a way to determine the initial resistance for the first regular training session, the heaviest resistance (in kilograms) that could be performed exactly five times (5RM) was also measured. The procedure for testing this was the same as for the 1RM test.

Magnetic Resonance Imaging
The thighs of both legs were scanned by means of magnetic resonance imaging (MRI) before and after training and 31 weeks of detraining. A Picker Edge 1.5-T MRI scanner (Picker International, Cleveland, OH) was used to obtain a series of axial slices extending from the superior border of the patella to the anterior superior iliac spine encompassing the entire quadriceps femoris muscle group. The images were produced by using 9-mm-thick (1 mm gap), T1 weighted axial scans, with an echo time of 14 milliseconds and a relaxation time of 700 milliseconds. Subjects were instructed not to eat or drink anything after midnight on the night before the scans, which were consistently 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 (National Institutes of Health, Bethesda, MD) for analysis. For each axial slice, the cross-sectional area (CSA) in square centimeters (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 to a point where the quadriceps muscle group was no longer reliably distinguishable from the adductor and hip flexor groups. The same number of slices proximal from the patella were 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 both subject identification and time point, performed 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 (CV) of 0.78%. The intrarater variability of total quadriceps volume assessed by repeat determination of the same set of axial scans on different days by the same investigator was 3.5%.

Muscle Volume 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, expressed in cubic centimeters (cm³).

Muscle Quality Calculation
The 1RM value in kilograms of the dominant leg was divided by the muscle volume of the dominant leg to arrive at a value for muscle quality. Muscle quality in this case is therefore representative of strength per unit of muscle volume (kg/cm³).

ST Program
The training program consisted of unilateral (one-legged) training of the knee extensors of the dominant leg, three times per week, for approximately 9 weeks. Training was performed on a Keiser K-300 air-powered knee extension machine that allows the subject to change the resistance easily without interrupting the cadence of the exercise. The un-
trained control leg was kept in a relaxed position throughout the training program.

Prior to the regular training sessions, subjects underwent three familiarization sessions during which they completed a typical training sequence with little or no resistance. Subjects performed a 3-minute 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. The first set was considered warm-up and consisted of five repetitions at 50% of the 1RM strength value. The second set consisted of five repetitions at the current 5RM value. The 5RM 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 5RM value, in which the resistance was lowered just enough to complete one or two more repetitions before reaching 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 5RM resistance, followed by 10 more repetitions for a total of 15 repetitions carried out in the same manner as described above for the 10 repetition set. The fifth set consisted of four or five repetitions at the 5RM resistance, followed by 15 more repetitions for a total of 20 repetitions performed in the same manner as the other sets. This procedure allowed subjects to use near maximal effort on every repetition while maintaining a relatively high training volume. The second, third, fourth, and fifth sets were preceded by rest periods lasting a minimum of 30, 90, 150, and 180 seconds, respectively. The concentric phase of the exercise took approximately 1 second, and the eccentric phase took ~2 seconds.

Detraining

Following completion of the unilateral ST program, subjects were instructed to resume their normal lifestyle, but to avoid any form of regular exercise for a 31-week time period. During this period subjects were contacted periodically to ensure that they did not participate in any form of regular exercise or make any other lifestyle changes during the 31 weeks of detraining. MRI scans were also taken at the end of the detraining period. These results were compared with those obtained before and after the unilateral training program.

Statistical Treatment

A repeated measures analysis of variance (ANOVA) was performed with two between-subjects factors (age and gender) and one within-subjects factor (time; Figure 1). Follow-up Tukey’s post hoc tests were utilized where warranted to assess within-group differences across time points, as well as between-group differences at each of the three time points. In addition, comparisons of the training gain and the detraining loss in muscle quality were made between groups, using a separate two-way ANOVA for each dependent variable (Figure 2). The level of significance was set at 0.05.

Figure 1. Age and gender comparisons of MQ levels before and after training and after detraining. There were no significant differences in MQ between age groups before training (p = NS). There was, however, a significantly greater MQ in young men than in older women before training (*) (p < .05). After training, all groups increased MQ significantly above baseline (†) (p < .05). The young women had significantly greater MQ than the older men and women (p < .05). MQ remained significantly elevated above baseline in 3 out of the 4 groups following 31 weeks of detraining. Values are mean ± SE. The sample sizes for each group were as follows: young men, n = 11; young women, n = 9; older men, n = 11; and older women, n = 11.
RESULTS

Subject Characteristics

At baseline the men in both age groups were significantly taller and heavier with a lower percentage of fat and a greater FFM than the women (p < .05; Table 1). The men in both age groups displayed a small but significant increase in body mass after training (p < .05). There were no significant changes in percentage of fat, or FFM in any of the groups as a result of the 9-week ST program (Table 1).

1RM Strength

The ST program resulted in significant increases in 1RM strength in all groups (p < .01; Table 2). The strength values remained significantly above baseline levels in all groups following the detraining period with the exception of older women.

Muscle Volume

Quadriiceps muscle volume increased significantly in the trained limb of all four groups following training (all p < .01; Table 2). Muscle volume returned to baseline levels in all groups, except the young men, who retained a significant amount of the muscle mass adaptation after 31 weeks of detraining (p < .05; Table 2).

Muscle Quality

Results from the three-way repeated measures ANOVA indicated a significant main effect for time (p < .001), i.e., an overall significant increase in MQ after training, but with no significant decline after detraining (Figure 1). There was a significant age × Time interaction (p < .01), indicating that young subjects had a greater MQ response to training than older subjects, which was qualified by a significant Gender × Age × Time interaction (p = .028). The three-

Table 1. Physical Characteristics Before and After Training*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Young Men (n = 11)</th>
<th>Young Women (n = 9)</th>
<th>Older Men (n = 11)</th>
<th>Older Women (n = 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>25 ± 3</td>
<td>26 ± 2</td>
<td>69 ± 3</td>
<td>68 ± 3</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.1 ± 9.4</td>
<td>167.6 ± 5.7</td>
<td>173.7 ± 4.7</td>
<td>161.4 ± 6.8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>82.3 ± 18.7</td>
<td>63.1 ± 12.5</td>
<td>80.3 ± 8.5</td>
<td>67.8 ± 8.9</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>22.9 ± 8.3</td>
<td>30.8 ± 6.6</td>
<td>29.1 ± 4.8</td>
<td>38.6 ± 6.2</td>
</tr>
<tr>
<td>FFM (kg)</td>
<td>62.3 ± 9.4</td>
<td>43.1 ± 5.9</td>
<td>56.9 ± 3.5</td>
<td>41.2 ± 3.7</td>
</tr>
</tbody>
</table>

*Values are mean ± SD.
†Significantly different than before training; p < .05.

Figure 2. Comparison of the MQ gain during training and the MQ loss during detraining in young and older men and women. Young women experienced a significantly greater MQ gain during training than any of the other groups (p < .05). Values are mean ± SE. Sample sizes were as follows: young men, n = 11; young women, n = 9; older men, n = 11; and older women, n = 11. The differences in detraining losses among the groups were not significantly different.
way interaction was apparently a function of the age effect having been caused entirely by a disproportionate rise in MQ among the young women. Conversely, young men did not differ from older men or women in their MQ response to training or detraining.

A follow-up post hoc analysis (Tukey) showed that at baseline, there was not a significant difference between age groups in either gender with respect to MQ. Baseline levels of MQ did, however, differ between the young men and the older women, with younger men having greater MQ values than the older women \( (p < .05; \text{Figure 1}) \). Figure 1 also shows MQ values at the detraining time point for the four groups. After 31 weeks of detraining, MQ values remained significantly elevated above baseline levels in all groups except the older women.

Additional analyses were performed using separate two-way ANOVAs for MQ gained in training and MQ lost during detraining (Figure 2). When the gain with training was used as the dependent variable, the significant age effect \( (p < .01; \text{young} > \text{older}) \) and the significant gender effect \( (p < .05; \text{women} > \text{men}) \) were both qualified by a significant Age \( \times \) Gender interaction, indicating that both effects were due to the large increase in young women. Young women increased their MQ with ST to a significantly greater degree than any of the other three groups \( (p < .05) \) (Figure 2). When the detraining loss in MQ was used as the dependent variable, there were no significant main effects present, suggesting that neither age nor gender affected the detraining loss of MQ. Even when percentage of change values was used, there were no significant differences among the groups for losses in MQ with detraining.

**Discussion**

To our knowledge, this is the first study to compare the effects of age and gender on MQ responses to ST and detraining, and the first to demonstrate that young women experience a significantly greater MQ response to ST than young men, older men, and older women. These results suggest that non-muscle-mass adaptations to ST occur to a greater extent in young women than the other age and gender groups. However, it is clear that factors unrelated to muscle mass account for a significant portion of the strength gains with training regardless of age or gender. Our observation that MQ values remained significantly elevated above baseline levels for at least 31 weeks after detraining in three out of the four groups illustrates that these non-muscle-mass adaptations are retained long after cessation of the ST stimulus. These adaptations are instrumental in preserving strength, despite declining muscle mass during the same time period.

Several previous investigations have reported greater relative increases in strength than in muscle size after ST in older subjects \( (11,15–17,20–22) \). Only a few of these studies, including a recent report from our laboratory \( (10) \), have reported MQ values before and after training. Welle and colleagues \( (11) \) studied the effects of age on the specific tension (MQ) response to ST. However, their use of 3RM strength divided by single-slice CSA to calculate MQ makes their findings difficult to compare with the results of the present study, which calculated MQ on the basis of 1RM strength divided by whole muscle volume. Nevertheless, Welle and colleagues \( (11) \) concluded that aging does not impair training-induced increases in MQ, which is in partial agreement with the results from the present study. However, no gender comparisons of the muscle quality response to ST were made in their study \( (11) \).

Our finding that young women had greater increases in MQ than young men conflicts with previous investigations that have suggested equivalent increases in MQ between young men and women in response to ST \( (23,24) \). Castro and colleagues \( (23) \) reported higher MQ values in strength-trained subjects compared with untrained subjects, but no difference between genders. Likewise, Cureton and colleagues \( (24) \) reported similar increases in MQ for young men and women after 16 weeks of ST. Methodological differences related to the measurement of MQ, study design, and the differences in the relative resistance and training volume of the ST stimulus may, at least in part, explain the discrepancy between these studies and the present investigation.

We are not aware of any previous literature with which to compare our data on the MQ response to detraining. Our finding of an elevated level of MQ 31 weeks after cessation of the ST program was an unexpected finding and was reflective of greater preservation in strength levels compared to muscle mass. These data imply that even prolonged inter-
ruptures in regularly performed ST exercise may not result in complete loss of ST-induced improvements in muscle function. Furthermore, these losses do not appear to be affected by age or gender, whether expressed in absolute or relative terms.

Although mechanical and architectural factors cannot be completely ruled out, it is more plausible that neuromuscular factors may account for the MQ increases with ST in all groups (25–28). Young and colleagues (25) acknowledged that the mechanism for training-induced increases in MQ is unknown, but that increases in motor unit recruitment are likely to be involved. Hakkinen and colleagues (26) made similar conclusions with reference to the strength gains that are independent of hypertrophy during the first few weeks of ST. However, they also observed significant decreases in the coactivation of the antagonist muscle groups following training in the elderly, which could also explain increases in MQ. Moreover, a ST-induced transformation of type II muscle fiber subtypes (from type IIb to IIa) has been reported in young and older men (27). To what extent, if any, this latter adaptation explains MQ increases is unclear, but there appears to be substantial support for the involvement of some type of neuromuscular adaptation that enhances contractile properties in the explanation of increased MQ with ST (25–28). Nevertheless, we were unable to find any potential mechanisms that would explain why women, particularly young women, might increase their MQ to a greater extent than men in response to ST.

In summary, ST increases MQ regardless of age or gender, indicating that strength gains were beyond that which can be explained by muscle mass gains. Young women experienced a larger gain in MQ with ST than did the other three age and gender groups. Finally, all groups, except older women, retained ST-induced increases in MQ for at least 31 weeks after the cessation of training.

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