Muscle Strength and Fiber Adaptations to a Year-long Resistance Training Program in Elderly Men and Women

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Background. To study the effects of resistance training on muscle strength and size in older people, we enrolled 8 men and 17 women (mean age 68.2 ± 1 SEM) into a one-year exercise trial.

Methods. Subjects were randomly assigned to exercise or control groups. Muscle biopsies were obtained from 11 subjects (8 exercisers, 3 controls) at baseline and after 15 weeks; exercisers underwent another biopsy at 30 weeks. After testing maximum strength using the 1-RM method, the exercisers began a 12-exercise circuit (3 sets of 8 repetitions at 75% of 1-RM), 3 times a week. The controls repeated the strength testing every 15 weeks. They were told to continue usual activities and not to start any exercise program.

Results. With exercise, muscle strength increased, average increases ranging from 30% (hip extensors) to 97% (hip flexors). Strength increased rapidly over 3 months, then plateaued for the duration of the experiment. No strength changes were observed in sedentary controls. Cross-sectional area of type I muscle fibers increased in exercisers by 15 weeks (29.4 ± 1%, p < .02) and after 30 weeks (58.3 ± 13.7%, p < .002) compared to baseline. Type II fiber area did not change at 15 weeks, but increased by 30 weeks of training (66.6 ± 9.5%, p < .0002).

Conclusions. These results suggest that prolonged moderate to high intensity resistance training may be carried out by healthy older adults with reasonable compliance, and that such training leads to sustained increases in muscle strength. These improvements are rapidly achieved and accompanied by hypertrophy of both type I and type II muscle fibers.

Many studies have shown that short-term resistance exercise training leads to changes in muscle strength and structure in young men and women (1–10), and in older men (11–14) and in older women (15). Strength gains achieved in these studies have been variously attributed to improvement in neuromuscular recruitment efficiency (16–20) as well as to muscle fiber hypertrophy (21,22).

Considerably less is known about the long-term adaptive responses to resistance exercise, particularly for older men and women. Two studies have examined the response of elderly women to 25 and 50 weeks of light resistance or combined aerobic and light resistance activity (23,24). For moderate to intense resistance activity in older women, no controlled study has exceeded 12 weeks (15). Although it is tempting to conclude that strength training could provide a variety of health benefits to older people, it is important to understand whether such training can lead to persistent improvement, with reasonable long-term compliance, before the wisdom of recommending such a program can be determined. To assess these issues, we therefore carried out a one-year trial of progressive resistance exercise in a group of elderly men and women.

Methods

Subjects. — Eight men and 17 women > 60 years of age (range 61–78 yr, mean 68.2 ± 1 SEM) were recruited by advertisements from the Palo Alto community. Volunteers were admitted to the Aging Study Unit, a clinical investigation ward, for a comprehensive screening procedure that included a health history questionnaire, physical examination, standard electrolyte panel, and resting electrocardiogram (ECG) to rule out preexisting conditions that could inhibit their participation in a weight-training program of moderate intensity. No volunteer was rejected on the basis of physical or medical conditions, but 10 individuals were either too young or stated that they could not report to the laboratory three times each week for a year. On completion of initial screening, subjects underwent a submaximal exercise test to determine the presence of ischemic heart disease. After passing all screening procedures, subjects were randomly assigned to either a control (n = 14) or exercise group (n = 11). On entry, subjects were either sedentary or moderately active and did not participate in any weight-lifting program. The protocol was approved by the Human Subjects Committee of Stanford University, and subjects provided written consent.

The initial study group consisted of 8 men and 17 women. The control group contained 10 women and 4 men, and the exercise group comprised 7 women and 4 men. Three women in the exercise group left the study for reasons unrelated to training after the 15-week testing session, and the remainder finished one year of weight training. At 15 weeks, 8 controls (5 women, 3 men) joined the exercise group. These 8 subjects completed 30 weeks of training. Therefore, 15- and 30-week training responses were ana-
lyzed for 16 exercisers and 6 controls, whereas 52-week responses were made for 8 exercisers and 6 controls.

**Submaximal exercise evaluation.** — All volunteers underwent a submaximal graded treadmill exercise test using the Balke protocol (25). Blood pressure, heart rate, and ECG were monitored during the test as were ratings of perceived exertion, using the Borg scale (26). The test was conducted by an exercise technologist with certification from the American College of Sports Medicine.

**Strength testing.** — All testing and training sessions were conducted at the Musculoskeletal Research Laboratory, VA Medical Center, Palo Alto. After the screening tests, but prior to beginning the training protocol, all subjects, exercisers and controls, received instruction on proper exercise technique on each of the weight-lifting machines, and carried out a series of repetitions at low intensity, under supervision, to familiarize themselves with each machine. One week later, subjects returned to the laboratory to be tested for maximum strength by the “one repetition maximum” (1-RM) method. One repetition maximum is defined as the maximum weight that can be lifted not more than once with acceptable form. Acceptable form means that the exercise is performed by the specific muscle group involved without the help of whole body momentum or of other muscle groups. To minimize injury or soreness, each strength-testing session began with a warm-up period that included walking and stretching and a warm-up set at low weights on each of the machines. Initial weights were set at levels close to the approximated maximal weight in order to decrease repetition fatigue. Weight increments were in the range of 2.5–10 lbs., depending on the machine. The maximum weight lifted by each subject was then recorded. According to guidelines for maximum strength testing validated and reported in our laboratory (15), the subjects rested for 30 seconds after each repetition and for 2 minutes after each exercise. The coefficient of variation for repeated measures in our laboratory is 2–5% for all strength tests in older women (15).

The 1-RM values were measured every 2 weeks in the exercise group for the first 15 weeks and every 3 weeks for the rest of the training period. The control group was tested after 15, 30, and 52 weeks.

**Training protocol.** — The progressive training program consisted of 12 different resistance exercises involving all major muscle groups (Table 1). Seven exercises were chosen to strengthen the lower extremities. Leg, bench, military, and triceps presses and upright rowing were performed on a Multistation Universal Spartacus (Universal Gym Equipment, Cedar Rapids, IA). Leg flexion and extension were performed on a Marcy Leg Trainer (Marcy Physical Fitness Products, Alhambra, CA). A Nautilus machine (Nautilus Sports/Medical Industries, Independence, VA) was used for back extension, and a Universal Total Hip Trainer (model 993494, Universal Gym Equipment) was used for all four hip exercises.

All training sessions were conducted under close supervision to ensure proper technique and decrease the risk of injury. Training sessions were conducted 3 times per week, and each session lasted approximately one hour. The subjects started and ended each session with 10-minute warm-up and cool-down periods that included walking and stretching. Subjects performed 3 sets of 8 repetitions for each exercise, with 1-minute rest between sets. The subjects were asked to execute the concentric phase of each exercise over 2 seconds, and the eccentric phase over 3 seconds. Subjects recorded daily weights lifted, numbers of repetitions and sets, and any difficulties experienced.

Weights were adjusted after each 1-RM determination to increase the intensity of lifting. Exercise intensity was initially set at 65% of individual 1-RM values for the first 3 weeks. After subsequent strength testing, loads were adjusted to 70% of their new 1-RM values for the next 6 weeks. For the remainder of the year, subjects exercised at 75% of 1-RM values, with retesting and load adjustment every 3 weeks.

The control group was asked not to participate in any weight-lifting program during the training period. They returned to the laboratory after 15, 30, and 52 weeks for maximal strength testing. After 15 weeks, members of the control group were given the option of joining the exercise group.

**Muscle biopsies.** — Needle biopsies were taken from the vastus lateralis muscle of the nondominant thigh under local anesthesia (Xylocaine, 1%) from subjects who volunteered for this optional part of the study (8 exercisers, 5 controls). The procedure was adapted from the method that we described and validated previously (15). Biopsies were taken from the same location at the beginning of the study, after 15 weeks, and after 30 weeks of training. Each sample was oriented under a stereoscope and embedded in tragacanth gum on a slice of cork and immediately frozen in isopentane cooled to its freezing point in liquid nitrogen (27). The samples were then stored at −90°C for histochemical analysis.

**Muscle histology.** — Muscle samples were cut into 8-mm thick slices in a cryostat (Histostat, model 975C, Cambridge Instruments, Buffalo, NY) at −20°C. The cross-sections were stained for myofibrillar ATPase at pH 9.4 after preincubation at pH 9.7 to differentiate type 1 and type 2 fibers (27). We did not differentiate fiber subtypes.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Muscle Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Leg extension</td>
<td>Quadriceps group</td>
</tr>
<tr>
<td>2. Leg flexion</td>
<td>Hamstrings group</td>
</tr>
<tr>
<td>3. Back extension</td>
<td>Erector spinae, gluteus maximus</td>
</tr>
<tr>
<td>4. Hip abduction</td>
<td>Gluteus medius</td>
</tr>
<tr>
<td>5. Hip adduction</td>
<td>Adductor magnus</td>
</tr>
<tr>
<td>6. Hip flexion</td>
<td>Iliopsoas</td>
</tr>
<tr>
<td>7. Hip extension</td>
<td>Gluteus maximus</td>
</tr>
<tr>
<td>8. Leg press</td>
<td>Quadriceps group</td>
</tr>
<tr>
<td>9. Bench press</td>
<td>Pectoralis major</td>
</tr>
<tr>
<td>10. Military press</td>
<td>Deltoide</td>
</tr>
<tr>
<td>11. Triceps press</td>
<td>Triceps</td>
</tr>
<tr>
<td>12. Upright rowing</td>
<td>Trapezius</td>
</tr>
</tbody>
</table>

Table 1. Exercise Circuit
The fiber area was determined using the Bioquant Digitizing Morphometry program for manual planimetry with a personal computer at a magnification of \( \times 660 \) (R and M Biometrics, Nashville, TN). The slides were masked for random analysis and the identity of each subject was not disclosed until after the data were analyzed. The cross-sectional areas of 20 fibers of each type were measured in duplicate, and the average reading was recorded. Following the methodological descriptions of Blomstrand et al. (28), only the fibers with defined borders and with true cross-section were assessed.

Data analysis. — Data were analyzed with the Statview II statistical package (Abacus Concepts, Berkeley, CA). Analytical methods included routine descriptive statistics, unpaired \( t \)-tests, and 2-way repeated measures analysis of variance. All tests were two-tailed, with a significance criterion, \( \alpha = .05 \). For multiple tests of muscle strength, the criterion for significance was taken as .05 divided by the number of tests (12), or \( p < .004 \).

RESULTS
The initial group of 11 exercisers, aged 67.2 ± 1.2 SEM yrs, with a mean weight and height of 69.6 ± 4.0 kg and 163.0 ± 2.7 cm, respectively, were not significantly different from participants in the control group (\( n = 14 \)), aged 68.8 ± 1.4 yrs, weight 66.0 ± 2.3 kg, and height 165.0 ± 2.3 cm. Protocol compliance was excellent. Subjects attended 98 ± 1.6% of scheduled exercise sessions and reported for makeup sessions for all exercise days that had been missed. There were no training-related injuries.

Muscle strength. — Baseline muscle strength of controls and exercisers did not differ (Table 2). In the exercise group, no significant differences were observed after 2 weeks of training compared to baseline in the 1-RM values for any muscle group. Training responses of the 8 controls who joined the exercisers after 15 weeks did not differ from those of the original exercisers, so their training data have been combined to simplify presentation. After 8 weeks of training, the exercisers showed significantly increased strength in all the muscle groups tested. After this time, further changes in strength tended to plateau, with only modest increases observed throughout the remainder of the training period. This trajectory was observed in all muscle groups, and a representative example is shown in Figure 1. After 15 weeks of training the strength values differed significantly between the exercise and control groups at all sites (\( p < .0004 \) to \( p < .0001 \)), and this difference persisted through 30 weeks (Table 3), and, for the 8 exercisers who completed 52 weeks of training, was present at one year (Table 2). By contrast, strength scores for the control group did not change significantly from baseline at any site at any time (Tables 2 and 3).

Muscle histology. — Muscle biopsies were taken from 3 controls and 8 exercisers at baseline and again after 15

![Figure 1. Changes in 1-RM values for knee extension over time. Results are given as percent changes ± SEM.](image)

### Table 2. Maximal Muscle Strength (1RM) Values at Baseline and 1 Year Post-Training*

<table>
<thead>
<tr>
<th>Exercises</th>
<th>Exercisers (( n = 8 ))</th>
<th>Controls (( n = 6 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>1 Year</td>
</tr>
<tr>
<td>Leg extension</td>
<td>28.9 ± 2.6</td>
<td>57.1 ± 5.1</td>
</tr>
<tr>
<td>Curl</td>
<td>16.3 ± 2.1</td>
<td>30.7 ± 4.0</td>
</tr>
<tr>
<td>Press</td>
<td>97.3 ± 5.6</td>
<td>150.9 ± 10.5</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>25.9 ± 1.7</td>
<td>50.1 ± 3.4</td>
</tr>
<tr>
<td>Extension</td>
<td>47.1 ± 1.6</td>
<td>99.9 ± 6.6</td>
</tr>
<tr>
<td>Abduction</td>
<td>24.5 ± 1.6</td>
<td>48.2 ± 4.3</td>
</tr>
<tr>
<td>Adduction</td>
<td>30.4 ± 2.3</td>
<td>50.6 ± 4.0</td>
</tr>
<tr>
<td>Back extension</td>
<td>44.1 ± 3.9</td>
<td>68.2 ± 5.4</td>
</tr>
<tr>
<td>Bench press</td>
<td>25.8 ± 2.2</td>
<td>39.5 ± 4.6</td>
</tr>
<tr>
<td>Military press</td>
<td>25.4 ± 1.8</td>
<td>34.1 ± 3.3</td>
</tr>
<tr>
<td>Triceps press</td>
<td>17.4 ± 1.4</td>
<td>25.7 ± 2.8</td>
</tr>
<tr>
<td>Upright row</td>
<td>17.4 ± 2.5</td>
<td>28.4 ± 4.1</td>
</tr>
</tbody>
</table>

*Values are mean ± SEM, reported in kg; \( p \)-values represent the differences in strength change over time between exercisers and controls, and are indicated as: *\( p < .001 \), †\( p < .0001 \), ‡\( p < .0004 \).
Table 3. Percent Change in Muscle Strength After 15 and 30 Weeks of Training

<table>
<thead>
<tr>
<th>Exercises</th>
<th>0-15 Weeks</th>
<th>0-30 Weeks*</th>
<th>Controls (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0-15 Weeks</td>
</tr>
<tr>
<td>Leg Extension</td>
<td>42.3 ± 6.7</td>
<td>61.2 ± 8.2</td>
<td>1.5 ± 4.6</td>
</tr>
<tr>
<td>Calf</td>
<td>39.1 ± 4.5</td>
<td>58.0 ± 7.6</td>
<td>0.7 ± 3.2</td>
</tr>
<tr>
<td>Press</td>
<td>23.5 ± 2.8</td>
<td>34.9 ± 3.1</td>
<td>-7.0 ± 3.0</td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>48.0 ± 6.2</td>
<td>62.4 ± 6.4</td>
<td>-10.5 ± 3.0</td>
</tr>
<tr>
<td>Extension</td>
<td>18.2 ± 1.9</td>
<td>26.5 ± 3.1</td>
<td>-5.1 ± 2.2</td>
</tr>
<tr>
<td>Abduction</td>
<td>44.0 ± 5.3</td>
<td>59.7 ± 6.1</td>
<td>-7.0 ± 2.8</td>
</tr>
<tr>
<td>Adduction</td>
<td>26.8 ± 2.6</td>
<td>40.6 ± 3.8</td>
<td>-11.6 ± 2.2</td>
</tr>
<tr>
<td>Back extension</td>
<td>34.8 ± 5.9</td>
<td>47.6 ± 7.3</td>
<td>-7.1 ± 1.6</td>
</tr>
<tr>
<td>Bench press</td>
<td>22.1 ± 2.0</td>
<td>30.8 ± 2.9</td>
<td>-7.2 ± 2.4</td>
</tr>
<tr>
<td>Military press</td>
<td>15.6 ± 1.7</td>
<td>23.4 ± 1.9</td>
<td>-1.7 ± 2.9</td>
</tr>
<tr>
<td>Triceps press</td>
<td>25.7 ± 3.2</td>
<td>34.9 ± 4.1</td>
<td>0 ± 3.2</td>
</tr>
<tr>
<td>Upright Row</td>
<td>33.9 ± 5.4</td>
<td>51.2 ± 8.2</td>
<td>-9.1 ± 3.2</td>
</tr>
</tbody>
</table>

* % increase in muscle strength \( p < .0001 \) to \( .0004 \) for all tests in the exercise group.
† In the control group no significant changes were observed over time for any test.

weeks. Two additional control subjects provided baseline samples, but one person refused to undergo rebiopsy, and the biopsy material from the second was inadequate for analysis. Thirty-week biopsies were taken only from the 8 exercisers. All samples were in good condition and freezing artifacts were minimal.

The initial mean fiber areas for type 1 and type 2 fibers did not differ significantly between groups (Table 4). After 15 weeks of training, the exercisers showed a significant increase in the mean fiber area for type 1 (\( p < .02 \)) but not type 2 fibers. Exercisers who were tested after 30 weeks of training showed a significant increase in type 2 fiber area (\( p < .0002 \)) and a further increase in type 1 fiber area (\( p < .002 \)). There was no significant relationship between changes in muscle strength and changes in fiber area.

**DISCUSSION**

We have shown that healthy elderly men and women were able to complete successfully a one-year program of progressive resistance exercise. This training program led to major increases in muscle strength and hypertrophy of both type 1 and type 2 muscle fibers. For each muscle group, the response to training was most rapid for the first 8 weeks. Indeed, for some muscles 95% of the total strength gained during the one-year intervention was achieved by 15 weeks. Thus, a fairly prompt attenuation of response was observed, and it is likely that to gain additional strength it will be necessary to increase the training loads or alter in some other way the training regimen.

In this program, gains in maximal strength were exercise-specific, ranging from 30.1% (hip extension) to 97% (hip flexion) over baseline values. Not surprisingly, baseline muscle strength was lower than that of young men and women tested previously in our laboratory, using the same 1-RM technique (29,30). Yet, with strength training, average muscle strength increased to levels that exceeded mean baseline values reported for young people entering exercise studies (6,8,29). To date, most exercise intervention studies in elderly people have been of relatively short duration, low intensity, and few exercises (13,14,23,24,31,32).

Some of the apparent increases in muscle strength that we observed might have reflected increased skill in manipulating the exercise machinery rather than true increases in muscle strength. We attempted to reduce this possibility by providing our subjects an extended session for equipment familiarization prior to testing. Moreover, comparison of 1-RM values between baseline and week 2 of training showed no significant differences, and measured increases over time did not differ if the 2-week values were substituted for the baseline data. Thus, we think that a learning artifact did not confound these results.

In the present study, we have shown a high degree of compliance over a full year of training at moderate to heavy intensity. Exercise studies have not frequently been randomized because investigators want to keep a high degree of compliance. In our study, three of the initial exercisers dropped out because of personal reasons not related to the exercise program. This attrition rate is comparable to the 40% attrition observed in a recent exercise study with young women (33).

We recognize that ideal study design dictates strict adherence to randomization throughout the duration of a protocol. In the present study, we permitted members of the control group to switch to the exercise program after 15 weeks. The reason for this policy was our concern that elderly subjects volunteering for an exercise study would not be likely to
accept enforced inactivity for a full year. Comparison of
the muscle strength responses after 15 and 30 weeks of training
showed no differences between individuals who had been
enrolled initially as exercisers and those who switched at 15
weeks. It is difficult to conceive that 30 or 52 weeks of
inactivity would increase muscle strength or fiber area.
Thus, if any confound were introduced by this policy, it
would probably be in the direction of loss of strength or
decreased fiber area. This would make the relative advantage
of our exercisers even greater than we observed.

The mechanisms involved in the observed gains in
strength are still not completely defined. Although Moritani
and De Vries (11) first suggested that increases in strength of
elderly men were primarily due to improved neuromuscular
recruitment, several recent studies clearly show that strength
training promotes an early hypertrophy response in elderly
men (3,13,14,31,34) and women (15). Nonetheless, the
correlations between observed gains in strength and changes
in fiber size are generally not significant (2,4,7,11,15),
leaving open the possibility that factors other than muscle
fiber hypertrophy may also play a role. Such factors include
improved efficiency of neuromuscular recruitment
(10,16,18,20) and changes in the contractile proteins (35).

We have previously shown that elderly women undergo
type 2 fiber hypertrophy after a 12-week strength training
period. In the current study, we demonstrate increased
cross-sectional area of both types 1 and 2 muscle fibers. Although
the 15-week results did not achieve significance for type 2
fibers, the average increase, 22%, was similar to that re-
ported previously (13,15). We attribute this lack of statisti-
cal significance to a relatively large variance in fiber areas
and a small number of subjects. Nonetheless, by 30 weeks
and beyond, highly significant increases in cross-sectional
areas were observed for both fiber types. These muscle fiber
areas were similar to those observed in young subjects
(8,36). Frontera et al. (13) and Larsson (3) also observed
significantly increased type 2 fiber area and weight training,
while Thorstenson et al. (37), Houston et al. (38), and Tesch et al. (5)
showed a more pronounced type 2 hypertrophy response in young men.
Larsson (3) found a more significant increase in type 2 fiber
area in response to a 15-week training program in older men.
However, Aniasson and Gustafsson (12) found no signi-
cificant change in the average cross-sectional area of type 2
fibers and a decrease in type 1 fiber area in elderly men who
trained for 12 weeks. This difference in muscle fiber adapta-
tion may have been due to a lower intensity training program
compared to the present study. The strength gains reported
by that group were also lower than those we observed.

Finally, our results demonstrate that healthy elderly peo-
ple can participate in sustained programs of moderately
intense resistance activity without obvious injury, and with
excellent compliance. Blood pressures and heart rates were
monitored frequently throughout the study, both prior to
initiating a training session, and immediately upon complet-
ing each exercise. In no case did we observe a systolic blood
pressure in excess of 170 mm Hg or a diastolic pressure
higher than 100 mm Hg, a finding that confirms earlier
findings (39,40) in elderly men and women. Although the
feasibility of resistance training as a strategy to improve the
strength of elderly men and women seems reasonable from
this study, a legitimate question remains about the generali-
yzability of our experience, since seniors in the Palo Alto
community are generally healthier and of higher socioeco-

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