Strength training and determinants of \( \text{VO}_2 \text{max} \) in older men

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Strength training and determinants of \( \text{VO}_2 \text{max} \) in older men. J. Appl. Physiol. 69(1): 329–333, 1990.—The effects of strength training on maximal aerobic power (\( \text{VO}_2 \text{max} \)) and some of its determinants were studied in 12 healthy older men (60–72 yr). They underwent 12 wk of strength conditioning of extensors and flexors of each knee with eight repetitions per set, three sets per session, and three sessions per week at 80% of the one repetition maximum (1 RM). Left knee extensors showed a 107% increase in 1 RM, a 10% increase in isokinetic strength at 60°/s, and a 23% increase in total work performed during 25 contractions on an isokinetic dynamometer. Strength measurements of the untrained left elbow extensors showed no change. Leg cycle ergometry, on cardiopulmonary function, hemoglobin concentration, erythrocyte volume, plasma volume, and total blood volume did not change. Biopsies of the vastus lateralis showed a 28% increase in mean fiber area, no change in fiber type distribution, a 15% increase in capillaries per fiber, and a 38% increase in citrate synthase activity. The data suggest that the small increase in leg cycle \( \text{VO}_2 \text{max} \) in older men may be due to adaptations in oxidative capacity and increased mass of the strength-trained muscles.

Materials and methods

Subjects. Twelve healthy, previously sedentary men between the ages of 60 and 72 yr volunteered for this study. The study design was explained to all subjects, and an informed written consent was obtained. The protocol was approved by the Tufts University-New England Medical Center Human Investigation Review Committee. Evaluations were carried out before training and after 12 wk of training.

Training. The subjects trained extensors and flexors of each knee on a thigh-knee dynamic machine (Universal, Cedar Rapids, IA) at 80% of the one repetition maximum (1 RM), under supervision, for 12 wk as previously described (11). The 1 RM, measured at the end of each week, was used to readjust the training load and keep the training stimulus constant at 80% 1 RM. The men performed three sets of eight repetitions at the set load, three times per week. All of the training sessions were preceded by a 10-min warm-up on a cycle ergometer at 50% of the pretraining maximal heart rate (HR\text{max}) and one 10-min stretching routine for the different muscles of the legs. This intensity and duration of exercise was selected because it is known not to induce significant changes in \( \text{VO}_2 \text{max} \) (1). Muscles strength and function. In addition to the weekly measurements of 1 RM of the strength-trained muscles, dynamic strength of the knee and elbow extensors and flexors was measured before and after the 12-wk program, using an isokinetic dynamometer (Cybex II) at a speed of 60°/s. The subjects were also asked to perform 25 maximal contractions on the dynamometer at a velocity of 180°/s for the elbow extensors and 240°/s for the knee extensors. Total work was calculated as the area of a triangle with the magnitude of work equal to the area of the triangle.

PROGRESSIVE RESISTANCE training is commonly used in the rehabilitation of geriatric patients, especially after illness or surgery. These exercises are intended to improve muscle strength and functional capacity, particularly ambulation, and ideally to allow the elderly person to return to independent living. After rehabilitation of elderly hospitalized patients, the habitual walking speed of each knee with eight repetitions per set, three sets per session, and three sessions per week at 80% of the one repetition maximum (1 RM). Left knee extensors showed a 107% increase in 1 RM, a 10% increase in isokinetic strength at 60°/s, and a 23% increase in total work performed during 25 contractions on an isokinetic dynamometer. Strength measurements of the untrained left elbow extensors showed no change. Leg cycle ergometry, on cardiopulmonary function, hemoglobin concentration, erythrocyte volume, plasma volume, and total blood volume did not change. Biopsies of the vastus lateralis showed a 28% increase in mean fiber area, no change in fiber type distribution, a 15% increase in capillaries per fiber, and a 38% increase in citrate synthase activity. The data suggest that the small increase in leg cycle \( \text{VO}_2 \text{max} \) in older men may be due to adaptations in oxidative capacity and increased mass of the strength-trained muscles.

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under the curve. The fatigue index, or muscle endurance index, was obtained from the ratio of the total work performed in the last five and first five repetitions. Results are reported for the left elbow and knee.

**Open-circuit spirometry.** Open-circuit spirometry methods were used for the collection of respiratory and metabolic data during both maximal arm and leg cycle ergometry. Expired gas was collected in meteorological balloons during the last 2–3 min of the test. Expired ventilatory volume measured with a Tissot gasometer, oxygen concentration by electrochemical O₂ analyzer (Applied Electrochemistry, Sunnyvale, CA), and CO₂ concentration by infrared CO₂ analyzer (Beckman, Schiller Park, IL) were used to calculate minute ventilation (VE), respiratory exchange ratio (R), and oxygen consumption (VO₂).

An increase in VO₂ of <150 ml/min with increasing power output is the classic criterion of Taylor and coworkers for achieving VO₂max (28). However, this has been derived from treadmill tests applied over several days, and its applicability during arm and leg cycle ergometry in elderly men has not been established. The plateauing of VO₂ is not a universal finding in younger subjects, but the peak VO₂ obtained during an incremental exercise test gives a reasonable approximation of VO₂max for that exercise mode (4). Therefore, in the present study, we defined VO₂max as the highest VO₂ attained at volitional fatigue. The facts that the R values were greater than 1.1 and that the HRmax coincided with the age-predicted values suggest that true VO₂max was achieved.

**Leg ergometry.** Leg exercise was conducted on an electrically braked cycle ergometer (Collins, Braintree, MA) with a continuous, multistage exercise protocol. The initial power output was set at 50 W and maintained for the first 2 min. Thereafter, the power output was increased by 25 W every minute until the volunteer could not sustain a pedaling rate of 60 rpm. HR was recorded at rest and every minute during the exercise test.

**Arm ergometry.** Upper extremity exercise was conducted using a Monark Rehab Trainer (Monark, Sweden). The protocol described by Wicks et al. (32) was used for determination of arm-specific VO₂max. The initial power output was loadless cranking at 60 rpm. Then the load was increased 15 W every minute until the volunteer could not sustain a rate of 60 rpm. Cranking rate was maintained constant with the aid of a metronome. The ergometer was placed with the fulcrum on level with the top of the shoulder, with a slight elbow flexion in the extended arm. The mouthpiece was suspended and placed so the subject could sit upright with the neck in a comfortable position. Crank height and chair distance from the table were measured to ensure unfamiliarity with the equipment or procedures. Heart rate was recorded at rest and every minute during the exercise test.

The arm and leg cycle ergometry tests were performed on the same day with a 30-min rest between tests. Valid and reliable assessments of VO₂ are possible under these conditions (27).

**Hematologic status.** Erythrocyte volume was measured before and after training using the ²ⁱCr-labeling technique (31). Total blood volume was estimated from hematocrit and erythrocyte volume.

**Muscle biopsy.** Samples were obtained by needle biopsy from the vastus lateralis (7). Biopsies of the elbow flexors were not taken. All biopsy samples from one individual were stained simultaneously for myofibrillar adenosine triphosphatase (ATPase) (6). Fiber type distribution and mean fiber area were determined as described previously (11). Areas without artifacts were photographed, projected onto a screen, and framed by following the cell borders. The capillaries were identified and confirmed by direct microscopy of the sections. Capillaries identified in the borders were counted as one-half. The capillary per fiber ratio was calculated as the number of capillaries in the area divided by the number of fibers in the same area (2). Citrate synthase (CS) activity, a marker of the muscle oxidative capacity, was measured in duplicate or triplicate in eight subjects (26).

**Fat-free body mass.** Fat-free body mass (FFM) was determined in the fasted subjects by hydrostatic weighing (24). Lung residual volume was determined at the time of the underwater weighing by the nitrogen-dilution method (33).

**Statistical analysis.** Results are reported as means ± SE. One-way analysis of variance with repeated measures and Tukey’s post hoc test were used to determine the effects of training. As the purpose of this study was to determine whether training produced an increase in the variables measured, a one-tailed test was used (18). Pearson’s coefficient of correlation was used to express the relationship between measures of interest. Statistical significance was accepted at P < 0.05.

**RESULTS**

As previously reported, the 12-wk strength training program had a major effect on the neuromuscular function of the left knee extensors, especially dynamic strength (1 RM), which increased from 20 ± 1 to 40 ± 2 kg (P < 0.001) (11). The knee extensors showed increased isokinetic strength (P = 0.024), total work capacity (P < 0.001), and fatigue index of the knee extensors (P = 0.028), with no effect on these variables in the untrained extensors of the elbow (Fig. 1).

VO₂max by leg cycle ergometry increased by 6.0% in 1/min, (P = 0.050) with no significant change in results expressed as ml·kg⁻¹·min⁻¹ (Table 1). VO₂max per unit of fat-free mass increased 5.2% (P = 0.034) (Fig. 2). There was no effect of strength training of the legs on arm cycle VO₂max determinations (Table 1, Fig. 2). There was no effect of training on cardiopulmonary function at rest, during leg cycle VO₂max, and during arm cycle VO₂max testing, as demonstrated by unchanged heart rates and ventilation (Table 1).

Hematologic status, measured by hemoglobin, erythrocyte volume, plasma volume, and total blood volume, was not changed by the strength training program (Table 2).
Strength training had a marked effect on morphology of the vastus lateralis muscle (11), with a 28.2% increase in mean fiber area \((P < 0.001)\) (Table 3). Changes suggestive of an increased aerobic capacity were a 15.1% increase in capillaries per fiber \((P = 0.042)\) and a 38.0% increase in CS activity \((P = 0.018)\).

There was a significant positive correlation between vastus lateralis CS activity and leg cycle \(V_{O_2\text{max}}\) for pre- and posttraining data combined \((r = 0.56, \ P = 0.04)\); however, there was no relationship between the change in CS activity and the improvement in leg cycle \(V_{O_2\text{max}}\) \((r = 0.57, \ P = 0.186)\). The correlation between the change in CS activity and the change in mean fiber area approached statistical significance \((r = 0.68; \ P = 0.06)\). There was no relationship between mean fiber area and leg cycle \(V_{O_2\text{max}}\). A significant positive correlation was found between total work performed by the left knee extensors and left elbow flexors in older men before and after 12 wk of resistance training of legs. Values are means ± SE.

**TABLE 1. Effects of strength training on \(V_{O_2\text{max}}\) and cardiopulmonary function measured by leg ergometry and arm ergometry in 12 older men**

<table>
<thead>
<tr>
<th>Week 0</th>
<th>Week 12</th>
<th>Training Effect ((P) value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{O_2\text{max}}) l/min</td>
<td>2.07±0.07</td>
<td>2.19±0.08</td>
</tr>
<tr>
<td>ml·kg(^{-1}·\text{min}^{-1})</td>
<td>26.9±0.8</td>
<td>28.3±1.1</td>
</tr>
<tr>
<td>ml·kg FFM(^{-1}·\text{min}^{-1})</td>
<td>38.6±1.2</td>
<td>40.5±1.6</td>
</tr>
<tr>
<td>HR(_{max}), beats/min</td>
<td>160±4</td>
<td>156±4</td>
</tr>
<tr>
<td>(V_E) (_{max}) l/min</td>
<td>75.2±5.0</td>
<td>78.4±4.8</td>
</tr>
</tbody>
</table>

**Leg ergometry (trained)**

**Arm ergometry (untrained)**

\(V_{O_2\text{max}}\) l/min | 1.41±0.05 | 1.41±0.06 | 0.481 |
ml·kg\(^{-1}·\text{min}^{-1}\) | 18.4±0.7 | 18.4±0.8 | 0.440 |
ml·kg FFM\(^{-1}·\text{min}^{-1}\) | 26.2±0.9 | 26.2±1.0 | 0.486 |
HR\(_{max}\), beats/min | 156±5 | 148±3 | 0.210 |
\(V_E\) \(_{max}\) l/min | 55.9±5.6 | 57.8±5.0 | 0.561 |

Values are means ± SE. Fat-free body mass (FFM) determined from hydrostatic weighing (24, 33). \(V_{O_2\text{max}}\), maximal aerobic power; HR\(_{max}\), maximal heart rate; \(V_E\) \(_{max}\), maximal minute ventilation.

**FIG. 1. Functional changes in left knee extensors and left elbow flexors in older men before and after 12 wk of resistance training of legs. Values are means ± SE.**

**FIG. 2. Maximal aerobic power \((V_{O_2\text{max}})\) per unit of fat-free body mass (FFM), measured by leg cycle ergometry and arm cycle ergometry in older men before and after 12 wk of resistance training of legs. Values are means ± SE.**

**TABLE 2. Effects of strength training on indexes of hematologic status in 12 older men**

<table>
<thead>
<tr>
<th>Week 0</th>
<th>Week 12</th>
<th>Training Effect ((P) value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemoglobin, mg/dl</td>
<td>15.1±0.3</td>
<td>14.6±0.2</td>
</tr>
<tr>
<td>Erythrocyte volume,* ml</td>
<td>1,799±44</td>
<td>1,826±52</td>
</tr>
<tr>
<td>Plasma volume, ml</td>
<td>3,189±85</td>
<td>3,194±74</td>
</tr>
<tr>
<td>Total blood volume, ml</td>
<td>4,986±120</td>
<td>5,021±115</td>
</tr>
</tbody>
</table>

Values are means ± SE. * Measured using \(^{51}\text{Cr}\) as a tracer for erythrocytes (31).

**TABLE 3. Effects of strength training on vastus lateralis muscle in 12 older men**

<table>
<thead>
<tr>
<th>Week 0</th>
<th>Week 12</th>
<th>Training Effect ((P) value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean fiber area, mm(^2)</td>
<td>4.51±7315</td>
<td>5.43±2384</td>
</tr>
<tr>
<td>Capillaries/fiber</td>
<td>1.14±0.05</td>
<td>1.60±0.08</td>
</tr>
<tr>
<td>Citrate synthase activity,* mmol·g(^{-1}·\text{min}^{-1})</td>
<td>9.6±1.1</td>
<td>13.1±1.1</td>
</tr>
</tbody>
</table>

Values are means ± SE. * Measured in 8 subjects.
DISCUSSION

Traditional weight training emphasizes heavy resistance (between 60 and 100% 1 RM), few repetitions, (1–10 per set), and frequent rest periods of 1–2 min between muscle contractions. In contrast, improvements in aerobic capacity have been shown to occur with exercise that involves large muscle groups, continuous and prolonged effort, and intensities substantially below \( V_{O2_{max}} \) (1).

Some authors have shown improved cardiorespiratory fitness with weight training in young subjects (12, 34), but in both cases circuit weight training was used. Circuit weight training involves moderate amounts of weight (40–50% 1 RM), several repetitions (15 per set), and brief intervals of ~20 s between stations or sets; therefore, it is more sustained and less intense than traditional weight training.

In young and middle-aged men, traditional strength training programs alter muscle structure and performance, with no increase in aerobic capacity (15, 16, 19). Hickson and co-workers (15) reported no change in \( V_{O2_{max}} \) (ml·kg\(^{-1}\)·min\(^{-1}\)) determined by leg cycle ergometry or treadmill exercise. The young men in that study performed heavy resistance exercise of the legs for 10 wk, increasing thigh girth, quadriceps strength, and endurance time to exhaustion while running or cycling at 100% of their pretraining \( V_{O2_{max}} \). Hurley and co-workers (16) found no change in treadmill \( V_{O2_{max}} \) in middle-aged men after 15 wk of Nautilus weight training. They found no change in hemodynamic response to submaximal treadmill exercise, measured by heart rate, blood pressure, and cardiac output. Rutherford and co-workers (19) carried out strength conditioning in young men and women, using a similar program to the design of the present study. After training the knee extensors for 12 wk at 80% 1 RM, they found a marked increase in isokinetic strength but no change in \( V_{O2_{max}} \) measured on a leg cycle ergometer. The results of the present study were different. Elderly men, whose neuromuscular and cardiorespiratory function is reduced, respond to heavy resistance training with large increases in strength and significant muscle hypertrophy (11) that are similar to the changes described for young men. However, the present data suggest that they also improve the capacity of some components of the oxygen transport system (Table 3), leading to a small increase in aerobic power (Table 1, Fig. 2).

The strength training program of this study did not affect arm cycle ergometry \( V_{O2_{max}} \), \( HR_{max} \), or maximal \( V_e \) during aerobic power testing, hemoglobin concentration, or blood volume. The changes that suggested an increased capacity for transporting and utilizing oxygen were found at the level of the vastus lateralis muscle. The increased density of capillaries per fiber and the increased CS activity (Table 3) in the biopsy taken from one of the strength-trained muscles may account for the slight but significant improvement in whole body capacity for oxygen utilization during the leg cycle \( V_{O2_{max}} \) test.

The increased capillarization and CS activity may be related to the strength training program itself or to undetermined changes in voluntary aerobic activity occurring at the same time. In the elderly, muscle weakness can impair the performance of endurance activities such as walking. There is a linear relationship between quadriceps strength and habitual walking speed in 90-yr-old subjects (8) and between gastrocnemius strength and walking speed in 60- to 70-yr-old men (5). It is possible that in the healthy older men of the present study, the increase in strength of the extensors and flexors of the knee facilitated greater everyday physical activity at a pace that produced an endurance-training effect. However, the physical activity questionnaires did not show changes in the habitual activity patterns of the men of this study during the 12 wk of strength training. In addition, there was no change in cardiorespiratory parameters (Table 1), as might be expected if endurance training had occurred. It seems more likely that the increase in \( V_{O2_{max}} \) detected with leg cycle ergometry was an effect of strength training on the leg muscles themselves.

Recent data have shown that a single bout of heavy resistance exercise in humans not only increases the rate of breakdown of phosphagens and glycogen but also significantly reduces intramuscular triglyceride stores (29). In isolated perfused rat hindquarter preparations, rhythmic tetanic stimulation simulating heavy exercise significantly reduces the concentration of endogenous triglycerides. Under these conditions, up to 62% of the total energy released may result from the oxidation of triglyceride stores in the muscle (28). Increased local triglyceride utilization is most likely associated with an increase in the enzymes of lipolysis, fat oxidation, and enzymes of the Krebs cycle such as CS and succinate dehydrogenase. Weight training has been shown to increase the activity of succinate dehydrogenase in animals (17). In young men, Grimby and co-workers (13) showed that an isometric-strength-training program increased strength by 26% and increased the activity of succinate dehydrogenase in the trained muscles by ~50%. During isometric exercise, they found no training-induced changes in blood flow, muscular utilization of ATP, creatine phosphate, or glycogen. They linked the increased performance capacity to a greater substrate utilization via oxidative pathways and speculated that the isometric training led to local adaptations in the muscle, as indicated by increased succinate dehydrogenase activity, allowing a more aerobic active metabolism during the rest periods between contractions.

The other local adaptation that would facilitate oxygen uptake by the trained muscles was the increase in capillaries per fiber (Table 3). Capillary supply in sedentary older men has been reported to be 1.40 ± 0.13 (3) and 1.61 ± 0.11 per fiber (14), which are similar to the present findings. These values in older men are ~50% lower than in young untrained men (30). The increased number of capillaries per fiber found in these older men is consistent with data obtained in young body builders (21) but not with data from Tesch et al. (30), who found no change or a decrease in capillaries per fiber after heavy resistance training in young men. The reasons for these discrepancies are not clear.

The results of this study show that heavy resistance training produced a variety of adaptations that were all
peripheral in nature. It is precisely at this level that the majority of the age-related changes in VO\textsubscript{2max} may occur (9). The largest effect was an increase in neuromuscular function (Fig. 1), but there was also an improvement in local determinants of oxygen utilization. There are four findings that suggest that the increase in whole body oxygen uptake during leg cycle ergometry after strength training was due to local adaptations of the muscle: 1) there was no change in VO\textsubscript{2max} measured by arm cycle ergometry involving muscles that were not strength trained; 2) there was a linear relationship between total work capacity of the legs and leg cycle VO\textsubscript{2max} which was not found for data obtained with arm cycle ergometry; 3) there was an increase in total mass of the muscles used in leg cycle ergometry; and 4) there was an increase in the capacity to extract and utilize oxygen in the vastus lateralis, as shown by greater capillary density and CS activity.

It has been shown that elderly men can readily adapt to heavy resistance exercise training, with changes in muscle mass, structure, and function (11). The present findings show that in healthy older men a strength training program produces changes in the exercised muscles that may lead to an improvement in aerobic capacity. It is likely that in subjects who are severely deconditioned, such as frail elderly women or elderly patients during rehabilitation after illness, the effects of resistance training on the capacity of the exercised muscles to utilize oxygen could have even greater effects on whole body measurements of VO\textsubscript{2max}.

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