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Effects of High-Intensity Resistance Training on Untrained Older Men. I. Strength, Cardiovascular, and Metabolic Responses

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Most resistance training studies of older subjects have emphasized low-intensity, short-term training programs that have concentrated on strength measurements. The purpose of this study was, in addition to the determination of strength, to assess intramuscular and transport factors that may be associated with strength increments. Eighteen untrained men ages 60–75 years volunteered for the study; 9 were randomly placed in the resistance-training group (RT), and the other half served as untrained (UT) or control subjects. RT subjects performed a 16-week high-intensity (85-90% 1 repetition maximum (RT]) resistance training program (2 ×/wk) consisting of 3 sets each to failure (6–8 repetitions based on 1 RM of 3 exercises): leg press (LP), half squat (HS), and leg extension (LE) with 1–2 minutes rest between sets. Pre- and post- training strength was measured for the 3 training exercises using a 1 RM protocol. Body fat was calculated using a 3-site skinfold method. Biopsies from the vastus lateralis m. were obtained for fiber type composition, cross-sectional area, and capillarization measurements. Exercise metabolism, electrocardiography, and arterial blood pressure were observed continuously during a progressive treadmill test, and resting echocardiographic data were recorded for all subjects. Pre- and post-training venous blood samples were analyzed for serum lipids. Resistance training caused significant changes in the following comparisons: % fat decreased in the RT group by almost 3%, strength improved for all exercises: LE = + 50.4%, LP = + 72.3%, HS = + 83.5%; type IIB fibers decreased and IIA fibers increased; cross-sectional areas of all fiber types (I, IIA, IIB) increased significantly, and capillary to fiber ratio increased but not significantly. No differences were noted for ECG and echocardiographic data. The RT group significantly improved treadmill performance and $\dot{V}O_2$max. Pre- and post-training serum lipids improved but not significantly. No significant changes occurred in any pre- to post-tests for the UT group. The results show that skeletal muscle in older, untrained men will respond with significant strength gains accompanied by considerable increases in fiber size and capillary density. Maximal working capacity, $\dot{V}O_2$max, and serum lipid profiles also benefited from high-intensity resistance training, but no changes were observed for HR max, or maximal responses of arterial blood pressure. Older men may not only tolerate very high intensity work loads but will exhibit intramuscular, cardiovascular, and metabolic changes similar to younger subjects.

METHODS to improve the quality of life for older individuals become more important as the aging population continues to grow. Loss of strength, including muscle atrophy, and decreasing aerobic capacity are well known responses associated with the aging process (1–6).

Declines in muscle strength and mass have been associated with mammalian aging (7), and the atrophy of muscle fibers with age has repeatedly been shown to be more pronounced in the fast, type II fibers than in the slow, type I fibers (8–10). Several studies have also demonstrated a decrease in fiber number with increasing age, and it has been shown that hypoplasia is more pronounced in type II (especially type IIB fibers) than in type I fibers (11,12).

As activity levels typically decline with increasing age, it is useful to distinguish between changes in skeletal muscle brought about by the aging process itself and those caused by disuse. Studies of unloading, whether utilizing immobilization (13), limb suspension (14), or microgravity (15,16) have reported decreases in muscle fiber cross-sectional areas and strength (17) that are similar to changes seen in aging.

Physical working capacity as measured by $\dot{V}O_2$max declines by about 1%/yr after the third decade of life (18), and muscle strength and cross-sectional area decrease significantly between the second and seventh decades (5,12). Both aerobic and resistance training seem to improve skeletal muscle capillarization in elderly men. Hepple and colleagues (19) reported an improvement in capillarization and aerobic capacity after both aerobic and resistance training, and Chilibeck and associates (20) demonstrated a strong correlation between capillarization of skeletal muscle and $\dot{V}O_2$ kinetics during exercise. Schantz (21) seems to support these studies. However, resistance-trained athletes failed to show similar changes (22). A study of master athletes, however, has shown that strength, oxidative capacity, and muscle capillarization can be maintained to some degree with exercise training (23,24). There is a decline in each of these functions with aging, even among older athletes who are training on a regular basis; thus, some loss of functional capacity may be due to the aging process itself rather than a more sedentary existence (25,26). Exercise, however, can apparently slow the decline in functional capacity even among previously sedentary older subjects (27,28).

Several studies have observed large increases in strength and muscle fiber diameter in older subjects with resistance training (29–33), and there is the possibility that weight training may slow or reverse muscle atrophy and strength decrements (2,34,35). It appears that resistance training can maintain muscle mass of older subjects which may, in turn, also prove valuable in maintaining the functional capacity of muscle. This functional capacity is reflected in significant increases in aerobic capacity of skeletal muscle (29,30) following resistance training.

Maximal heart rate decreases with aging, whereas submaximal heart rate increases for a standard level of exercise intensity (26,36,37). A decrease in left ventricular contractile force and increases in total peripheral resistance (TPR) limit stroke volume and elevate systolic and diastolic arterial pressures in elderly people (38–40). Echocardiographic analysis of endurance-trained elderly men has revealed volume-overload left ventricular hypertrophy and enhanced stroke volume (38, 41–43).

Older adults are quite susceptible to dyslipidemia, and this condition is most likely related to diet and inactivity. However, such factors as obesity, diabetes, and other metabolic diseases may also be involved. Fat-free mass (FFM) generally decreases and fat mass (FM) increases with age (44,45), but it is difficult to determine whether inactivity, the aging process, or both are responsible for these changes. Resistance training studies involving older subjects have shown decreases in FM following training (35,46,47). Although some studies have indicated that increased total cholesterol (TC) and high levels of low-density lipoprotein-bound cholesterol (LDL-C) are more compatible with obesity than with physical activity, Tamai and colleagues (48) have shown that high-density lipoprotein-bound cholesterol (HDL-C) is higher and total cholesterol/HDL-C ratio is lower in endurance-trained elderly men than in untrained men. Other studies (49,50) suggest that HDL-C in healthy elderly men is more closely related to fitness, body fat, and fat distribution than to age. Low-intensity endurance training appears to exert no beneficial effect on lipoprotein profiles of elderly adults. However, Pavlou (51) and Schwartz (52) and colleagues have shown that older subjects respond in a similar fashion as younger subjects to high-intensity aerobic training. Triglycerides (TG) decreased and HDL-C increased, but no changes occurred in total cholesterol or LDL-C. Lipid profiles of resistance-trained elderly subjects have not been reported. However, increases in the oxidative properties of skeletal muscle fibers of younger subjects as a result of high-intensity resistance training (53,54) may also benefit lipoprotein/cholesterol ratios.

Past and current research of aging skeletal muscle and its response to exercise seems to have focused primarily on evaluation of strength with minimal references to intramuscular changes, and most of this research has used low-intensity or short-duration weight training. The purpose of this study was to examine the responses of skeletal muscle and its transport mechanisms of aged subjects to a high-intensity, progressive weight training regimen of relatively long duration.

Methods

Subjects.—Of the 28 male subjects who responded to our advertisements, 22 were determined fit for resistance training based on a definitive medical examination and treadmill stress test. Although most exhibited some form of either a musculoskeletal or cardiovascular problem or a combination thereof, these did not contraindicate participation in a resistance training program. All subjects were physically active but none had previously engaged in heavy resistance training. Both verbal and written consent were obtained from each subject prior to testing and training, and the study was approved by the Ohio University Institutional Review Board for Human Subjects. Subjects were randomly assigned to either the control, untrained (UT) group (10 subjects) or to the experimental, resistance-trained (RT) group (12 subjects). Three RT and one UT subject(s) withdrew from the study because of minor injuries or previous medical problems exacerbated by testing or training. Average age of the RT was 63.7 ± 5.0 (mean ± *SD*) years and that of the UT was 66.2 ± 6.5 years. Anthropometric measurements, including a three-site skinfold analysis for estimation of body density (55) and calculation of percent body fat (56) were determined before and after training. Pertinent physical characteristics appear in Table 1.

Maximal strength testing.—Strength testing was performed at the beginning and completion of the study. For the measurement of one repetition maximum (1 RM), subjects completed 2 sets of 10 repetitions (at approximately 40–60% of 1 RM) followed by 3 repetitions at approximately 75% of 1 RM and 1 repetition at 90% of 1 RM. Weight was then gradually increased for subsequent sets until failure was reached. One RM, defined to be the heaviest weight that a subject could lift while maintaining acceptable exercise

Table 1. Anthropometric Measurements for Resistance-Trained and Untrained Groups

			Body Fat		
	Age (yrs)	Height (cm)	Weight (kg)	(%)	Fat-Free Mass (kg)
Resistance-trained (n = 9)					
Pre	63.7 ± 5.0	178.2 ± 8.5	83.8 ± 17.6	24.5 ± 5.4*	63.3 ± 4.3
Post	63.9 ± 5.2	178.2 ± 8.5	82.2 ± 18.2	21.6 ± 5.0	64.4 ± 5.1
Untrained (n = 9)					
Pre	66.2 ± 6.5	178.5 ± 5.8	80.2 ± 4.5	21.6 ± 5.2	62.9 ± 4.8
Post	66.4 ± 6.5	178.5 ± 5.9	80.6 ± 4.7	22.8 ± 6.0	62.2 ± 4.6

Note: Values represent means ± standard deviation.

*There was a significant interaction between groups and time effect for percent body fat. Preresistance-trained value was significantly different than postresistance-trained and pre- and postuntrained values ($p < .01$).

technique, was achieved within 5–6 sets. One RM testing began with the leg extension exercise followed by the double leg press and half-squat in that order. A 20–30 minute recovery period was allotted between each of the three exercise tests. Heart rate was monitored continuously by Polar Vantage XL (Polar CIC, Port Washington, NY) during testing, and blood pressure was checked periodically by auscultation.

Muscle biopsies.—Percutaneous muscle biopsies were taken from the vastus lateralis m. before and after 16 weeks of resistance training following the procedures described in the companion article by Hikida and colleagues (57).

Capillary analysis was begun with serial sectioning and mounting on coverslips of the same biopsy samples used for fiber typing and cross-sectional area determination (57). Capillaries were identified using a biotinylated-lectin procedure [*Ulex europaeus* agglutinin I; Vector Laboratories, Burlingame, CA (58)]. After drying the samples, the capillaries were distinguished by their black stain from muscle fibers that stained blue-green. Capillaries were counted directly under the microscope, whereas corresponding fiber types were determined by referring to the photomontages of mATPase-stained muscle samples corresponding to those samples serially stained for the capillaries. Fifty muscle fibers of each major fiber type (types I, IIA, and IIB) were analyzed.

Capillary density and capillary-to-fiber ratio were determined via an NIH imaging program (Macintosh computer) described previously in measurement of fiber cross-sectional area (57). For capillary density, the number of capillaries visible on the screen was determined, and this was divided by the area of the region under study (0.54 mm^2). This calculation was made for three different areas of each muscle sample, and results were pooled to give a single capillary density measurement. For capillary-to-fiber ratio, a similar analysis was utilized. All capillaries surrounding muscle fibers on the screen (again, 0.54 mm^2 area) were counted and divided by the number of fibers visible. This calculation was also made on 3 areas for each muscle sample, and results were pooled to yield a single value for capillary-to-fiber ratio. Capillary sharing was not taken into account, as these calculations reflect absolute numbers of capillaries surrounding each fiber.

Peak aerobic capacity.—Oxygen consumption was measured by computerized open-circuit spirometry, TEEM100 (AeroSport, Ann Arbor, MI), and heart rate and rhythm were monitored via 12-lead ECG during a standard Bruce treadmill protocol. Exercise blood pressure was measured every 3 minutes by auscultation.

Echocardiography.—Left ventricular structure was evaluated at rest using a Vingmed (Horten, Norway) CFM 750 echocardiographic unit with a 2.5 MHz mechanical transducer. Measurements were obtained using a 2-D guided m-mode evaluation of the left ventricle according to the criteria of the American Society of Echocardiography (59). During each evaluation a minimum of three sets of data were obtained and measured on-screen with electronic calipers. Each evaluation was recorded on videotape. The sets of data were examined at the end of the study, and the data set with the best echocardiographic quality was used for statistical evaluation. In this data set three consecutive beats were evaluated, analyzed for reproducibility (no significant differences were found), and averaged values were used for statistical evaluation. The following end diastolic measurements were used to determine changes in left ventricular structure: interventricular septum thickness (IVST), left ventricular internal dimension (LVID), posterior left ventricular wall thickness (PLVWT). Left ventricular mass (LVM) was calculated using the Penn convention equation: $LVM = 1.04\ (IVST + LVID + PWT)^3 - 14$. Mean wall thickness (MWT) and relative wall thickness (RWT) were calculated as follows: ($MWT = (IVST + PWT)/2$), $RWT = (IVST + PWT)/LVID$).

Hematology.—Following a 12-hour fast, pre- and post-training venous blood samples were drawn from the antecubital vein and were analyzed spectrophotometrically for serum lipids.

Statistical analysis.—A Student's *t* test was used to compare baseline values for the study groups. Two-way repeated measures analysis of variance (ANOVA), with time as a within-subject factor and treatment (resistance training) as a between-subjects factor, was used to compare the experimental and control groups over time. Super ANOVA version 1.1 and Instat 2.0 were used for the analyses; results were deemed statistically significant if the p value was $\leq .05$.

Training protocol.—Subjects in the experimental (RT) group trained twice a week for 16 weeks, and training sessions were separated by at least 48 hours. The training program used the same exercises as those involved with the 1 RM testing (double leg extension, double leg press, and half squat); all were designed to increase strength in the m. quadriceps femoris. These exercises were performed in the order listed above for each training session. Subjects with systolic blood pressure greater than 140 mmHg or a diastolic reading greater than 90 mmHg before exercise were monitored between exercise sets throughout each training session. Heart rate monitors were also worn by all subjects while exercising to compare cardiac responses among the specific exercises and accumulative effects of each exercise session and to assist in controlling training intensity. No cardiovascular problems or unusual episodes occurred during training. Each workout session consisted of 5 minutes of stretching and low-intensity (less than 50 Watts) warm-up on either a stationary cycle or rowing ergometer. The warm-up period was followed by one set of 10 repetitions of 50% of each subject's workout or training load (85–90% of 1 RM). This initial set was followed by 3 sets to failure of 6–8 repetitions at 85–90% of 1 RM with approximately 2 min rest between sets. Resistance (weights) was progressively increased to maintain a range of 6–8 repetitions per set for each exercise. This lifting procedure was followed for each of the 3 exercises in order. A 5 minute period of stretching and low-intensity cool-down on the cycle or rowing ergometer ended each exercise session. Although exercise intensity was higher than usually recommended for this age group, all subjects successfully tolerated the workload. However, the subjects were closely monitored and motivated by training assistants. With the exception of some early attrition by a few subjects because of injury, there was 100% compliance among the subjects and no complaints of excess or intolerable muscle soreness or fatigue.

Results

Physical characteristics of subjects.—Baseline values for age, height, weight, and percent body fat did not differ between the resistance trained (RT) and untrained (UT) groups; however, for percent body fat, the interaction between group and time was significant ($p = .01$); this indicates that percent body fat decreased significantly in the RT group ($p < .01$), while increasing (nonsignificantly) in the UT subjects. There was neither a significant main effect for group nor time (Table 1).

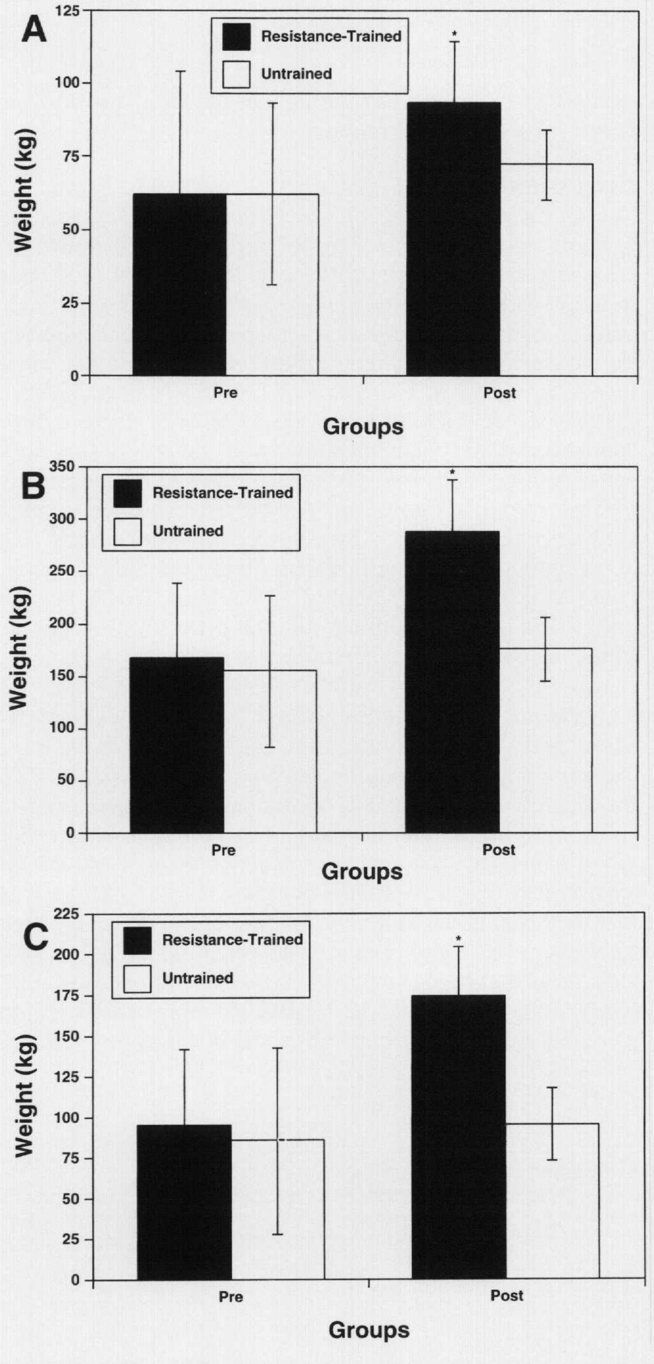

Figure 1. **A**, leg extension strength. **B**, leg press strength; **C**, half squat strength. Sample size 9 for resistance-trained, 9 for untrained. *Significant interaction between treatment and time effect; significant from preresistance training group and pre- and postuntrained group ($p < .0001$).

Muscle strength.—Baseline or pretraining values of maximal dynamic strength, as measured by 1RM testing, did not differ significantly between the RT and UT groups (see Figure 1). Sixteen weeks of progressive resistance training produced a significant increase in strength for all three lower limb exercises in the RT group. These increases of 1 RM strength from pretraining values were observed as 50.4% for leg extension, 72.3% for leg press, and 83.5% for half squat, and all were significant increases ($p < .0001$). There were no changes in strength for any of the exercises in the UT group.

Muscle biopsies.—There was an observable hierarchy of capillarization specific to each muscle fiber type. Although the differences in capillarization between fiber types were not statistically significant, type I fibers had more capillaries surrounding them than either the IIA or IIB fibers. The IIA fibers, however, were surrounded by an intermediate number of capillaries, and the IIB fibers had fewer capillaries than either of the other fiber types (Table 2). An increase in the number of capillaries per muscle fiber was seen with resistance training, indicating formation of new capillaries within the muscle. However, the 19% increase in capillarization in the RT group was not statistically significant. This relationship occurred in both experimental and control groups. This increase was not specific to any fiber type, as the number of capillaries surrounding muscle fibers of types I, IIA, and IIB did not change significantly over time between the two groups. Capillary density (measured as capillaries per mm^2) was also unchanged with training.

Peak aerobic capacity.—Results of pre- and post-training treadmill tests (Bruce protocol) are shown in Table 3. Mean pretraining treadmill time to exhaustion, $\dot{V}O_2$peak, absolute and relative (body weight and FFM), were not significantly different between the two groups. However, there was a significant interaction effect between group and time for all four variables: treadmill, time to exhaustion, peak $\dot{V}O_2$ abs, and peak $\dot{V}O_2$ rel to body weight ($p < .01$), and peak $\dot{V}O_2$ rel to FFM ($p < .05$). This indicates that all aerobic responses improved significantly for the trained group, whereas no significant changes in these variables were noted in the untrained group. Pre- and post-training average peak heart rates recorded during the Bruce protocol did not differ in either group, and neither did they differ between groups for either the pre- or post-training tests. The most significant difference in heart rate (HR) occurred during minute 4 of the Bruce protocol. During the pretraining treadmill test, the groups exhibited a similar response for min 4: RT = 121 b/min, and UT = 120 b/min, whereas the post-training test HR comparison for this same exercise intensity revealed a significantly lower HR response for RT group: 102 b/min vs 124 b/min for the UT group. Peak sys-

Table 2. Muscle Capillarization (Caps) for Resistance-Trained and Untrained Groups

	No. Caps/Type I	No. Caps/Type IIA	No. Caps/Type IIB	No. Caps/Total fiber	No. Caps/mm^2
Resistance-trained ($n = 9$)					
Pre	4.2 ± 0.4	3.8 ± 0.3	2.7 ± 0.1	1.5 ± 0.2	256 ± 30
Post	4.4 ± 0.6	4.1 ± 0.5	3.0 ± 0.4	1.8 ± 0.4	262 ± 48
Untrained ($n = 9$)					
Pre	4.3 ± 0.7	3.9 ± 0.4	3.0 ± 0.7	1.7 ± 0.4	295 ± 53
Post	4.3 ± 0.4	3.8 ± 0.3	3.1 ± 0.5	1.6 ± 0.3	296 ± 56

Notes: Values represent means ± standard deviation; n = number of subjects from whom adequate biopsy material was obtained; no significant group, time, or interaction effects were found.

tolic pressures did not differ within or between groups following training.

Echocardiography.—There were no significant changes in cardiac structure or dimensions as indicated by absolute echocardiography values (Table 4), and there were no significant differences between groups over time. IVST, LVID, posterior left ventricular wall thickness, LVM, MWT, and RWT, did not change for either group. Because there were no appreciable pre- to post-training changes in body surface area or significant changes in absolute echocardiographic data for either group of subjects, relative data were not reported.

Hematology.—Most serum lipid markers improved for the RT group following resistance training, but these changes were not statistically significant. The UT group showed no significant changes in any of these markers (Table 5).

Training.—Although repeated 1 RM measurements were not made throughout the study, the time course of strength gains can be demonstrated by examination of the increases in 8 RM strength that occurred with each exercise over time. This measure of strength was known because it corresponded to the workout loads of the subjects and had to be regularly increased throughout the study to maintain the desired 6–8 RM range for each exercise. A weakness of many previous training studies has been the failure to adequately maintain the desired intensity of exercise as training progressed. While a brief plateau was observed after 5 weeks (10 training sessions), strength gains were observed throughout the duration of the study for each of the exercises and were continuing to increase even as training ended (Figure 2). Desired intensity (85–90% 1 RM) for all three exercises was maintained throughout the study by ensuring progressive resistance training.

Discussion

Body composition.—The RT group significantly decreased percent body fat following 16 weeks of resistance training, and the UT group showed slight but nonsignificant percent body fat changes pre- to post-training (Table 1). Previous resistance training studies (60–62), including those involving elderly men and women (35,46,47), have reported that resistance training increased FFM as well as significantly decreasing percent body fat in the exercising subjects. Although our trained subjects showed an increase in FFM, it was not significant. An earlier resistance training study of elderly subjects by Chilibeck and colleagues (20) also reported a decrease in percent body fat without a concomitant change in FFM or FM. The relative loss in percent body fat in our older subjects did not differ from responses found in younger resistance-trained subjects (60–62).

Muscular strength.—Significant gains in maximal dynamic strength (1 RM) were observed for each of the three exercises in the RT group: +50.4% for leg extension; +72.3 for double leg press; and +83.5% for half squat. These strength gains were larger than in many of the previous studies involving this age group, where subjects trained at a lower intensity; less than 75% 1 RM as opposed to 85–90% 1 RM that was used in our study, or for shorter duration; less than 12 weeks (35,63–66). Other protocols in which aging subjects trained at higher intensities (80% 1 RM) and for relatively long duration (>12 weeks) demonstrated strength gains nearly equal to those observed in this study (29–33,

Table 3. Treadmill Data for Resistance-Trained and Untrained Groups, Bruce Treadmill Protocol

	Treadmill Time (min)	$\dot{V}O_2$ (L/min)	$\dot{V}O_2$ (ml/kg/min)	$\dot{V}O_2$/FFM (ml/kg/min)
Resistance-trained ($n = 9$)				
Pre	7.83 ± 1.98	2.67 ± 0.39	31.9 ± 3.55	42.2 ± 5.1
Post	8.53 ± 2.23**	2.87 ± 0.48**	34.9 ± 4.77**	44.6 ± 4.8*
Untrained ($n = 9$)				
Pre	8.83 ± 2.41	2.65 ± 0.49	33.1 ± 6.18	42.1 ± 6.0
Post	8.17 ± 2.06	2.58 ± 0.62	32.0 ± 7.42	41.5 ± 4.9

Notes: Values represent means ± standard deviation. There was a significant interaction between group and time effect for all four variables. $^*p < .05$; postresistance trained value was significantly different from preresistance and pre- and postuntrained values. $^{**}p < .01$; postresistance trained values were significantly different from preresistance and pre- and postuntrained values.

Table 4. Absolute Echocardiographic Data for Resistance-Trained and Untrained Groups

	IVST (cm)	LVID (cm)	PLVWT (cm)	LVM (g)	MWT (cm)	RWT (cm/cm)
Resistance-trained (n = 9)						
Pre	1.28 ± 0.30	5.01 ± 0.65	1.00 ± 0.21	268 ± 109	1.14 ± 0.23	0.46 ± 0.09
Post	1.20 ± 0.24	5.22 ± 0.69	0.94 ± 0.17	258 ± 81	1.07 ± 0.13	0.41 ± 0.06
Untrained (n = 9)						
Pre	1.27 ± 0.22	4.91 ± 0.29	1.04 ± 0.18	265 ± 40	1.16 ± 0.14	0.47 ± 0.08
Post	1.36 ± 0.23	4.95 ± 0.36	1.01 ± 0.24	274 ± 45	1.18 ± 0.10	0.47 ± 0.06

Notes: Values represent means ± standard deviation. IVST = Interventricular septum thickness; LVID = Left ventricular internal dimension; PLVWT = Posterior left ventricular wall thickness; LVM = Left ventricular mass; MWT = Mean wall thickness; RWT = Relative wall thickness.

67–71). The amount that strength increases may depend upon the initial level of conditioning, as subjects of extreme age showed the greatest improvement in strength after training (32). It is therefore possible for elderly men to perform supervised resistance training at very high intensities and at the same time tolerate absolute workloads comparable to younger subjects. Excessive strength gains resulted.

Muscle biopsies.—It appears that skeletal muscle of older untrained subjects, if introduced to a highly specific and localized resistance training regimen of sufficient intensity (85–90% 1 RM), minimal frequency (2 days/week), and of relatively long duration (16 weeks), will respond with relative strength gains comparable to or even surpassing those of younger subjects following a similar training protocol (62). The strength gains were accompanied by transitions in the fast fiber population (57). The percentage of IIA fibers showed a strong tendency to increase, whereas the percentage of IIB fibers decreased significantly ($p < .05$). Significant increases in cross-sectional areas were observed for all major fiber types. These intramuscular responses are consistent with significant increases in strength, and these findings were similar to previous data reported for younger subjects (61,62). It is not possible to determine the specific roles of neural and hypertrophic influences on the strength gains in this study, but it is evident that hypertrophy contributes significantly to strength improvement in older subjects just as it does in their younger counterparts. It is therefore possible that high-intensity resistance training may prevent atrophy and loss of muscle fibers and motor units (10,62,72,73) that are often associated with aging and inactivity.

Muscle capillarization increases with endurance training in both young and old populations as well as with resistance training in young subjects (20,25,74–77). However, very little is known about the effects of high-intensity progressive resistance training on capillary supply in aging muscle. Resistance training studies with young subjects have produced conflicting results; Luthi and associates (78) showed no change in capillary supply, whereas Tesch and colleagues (22) reported a decreased capillary density after resistance training. Results of our study suggested that a hierarchy existed for muscle capillarization that was fiber-type specific; more capillaries surrounding type I fibers than the other fiber types (see Table 2). This hierarchy was unaffected by training and agrees with the results of other studies (79, 80), which demonstrated that muscle fiber capillarization is related to the quantity of mitochondria and, thus, the oxidative capacity of the fiber (I > IIA > IIB). Nonsignificant changes were observed for post-training capillary density (# cap/mm^2) for the RT group. This is not surprising because significant hypertrophy was observed in all fiber types (57), and capillary growth could have been masked by the increased area occupied by the muscle fibers. The number of capillaries per muscle fiber (pooled for all fiber types) tended to increase (19% with training, although not statistically significant), which seemed to indicate a physiological change. This relationship is thought to be a sensitive indicator of capillary proliferation as it is unaffected by changes in muscle fiber cross-sectional area (81). Our results agree with muscle capillary data previously reported for elderly subjects who had resistance training. Frontera and colleagues (68) found that capillary-to-fiber ratio increased 15% after 12 weeks of high-intensity resistance training, whereas Hepple and associates (70) reported similar changes following 9 weeks of resistance training. Subjects in the Frontera study trained 3 times a week, so that the total number of training sessions, 36, was similar to the total 32 training sessions in our study. Since capillary-to-fiber ratio is directly proportional to a muscle fiber's oxidative capacity (82), there is strong evidence, when combined with the possible fast fiber type conversions to more oxidative fiber types (IIA or IIAB), for an increased oxidative response to high-intensity resistance

Table 5. Hematology–Lipid Profile for Resistance-Trained and Untrained Groups

	Cholesterol (mg/dl)	Triglycerides (mg/dl)	HDL-C (mg/dl)	LDL-C (mg/dl)	VLDL-C (mg/dl)	C/HDL ratio
Resistance-trained (n = 7)						
Pre	229.9 ± 46.81	121.7 ± 39.41	38.8 ± 8.30	166.8 ± 41.62	24.2 ± 6.88	5.93 ± 2.10
Post	213.9 ± 44.22	99.8 ± 32.14	46.9 ± 7.62	144.4 ± 35.56	19.9 ± 7.84	4.56 ± 1.86
Untrained (n = 7)						
Pre	204.9 ± 24.47	142.2 ± 42.65	36.9 ± 7.77	139.5 ± 28.60	28.4 ± 8.59	5.55 ± 1.52
Post	209.3 ± 32.84	141.9 ± 46.54	40.7 ± 9.31	139.7 ± 32.51	28.4 ± 9.22	5.14 ± 1.31

Notes: Values represent means ± standard deviation.

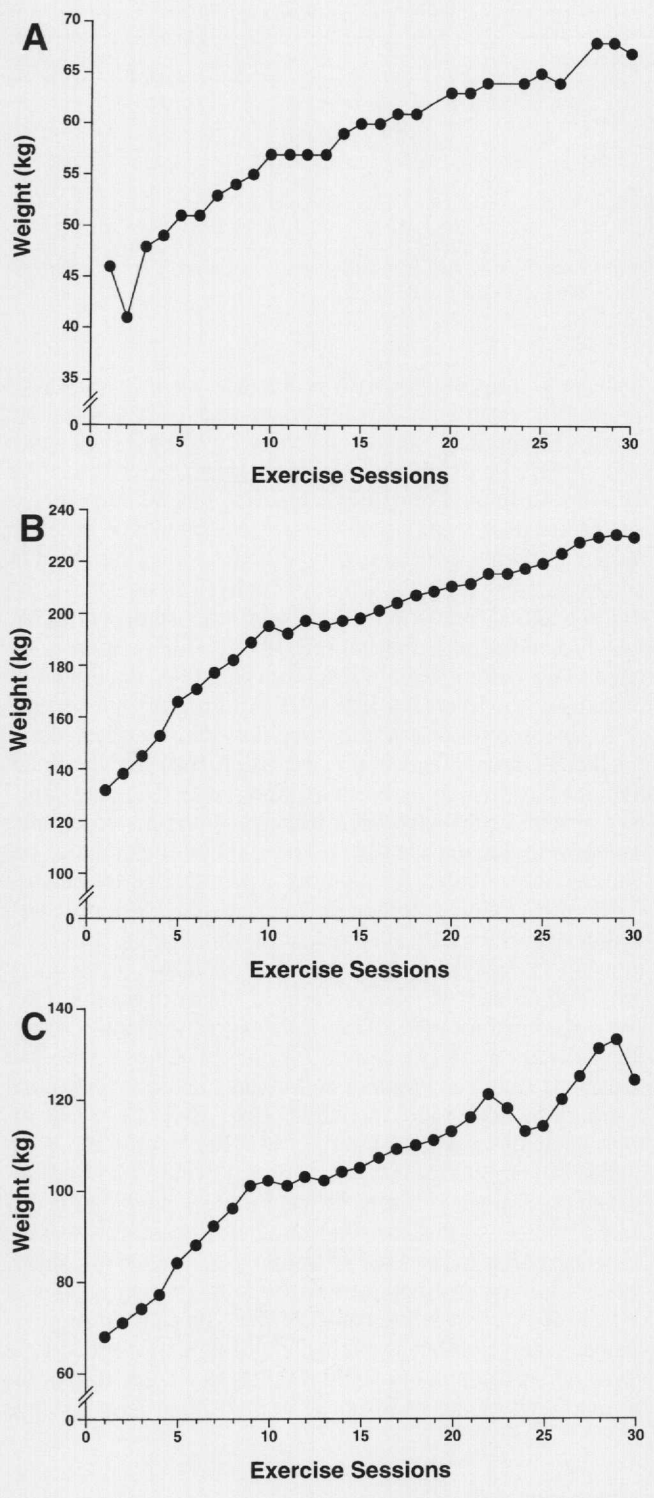

Figure 2. **A**, mean total weight lifted for leg extension per workout per subject; **B**, mean total weight lifted for leg press per workout per subject; **C**, mean total weight lifted for half squat per workout per subject.

training in the elderly population. Both Hepple and Chilibeck and colleagues (19,20) suggest a strong relationship between increased capillarization and improved $\dot{V}O_2$ kinetics. The mechanism of angiogenesis in skeletal muscle is not known with certainty, but it is believed to involve rate of blood flow to muscle fibers (83), ischemia (84), or muscle damage (85). Any of these responses could occur with high-intensity resistance training and account for the increased capillarization. It has also been suggested that capillary proliferation lags behind mammalian muscle hypertrophy (86) and may explain why the capillary changes were of a lower magnitude than the increases observed in muscle cross-sectional area. However, in a more recent study (87), it was reported that there was a strong relationship between angiogenesis and hypertrophy. It is clear that the relationship between these two factors needs further study.

Peak aerobic capacity.—Several studies have reported that resistance training has little or no effect on cardiorespiratory endurance (88). However, a significant increase was observed for absolute and relative values of $\dot{V}O_2$peak for our RT subjects. A significant increase was also observed for pre- to post-treadmill time for the resistance-trained group. Although no difference was noted for peak treadmill test heart rates between the RT group and UT group, it was interesting to note that there was no difference between heart rates for the two groups at the fourth min of the pretraining Bruce protocol; however, a significant difference was recorded for this same time period in the Bruce post-training test: 102 b/min for RT group and 124 b/min for UT group. The RT group was able to achieve a steady state at a lower heart rate for a given exercise intensity, responses not observed for the UT group. Our cardiorespiratory data suggest that high-intensity resistance training in older subjects may, indeed, act as an aerobic stimulus and agree with previous findings (19,30,68). Inclusion of an aerobic component is further substantiated by the significant conversion of IIB to IIA or IIAB fibers and increased capillarization (57). It may be that the initial sedentary state of the subjects in combination with the accumulative effects of repeated resistance training exercises served to improve the capacity of the muscle to use oxygen. Intramuscular peripheral changes affecting oxygen uptake and aerobic metabolism have been discussed previously and appear similar to our findings (68). It is also possible that the significant strength increases exhibited by the RT group may have, at least in part, accounted for the increased time to exhaustion on the treadmill following training. Peak HR and blood pressure during the treadmill test did not differ between or within groups from pre- to post-training. There were also no differences between or within groups for post-training HR and blood pressure during lifting at 60, 80, and 100% of the post-training 1 RM. Therefore, post-training HR and blood pressure responses were the same as the pretraining values when the same relative work loads were used, and these findings agree with those of McCartney and colleagues (89). Heart rate and blood pressure were not measured for pre- to post-comparison at absolute work loads. It has been suggested that cardiovascular control mechanisms are more closely associated with relative intensity rather than to the absolute effects of the resistance (89). Heart rate and blood pressure responses to an isometric exercise did differ between young and older men, as the older subjects had a lower heart rate and a higher blood pressure response than their younger counterparts, and the differences were exaggerated as muscle tension increased (90). However, these responses may not apply during isotonic loading used in our study.

Echocardiography.—The aging process is associated with a number of cardiac changes. Several studies have reported increasing left ventricular hypertrophy; although left ventricular systolic function seems little affected by aging, left ventricular diastolic filling appears to be compromised (91). Recent studies have indicated that endurance exercise training of older subjects can reverse ventricular diastolic dysfunction (92,93). However, there have been only a few references to the effects of resistance training on cardiac functions of elderly people. Sagvi and associates (94) recently examined the effects of sustained static muscle contraction on left ventricular systolic function via Doppler echocardiography and reported that elderly weight lifters showed greater left ventricular systolic improvement than those of three younger groups of subjects. Because the resistance exercise in this study was isometric, it is not possible to make accurate comparisons with cardiac responses observed for our subjects. Resistance training is usually associated with increased cardiac wall thickness and left ventricular, mass which are thought to occur because of the transient elevation in blood pressure during training (95).

Echocardiographic and magnetic resonance imaging (MRI) data indicate that resistance-trained athletes have enlarged posterior left ventricular and interventricular septum wall diameters (95–97), and these results suggest a training afterload effect. However, other studies have reported that resistance training improves both ventricular and atrial volumes (96,98), and that absolute values for left ventricular mass and volumes did not differ between bodybuilders and endurance-trained athletes; when these data were expressed relative to body weight, however, the endurance athletes had significantly greater values for mass and volumes. In fact, when ventricular mass and volumes of resistance-trained athletes are expressed relative to body weight or FFM, they do not differ from normal untrained subjects.

There were no indications from the resting echocardiographic evaluation of our elderly subjects to suggest the development of left ventricular hypertrophy as the result of resistance training. The occurrence of concentric left ventricular hypertrophy has been suggested to be a normal adaptation to the pressure load produced by resistance training or sports that contain a high static demand (99), but this was not observed in our subjects and may be due to the limited duration of this study. However, the nonsignificant changes in wall thickness, left ventricular chamber size, and the relative wall thickness tend to suggest some eccentric left ventricular hypertrophy. Although high-intensity resistance training has often been contraindicated for older subjects, none of the echocardiographic, electrocardiographic, or blood pressure data indicated pathologies resulting from this study. To our knowledge, no other studies have examined the effects of resistance training on cardiac structure in this population.

Hematology.—No statistically significant changes were noted for any specific blood lipid-related tests for either of the two groups of subjects; however, each of the lipid markers for the RT group showed appreciable improvement following training. The reduction of total cholesterol (TC) and very low-density lipoproteins (VLDL-C) and, more importantly, a decrease in total cholesterol/high density lipoprotein (HDL-C) ratio, indicate a possible physiological effect of resistance training on our elderly subjects and a very positive trend. TC/HDL-C ratio for the RT group was lowered from a high risk value (>5.2) for developing coronary artery disease to a moderate risk value (<4.5). Resistance-trained younger male athletes have exhibited wide variability in serum lipid profiles (53,54). The lipid profiles of body builders are similar to those of distance runners, but power lifters exhibited lower HDL-C and higher LDL-C values than runners; these comparisons were relative to age, body density, and anabolic–androgenic steroid use; synthetic testosterone tends to lower HDL-C values (100,101). Although it appears that high-volume resistance training programs (low resistance–high repetitions) and aerobic endurance training programs probably have had the most effect on lipid profiles, similar responses were observed for our older male subjects following a very high-intensity resistance training program (high resistance–low repetitions) of relatively long duration. This change represents a meaningful health benefit and is similar to observations following strictly endurance training (27). Despite exercising only two sessions per week, the intensity of the work was of a sufficient stimulus to cause improvement in serum lipids, and this response may be unique to aging subjects who had previously experienced a very sedentary existence.

Training.—Although recommendations of exercise training intensity and duration for aging subjects have been, for the most part, quite conservative, it is clear that not only is it possible for elderly people to tolerate resistance training of high-intensity (85–90%) and long duration (16 weeks), but that a regimen of this type may be necessary to elicit optimal physiological responses in this age group.

Furthermore, this study demonstrated that although a brief plateau was observed at about 5 weeks (10 training sessions), muscular strength continued to increase throughout the training period for each of the three exercises. No plateau of strength responses was shown in a study where exercise intensity was low (70). Other studies of longer duration and higher intensity resistance training involving an elderly population also produced no strength plateaus (29,69,89). Our data suggest that healthy older male subjects can safely tolerate high-intensity resistance training on a progressive basis, and there seems to be no limit to maximal strength increases that these subjects can achieve with this type of training, provided it is of sufficient duration.

Conclusions

Based on our findings, several important points can be made. First, it is clear that skeletal muscle in elderly, previously untrained men will respond with significant strength gains accompanied by considerable hypertrophy if sufficiently stressed at a high enough intensity for a relatively long period of time. Furthermore, significant hypertrophic and fiber conversion responses were also accompanied by an increase in the number of capillaries per fiber, and because capillary and capillary density remained unchanged, there was no "dilution effect." These changes were similar to responses of resistance-trained young subjects. Finally, peak aerobic and maximal working capacities showed significant improvements, whereas cardiac mass and volume were unaffected in both groups of subjects. Changes in capillarization and serum lipid profiles, although improved, were nonsignificant. These nonsignificant responses may be due, in part, to the rather modest sample size.

These changes were induced by 16 weeks of relatively high-intensity resistance training (85–90% 1 RM), which demonstrated that elderly men can not only tolerate these very high workloads but will exhibit muscular changes similar to their younger counterparts.

Results of this study suggest that (a) the level of exercise intensity to maximize results of resistance-trained elderly men may need reevaluation, and (b) high-intensity resistance training can be practiced by reasonably healthy aging men and can be safely incorporated as part of any general fitness program for this population.

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