High-Intensity Strength Training in Nonagenarians: Effects on Skeletal Muscle

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High-Intensity Strength Training in Nonagenarians

Effects on Skeletal Muscle

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Muscle dysfunction and associated mobility impairment, common among the frail elderly, increase the risk of falls, fractures, and functional dependency. We sought to characterize the muscle weakness of the very old and its reversibility through strength training. Ten frail, institutionalized volunteers aged 90 ± 1 years undertook 8 weeks of high-intensity resistance training. Initially, quadriceps strength was correlated negatively with walking time ($r = -.745$). Fat-free mass ($r = .732$) and regional muscle mass ($r = .752$) were correlated positively with muscle strength. Strength gains averaged 174% ± 31% (mean ± SEM) in the 9 subjects who completed training. Midthigh muscle area increased 9.0% ± 4.5%. Mean tandem gait speed improved 48% after training. We conclude that high-resistance weight training leads to significant gains in muscle strength, size, and functional mobility among frail residents of nursing homes up to 96 years of age.

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A DECLINE in muscle strength is one of the more predictable features of aging.[1] However, the contributions of biologic aging, cumulative diseases, a sedentary life-style, and nutritional inadequacies to the pathogenesis of this syndrome are unclear. The controversy rests in part on the observation that type II fiber atrophy in skeletal muscle is common to disuse syndromes,[2] undernutrition,[3] and aging itself.[4] Theoretically, it should be possible to intervene in the atrophy of disuse with strength training, thereby reversing some portion of the "age-related" decline in muscle function. Although the safety and efficacy of high-resistance strength training has been demonstrated in healthy older men,[5] a similar intervention in frail, institutionalized elderly men or women has not been studied. Because muscle weakness in the frail elderly has been linked to recurrent falls[6,7] (a major cause of morbidity and mortality[8]), the clinical relevance of such an intervention is clear. Therefore, this study was undertaken to determine the feasibility and the physiological consequences of high-resistance strength training in the frail elderly.

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SUBJECTS AND METHODS

Subject Selection

Subjects were recruited from among the residents of the Hebrew Rehabilitation Center for Aged, Boston, Mass, a 725-bed, multilevel academic long-term care facility. The protocol was approved by the Human Investigations Review Committees of Tufts University and Hebrew Rehabilitation Center for Aged. Eligible residents were ambulatory, not acutely ill, able to follow simple commands, and not suffering from unstable cardiovascular disease or other uncontrolled chronic conditions that would interfere with the safety and conduct of the training protocol.

Subject Characteristics

A chart review was used to obtain medical history and functional status. Fasting weight was measured to the nearest 0.1 kg using a balance beam scale. Height was measured to the nearest 1.0 mm using a wall-mounted ruler. Skin folds were measured by a single investigator (E.C.M.) at seven sites to the nearest 0.5 mm using a standard technique.[9]

Body composition was further assessed using the dilution space of the stable isotope $H_2^{18}O$ to calculate total body water, with analysis by isotope ratio mass spectrometry (Sira 10, VG-Isogas, Cambridge, England).[10,11]

Table 1.—Clinical Characteristics of the 10 Subjects

Characteristic	Mean ± SEM	Range*
Age, y	90.2 ± 1.1	86-96
Sex, No.		
F	6	NA
M	4	NA
Length of stay, y	3.4 ± 0.8	0.7-8.3
No. of subjects with pattern of care		
Level 1	4	NA
Level 2	6	NA
No. of subjects with a history of falls	8	NA
No. of subjects with habitual use of an ambulatory assistive device	7	NA
No. of chronic diseases/person	4.5 ± 0.6	2-7
No. of daily medications/person	4.4 ± 0.8	0-9

*NA indicates not applicable.

A 3-day diet record was obtained by weighing all food and beverage portions before and after consumption. Food records were then coded and analyzed by the Human Nutrition Research Center Division of Scientific Computing using the US Department of Agriculture Nutrient Data Base (GRAND, release YYM 879, US Department of Agriculture-Agricultural Research Service Grand Forks Human Nutrition Research Center) and the 1980 recommended daily allowance for adults aged 51 years or older.[12]

Muscle strength of the knee extensors (quadriceps femoris) was measured using a standard weight-and-pulley system (NK 665, G. E. Miller, New York, NY). The *one repetition* maximum was defined as the highest weight the seated subject could lift one time only from 90° of knee flexion to maximal knee extension.[13] After familiarization with the equipment, right and left legs were tested sequentially with continuous-monitoring electrocardiograms and blood pressure monitoring every 3 to 4 minutes during initial sessions. Weights were added in small increments (0.5 to 1.0 kg), resting 30 seconds between lifts, until the subject could no longer fully extend the knee. The coefficient of variation of this technique in this population is 13%.

Functional mobility was tested by the chair stand maneuver and gait observations. For these tests, the best of two or three trials was reported. The subject was timed to the nearest 0.1 second while attempting to rise without using his or her arms from a hard, straight-backed chair with a seat height of 43 cm. Habitual and tandem gait speed were assessed during a 6-m walk.

Regional body composition was determined using computed tomography (CT) scans of the nondominant thigh with the subject supine and the leg relaxed. A CT scanner (Siemens DR3 CT Scanner, Somatom-Siemens, Erlangen, Federal Republic of Germany) was used to obtain a 4-second scan with a width of 8 mm at the midpoint between the inguinal crease and the proximal pole of the patella. The CT images were digitized by optical density and analyzed as previously described.[5] The areas calculated to the nearest 0.01 cm^2 were total leg, total fat, subcutaneous fat, intramuscular fat, total muscle, quadriceps, hamstrings and adductors, and bone. All scans were analyzed in "blinded" fashion by a single investigator (M.A.F.), with the mean of triplicate calculations reported. The coefficient of variation of this technique in our laboratory is 0.5% to 1.5%.

Training Protocol

The 8-week training protocol used was an adaptation of standard rehabilitation principles of progressive-resistance training, employing concentric (lifting) and eccentric (lowering) muscle contraction.[15] The initial one repetition maximum was used to set the load for the first week at 50% of the one repetition maximum. Three times per week the subjects performed three sets of eight repetitions with each leg in 6 to 9 seconds per repetition, with a 1- to 2-minute rest period between sets. By the second week, or as tolerated, the load was increased to 80% of the one repetition maximum. The one repetition maximum was remeasured every 2 weeks and the training stimulus adjusted to keep the load at 80% of the new one repetition maximum. Training was conducted under constant individual supervision by one of the study investigators, with intermittent monitoring of pulse rate and blood pressure.

All physiological measurements were obtained at baseline and repeated within 1 week of completion of training. One repetition maximum measurements additionally were repeated after 2 and 4 weeks of detraining.

STATISTICAL ANALYSIS

All data are reported as mean ± SEM. Differences before and after training were analyzed by repeated measures analysis of variance using the Neuman-Keuls Test for differences between group means or paired t tests as appropriate. All t tests were two tailed, unless otherwise specified in the text. Relationships between variables of interest were determined using least-squares linear regression. Significance was assumed at the 5% level. All statistical analyses were carried out using the SAS[16] statistical package on a computer.

RESULTS

Baseline Characteristics

Medical and Functional Status.— At the time of the study, the long-term care facility housed 712 residents with an average age of 87.9 years. Seventy-five percent of the residents were women; all residents were divided into three levels of care: level 1, independent or minimal assistance with activities of daily living (21.5%); level 2, moderate assistance (29.9%); and level 3, maximal assistance (48.6%). Among the first 36 residents screened, 22 (61%) qualified for the study, of whom 10 (45%) gave informed consent and were enrolled in the study. Reasons for exclusion included recent myocardial infarction or fracture, behavioral disturbance, and severe arthritis.

The clinical characteristics of the 10 subjects enrolled in the protocol are given in Table 1. The most common medical diagnoses were osteoarthritis (7 subjects), coronary artery disease (6 subjects), osteoporotic fracture (6 subjects), and hypertension (4 subjects). Medications were prescribed primarily for gastrointestinal tract (31%), cardiovascular (25%), neuropsychiatric (14%), or analgesic (8%) indications.

Nutritional Status.— Four of 10 subjects had anthropometric evidence of undernutrition, as they were between 72% and 88% of ideal body weight according to the Gerontology Research Center tables.[17] Fat-free mass, as estimated by the dilution space of $H_2{}^{18}O$, was higher in men than women (41.6 ± 2.2 kg vs 35.4 ± 1.7 kg, $P = .05$). The sum of seven skin-fold measurements was correlated highly with percent body fat calculated from the difference between body mass and fat-free mass ($r = .89$, $P < .001$).

Dietary intake of energy was adequate at 29.1 ± 2.2 kcal/kg per day, and protein intake averaged 1.3 ± 0.1 g/kg per day. However, substantial proportions of the group did not obtain the recommended daily allowance for im-

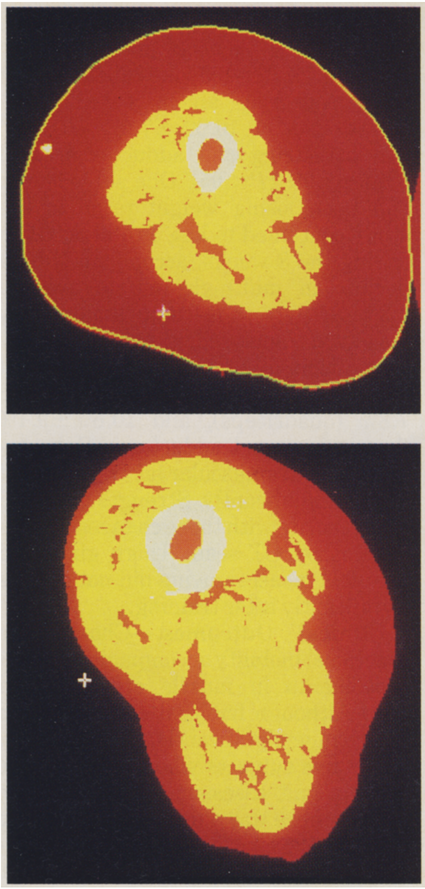

Fig 1.—Computed tomographic scans of the midthigh digitized by optical density. Top, A 90-year-old woman who is ambulatory with a wheelchair. Bottom, An 87-year-old man who is independently ambulatory. Red indicates fat; yellow, muscle; and white, bone.

Table 2.—Baseline Midthigh Composition by Computed Tomography Among Eight Subjects*

Component	Area, cm²	Relative Area, %
Total leg	162.55 ± 19.75	100
Total muscle	51.16 ± 2.93	31
Quadriceps	18.68 ± 1.47	11
Hamstrings and adductors	32.49 ± 2.21	20
Total fat	106.07 ± 18.01	65
Subcutaneous	97.60 ± 17.62	60
Intramuscular	8.46 ± 1.14	5

*Computed tomographic scans could not be digitized in two subjects due to technical problems. All area values are expressed as means ± SEMs.

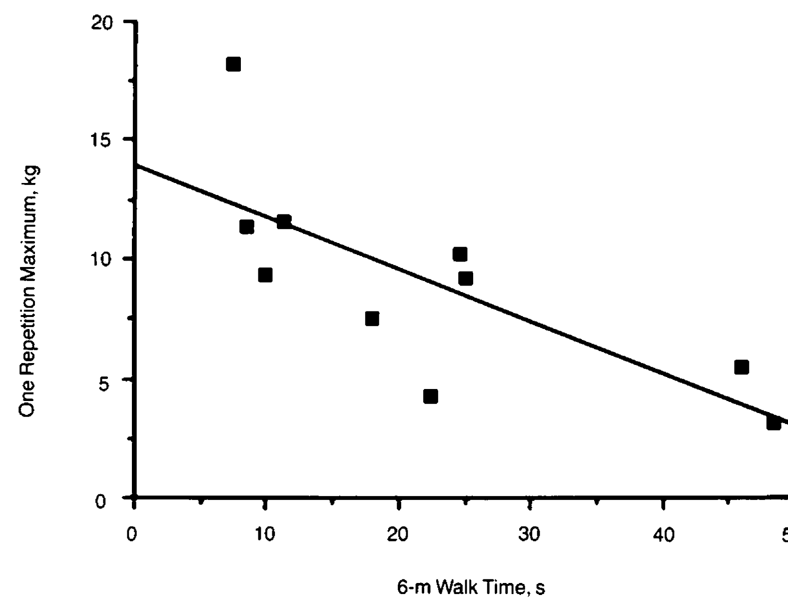

Fig 2.—Initial muscle strength and functional mobility. One repetition maximum vs the time taken to walk 6 m at baseline ($r = -.745$, $P<.01$).

portant micronutrients from their diet.

Digitized CT scan images of two representative subjects (one man and one woman), shown in Fig 1, are notable for the large amounts of subcutaneous and intramuscular fat. Midthigh composition before training is displayed in Table 2. Muscle accounted for only 31% of the total cross-sectional area of the thigh. Regional muscle area by CT scan was related directly to total body fat-free mass ($r = .98$, $P<.0001$).

Baseline Muscle Function

Dynamic quadriceps (knee-extensor) strength of the 10 subjects was 9.0 ± 1.4 kg on the right and 8.9 ± 1.7 kg on the left. No significant effect of sex, length of institutionalization, or level of care was seen. The one repetition maximum was correlated positively with fat-free mass ($r = .732$, $P<.01$) and midthigh muscle area ($r = .752$, $P<.01$). Simple linear regression showed a significant relationship ($P<.01$) between muscle strength at baseline and dietary intakes of vitamin B_6 ($r = .745$), magnesium ($r = .792$), and potassium ($r = .745$), but not total calories.

The time taken to stand from a chair averaged 2.2 ± 0.5 seconds and was related inversely to dominant quadriceps strength ($r = -.630$, $P<.05$). The 6-m walk time ranged from 7.4 to 48.3 seconds, with an average of 22.2 ± 4.6 seconds, and also was related inversely to the dominant leg one repetition maximum ($r = -.745$, $P<.01$) (Fig 2). A similar pattern was seen for the number of steps in the 6-m walk ($r = -.717$, $P<.01$).

Seven subjects were able to tandem walk (heel-to-toe) the 6-m distance in an average of 42.7 ± 10.3 seconds. Tandem walking time was related inversely to dominant quadriceps strength ($r = -.786$, $P<.05$).

Response to Training

Tolerance of Training Regimen.—Nine of 10 subjects completed the training protocol. One man aged 86 years stopped at 4 weeks at our suggestion because of a straining sensation during training at the site of a previously repaired inguinal hernia. The attendance rate was 98.8% for the 8-week program in the 9 subjects who completed the study. No cardiovascular complications were seen. Blood pressure and pulse rate varied little (systolic blood pressure, <10 mm Hg; pulse rate, <5 beats/min) during the training sessions. Four subjects infrequently experienced minor hip or knee discomfort during exercise, but no one required analgesic medications or missed training sessions because of this. All participants were able to perform the exercises as planned, averaging a load of 79.5% of their one repetition maximum.

Muscle Strength.—Gains in muscle strength were highly significant and clinically meaningful in all subjects. The average strength gain at 8 weeks was

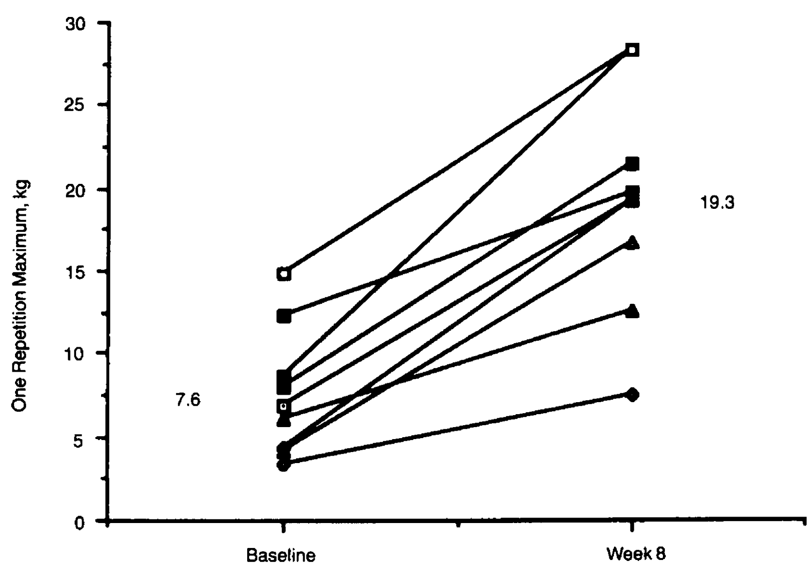

Fig 3.—Effects of weight training on knee extensor strength. Maximum left knee extensor strength before and after 8 weeks of high-intensity progressive-resistance training in nine subjects aged 87 to 96 years ($P<.0001$ compared with baseline). Similar strength gains were seen in the right leg (see text). Symbols represent individual subjects.

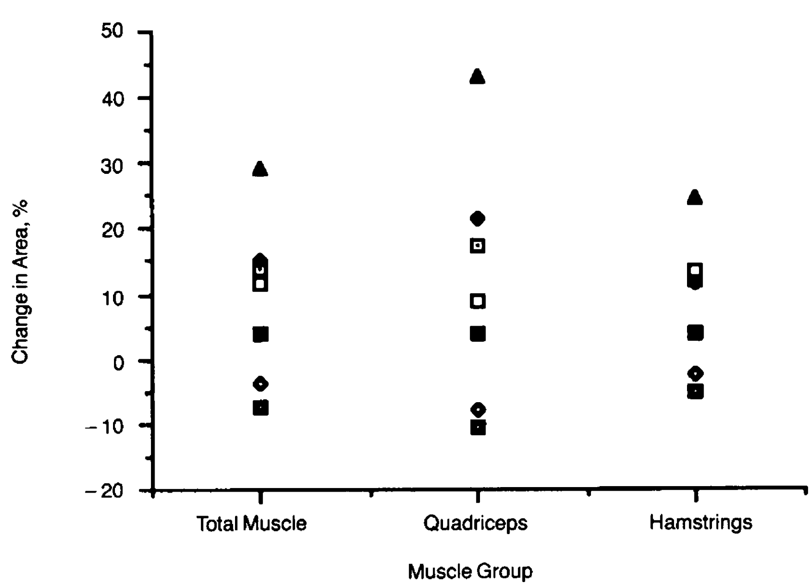

Fig 4.—Muscle hypertrophy due to strength training. Percent change in muscle area of the nondominant midthigh by computed tomographic scan after 8 weeks of strength training in seven subjects. Total muscle area increased 9.0% ± 4.7% ($P=.05$); quadriceps area, 10.9% ± 7.0% ($P=.09$); and hamstring and adductors area, 8.4% ± 3.9% ($P<.05$). Symbols represent individual subjects.

174% ± 31% (167% ± 28% on the right and 180% ± 33% on the left, $P<.0001$). Absolute weight lifted increased from 8.02 ± 1.0 kg to 20.6 ± 2.4 kg with the right leg and from 7.6 ± 1.3 kg to 19.3 ± 2.2 kg with the left leg. Individual strength gains are shown in Fig 3. Strength gain was progressive throughout the protocol and had not plateaued at 8 weeks. Responsiveness to training was not different in men vs women.

Muscle Size.—Seven subjects had CT scans digitized before and after training, and muscle area increased in five of them. As shown in Fig 4, total midthigh muscle area increased 9.0% ± 4.7% ($P=.05$, one-tailed paired t test), reflecting an increased quadriceps area of 10.9% ± 7.0% ($P=.09$) and hamstring and adductor area of 8.4% ± 3.9% ($P<.05$). One subject who had been losing weight prior to the study continued to lose a total of 3.2 kg during the 8 weeks, accompanied by a decline in midthigh muscle area of 4.3%. If only those with stable body weight are analyzed, the mean muscle area increases are significant at $P<.05$: 11.7% ± 5.0% (total), 14.5% ± 7.8% (quadriceps), and 10.6% ± 9.1% (hamstrings and adductors). Subcutaneous or intramuscular fat areas did not change significantly. Strength gains did not correlate with these changes in muscle size by CT scan. Thigh girth and skin-fold measurements did not change significantly after training.

Clinical Outcomes.—Changes in functional mobility accompanied the improvements in muscle strength and size. Although habitual gait speed did not change significantly with training, in the five subjects who completed the tandem gait assessment at both time points, there was a decrease in walking time, from 43.4 ± 25.7 to 29.6 ± 22.4 seconds ($P=.05$, one-tailed paired t test). This represents a 48% improvement in tandem gait speed, from 13.8 cm per second to 20.4 cm per second. Two subjects no longer used canes to walk at the end of the study. One of three subjects who could not initially rise from a chair without use of the arms became able to do so.

No significant changes were noted after training in overall nutritional status, total body composition, or functional status. None of the participants experienced any falls during the protocol.

Detraining Effects

All subjects resumed their sedentary life-style after the experimental intervention ended. In seven of nine subjects who completed the study, one repetition maximum testing was repeated after 2 and 4 weeks of detraining. In these subjects, dominant quadriceps strength declined from a peak of 136% ± 16% above baseline at week 8, to 115% ± 23% at week 10, to 92% ± 23% at week 12 ($P<.05$). Thus, a significant 32% loss of maximum strength was seen after only 4 weeks of detraining.

COMMENT

The major finding of the study is that a high-intensity weight-training program is capable of inducing dramatic increases in muscle strength in frail men and women up to 96 years of age. The

Table 3.—Strength Training Trials in the Elderly

Source	No. of Subjects/ Sex	Mean Age, y	Type of Training*	Resistance	Duration, wk†	Muscle Group	Mean Strength Increase, %
Perkins and Kaiser[20]	15/F	73.6	Static	High	6	Knee extensors	57
	5/M		Dynamic	Moderate	6	Knee extensors	64
Liemohn[21]	6/M	61-70	Static	High	6	Knee extensors and flexors	17 and 24, respectively
Aniansson and Gustafsson[22]	12/M	71	Static and dynamic	Low	12	Knee extensors	9-22
	12/M (controls)	...	...	...	...	None	0
Moritani and deVries[23]	5/M	70	Dynamic	High	8	Elbow flexors	23
	5/M	22					30
Larsson[24]	18/M	22-65	Dynamic	Low	15	Knee extensors	2.9-7.5‡
Kauffman[25]	10/F	69	Static	High	6	Abductor digiti minimi	72
	10/F	23					95
Frontera et al[5]	12/M	60-72	Dynamic	High	12	Knee extensors and flexors	107 and 227, respectively
Hagberg et al[26]	23/M, F	70-79	Dynamic	Low-moderate	26	Upper and lower body	18 and 9, respectively
Current study	10/M, F	90	Dynamic	High	8	Knee extensors	174

*Static indicates isometric; dynamic, isotonic.
†All training sessions were conducted 3 days per week except for those by Larsson,[24] which were 2 days per week.
‡Not significant.

increase in lower-extremity strength ranged from 61% to 374% over baseline, with subjects demonstrating a threefold to fourfold increase on average in as little as 8 weeks. Because muscle strength decreases by perhaps 30% to 40% during the course of the adult life span,[1,18] it is likely that at the end of training these subjects were stronger than they had been many years previously.

This potential for reversal of "age-related" muscle weakness has been unexploited. Despite the evidence from studies of younger individuals that muscle will only hypertrophy and show large gains in strength in response to high loads (>40% of maximum),[15,19] there has been reluctance to apply this principle to the training of older individuals.

The published studies of weight training in the elderly are listed in Table 3. Except for the current study, all trials have involved healthy, community-dwelling individuals younger than 80 years. Six weeks of exclusively static muscle training has been reported to produce increments of 17% to 72% over baseline maximal isometric strength in elderly subjects.[20,21,25] The number of repetitions performed seems to have a major influence on strength gains achieved.

The remaining strength training trials have utilized dynamic training (weight-lifting) techniques and are, thus, more directly comparable with our study. Low-to-moderate resistance training has produced little or no increase in strength in older subjects, as seen in the reports of Aniansson and Gustafsson,[22] Larsson,[24] and Hagberg et al.[26] Moritani and deVries[23] used high-intensity training (66% of the one repetition maximum) and reported similar improvements in isometric strength of the elbow flexors of young and older men (30% vs 23%). This modest response may be attributed to the fact that strength gains are specific to the type of training employed, and dynamic training will not result in large gains in isometric strength, or vice versa.[27] Only one previous report of dynamic strength gains in older subjects after high-intensity weight lifting has been published. In this study by Frontera et al,[5] also from our laboratory, strength increased by an average of 107% in the knee extensors and 227% in the knee flexors after 12 weeks of training in a group of healthy men aged 60 to 72 years.

The favorable response to strength training in our subjects is remarkable in light of their very advanced age, extremely sedentary habits, multiple chronic diseases and functional disabilities, and nutritional inadequacies. The relationship we observed between muscle strength and fat-free mass suggests that preservation of fat-free mass, whether through activity or nutritional intake, is an important determinant of muscle strength in very old age. We hypothesized that disuse atrophy was the major contributor to the muscle dysfunction in these nursing home residents and that without altering any of the other factors, some reversal of the muscle weakness and atrophy would be possible. Our findings suggest that a portion of the muscle weakness attributed to aging may be modifiable through exercise.

The mechanism of strength gain deserves comment. The magnitude of the response precludes "familiarization" with the equipment as an important factor. We have found that repeated one repetition maximum testing in this population without intervention produces a change of only 8.4% from initial testing (M.A.F., unpublished observations, 1989).

It has been a widely held view that strength gains in older subjects are due to improved neural recruitment patterns rather than hypertrophy of the muscle fibers. This is based primarily on animal studies that show an age-related decrement in exercise-induced hypertrophy in the rat,[28] as well as the finding that no muscle hypertrophy (as estimated by anthropometric measurements) accompanied the strength gains in the older men studied by Moritani and deVries.[23] However, when more sensitive techniques are used, such as fiber area by muscle biopsy[5,22,24] or cross-sectional area by CT scan,[5] muscle hypertrophy seems to account for a portion of the strength gains observed in the elderly. Similarly, we have shown that even in individuals in their 10th decade of life, muscle hypertrophy can be induced with standard progressive-resistance training techniques. Although we did not train the muscles of the posterior thigh directly, these muscles also are active in stabilizing the knee during the quadriceps training protocol, particularly as the weight is lowered slowly against gravity. Thus, some augmentation of strength and size is expected in this muscle group as well. As the CT scan images demonstrate (Fig 1), the large amount of subcutaneous and intramuscular fat precludes the use of anthropometry to detect changes of this nature. The augmentation of muscle size is of similar magnitude as that reported by others using CT imaging[5,29-32] after training in younger subjects (3% to 22%).

The strength gains we observed also may be attributed to improved neural recruitment patterns. As has been noted in previous studies,[5,23] no direct correlation was noted between the degree of hypertrophy and the relative strength gains in our subjects. Additionally, some strength gains occurred within 2 weeks, before hypertrophy would have been a factor.

The training regimen employed was well tolerated despite the underlying medical conditions of the subjects. Cardiovascular complications were not seen, and because of the slow pace of the exercise, insignificant variation in pulse rate and blood pressure was observed. No exacerbations of underlying degenerative joint disease occurred in seven subjects with this diagnosis.

Because we trained only one muscle group, we did not anticipate or observe changes in total body muscle mass or activities of daily living. Habitual gait speed is a function of endurance capacity, joint mobility, balance, and lower-extremity muscle strength.[33,34] We found a strong inverse relationship between quadriceps strength and walking time at baseline. It is likely that to improve habitual gait speed, exercises to improve endurance as well as strength would be required. However, tandem gait speed, a task that requires primarily muscle strength and balance, improved 48% after training.

Muscle weakness in the frail elderly is a multifactorial phenomenon that has been linked to the high prevalence of falls and immobility in this population.[35] We have demonstrated that high-intensity strength training is feasible and is associated with significant gains in strength and muscle hypertrophy in individuals up to 96 years of age. However, just as in younger individuals,[36] these changes in muscle function are not maintained in the absence of continued training. Therefore, sustained improvements in clinical function requires an ongoing program of muscle reconditioning. Our observations regarding the safety of strength training, even among frail elderly with underlying cardiovascular disease, should be emphasized because the known hazards of immobility and falls[6,8] seem to outweigh the potential risks of muscle strengthening interventions in this population. Future research will explore further the physiological mechanisms and clinical consequences of this reversal of muscle dysfunction in elderly individuals.

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References

1. Larsson L, Grimby G, Karlsson J. Muscle strength and speed of movement in relation to age and muscle morphology. *J Appl Physiol.* 1979;46:451-456.
2. Grimby G, Gustafsson E, Peterson L, Ranstrom P. Quadriceps function and training after knee ligament surgery. *Med Sci Sports Exerc.* 1980;12:70-75.
3. Jeejeebhoy KN. Muscle function and nutrition. *Gut.* 1986;27:25-39.
4. Larsson L, Sjodin B, Karlsson J. Histochemical and biochemical changes in human skeletal muscle with age in sedentary males, age 22-65 years. *Acta Physiol Scand.* 1978;103:31-39.
5. Frontera WR, Meredith CN, O'Reilly KP, Knuttgen HG, Evans WJ. Strength conditioning in older men: skeletal muscle hypertrophy and improved function. *J Appl Physiol.* 1988;64:1038-1044.
6. Aniansson A, Zetterberg C. Impaired muscle function with aging: a background factor in the incidence of fractures of the proximal end of the femur. *Clin Orthop.* 1984;191:193-201.
7. Nevitt MC, Cummings SR, Kidd S, Black D. Risk factors for recurrent nonsyncopal falls: a prospective study. *JAMA.* 1989;261:2663-2668.
8. Baker SP, Harvey AH. Fall injuries in the elderly. *Clin Geriatr Med.* 1985;1:501-512.
9. Harrison GG, Buskirk ER, Carter JEL, et al. Skinfold thicknesses and measurement technique. In: Gohman TG, Roche AF, Martorell R, eds. *Anthropometric Standardization Reference Manual.* Champaign, Ill: Human Kinetics Books; 1988:55-80.
10. Schoeller DA, van Santen E, Peterson DW, Dietz W, Jaspan J, Klein PD. Total body water measurement in humans with ^{18}O and ^{2}H labeled water. *Am J Clin Nutr.* 1980;33:2686-2693.
11. Sheng H-P, Higgins RA. A review of body composition studies with emphasis on total body water and fat. *Am J Clin Nutr.* 1979;32:630-647.
12. National Research Council. *Recommended Dietary Allowances.* 9th ed. Washington, DC: National Academy of Sciences; 1980.
13. McDonaugh MJ, Davies CT. Adaptive response of mammalian skeletal muscle to exercise with high loads. *Eur J Appl Physiol.* 1984;52:139-155.
14. Borkan GA, Hutts DE, Gerzof SG, Robbins AH, Silbert CK. Age changes in body composition revealed by computed tomography. *J Gerontol.* 1983;38:673-677.
15. Delorme TL. Restoration of muscle power by heavy resistance exercise. *J Bone Joint Surg.* 1945;27:645-667.
16. *SAS Statistical Package.* 6th ed. Cary, NC: SAS Institute Inc; 1985.
17. Andres R. Mortality and obesity: the rationale for age-specific height-weight tables. In: Andres R, Bierman EL, Hazzard WR. eds. *Principles of Geriatric Medicine.* New York, NY: McGraw-Hill International Book Co; 1985:311.
18. Larsson L, Grimby G, Karlsson J. Muscle strength and speed of movement in relation to age and muscle morphology. *J Appl Physiol.* 1979;46:451-456.
19. Thorstensson A, Hutten B, vonDobelin W, Karlsson J. Effect of strength training on enzyme activities and fibre characteristics in human skeletal muscle. *Acta Physiol Scand.* 1976;96:392-398.
20. Perkins LC, Kaiser HL. Results of short-term isotonic and isometric exercise programs in persons over sixty. *Phys Ther Rev.* 1961;41:633-635.
21. Liemohn WP. Strength and aging: an exploratory study. *Int J Aging Hum Dev.* 1975;6:347-357.
22. Aniansson A, Gustafsson E. Physical training in elderly man with special reference to quadriceps muscle strength and morphology. *Clin Physiol.* 1981;1:87-98.
23. Moritani T, deVries HA. Potential for gross muscle hypertrophy in older men. *J Gerontol.* 1980;35:672-682.
24. Larsson L. Physical training effects on muscle morphology in sedentary males at different ages. *Med Sci Sports Exerc.* 1982;14:203-206.
25. Kauffman TL. Strength training effect in young and aged women. *Arch Phys Med Rehabil.* 1985;65:223-226.
26. Hagberg JM, Graves JE, Limacher M, et al. Cardiovascular responses of 70 to 79-yr-old men and women to exercise training. *J Appl Physiol.* 1989;66:2589-2594.
27. Duchateau J, Hainaut K. Isometric or dynamic training: differential effects on mechanical properties of a human muscle. *J Appl Physiol.* 1984;6:296-301.
28. Goldspink G, Howells K. Work-induced hypertrophy in exercised normal muscles of different ages and the reversibility of hypertrophy after cessation of exercise. *J Physiol.* 1974;239:179-193.
29. Luthi JM, Howald H, Classen H, Rosler K, Vock P, Hoppeler H. Structural changes in skeletal muscle tissue with heavy resistance exercise. *Int J Sports Med.* 1986;7:123-127.
30. Cureton KJ, Collins MA, Hill DW, McElhannon FM, Davis PL. Exercise-induced muscle hypertrophy in men and women. *Med Sci Sports Exerc.* 1986;18(suppl):S77.
31. Ingemann-Hansen T, Halkjaer-Kristensen J. Computerized tomographic determinations of human thigh components. *Scand J Rehabil Med.* 1980;12:17-31.
32. Horber FF, Scheidegger JR, Grunig BE, Frey FJ. Evidence that prednisone-induced myopathy is reversed by physical training. *J Clin Endocrinol Metab.* 1985;61:83-88.
33. Bassey EJ, Fentem PH, Macdonald IC, Scriven PM. Self-paced walking as a method for exercise testing in elderly and young men. *Clin Sci Mol Med.* 1977;51:609-612.
34. Bassey EJ, Bendall MJ, Pearson M. Muscle strength in the triceps surae and objectively measured customary walking activity in men and women over 65 years of age. *Clin Sci.* 1988;74:85-89.
35. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *N Engl J Med.* 1988;319:1701-1707.
36. Thorstensson A. Observation on strength training and detraining. *Acta Physiol Scand.* 1977;100:491-493.