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Favorable Neuromuscular and Cardiovascular Responses to 7 Days of Exercise With an Eccentric Overload in Elderly Women

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The metabolic, cardiovascular, and neural cost of eccentric muscle contraction is less than that of concentric contraction, but the strength and neural adaptations in eccentric contractions are significantly greater following resistive exercise. We thus compared the short-term effects of exercise with an eccentric overload ($n = 10$) with those of exercise with a standard load distribution ($n = 10$) in ostensibly healthy sedentary elderly women (mean age 71.4). Subjects were tested for concentric and eccentric three-repetition maximum, maximal isokinetic eccentric and concentric and isometric force, and associated electromyographic activity of selected thigh muscles before and after 7 consecutive days of exercise training of the left knee extensors. The exercise program was designed so that the total weight lifted was similar between eccentric overload and standard groups, but the eccentric overload group exercised with an approximately 50% greater eccentric load. Control subjects did not exercise ($n = 10$). There was a 46% increase in the total weight lifted over 7 days. When all strength measures were combined, the eccentric overload group's strength gains were 1.8-fold greater than those of the standard group, and the cardiovascular stress in terms of heart rate, mean arterial pressure, rate pressure product, and perceived exertion was significantly lower. The increases in muscle strength were achieved by increased muscle activation, but the strength gains were independent of the changes in antagonistic muscle coactivity. Because the strength gains occurred after a short period of exercise at a relatively low intensity and cardiovascular demand, the prescription of exercise with an eccentric overload appears suitable for elders, individuals deconditioned as a result of an injury, and the chronically diseased.

THE large age-related loss of muscle strength is well documented (1). Strength loss with age has serious health consequences because it is linked to sarcopenia, that is, loss of muscle mass and muscle function (2). In several studies it has been demonstrated that strength loss may be related to a loss of balance, risk of falling, and to a general impairment of locomotion (1,3,4). Because aged skeletal muscles retain their responsiveness to mechanical stimuli in terms of strength gains, muscle activation, and muscle hypertrophy (4,5,6), it is important to identify the most effective exercise modalities to remedy, offset, or perhaps reverse age-associated strength loss.

To this aim we sought to exploit a unique property of aged muscle. Whereas the strength loss is 50% during isometric and concentric contractions, the eccentric muscle weakness that is due to age is only 20% in men or even absent in women and other mammals when muscles lengthen (7,8,9). A few studies have also demonstrated that eccentric strength gains following resistive training are much greater than concentric or isometric strength gains in elderly (10,11) and young adults (12,13). Because skeletal muscles produce significantly greater force during an eccentric contraction than they do during a concentric one and because the critical stimulus for strength gains and muscle hypertrophy is the magnitude of mechanical stress (12,13,14), it is conceivable that an exercise program composed of a larger than usual eccentric component may lead to greater strength gains.

There is some evidence to support this hypothesis. Concentric strength gains were significantly greater after 12 weeks of training in a group of elders who exercised on specially designed equipment that allowed a 50% overloading of the eccentric movement phase, compared with another group of subjects who used standard weight lifting (15). Eccentric overloading is reasonable, because during exercise the eccentric phase can be as much as 50% underloaded compared with the concentric phase (12). Overloading the eccentric phase during resistive exercise has several potential benefits for the aged. The metabolic cost of eccentric exercise at the same absolute load is less than concentric exercise (16), as is the cardiovascular stress in the aged (17). In addition, significant isometric strength gains occur at a fraction of the metabolic cost during eccentric compared with concentric cycling (18). The large increases in eccentric strength and electromyographic activity after eccentric exercise training in young subjects may also signify the potential for strength gains in the aged (10,11,19). Therefore, we hypothesized that by emphasizing eccentric contractions, eccentric overloading will lead to rapid strength gains at low cardiovascular stress in elderly subjects. The purpose of the study was to compare the effects of 7 days of eccentric overload and standard resistive exercise training on strength, cardiovascular stress, and muscle activation in elderly women.

METHODS

Subjects and Design

Subjects were 30 ostensibly healthy (26 Caucasian, 4 African American) women who had not exercised more than once a week during the 3 years preceding the study. Subjects' mean ($\pm$SD) age, height, and mass were 71.4 ($\pm$4.8) years, 1.61

(±0.07) m, and 72.3 (±7.2) kg, respectively. All subjects were right leg dominant based on a ball-kicking test. Subjects were required to provide their family physician's approval to participate in the study. This approval letter and a medical questionnaire were used to determine whether a subject would qualify for the study. Subjects were excluded who had more than two risk factors for coronary artery disease (20), a history of falls, osteoporosis, osteoarthritis, orthopedic or neurological conditions (i.e., stroke), medications that cause dizziness, smoking, a body mass/height^2 ratio greater than 28 kg/m^2, blood pressure <140/90 mm Hg, or a heart condition. Prior to testing, subjects read and signed a written informed consent document approved by the University's Policy and Review Committee on Human Research.

Subjects underwent an initial test, 7 consecutive days of exercise training, and a final test. The tests involved an assessment of leg strength, using a three-repetition maximum (3RM) protocol, and isokinetic and isometric quadriceps strength and associated surface electromyography (EMG). Subjects were ranked based on 3RM strength, and from trios of ranked subjects one subject was randomly assigned to the eccentric overload (*n* = 10), one to the standard (*n* = 10), and one to the nonexercising control (*n* = 10) group.

Testing Protocols

Voluntary isometric and isokinetic strength.— Voluntary isometric and isokinetic eccentric and concentric quadriceps strength of the left leg were measured on a dynamometer (Kin-Com 500H, Chattecx, Inc., Chattanooga, TN). These tests were necessary to assess the changes in muscle strength independent of learning that occur with weight training (21). As a warm-up, subjects rode a bicycle ergometer at 60 rpm for 5 minutes at a resistance of 1–2 kg and performed 3 minutes of lower extremity stretching. After the warm-up, subjects were seated on the dynamometer's seat with a hip angle of 1.92 rad. The center of the knee joint was aligned with the axis of the dynamometer's power shaft. Crossover shoulder straps, a lap belt, a knee strap, and an ankle cuff were used to minimize extraneous movements. The leg was fastened to the dynamometer's lever arm just above the lateral malleolus with a padded cuff that contained the strain gauge. The position of the cuff on the lever arm was adjusted individually to accommodate subjects of different size. The distance between the strain gauge and the lever arm's axis of rotation was recorded and entered in the computer as the lever arm length. The knee angle anatomical zero was set at 3.14 rad. The weight of the leg was determined at 3.14 rad of knee joint position. Using these procedures, the dynamometer's software corrected the force exerted by the subject for the gravitational effects of leg mass. Familiarization with the dynamometer included two trials of 50%, 75%, and 90% of perceived maximal intensity isometric, eccentric, and concentric contractions separated by 1 minute of rest. Subjects were not allowed to grasp the seat and kept their hands in their laps.

Maximal isometric force was measured at 1.14 rad of knee flexion. Subjects performed three, maximal effort, 5-second trials with 1 minute of rest between trials. Subjects also performed three, maximal effort, eccentric and concen-

tric isokinetic quadriceps contractions at 1.57 rad/s. We used this specific testing speed because it resembled the estimated knee joint angular velocity of the knee extension used during exercise training. Each quadriceps contraction was followed by a hamstring contraction with a 1-second pause between the efforts. There was 1 minute of rest between conditions. The order of isometric and dynamic testing was systematically alternated between subjects. Peak dynamic forces were digitized at 1.14 rad of knee flexion. The highest force value of the three trials was used in the statistical analyses.

Surface EMG.—Prior to dynamometry, the surfaces of the skin over the belly of the left vastus lateralis, vastus medialis, and the biceps femoris and over the right fibula head were palpated, shaved, and washed with alcohol. We recorded from these two synergistic quadriceps muscles because adaptations may be non-uniform in the quadriceps (22). Two single-use diagnostic electrocardiogram (ECG) electrodes (ConMed Inc., Utica, NY), touching rim to rim, were placed on each muscle belly with a 3.5 cm center-to-center interelectrode distance to detect surface EMG activity. One ground electrode was placed on the skin over the right fibula head.

The EMG data were collected with the TeleMyo telemetric hardware system (Noraxon USA, Inc., Scottsdale, AZ). The system includes a 16 × 7 × 2.5 cm, 0.5 kg, 9 V, battery-powered transmitter tied to the subject's waist with a cloth belt. The transmitter contains a crystal locked dielectric oscillator module, a microprocessor, and an eight-channel, 12-bit analog-to-digital converter. Up to eight channels of digitized EMG signals are transmitted to the receiver over one of 10 radio channels in the 906- to 924-MHz radio frequency range. In the receiver the digitized signals are reconstructed into eight channels of analog data. Each EMG signal has a bandwidth of 3 dB at 16–500 Hz. The lower cutoff filter is a first-order high-pass design, and the upper cutoff filter is a sixth-order Butterworth low-pass design. The differential amplifier has a gain of 2000, an input impedance of 10 MΩ, and a common mode rejection ratio of 130 dB. In the transmitter a proprietary electronic feedback circuit isolates and removes the low-frequency noise component from the signal. The noise component is transmitted to the receiver separately from the EMG-only signals on one of the 10 radio frequency channels. The analog EMG data from the receiver as well as the force and the knee joint position data from the dynamometer's analog-to-digital converter board were forwarded to the 12-bit analog-to-digital converter (Keithley Metrabyte, DAS-1402, Taunton, MA) that resides in the Pentium personal computer. All five signals were then digitized by the Myosoft software at 1 kHz (Noraxon Inc., Scottsdale, AZ).

EMG data reduction consisted of the root-mean-square (rms) conversion of the direct EMG data by a 20-millisecond smoothing window. The trial with the highest force was identified, and in these trials the corresponding peak rms EMG activity was digitized for the three muscles. Biceps femoris coactivity during the quadriceps testing was computed as the quotient of peak rms amplitude of the biceps femoris divided by the peak rms amplitude of the vastus lateralis. Figure 1 displays typical force and EMG recordings in one subject before and after the 7-day exercise program.
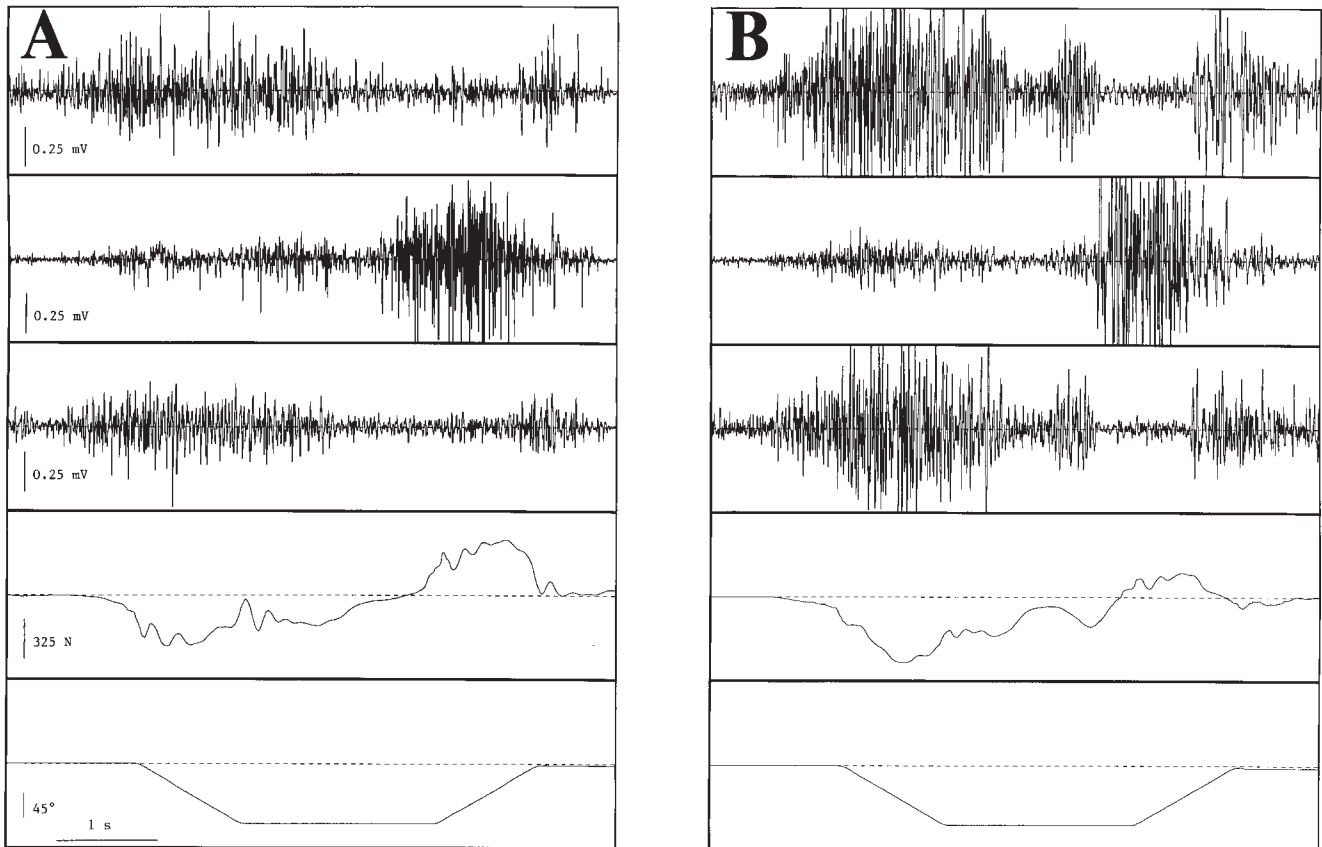
Figure 1. Direct surface electromyographic activity of the vastus lateralis, biceps femoris, and vastus medialis and the associated eccentric force and knee joint position before, **A**, and after, **B**, 7 days of eccentric overload exercise training of the quadriceps muscle in a 81-year-old previously sedentary woman. In both panels the tracings depict, from top to bottom, vastus lateralis, biceps femoris, and vastus medialis electromyograms as well as force and knee joint position. One quadriceps (downward deviation in force) and one hamstring effort is illustrated at 90°/s. Scales refer to both panels.

Three-repetition maximum.—Unilateral (left leg) concentric 3RM and eccentric 3RM of the quadriceps muscle were determined on a separate day relative to the tests administered on the dynamometer. The 3RM tests were performed on a Cybex knee extension unit (Model 4100, Cybex Inc., Owatonna, MN).

Concentric and eccentric 3RMs were defined as the amount of weight a subject was able to lift or lower three times, respectively. We used a 3RM and not a 1RM because in our experience, elders better tolerate 3RM than 1RM testing as a result of the lighter weight. Concentric 3RM was determined first. At a three-count pace, subjects lifted and lowered the weight with one smooth movement during each phase. The weight for the first attempt was approximately 50% of the estimated 3RM weight. Weight was progressively added in 10- to 45-N increments until the 3RM was reached with ~3 minutes of rest between efforts.

Next the eccentric 3RM was assessed. The technician manually lifted the weight that was one step below the previously determined concentric 3RM. The subject extended her knee, the technician let the weight go, and the subject lowered the weight at a three-count pace of a metronome from 3 rad to 1.57 rad of knee joint position. This cycle was repeated until the subject could no longer lower the weight three times in a controlled fashion. No subject did more than six attempts to reach the concentric and eccentric 3RM, respectively.

Heart Rate, Blood Pressure, and Perceived Exertion

Before, during, and after each exercise training session, systolic blood pressure (SBP), diastolic blood pressure (DBP), and heart rate (HR) were measured with an automated, battery powered, digital blood pressure monitor (Sunbeam, Model 7654, Bay Springs, MS). The monitor had a sensitivity of 1 mm Hg, a range of 20–280 mm Hg, and the capability to also record heart rate. The left arm rested on an arm support adjusted to heart level. Mean arterial pressure (MAP) was computed as $MAP = DBP + [0.33/(SBP - DBP)]$ and rate pressure product (RPP) was computed as $RPP = HR \times SBP \times 10^{-2}$. Subjects sat for 5 minutes after they arrived and a resting blood pressure measurement was taken. A second measurement was taken immediately after the last contraction of the last exercise bout, and after 5 minutes of seated rest following the last contraction. For the second measurement the cuff inflation was timed so that the reading could be done no later than 15 seconds after the last contraction of the last exercise bout. Control subjects reported to the gymnasium three times over the 7-day period for blood pressure measurements. After each

blood pressure measurement, subjects rated their perceived exertion on a scale of 6 to 20, with 7 being very, very light and 19 being very, very hard (23).

Training Protocol

After the resting blood pressure measurement, subjects warmed up for each session by riding a bicycle ergometer for 5 minutes at 1 kg, and then they stretched for a few minutes. Exercise training consisted of five to six sets of 9–12 repetitions of unilateral (left) knee extension–flexion exercise for 7 consecutive days. There was 3 minutes of rest between sets to avoid overtraining.

Subjects exercised on the same Cybex machine that was used for the 3RM testing. Unilateral knee extension was the choice of exercise to isolate the quadriceps muscle group. Subjects assigned to the "standard" group exercised by using a conventional sequence of knee extension (concentric quadriceps contraction) and knee flexion (eccentric quadriceps contraction). Subjects in the eccentric overload group also used a knee extension–flexion sequence, but an overload of 50% was added during the lowering phase (knee flexion, eccentric quadriceps contraction). In a previous study the flexion phase was approximately 50% underloaded relative to the knee extension phase using the leg press (12).

The training programs were designed so that the total weight lifted by the two groups was similar. The eccentric overload was accomplished by a technician's manually attaching extra weight plates to the main weight stack at the instant the subject reached the end point of the knee extension phase. The extra load was removed after the lowering phase was completed. As a way to equate total load in the two groups, the eccentric overload subjects performed fewer repetitions. Normally if a subject in the standard group lifted 23 kg of mass, she would perform six sets of 12 repetitions, 23 kg for both the concentric and the eccentric phases, for a total of 3312 kg. To equate the load, the paired eccentric overload subject would perform six sets of 9.5 repetitions, 23 kg concentrically and 35 kg eccentrically, a 50% overload, for a total of 3306 kg. The 9.5 repetition was accomplished by having the subject perform nine repetitions for the odd number of sets and 10 repetitions for the even number of sets. It was necessary to determine the exact repetition number prior to the workouts for each exercise bout for the eccentric overload subjects. Matched pairs of subjects were monitored so that as one subject improved, the paired subject's exercise volume was adjusted to equate poundages between the two subjects. The weight, the number of repetitions, and number of sets performed by each subject were recorded for the seven training sessions. The compliance during the 7 days of exercise training was 100%.

Statistical Analyses

All data analyses were performed with BMDP PC-90 software. Reliability of the criterion measures was determined in 10 nonexercising control subjects who were tested twice, 7 days apart. We expected random changes in control subjects' isometric, eccentric, and concentric strength, and these measures were included in one reliability analysis. The same was done for the EMG measures. Reliability was estimated by a Pearson product moment correlation coefficient, and the differences in the means of the repeated measurements were analyzed with a paired, two-tailed t test.

Resting, exercise, and recovery heart rate and blood pressure data were averaged over the 7-day period for each subject, and these mean values were compared with a group (eccentric overload, standard, or control) by time (rest, exercise, or recovery) analysis of variance with repeated measures on time.

Because eccentric, isometric, and concentric forces are substantially different and an analysis of covariance would misleadingly adjust the post-training scores for these initial differences, these analyses were done on the gain scores (i.e., absolute changes). A Dunnett's test was used to determine if the gain scores were significantly different from zero. Next, a group (eccentric overload, standard, or control) by contraction mode (eccentric, concentric) analysis of variance with repeated measures on the contraction mode was used to analyze the changes in concentric 3RM and eccentric 3RM. A group (eccentric overload, standard, or control) by contraction mode (eccentric, concentric, or isometric) analysis of variance with repeated measures on the last factor was used to analyze the gains in isokinetic and isometric forces as well as the changes in EMG activity. The total mean weight lifted during exercise training was analyzed with a group by contraction mode by time analysis of variance with repeated measures on the last two factors. Tukey's post hoc contrast was used to identify the means that were significantly different ($p < .05$).

RESULTS

Reliability

Repeated measures of 3RM strength, isokinetic eccentric and concentric and isometric forces and the associated measures of vastus lateralis, vastus medialis, and biceps femoris EMG activity and the measures of 3RMs were stable and reliable. The correlation coefficients for these measures ranged from $r = .88$ (strength measures) to $r = .96$ (concentric 3RM), with the largest percent mean difference of -3.1% (EMG measures). Even though these changes were relatively large (control group's data are in Figures 3 and 4 below), they were a fraction of the changes of the training groups and functionally were not significant.

Exercise Training Data

All subjects completed the study without injury. Table 1 shows the total mean weight lifted and lowered by the two groups. The group by contraction mode interaction ($F = 0.7$, $p = .6687$) and the group main effect ($F = 1.3$, $p = .7799$) were not significant. The time main effect was significant and the 46% increase in the total weight lifted from day 1 to day 7 signifies that a training adaptation occurred ($F = 12.5$, $p = .0001$). The actual training loads corresponded to approximately 80% of the 3RM or approximately 60% of the 1RM.

The group by movement phase (concentric, eccentric) interaction for total mean weight was significant ($F = 19.5$, $p = .0001$). Over the 7 days, the total mean weight lowered in the eccentric phase ($42,479 \pm 4673$ N) was 54% ($\pm 18\%$) more than the weight lifted in the concentric phase ($27,594 \pm 3863$ N) in the eccentric overload group. The total mean

Table 1. Mean Total Weight Lifted by Subjects[†]

Day	Eccentric Overload[‡]		Standard Load[‡]		Time Means[‡,§]	
	Mean	SD	Mean	SD	Mean	SD
1	8,264	4,021	8,119	2,967	8,192	3,494
2	8,638	4,321	8,742	3,099	8,690*	3,710
3	9,351	3,917	9,144	3,332	9,248*	3,625
4	9,717	3,833	9,671	3,374	9,694	3,604
5	10,788	4,241	10,639	4,184	10,714*	4,213
6	11,439	4,372	11,356	4,429	11,398*	4,401
7	11,876	4,111	11,967	4,235	11,922*	4,173
Group means[‖]	10,010	4,117	9,948	3,600		

*Significantly different from previous values ($p < .05$).

[†]The mean total weight lifted was during a 7-day eccentric overload ($n = 10$) and standard load ($n = 10$) unilateral knee extension weight lifting exercise program.

[‡]All values are in Newtons.

[§]"Time means" refers to the time main effect computed by averaging the weights across groups for each day. For the time main effect, the weight versus day relationship is described by the $y = 645.4x + 7398$ linear regression equation ($r = .98$, $F = 400.0$, $p = .0001$).

[‖]"Group means" refers to the group main effect computed by averaging the weights for the 7 days.

Table 2. PHR, MAP, RPP, and RPE Data Combined Over 7 Days of Exercise

Variable	Group	Rest		Exercise		Recovery	
HR, b min^{-1}	Eccentric overload	69	(10)	90*	(14)	75	(13)
	Standard	65	(12)	102*[†]	(16)	86[†]	(15)
	Control[‡]	67	(10)	62	(8)	63	(9)
MAP, mm Hg	Eccentric overload	99	(9)	117*	(21)	82	(15)
	Standard	99	(12)	132*[†]	(27)	113[†]	(19)
	Control[‡]	98	(10)	94	(8)	97	(9)
RPP[§]	Eccentric overload	90	(1)	151	(3)	107	(2)
	Standard	86	(1)	191*[†]	(5)	135[†]	(4)
	Control[‡]	86	(1)	76	(2)	78	(1)
RPE[‖]	Eccentric overload	7	(2)	10*	(3)	8	(2)
	Standard	7	(1)	13*[†]	(3)	7	(2)
	Control[‡]	6	(0)	6	(0)	6	(0)

Notes: The data are for the heart rate (HR), mean arterial pressure (MAP), rate pressure product (RPP), and rate of perceived exertion (RPE) at rest, immediately after the last exercise bout (exercise) with a standard load or an eccentric overload, and after 5 minutes of recovery; controls did not exercise. All values are mean (SD).

*$p < .05$ compared to rest and recovery.

[†]$p < .05$ compared to eccentric overload.

[‡]Differences relative to the control group are not noted for clarity.

[§]RPP is expressed in b min^{-1} mm Hg $\times 10^{-2}$.

[‖]An RPE value of 10 denotes "very light" and 13 denotes "somewhat hard" (23).

weight was, by design, similar for the lowering and lifting phases of the knee extension exercise in the standard group, at 34,819 ($\pm$ 4526) N and 34,819 ($\pm$ 4526) N, respectively. The eccentric overload group thus lowered 22% more weight and lifted 21% less weight than the standard group (both $p < .0001$).

When data are combined from all subjects, the resting SBP, DBP, MAP, and HR were 130, 83, and 98 mm Hg and 67 b min^{-1}, all within normal range for this age group. Table 2 shows the HR, MAP, RPP, and perceived exertion data combined over the 7 days of exercise. The data were combined over 7 days because we did not observe a substantial increase or decrease in these variables over 7 days. The control subjects did not show significant changes in any of these variables. There was a significant group by time (rest, exercise, or recovery) interaction for HR ($F = 5.4$, $p = .0032$), MAP ($F = 6.4$, $p = .0349$), RPP ($F = 7.9$, $p = .0087$), and rate of perceived exertion (RPE; $F = 3.2$, $p = .0464$, control group excluded). Exercise in both training groups significantly raised the HR, MAP, RPP, and RPE. The standard group had a 12-beat greater HR response to exercise than the eccentric overload group ($p < .05$) and also remained more elevated by nine beats after recovery ($p < .05$). The exercise MAP was 15 units greater in the standard group than in the eccentric overload group and remained 11 units higher in recovery (both $p < .05$). The exercise RPP was 40 units greater in the standard group than in the eccentric overload group and remained 28 units higher in recovery ($p < .05$). Perceived exertion during exercise was 3 units higher in the standard group than in the eccentric overload group ($p < .05$), but the RPE was similar in recovery.

Changes in 3RM

Figure 2 shows the group by contraction mode significant interaction of the 3RM gain scores ($F = 12.9$, $p = .0001$).

The Eccentric 3RM increased by 33% or 98 N, to 397 ($\pm$ 107) from 299 ($\pm$ 89) in the eccentric overload group, and by 18% or 54 N, to 361 ($\pm$ 98) from 307 ($\pm$ 107) in the standard group. The 98-N gain in the eccentric overload group was significantly more than the 54-N gain in the standard group ($p < .05$). The 98-N and 54-N gains were both greater than zero ($p < .0001$). The change in the control group was 9 N.

The concentric 3RM increased by 43% or 62 N, to 205 ($\pm$ 54) from 143 ($\pm$ 40) N in the eccentric overload and by 43% or 63 N, to 210 ($\pm$ 62) from 147 ($\pm$ 53) N in the standard group (both $p < .05$). The concentric 3RM gains were similar in the two groups. The 62-N and 63-N gains in the
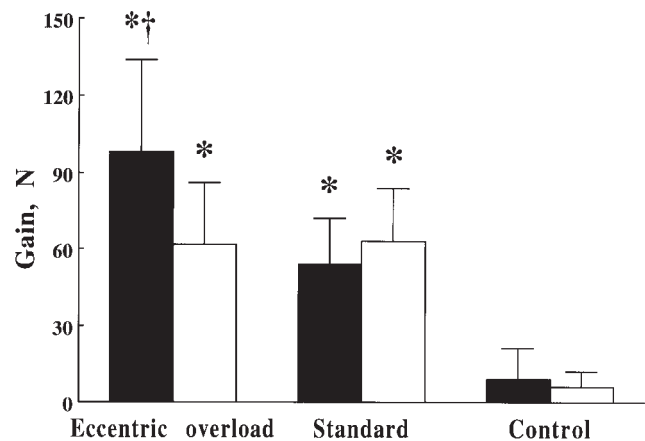

Figure 2. Absolute gains (in Newtons) in eccentric (closed bars) 3RM and concentric (open bars) 3RM in the eccentric overload, standard, and control groups. * Denotes significant pretraining to posttraining change; [†] denotes significantly greater changes than any other changes; ($p < .05$). Vertical bars denote +1 standard deviation.

two groups were greater than zero ($p < .0001$). In the eccentric overload group, the 98-N gain in eccentric 3RM was significantly more than the 62-N gain in concentric 3RM ($p < .05$). In the standard group, the 63-N gain in concentric and the 54-N gain in eccentric 3RM were statistically similar ($p > .05$). The change in the control group was 2 N.

Changes in Isokinetic and Isometric Forces

Subjects' baseline force production followed the force-velocity relationship; that is, the concentric force (262 ± 72 N) was the least, exceeded by isometric (382 ± 72 N) and eccentric forces (524 ± 110 N). Figure 3 shows the significant group by contraction mode interaction of the gain scores ($F = 7.7$, $p = .0037$). In the eccentric overload group, the gains of 100 N or 19%, 61 N or 16%, and 41 N or 16% in eccentric, isometric, and concentric forces were greater than zero (all $p < .0001$). In the standard group, gains of 49 N or 9% in eccentric force were greater than zero ($p < .0001$) but the 19-N or 5% isometric and 19-N or 7% concentric gains were not greater than zero ($p > .05$). In the eccentric overload group the 100-N gain in eccentric force was significantly more than any other gains, and its 61-N isometric gain was greater than the standard group's 19-N isometric gain ($p < .05$). The greatest change in the control group was −9 N or −2% in eccentric force.

Changes in EMG Activity

Changes in EMG activity of the vastus lateralis and medialis were proportional to the changes in isokinetic and isometric forces. Figure 4 shows that the group by contraction mode interaction of the gain scores was significant for vastus lateralis (VL) EMG activity ($F = 6.6$, $p = .0044$). The eccentric overload group's 27%, 21%, and 13% gain in VL EMG activity measured during eccentric, isometric, and concentric tests, respectively, exceeded zero ($p < .0001$). The standard group's 13% gain in VL EMG activity measured during the eccentric test was also greater than zero ($p < .0001$).

In the eccentric overload group, VL EMG activity during the eccentric test increased by 207 μV, significantly more than the 168-μV increase during the isometric test or the 106-μV gain during the concentric test ($p < .05$). In the standard group, the 107-μV gain during the eccentric test was significantly more than the 36-μV gain during the isometric test ($p < .05$). The largest change in the control group was −65 μV. The direction and magnitude of the changes were similar in the vastus medialis compared with those of the vastus lateralis (data not shown).

The biceps femoris EMG coactivity was determined relative to the EMG activity of the vastus lateralis during eccentric, isometric, and concentric contractions. None of the analyses yielded significant changes. The absolute amount of biceps femoris coactivity did not change with 7 days of exercise training, and the mean values (combined across the three contraction modes) were 165 ($\pm$ 38) μV, 160 ($\pm$ 22) μV, and 167 ($\pm$ 30) μV in the eccentric overload, standard, and control groups, respectively. The ratio of biceps femoris to vastus lateralis coactivity slightly decreased as the absolute VL activity increased (Figure 4). The pretraining versus post-training mean coactivity ratios (combined across the three
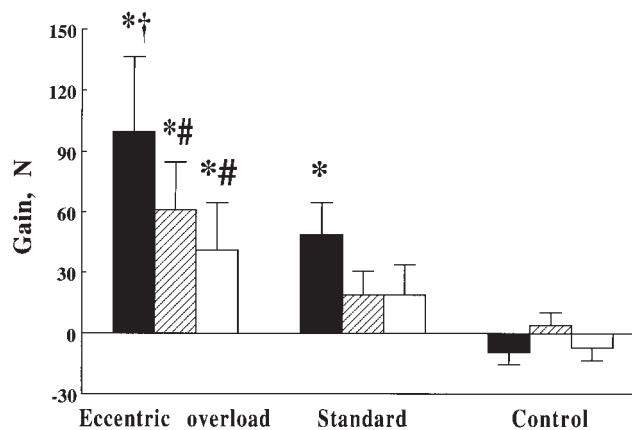

Figure 3. Absolute changes in isokinetic eccentric (filled bars), isometric (hatched bars), and isokinetic concentric (open bars) forces in the eccentric overload, standard, and control groups. * Denotes significant pretraining to post-training change; † denotes significantly greater change than any other changes; and # denotes significantly greater gains than the standard group in the same test condition ($p < .05$). Vertical bars denote +1 standard deviation.

contraction modes) were 0.22 ($\pm$ 10) versus 0.18 ($\pm$ 0.09) in the eccentric overload group, 0.20 ($\pm$ 0.12) versus 0.17 ($\pm$ 0.10) in the standard group, and 0.20 ($\pm$ 0.11) versus 0.21 ($\pm$ 0.12) in the control group, respectively.

DISCUSSION

The main findings of the present study were that short-term exercise with an eccentric overload resulted in greater isokinetic eccentric, isometric, and concentric strength gains and less cardiovascular stress than conventional resistive exercise in elderly women. The greater isokinetic eccentric, isometric, and concentric strength gains were associated with proportional changes in muscle activation measured by surface
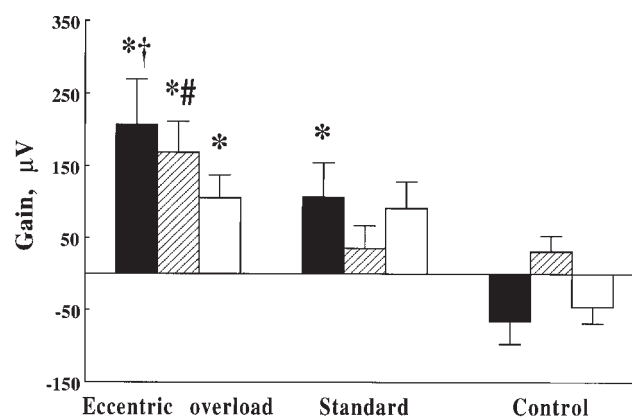

Figure 4. Absolute changes in vastus lateralis root-mean-squared electromyographic activity during isokinetic eccentric (filled bars), isometric (hatched bars), and isokinetic concentric (open bars) forces in the eccentric overload, standard, and control groups. * Denotes significant pretraining to post-training gain; † denotes a significantly greater gain than any other changes; and # denotes significantly greater gain than the standard group in the same test condition ($p < .05$). Vertical bars denote +1 standard deviation.

EMG. The strength gains were independent of the changes in antagonistic muscle activation.

We hypothesized that resistive exercise with an eccentric overload would result in greater gains in muscle strength compared with exercise that uses a conventional load distribution in elderly women. The results confirmed this prediction within the confines of the specificity principle of exercise. The grand average of strength gains in all measures of muscle strength was approximately 1.8-fold greater in the eccentric overload group (72 N) than in the standard group (41 N). However, the eccentric gains were approximately twofold greater than the concentric gains in the eccentric overload group, and the eccentric and concentric gains were similar, 52 N and 41 N, in the standard group. These findings are consistent with data reported in earlier studies concerning strong specificity of adaptations to exercise with pure concentric and eccentric contractions in young subjects (12,13,24,25).

Because of the logistical difficulties in administering an eccentric overload exercise program, it is not surprising that there is a paucity of data on exercise with an accentuated eccentric load, regardless of the subjects' age (15,26). Nichols and colleagues reported superior gains in muscle strength after 12 weeks of eccentric overload compared with standard exercise training in elderly adults, but improvements in mobility were independent of the training mode (15). In contrast, Godard and colleagues reported no significant differences in strength gains after 30 sessions of eccentric overload training and standard exercise training (26). One explanation for this latter finding could be that Godard and colleagues used concentric-only test contractions that were insensitive to changes induced by the accentuated eccentric training. Comparisons between these studies (15,26) and the present work are difficult because of the differences in subject populations, total work, number of repetitions, intensity of exercise, the magnitude of eccentric overload, equipment design, and the outcome measures.

We controlled for total load to determine the net effect of eccentric overload and to avoid the confounding effects that might have occurred had both total load and the composition of total load been different in the two exercise groups. However, such a paradigm complicates the interpretation of the magnitude of eccentric overload, as was also the case in a previous study (15). Within the eccentric overload group the eccentric phase relative to the concentric phase was overloaded by approximately 50%, but compared with the standard group, the overload was only approximately 22%. The reason for the less than 50% between-group eccentric overload is explained by the fewer number of repetitions used by the eccentric overload group to account for the greater eccentric load and equate total weight between the two groups. Nevertheless, the present results demonstrate the potency of eccentric contractions for strength gains because, by the most conservative estimates, a mere 20% overload resulted in superior isokinetic eccentric, isometric, and concentric strength after short-term (present study) and chronic exercise training (15).

Exercise with an eccentric overload may be particularly suitable for elders because a larger portion of the total work is performed with less cardiovascular stress. The metabolic cost of lengthening compared with shortening contractions at the same absolute force is less (16). Recent experiments have also demonstrated that 6 weeks of eccentric bicycle training using up to 700% greater work rates than concentric bicycle training resulted in significantly greater isometric strength gains (18). The eccentric work rates required less metabolic cost compared with the concentric work rates. With the use of the leg press exercise, it was also demonstrated that the concentric portion of the work was chiefly responsible for the total metabolic cost of exercise (27). We have no metabolic data in the present work, but the current results are in close agreement with the lower cardiovascular stress observed in elderly subjects during submaximal concentric and eccentric isokinetic knee extension exercise at the same absolute torque (17). Over a 2-minute exercise bout, these authors reported a 13% lower HR, 16% lower MAP, 30% less RPP, and 17% lower RPE during the eccentric compared with the concentric bout (17). At the same total work, our eccentric overload compared with the standard group had a 27% lower HR, 15% lower MAP, 54% lower RPP, and 43% lower RPE during exercise. Taken together, these data have important implications for designing exercise programs for elders with or without a cardiac condition, because muscle strength can be increased at a much faster rate at a lower metabolic, cardiovascular, and perceived stress. We must point out that the present work emphasizing eccentric contractions indicated, in agreement with previous studies, neither an elevation nor a reduction in resting HR, MAP, or RPP (17,18,27,28).

For many years the concept has been promoted that low-intensity exercise does not lead to substantial neuromuscular adaptations (14). We observed that exercising at an intensity of approximately 60% of maximum resulted in marked and rapid gains in strength. There is accumulating evidence suggesting that low-intensity exercise does result in substantial changes in muscle strength, muscle fiber size, mobility, and bone mineral density in the aged (29,30,31). Exercise intensity as low as 45% has significantly improved the 1RM strength in some exercises (15). That lower-intensity exercise may bring about meaningful adaptations is especially relevant for elders and the chronically diseased.

Strength gains in previous resistive exercise training studies using conventional weight lifting ranged from 0.5% to 8% per session in elderly adults. For example, strength training of a small hand muscle resulted in 3.8% per session gain in the training load and 1.1% per session increase in the maximal isometric force in both young and old subjects (6). High-intensity strength training of the large quadriceps muscle resulted in 7.3% per session increase in the training load in 90-year-old subjects (5). Using eccentric overload, strength gains were 3% per session for the first 2 weeks and 1.2% per session over the entire 14-week period in elders, with smaller gains occurring in elderly subjects who exercised with conventional weight lifting (15). In young subjects, eccentric overload training resulted in an approximately 4.8% per session strength gain over 10 weeks (26). In the present work, the rate of strength gain per session was comparable with the gains in these two studies, at 3.6% and 2.1% per session in the eccentric overload and standard groups, respectively. The average strength gains per session

computations are somewhat misleading, as it is unclear whether these rates of gains would be maintained over longer time periods. In most (6,15) but not all cases (5), the rate of strength gain plateaus after several weeks of resistive exercise.

It is also worth noting that the daily loads increased linearly from day to day (Table 1), suggesting that the low exercise intensity prevented overtraining or injury. Although eccentric contractions are linked to myofibrillar disruption, especially in the aged (32), our pilot data revealed a complete absence of muscle damage in old subjects following 7 days of accentuated eccentric exercise (33). The susceptibility of aged mammalian muscle to damage may be less than previously thought (32,34), considering the newer data on the resilience of the aged muscle to damage during resistive exercise (33,35) and that less muscle damage occurs with repeated eccentric actions (36).

Only a few studies have measured eccentric strength following exercise training in the aged (10,11). Although in these studies a combination of muscle contractions were used, in both studies eccentric strength gains were approximately twofold greater than the concentric gains. In another study of 68-year-old women, strength gains occurred only in eccentric strength of the dorsiflexor muscle group that was trained with eccentric contractions (19). The present data corroborate these findings, as eccentric strength gains were approximately twofold greater than concentric gains in the eccentric overload group; even in the standard group in which the eccentric actions were not emphasized, the eccentric strength gains exceeded concentric gains by 11 N. The greater adaptation in eccentric than in concentric strength is intriguing, especially if one considers the critical role of eccentric muscle function in high-risk activities such as stair descent (37). Future studies will have to determine whether these large adaptations in eccentric strength are correlated with improved function in activities of daily living, which frequently is not the case (1,15).

It is well established that the initial adaptations to resistive exercise training are neural in nature (38). As in the present work, large initial strength gains have been reported to occur rapidly, presumably as a result of neural adaptation, because after only one or two exercise sessions, strength gains approximated the gains achieved over weeks of training (39,40). These initial strength gains are most likely mediated by increased muscle activation that appears as an increase in the surface EMG activity, caused by an increase in both the number of activated motor units and their discharge rate (41). In many cases strength training increased maximal force and EMG activity associated with this maximal force in parallel (e.g. 13,42), but in several studies the increase in maximal force occurred without an increase in EMG activity (43,44). The data are more consistent in the few studies of aged subjects, indicating parallel increases in maximal force and associated EMG activity following resistive exercise training (45,46,47). Our data of significantly greater increases in EMG activity associated with eccentric strength are in agreement with the substantially greater neural adaptations in EMG activity measured during maximal eccentric but not concentric muscle contractions reported previously in aged (10) and young subjects (13). The mechanism of the large increase in eccentric

strength and EMG is unclear, but it may be related to an improved muscle coordination (21) or a removal of neural inhibition associated with high-force eccentric efforts (48,49).

Another neural mechanism to underlie the large eccentric strength gains could be the reduced antagonistic muscle coactivity (38), but there is limited data to support this hypothesis (50). This is a complicated issue because the expected magnitude of coactivity is unknown in healthy young and elderly subjects. It is clear that antagonistic coactivity varies according to the type of muscle action (51), task familiarity (51), practice (52), training history (53), age (54), movement velocity (55), and disability (56). The complexity of this issue is illustrated by the observation that, against intuition, the biceps femoris coactivity during maximal effort quadriceps tasks was similar in able-bodied subjects and stroke patients with spastic muscles (56).

There is only one study in which isometric exercise training of the knee extensors over 24 sessions in 8 weeks resulted in a 20% reduction in the absolute magnitude of hamstring coactivity in young subjects (50). In another work, 6 months of resistive exercise training reduced biceps femoris coactivity from 24% to 21% and from 31% to 24% in 70-year old men and women (46). Although statistically significant, such small changes must have contributed very little to the increased agonist force after training. In this study the agonist EMG activity increased 14% and 17% and the antagonist-to-agonist EMG ratio decreased (46). Thus, the absolute magnitude of antagonistic muscle activity must have remained the same. That is, the reduction in the ratio was driven by the increased agonist EMG activity and not by a reduction in the absolute amount of coactivity (46). After 7 days of resistive exercise, we observed a small reduction in the antagonist-to-agonist EMG ratio. These data are consistent with studies that reported no change in this ratio after exercise training with pure eccentric and concentric contractions of arm and leg muscles (13,24,57). Perhaps we would have seen changes in muscle coactivity had we taken EMG measurements during the knee extension movement the subjects used as the training exercise and not under isokinetic or isometric conditions on the dynamometer (38). At any rate, the strength gains seen after short-term resistive training do not seem to be mediated by a reduction in muscle coactivity under the current experimental conditions.

In conclusion, acute knee extension exercise training with an eccentric overload compared with exercise composed of a conventional loading resulted in greater eccentric 3RM and isokinetic eccentric, isometric, and concentric strength gains with significantly lower cardiovascular stress. The increases in muscle strength were achieved by increased muscle activation, but the strength gains were independent of the changes in antagonistic muscle coactivity. Because the strength gains occurred after a short period of exercise at a low intensity and cardiovascular demand, a prescription of exercise with an eccentric overload appears suitable for elders, individuals deconditioned as a result of an injury, and the chronically diseased.

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