Positive adaptations to weight-lifting training in the elderly

ALLAN B. BROWN, NEIL McCARTNEY, AND DIGBY G. SALE
Department of Physical Education, McMaster University, Hamilton, Ontario L8S 4K1, Canada

Positive adaptations to weight-lifting training in the elderly. J. Appl. Physiol. 69(5):1725-1733, 1990.—Maximal weight-lifting performance, isometric strength, isokinetic torque, whole muscle and individual fiber cross-sectional areas, and muscle evoked contractile properties were assessed in 14 elderly males before and after 12 wk of weight-lifting training. Dynamic elbow flexion training of one arm resulted in a significant 48% mean increase in the maximal load that could be lifted once (1 RM) and a smaller improvement in isokinetic torque (8.8%) but no change in isometric strength. In the contralateral control arm, 1 RM and isokinetic torque increased by 12.7 and 6.5%, respectively, but isometric strength did not change. The interpolated twitch technique confirmed complete motor unit activation during a maximal isometric contraction of the elbow flexors before and after the training. Bilateral leg press training effected mean increases of 17 and 23% in isokinetic torque and, 17.4% in the trained arm but did not change the control arm. The increase in the mean area of type II fibers in the biceps brachii muscle in the trained arm (30.2%) was greater than the corresponding change in the control arm (10.7%, P < 0.05). The most significant change in the evoked contractile properties of the trained elbow flexors was the increase in twitch half-relaxation time. It is concluded that older individuals retain the potential for significant increases in strength performance and upper limb muscle hypertrophy in response to overload training.

SKELETAL MUSCLE STRENGTH has been found to increase up to 30 yr of age, to plateau until ~50 yr, and to decline slowly thereafter (19). In older individuals, peripheral muscle weakness may compromise common activities of daily living, such as rising from a low chair or lavatory seat (38), and may lead to dependency on others. The relative contributions of changes in the neuromuscular system and progressive inactivity to the reduction in strength with aging are unclear.

The maximal cross-sectional area of the quadriceps muscles may be 25% lower in the eighth decade than in the third decade (39). This decrease has been attributed to small reductions in the size of type II fibers (13) and to a progressive loss in the total number of muscle fibers (21, 22), particularly the type II moiety (19, 20). Evidence from electrophysiological studies indicates that the loss of the type II fibers is secondary to motoneuron cell death (6); the fiber type grouping and enclosed fibers that are seen in histological sections of older muscles lend support to this finding (13). Based on the similar reductions in muscle mass and strength with aging and evidence for the preservation of specific tension in muscle, Grimby and Saltin (14) have suggested that quantitative rather than qualitative changes within muscles account for most of the strength loss.

The extent to which reductions in strength with aging may be overcome by appropriate physical training is uncertain. There are relatively few published studies on the effects of strength training in the elderly, and in most of these isometric training of very small muscle groups (17) or calisthenics and elastic bands (2, 3) have been used rather than progressive resistance training. Variable increases in strength have occurred after all forms of training, but the greatest gains were reported recently by Frontera and colleagues (11). These investigators noted increases of >100% in the strength of the knee extensors and flexors after 12 wk of weight-lifting training, along with evidence of considerable muscle hypertrophy. This is in contrast to other short-term studies of strength training in the elderly, which have demonstrated gains in the strength of knee extensors (3) and elbow flexors (28) with little or no evidence of muscle hypertrophy, suggesting that the improvements were due to neural adaptations.

The present work was designed to extend previous observations by investigating the effects of strength training on muscle strength, whole muscle and muscle fiber cross-sectional areas, muscle contractile properties, and the completeness of motor unit activation in older men.

METHODS

Subjects. Fourteen healthy 60- to 70-yr-old male volunteers took part in this study (means ± SD: age 63 ± 2.7 yr, height 174 ± 5.5 cm, weight 79 ± 7.7 kg). None had prior experience with weight-lifting training. All subjects gave their informed consent, and the study was approved by the appropriate Institutional Review Committee. Before acceptance into the study subjects performed a progressive incremental cycle ergometer test (15) to detect any signs of latent heart disease or severe pulmonary impairment; such individuals were excluded from the study.

Study design. The study was designed so that the subjects would specifically train the elbow flexors of one arm only ("trained" arm), affording a within-subject control and thus reducing the need for a control group of subjects. It should be emphasized, however, that although the "untrained" control arm did not receive specific elbow flexion training on the device to be described below, it was involved in two other exercises (bench press
and seated dead lift) that would have provided a mild training stimulus to the elbow flexors. The training regimen incorporated additional arm, leg, and trunk exercises to provide an overall conditioning stimulus. Post-training, changes in weight-lifting capacity were evaluated in all the arm and leg exercises but not in movements primarily involving the trunk.

Training. Training was done on 3 alternate days each week for 12 wk. Bilateral leg press, supine bench press, and seated dead lift exercises were done on a multistation weight-lifting machine (Global Gym, Downsview, Ontario, Canada); bent-leg abdominal curls were performed on a padded station on the floor. One arm was selected at random, and the elbow flexors were trained on a custom-built weight-lifting apparatus (Rubicon Industries, Stoney Creek, Ontario). Exercises were done in a circuit set system, with 2-min pauses between sets. Each set comprised 10 repetitions in bench press and arm curl exercise, 15 repetitions in leg press, and 12–20 repetitions in the seated dead lift and abdominal curl exercises. The bench press was performed supine as a repeated bilateral arm press exercise from an initial position close to the chest. For the arm curl exercise the subjects were seated and began the movement with the arm in a fully extended position with the palm facing up. The elbow was flexed through a full range of movement to lift the weight before being returned to full extension. The bilateral leg press exercise was performed in a seated position with the back fully supported and the feet resting on a footplate. The exercise consisted of simultaneous hip and knee extension and ankle plantar flexion. Subjects began the movement with the knees flexed at 90° and then lifted the weight by straightening the legs before resuming the starting position. Training progressed from two sets of each exercise at 50% of the initial one-repetition maximum (1 RM) to four sets at 70–90% of 1 RM over the course of the study. Throughout the training program the weights were adjusted to restrict the number of repetitions in each set to the required number.

Measurement of voluntary strength, torque, and weight-lifting capacity. Weight-lifting capacity was measured as the heaviest weight that could be lifted once throughout the complete range of movement (1 RM). Testing took place on 2 separate days, and the heaviest weight lifted was recorded as the pretraining value. The movements tested were unilateral arm curl, bilateral leg press, and supine bench press. After the training program, the 1 RM was again determined, and in addition each subject did as many repetitions as possible with the pretraining 1 RM to provide a measure of endurance. In this endurance test, repetitions were done at a rate of 10/min, the same rate used in the training.

Maximal concentric contraction torque of the elbow flexors was measured on a Cybex isokinetic dynamometer (Lumex, Ronkonkoma, NY) before and after the training period. Unilateral elbow flexion was performed at angular velocities of 0.52, 2.09, 3.14, 4.19, and 5.24 rad/s (30, 120, 180, 240, and 300°/s) in random sequence. For each contraction, peak torque was taken as the highest value attained regardless of where it occurred in the range of movement. The best performance of three trials at each velocity was recorded as the maximal value.

Bilateral leg press (simultaneous hip and knee extension and ankle plantar flexion) torque was measured as described in detail previously (37). Briefly, a leg press apparatus was coupled to a Cybex dynamometer, and the resulting 4:1 gear reduction enabled the Cybex to accommodate the large torques that can be generated in a bilateral leg press maneuver. However, because this arrangement also restricts the maximal angular velocity of the instrument’s lever arm to 1.31 rad/s (75°/s) compared with the usual 5.24 rad/s (300°/s), measurements were recorded during three trials at lever arm angular velocities of 0.26 and 1.31 rad/s. The maximal voluntary isometric strength of the elbow flexors of each arm was measured on a custom-built apparatus as described in detail elsewhere (25). Subjects did two maximal voluntary contractions (MVCs) separated by 2 min of rest at joint angles of 1.31, 2.09, and 2.88 rad (75, 120, and 105°); the order of testing was selected at random, and the highest torque in the two trials was recorded as the maximal value.

Motor unit activation. The extent of motor unit activation during the MVCs was assessed using the interpolated twitch technique as described by Belanger and McComas (4). A supramaximal electrical stimulus was delivered to the involved muscles during the MVCs. If an increment occurred on the MVC torque recording, the magnitude of the increment, expressed as a percentage of the maximal twitch magnitude evoked at rest, represented that portion of the muscle mass not activated by the voluntary effort. The method cannot distinguish between incomplete recruitment or insufficient motor unit firing rate as being responsible for the increment on the torque recording; hence the term activation is used (4). Therefore complete activation, as indicated by no increment on the torque recording, implies that all motor units have been recruited and are firing at rates sufficient to produce maximal tetanic force.

Measurement of evoked muscle contractile properties. The evoked contractile properties of the elbow flexors were determined in each arm by use of the same apparatus and joint angles previously employed for the measurement of isometric MVC. The assessment of evoked twitch torque always preceded the testing of isometric MVC to obviate the potentiation of the twitch by a maximal effort (36). Twitch contractions were evoked by percutaneous nerve stimulation as described in detail previously (25). Briefly, the contractions were evoked by percutaneous electrical stimulation via two lead plate electrodes, which were encased in moistened gauze impregnated with conducting medium. One electrode was placed on the motor point of the biceps, and the other was placed on the ventral surface of the forearm just below the elbow. The latter placement ensured stimulation of brachioradialis and brachialis as well as biceps. Stimuli were rectangular voltage pulses of 50- or 100-μs duration, delivered by a Devices stimulator (Medical Systems). When no further increases in torque could be produced by additional increases in the stimulus intensity, the twitch contraction was considered to be maximal. The data were displayed on a storage oscilloscope (Hewlett-Packard 120 1B) and analyzed on-line by use of a laboratory computer (PDP 11-03, Digital Equip-
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Measurement. Measurements included maximal twitch torque, contraction time, half-relaxation time, maximal rates of torque development and relaxation, and torque-time integral.

Measurement of muscle size. The cross-sectional areas of the flexors and extensors of the elbows and knees were measured from computerized tomography scans as reported previously (24). Included in the flexor compartment of the arm were biceps brachii and brachialis but not brachioradialis; the arm extensors were triceps brachii. The knee extensor compartment comprised the four quadriceps heads, and the knee flexor compartment also included the adductor muscles. The legs were scanned simultaneously at a point corresponding to 50% of the upper leg length as measured from the head of the fibula up to the lateral point of the greater trochanter. The arms were scanned individually at a point corresponding to 40% of the upper arm length up from the lateral epicondyle of the humerus to the acromion process.

Measurement of the muscle fiber characteristics. Muscle fiber characteristics of the biceps brachii muscle (long head) in both the trained and untrained arms were determined from percutaneous needle biopsy samples using established procedures (24). Measurements comprised fiber type distribution and the mean cross-sectional areas of type I (or slow-twitch, ST) and II (or fast-twitch, FT) fibers.

Statistical analyses. Descriptive statistics included means ± SE. Overall training effects were evaluated by analysis of variance techniques; specific differences were tested using the Tukey A method. The critical level for statistical significance was established at \( P = 0.05 \).

RESULTS

All subjects were able to successfully complete the training without injury.

Weight-lifting capacity. The 1 RM loads in all three weight-lifting exercises increased significantly \( (P < 0.001) \) after the training (Figs. 1 and 2). The single arm curl 1 RM was higher in both arms after the training \( (P < 0.05) \), but the mean increase in the trained arm \( (48.4\%) \) was greater \( (P < 0.05) \) than the increase in the control arm \( (12.7\%; \) Fig. 2). In addition, the absolute endurance was substantially increased after the training, inasmuch as subjects were able to lift their pretraining 1 RM an average of 7-19 times in the trained limbs and 7 times in the control arm (Table 1).

Isokinetic torque. The maximum isokinetic torque in bilateral leg press exercise performed at 0.26 and 1.31 rad/s increased by 17 and 18%, respectively, after the training (Fig. 1). During elbow flexion at the five angular velocities, the mean gains in the trained arm \( (8.8\%, P < 0.01) \) were similar to those in the control arm \( (6.5\%, P < 0.05) \) (Fig. 3).

Isometric strength. During maximal isometric contractions of the elbow flexors, torque measurements demonstrated the well-established variation with joint angle, but there was no significant change in the maximum torque in either arm after the intervention period (Fig. 3). The failure of an interpolated stimulus to produce additional isometric torque confirmed that the subjects were able to achieve complete motor unit activation \( (98\%) \) both before and after the training.

Evoked muscle contractile properties. After training, increases in the maximal evoked twitch torque were recorded at elbow joint angles of 2.09 (9.1%) and 2.88 rad (11.6%) in the trained arm and at 2.88 rad (11.9%) in the untrained arm \( (P < 0.05) \) (Fig. 4); there was also a significant decrease \( (P < 0.05) \) in evoked twitch torque in the untrained arm at 2.09 rad (11.2%). The twitch torque-time integral increased significantly \( (P = 0.007) \) in the trained arm after training at elbow joint angles of 2.09 and 2.88 rad, but there was no change in the control arm (Fig. 4). The maximal rate of torque development decreased \( (P < 0.05) \) in the untrained elbow flexors at the 2.09-rad angle and increased significantly \( (P < 0.05) \) in both arms at the 2.88 rad position, but there was no change at the other joint positions (Fig. 5). The times to attain peak twitch torque (Fig. 6) and the maximal rates of torque relaxation (Fig. 5) were similar in both arms.
before and after the training. The half-relaxation times were greater in the trained arm at all joint angles after training ($P < 0.05$) and remained unchanged in the control arm (Fig. 6).

Muscle cross-sectional area. Training resulted in an increase of 17.4% (16.7 to 19.6 cm²; $P < 0.001$) in the mean maximal cross-sectional area of the elbow flexors in the trained arm but no change in the control arm (Fig. 2). In contrast, there was a small but significant ($P = 0.035$) increase in the maximal cross-sectional area of the elbow extensors in the control arm (22.1 to 23.7 cm²) but less of a gain in the trained arm. It should be noted that the term “trained” refers only to the elbow flexors, because the elbow extensors of both arms received a training stimulus from the bench press exercise.

Before training the flexor-to-extensor area ratio was similar in both arms (0.79 and 0.80), but after training the ratio was higher ($P = 0.042$) in the trained arm (0.89) than in the control arm (0.76; Fig. 2).

There were significant ($P < 0.01$) increases after training in the mean maximal cross-sectional areas of the knee flexors (3.6 cm², 4.4%) and extensors (6.9 cm², 9.9%) in the right leg only despite the fact that both legs were trained simultaneously in bilateral movements.

Muscle fiber characteristics. After training, there was a significant ($P < 0.005$) increase in the mean cross-sectional areas of both type I (ST) and II (FT) fibers from the biceps brachii muscle of each arm (Fig. 7). However, mean type II fiber area increased more in the arm that received the more direct training stimulus (trained arm, 30.2%, $P < 0.05$) than in the less directly trained arm (untrained arm, 10.7%; Fig. 7). Type II fiber area in the trained arm increased more than type I area; consequently, there was a significant ($P < 0.05$) increase in
the type II-to-I (FS-to-ST) area ratio (1.13 to 1.29). In contrast, the FS-to-ST area ratio did not increase significantly in the untrained arm (Fig. 7). The percent distribution of type I fibers in the biceps muscles of both the trained (40%) and untrained arm (45%) remained constant.

DISCUSSION

Changes in muscle performance and muscle size. The major finding in the present study was that the older men responded to weight-lifting training in a qualitatively similar manner as young men, with large increases in the maximal load that could be lifted and accompanying enlargement of whole muscle and muscle fiber areas.

Previous studies of strength training in the elderly have produced conflicting results. Moritani and deVries (28) reported an increase in weight-lifting capacity of the trained elbow flexors of 23% but no change in upper arm girth after 8 wk of progressive weight-lifting exercise. Aniansson and Gustafsson (2) found a similar increase in isokinetic torque of the knee extensors and no significant increment in the cross-sectional areas of individual muscle fibers after 12 wk of training with body weight as resistance. In contrast, a recent study by Frontera et al. (11) was the first to show that older leg muscles could respond to intense resistance training with significant increases in muscle and muscle fiber size. Now the present study has shown that older arm muscles can also hypertrophy in response to strength training.

The latter two studies showed a similar general pattern of results. There was a very large increase in weight-lifting performance, a much smaller and sometimes insignificant increase in less specific isometric and isokinetic tests, and increases in muscle and muscle fiber size that were considerably smaller than the increases in weight-lifting performance but were similar to or moderately greater than the increases in the less specific performance measures.

However, there were notable differences between the two studies. Frontera et al. (11) found a much larger increase (107 vs. 48%) in weight-lifting performance, but we found a slightly greater increase (17.4 vs. 11.9%) in muscle cross-sectional area. Whereas a similar increase in type II fiber area was found in both studies (our study 30%, Frontera et al. 27.6%), a larger increase in type I fiber area was found by Frontera et al. (33.5%) than by us (13.7%). Thus our data gave the commonly observed pattern of greater hypertrophy of type II fibers and consequently an increase in the type II-to-I area ratio (7, 23, 34), whereas Frontera et al. (11) found equal enlargement of type I and II fibers.

There was a high degree of specificity in the training response. Strength performance measured on the training device (weight lifting) increased far more than in the less familiar isometric and isokinetic tests. Indeed, isometric and isokinetic performance failed to increase sig-
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1.05 1.75 2.44 1.05 1.75 2.44

ELBOW JOINT ANGLE, rad

- 80
- 70
- 60
- 50
- 40
- 30
- 20
- 10
- 0

Contraction times (top) and half-relaxation times (bottom) during electrically evoked twitch contractions of elbow flexors of both arms before (open circles) and after (filled circles) training. * P < 0.05, change after training.

A puzzling finding was the lack of a significantly greater increase in weight-lifting performance and a substantial amount of hypertrophy (17%). The observed specificity points to the important role of nervous system adaptations in the response to strength training, in particular the role of learning and coordination (30). The implication for the design of strength-training programs for the elderly is that the training exercises should simulate as closely as possible the most common strength-requiring tasks likely to be encountered by this population. Such an approach will ensure the best possible return on the training investment.

A puzzling finding was the lack of a significantly greater increase in isometric and isokinetic performance in the trained vs. untrained arm, because the trained arm underwent a greater increase in muscle and muscle fiber cross-sectional area. A greater increase in strength would be expected to accompany a greater increase in muscle mass. Such a finding is not unique to our study. In the study of Frontera et al. (11), the right knee extensors failed to increase isometric strength despite an 11.9% increase in muscle cross-sectional area. A greater increase in strength would be expected to accompany a greater increase in muscle mass. Such a finding is not unique to our study. In the study of Frontera et al. (11), the right knee extensors failed to increase isometric strength despite an 11.9% increase in muscle cross-sectional area. In the left knee extensors the increase in isometric strength (7.7%) was slightly less than the increase in muscle size (9.3%). Weight training in young men caused a greater increase in muscle cross-sectional area (10-17%) than isometric strength (4-5%); weight-lifting performance increased 24-42% (9). In a recent study in our laboratory (unpublished observations) we did not find a significant increase in isometric strength after 5 mo of weight training by young men despite significant increases in weight-lifting performance and muscle cross-sectional area. Finally, in a recent study no increase was found in the peak isometric force of overloaded rat soleus despite significant increases in muscle mass and muscle fiber area (16).

It is difficult to explain why any measure of strength would not increase if muscle size increased. Perhaps in the present study training caused a "negative" neural adaptation, which took the form of inhibition of the elbow flexors during isometric contractions, thereby preventing increased force despite hypertrophy. This explanation can be excluded because motor unit activation in the flexors was near maximal and similar before and after training. A counterproductive neural adaptation might have taken the form of increased cocontraction of antagonists; thus increased cocontraction of triceps in the less familiar isometric task may have offset the increased contractile force of the agonists (elbow flexors). We have no data related to this possibility, although there is one report of greater cocontraction in the leg.
muscles of trained power athletes than endurance athletes (29). In view of the many complex ways in which the muscles acting at the elbow joint can be activated and coordinated (5), such seemingly counterproductive adaptations cannot be ruled out.

Perhaps the observed hypertrophy did not increase the intrinsic force-generating capacity of the muscle. It cannot be argued that hypertrophy in these older muscles was entirely the result of connective tissue proliferation, because the increase in fiber size was at least equivalent to that of the whole muscle. Furthermore, the greatly hypertrophied muscles of bodybuilders show no evidence of connective tissue proliferation (32). In the previously cited study of rat soleus (16), hypertrophy after 30 days of overload was not associated with connective tissue proliferation, an increase in interstitial fluid volume, or a decrease in protein content. These authors suggested that ultrastructural examination of myofibrils and cytoarchitecture and assessment of possible alterations in excitation-contraction coupling might help uncover the mechanisms responsible for the decrease in specific tension (i.e., the force developed per unit muscle cross-sectional area) that can accompany hypertrophy. Whatever the mechanisms, they may account for the pattern of results found in the present study.

A notable observation was that muscle size increased significantly only in the right knee extensors and flexors even though both legs were trained simultaneously in a bilateral leg press movement. Perhaps most of the subjects were right limb dominant and unintentionally favored this limb during training.

In addition to the substantial gains in maximal weightlifting capacity in this study, there was a notable improvement in muscular endurance during repeated lifting. After the training, subjects were able to lift their pretraining 1 RM from (range) 4 to 34 times in the trained limbs but only from 1 to 16 times in the untrained arm. By the seventh decade of life, losses in strength and power often interfere with many common activities of daily living, such as lifting and carrying, raising and lowering body weight, and walking. It seems likely that increases in muscular endurance of the type reported here might enable seniors to accomplish certain tasks that may otherwise prove to be impossible or extremely fatiguing.

Evoked twitch contractile properties. In the present study twitch torque increased in the trained arm at two of the three joint angles tested; however, a similar increase occurred at one of the joint angles in the untrained arm. Therefore, there was no convincing evidence of a greater increase in twitch torque in the trained arm. These results are consistent with the lack of a greater voluntary isometric strength increase in the trained arm. Of the previously discussed mechanisms that might account for the failure of voluntary isometric strength to increase despite hypertrophy, only the possible decrease in specific tension can be offered to explain the failure of twitch torque to increase more in the more hypertrophied trained arm. Bodybuilders and weight lifters do have greater evoked twitch force than untrained men (33); however, these athletes had trained for many years and possessed greatly hypertrophied muscles. A greater degree of hypertrophy than we observed in the present study may be necessary before absolute muscle force begins to increase. Thus previous short-term longitudinal strength-training studies (1, 8, 26) in young subjects have mainly not shown increases in the evoked twitch and tetanic tension (Ref. 10 is an exception).

We elected not to use tetanic stimulation because of the extreme discomfort associated with the procedure. A limitation of using twitch torque as a measure of force-generating capacity is that the twitch response would be very sensitive to any alteration in excitation-contraction coupling; indeed, some investigators (10) use the twitch response as a measure of excitation-contraction coupling and the tetanic response as the measure of intrinsic force. It is possible that twitch and tetanic force could change independently. In a sense this happened in the present study. There was an increase in twitch but not tetanic (MVC with full activation) torque in both arms. If the increase in twitch torque was an adaptation to training, we cannot explain why the response was not greater in the more intensely trained arm.

Time to peak twitch torque did not change significantly in the trained arm, but there was a significant increase in half-relaxation time, in agreement with similar observations in young adults after strength training (18). The increase in half relaxation time contributed to the increase in the twitch torque-time integral. The prolongation of the twitch contraction would shift the force-frequency relationship to the left, thereby allowing maximal tetanic tension to be achieved at a lower motor unit firing frequency. This adaptation coupled with the already observed slowing of older muscles even without training (35) should allow strength-trained seniors to achieve maximal muscle force at lower motor unit firing rates than their younger counterparts. Lower firing rates might also increase resistance to fatigue.

There was an apparent joint angle specificity in the changes in some of the twitch properties. At the smallest joint angle where the elbow flexors were at their shortest length, there were no changes in twitch torque, torque-time integral, or maximum rate of torque development. In contrast, at the largest joint angle and longest muscle length, these measures increased significantly but similarly in both trained and untrained (actually received a mild training stimulus) and trained arms. The lack of change at the short muscle length may have resulted from the large series compliance at this length, which prevented all but a small part of the developed tension from being registered externally. The potential torque would already have been small because of the short muscle length. We are not able to explain why the untrained arm showed a decrease in twitch torque at the intermediate joint angle and muscle length after training while the trained arm showed an increase. Although the changes in MVC were not significant, the pattern of results was similar to that for twitch torque, namely, at the intermediate joint angle a decrease in the untrained arm but an increase in the trained arm. This pattern of results may have been influenced by the resistance pattern of the arm-training device because only the trained arm used it.

Motor unit activation. The elderly men in this study were able to fully activate their elbow flexors in maximal
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Isometric contractions even before the training began. This observation confirms a previous report that the elderly are not impaired in the ability to activate muscles in voluntary isometric contractions (35). Both studies used the interpolated twitch method of assessing motor unit activation (4).

The method assumes that if no increment in torque occurs on a voluntary contraction recording when a supramaximal stimulus is superimposed, then the involved muscles have been fully activated. One possible criticism of the method might be that if the stimulus failed to fully activate the muscle and if the part not activated by stimulation was the same part not activated by voluntary effort, then it would be falsely concluded that voluntary activation was complete. However, such a happening is quite unlikely. Moreover, whereas the method is most sensitive when all motor axons have been stimulated, failure to do so does not invalidate the method (27, 31). The procedure that we and others have used to ensure the greatest possible activation by stimulation has been to use a stimulus intensity well in excess of that needed to evoke a maximal twitch response, the assumption being that no further increases in torque despite increases in stimulus intensity provide evidence that all motor fibers have been stimulated. Another indication that our stimulation maximally activated the elbow flexors was that the evoked twitch torque at rest (~8 N-m) was what you would expect for a tetanic (or MVC with full activation) torque of ~60 N-m, i.e., a twitch-to-tetanus ratio of ~0.15 for the elbow flexors (12, 26).

It must be emphasized that we determined motor unit activation only for isometric contractions, the contraction mode in which no improvement occurred after training. It is possible that before training the subjects were not able to fully activate their muscles in the weight-lifting and isokinetic tasks in which performance improved.

In summary, we have demonstrated that older males can respond to progressive weight-lifting training with increases in dynamic muscle performance and whole muscle and muscle fiber size that compare favorably with responses seen in young men. These observations raise the encouraging prospect that the rate of decline in strength and muscle mass in old age and the accompanying loss of independent functional capacity can be reduced or even reversed by appropriate resistance training programs.

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Address for reprints requests: N. McCartney, Dept. of Physical Education, McMaster University, 1280 Main St. West, Hamilton, Ontario L8S 4K1, Canada.

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