Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse

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Suetta, Charlotte, Per Aagaard, Anna Rosted, Ane K. Jakobsen, Benn Duus, Michael Kjaer, and S. Peter Magnusson. Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. J Appl Physiol 97: 1954–1961, 2004. First published July 9, 2004; doi:10.1152/japplphysiol.01307.2003.—The ability to develop muscle force rapidly may be a very important factor to prevent a fall and to perform other tasks of daily life. However, information is still lacking on the range of training-induced neuromuscular adaptations in elderly humans recovering from a period of disuse. Therefore, the present study examined the effect of three types of training regimes after unilateral prolonged disuse and subsequent hip-replacement surgery on maximal muscle strength, rapid muscle force [rate of force development (RFD)], muscle activation, and muscle size. Thirty-six subjects (60–86 yr) were randomized to a 12-wk rehabilitation program consisting of either 1) strength training (3 times/wk for 12 wk), 2) electrical muscle stimulation (1 h/day for 12 wk), or 3) standard rehabilitation (1 h/day for 12 wk). The nonoperated side did not receive any intervention and thereby served as a within-subject control. Thirty subjects completed the trial. In the strength-training group, significant increases were observed in maximal isometric muscle strength (24%, P < 0.01), contractile RFD (26–45%, P < 0.05), and contractile impulse (27–32%, P < 0.05). No significant changes were seen in the two other training groups or in the nontrained legs of all three groups. Mean electromyogram signal amplitude of vastus lateralis was larger in the strength-training than in the standard-rehabilitation group at 5 and 12 wk (P < 0.05). In contrast to traditional physiotherapy and electrical stimulation, strength training increased muscle mass, maximal isometric strength, RFD, and muscle activation in elderly men and women recovering from long-term muscle disuse and subsequent hip surgery. The improvement in both muscle mass and neural function is likely to have important functional implications for elderly individuals.

ageing; atrophy; rehabilitation; electromyogram

THE DEBILITATING EFFECTS of disuse on maximal muscle strength (4, 40), muscle mass (13, 21, 35), and muscle activation (44) are well documented and occur already during the first week of immobilization. Most of the current knowledge concerning the effect of immobilization on skeletal muscle is based on studies in healthy young individuals during bed rest (35), limb unloading (9), and spaceflight (13, 36) or in young patients recovering from anterior cruciate ligament reconstruction (5, 19, 55). However, because elderly persons in particularly are prone to periods of immobilization and disuse either due to joint pain or hospitalization (11), it appears paramount to gain a better understanding of how immobilization affects muscle size and neural function in this population, as well as to identify training regimes that ensure an effective rehabilitation.

It is well known that, with increasing age, muscle strength and muscle power decrease for both sexes, especially beyond the sixth decade (10, 22, 42, 48, 53, 56). Interestingly, it has been shown that the ability to develop high muscle power declines more rapidly and relates more to functional performance than to maximal muscle strength (7, 48, 53). In daily life, however, many types of movements, such as preventing a fall, are characterized by a limited time to develop force (0–200 ms), which is considerably less time than it takes to achieve maximal contraction force (~400–600 ms) (2, 51). Consequently, during such time-restricted contraction conditions (<200 ms), the ability to develop a rapid rise in muscle force [i.e., a high rate of force development (RFD) = force/time] may become more important than maximal muscle force and power. Despite this, limited information is available on training-induced neuromuscular adaptations in elderly subjects after a period of immobilization.

Previously, RFD has been investigated in young, healthy individuals (2, 46, 51) and has been demonstrated to increase in response to heavy strength training (2, 46, 51) and combined strength/power training (26), whereas low strength training seems to have no effects (46). In elderly individuals, RFD is reduced compared with young individuals of both genders (12, 30, 33, 50, 54); however, combined power/strength training has been shown to induce marked increases in RFD and muscle activation [electromyogram (EMG) amplitude] in healthy, elderly individuals of both genders (24, 25, 27). The effect of strength training on RFD has not previously been investigated in elderly subjects who recover from a period of immobilization.

Another method to restore muscular function after immobilization is by the application of percutaneous neuromuscular electrical stimulation (NMES), which has been used primarily in young patients rehabilitating from anterior cruciate ligament reconstruction (5, 19), whereas studies on elderly subjects are scarce (41, 43). None of the aforementioned studies have evaluated the effect of NMES on muscle activation and rapid muscle strength properties. Because muscle contraction induced by NMES partly bypasses the central nervous system (CNS), it could be hypothesized that training involving volitional strength exercise more effectively improves neuromuscular function and RFD. On the other hand, NMES might be a more tolerable training modality for frail, elderly individuals.

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Therefore, the purpose of the present study was to compare the effect of additional unilateral strength training or electrical muscle stimulation with conventional physiotherapy on neuromuscular adaptation in a group of elderly individuals rehabilitating from unilateral, long-term disuse and immobilization. Measurements were focused on the type and magnitude of neuromuscular adaptation in the very early phase of muscle contraction (0–200 ms), with respect to RFD and muscle activation. Furthermore, the study evaluated the effect of strength training vs. electrical muscle stimulation to compare the neuromuscular adaptation to training involving either the functioning nervous system or training using peripheral muscle stimulation, which bypasses efferent motor output of the CNS.

METHODS

Subjects. The study was designed as a prospective randomized controlled study and included 36 elderly individuals with long-term unilateral disuse due to osteoarthritis of the hip. Subjects were scheduled for primary unilateral hip-replacement operation at Bispebjerg University Hospital, Copenhagen, Denmark. Eligibility criteria included age over 60 yr and radiological and clinical hip osteoarthritis. All subjects were carefully examined by a blinded physician to exclude subjects with cardiological, neurological, or cognitive problems. Also, lower limb problems other from the hip osteoarthritis and/or pain during testing or training measured on a visual analog scale (>3) were exclusion criteria.

Subjects were randomly allocated to one of the following groups after baseline tests: 1) standard rehabilitation (SR), 2) SR plus unilateral strength training (ST), or 3) SR plus unilateral NMES (ES). The ST and ES groups only performed the additional training on the operated leg so that the nonoperated side could serve as a within-subject control; the SR group served as a control group.

Subjects were retested 5 and 12 wk after surgery. Measurement outcomes were quadriceps muscle cross-sectional area (CSA), maximal voluntary isometric quadriceps strength, rapid muscle force defined as the contractile RFD (change in force/change in time), normalized RFD, and contractile impulse (force dt). EMG recordings were obtained in vastus lateralis (VL), vastus medialis (VM), and rectus femoris during maximal isometric quadriceps contraction (2) to evaluate the change in muscle activation induced by the different training regimes. The ethics committee of Copenhagen approved the study in accordance with the Helsinki Declaration, and written, informed consent was obtained from all participants.

Maximal isometric muscle strength and RFD. Muscle strength was measured as the maximal voluntary isometric knee extension torque exerted in an isokinetic dynamometer (KinCom; Kinetic Communicator, Chattanooga, Chattanooga, TN). The reliability and validity of this dynamometer have been verified in detail elsewhere (14). Subjects were seated 10° reclined and firmly strapped at the hip and thigh. The axis of rotation of the dynamometer lever arm was visually aligned to the axis of the lateral femur condyle of the subject, and the lower leg was attached to the lever arm of the dynamometer just above the medial malleolus. Individual setting of the seat, backrest, dynamometer head, and lever arm length was registered, so identical positioning was secured at all time points. To correct for the effect of gravity, the passive mass of the lower leg was measured by the dynamometer at a knee joint angle of 45° (3). Subjects were carefully instructed to contract as fast and hard as possible. Visual feedback was provided to the subjects as a real-time display of the dynamometer force output on a computer screen (34). After careful warm-up with several dynamic and submaximal isometric contractions, subjects performed three maximal isometric contractions at a knee joint angle of 60° (0° = full knee extension). The trial with the highest maximal voluntary contraction was selected for further analyses (2). All measurements were performed on both thighs and were preceded by a familiarization trial that was conducted on a separate day. The nonaffected side was tested first to increase subjects’ comfort with the procedure, as described in detail elsewhere (2). Contractile RFD was derived as the average slope of the initial phase of the force-time curve (change in force/change in time) at 30, 50, 100, and 200 ms relative to the onset of contraction. Onset of contraction was defined as the instant where force increased 3.5 N·m above the rising baseline level, corresponding to ~2% of the peak moment. Contractile impulse was determined as the area under the force-time curve (f·force dt) in the same time interval. By incorporating the aspect of contraction shape, contractile impulse provides important information concerning rapid muscle strength characteristics, although this parameter is only rarely reported (2, 6).

Normalzed RFD was calculated as the slope of the force-time curve normalized relative to CSA. The measurement procedure has been described in more detail elsewhere (2).

EMG recordings. After careful preparation of the skin by shaving and cleaning with alcohol, pairs of surface electrodes (Medicotest Q-10-A, 20-mm interelectrode distance) were placed over the belly of VL, VM, and rectus femoris. All electrode positions were carefully measured in each subject to ensure identical recording sites throughout all tests. The EMG electrodes were connected directly to small custom-built preamplifiers, and the EMG signals were led through shielded wires to custom-built amplifiers with a frequency response of 100 Hz to 10 kHz, with bandwidth and common mode rejection ratio exceeding 100 dB. EMG and dynamometer strain gauge signals were synchronously sampled at a 1,000-Hz analog-to-digital conversion rate using an external analog-to-digital converter (dt 2801-A, Data Translation, Marlboro, MA). During later offline analysis, EMG signals were digitally high-pass filtered with a fourth-order, zero-lag Butterworth filter with a 5-Hz cutoff frequency, followed by a moving root mean square filter with a time constant of 50 ms. To reflect neural adaptation in the early phase of contraction, integrated EMG of the root mean square-filtered signal was calculated in time intervals of 0–30, 50, 100, and 200 ms relative to the onset of EMG integration, which was initiated 70 ms before force onset to account for electromechanical delay (2). To yield mean average voltage (MAV), integrated EMG was divided by integration time (MAV = integrated EMG/integration time).

Muscle CSA. CSA of the quadriceps femoris muscle was obtained by computed tomography (Picker 5000) with an image matrix of 512 × 512 pixels, slice thickness of 8 mm, and scanning time of 5 s. The scans of the quadriceps muscle were obtained at the midpoint between the great trochanter and lateral joint line of the knee. Each scan was blinded, CSA was measured three times by a radiologist, and the mean value was recorded as the result. The coefficient of variation between two consecutive measurements was <2%.

Strength training. Strength training was performed as unilateral progressive training of the leg muscles with the focus on the quadriceps muscle of the affected limb. During hospitalization, patients performed daily unilateral knee extension exercises (3 × 10 repetitions) in a sitting position with sandbags strapped to the ankle of the operated leg. As soon as possible (approximately day 7), training was performed in adjustable leg-press and knee-extension machines (Technogym International) three times per week. After a 10-min warm-up on a stationary bicycle, sitting knee-extension and leg-press exercises in a supine position were performed. Training intensity was decreased from 20 to 12 repetition maximum (RM; 3–5 sets × 10 repetitions) from weeks 0 to 6 to avoid injuries and was thereafter maintained at 8 RM (3–5 sets × 8 repetitions). The training load was adjusted on a weekly basis, and in the final 6–8 wk, when the subjects were familiar with the training, they were supervised to perform the exercises as rapidly as possible in the concentric phase and keep a slow speed in the eccentric phase (8). The ES group began the stimulation program on the affected side the first day after surgery. Subjects were carefully instructed in the use of the stimulator and placement of the electrodes. The stimulator was a pocket-size, battery-operated device (Elpa...
2000, Biofina) that delivered a constant biphasic current (0–60 mA). After careful preparation of the skin, two electrodes (Bio-Flex, 50 × 89 mm) were placed over the quadriceps muscle 5 cm below the inguinal ligament and 5 cm above the patella. The pulse rate was 40 Hz with a pulse width of 250 μs, and each stimulation lasted for 10 s followed by 20 s of rest. The amplitude increased and decreased gradually the first and last 2 s. The intensity of the stimulation was adjusted according to individual subject tolerance. The stimulation regimen was applied for 1 h per day on the affected leg for 12 wk. All subjects registered daily the total stimulation time and intensity. After discharge from hospital, the stimulator was used at home, and weekly controls were conducted in the physiotherapy department to ensure the stimulation was performed correctly.

SR. The SR group, as well as the two other subject groups, were provided the same rehabilitation procedure for hip-replacement patients at Bispebjerg Hospital. The rehabilitation program consisted of a home-based training program that included 15 physiotherapy exercises aimed at improving function, range of motion, and muscle strength around the hip. No external loads or rubber bands were used in the program. During the hospital stay, all subjects were trained in all 15 exercises by an experienced physiotherapist, who was blinded to the intervention. All subjects received a pamphlet with the 15 exercises and instructions for the exercises twice a day and to come to weekly controls in the physiotherapy department.

Statistical analysis. Nonparametric statistics were used for the analyses, since not all data met the criterion of normality. To evaluate the effect of intervention over time, a Friedman test was used with post hoc Wilcoxon test. Any between-group differences were analysed with Kruskall-Wallis tests and subsequently the Mann-Whitney U-test. Data are presented as means ± SE. A P value of <0.05 was considered significant.

RESULTS

Thirty of the 36 subjects completed the study. Two subjects from the SR group withdrew immediately because of dissatisfaction with the randomization outcome, two subjects became ill for reasons unrelated to the study, and two withdrew because of personal problems. There was no difference between the three groups with respect to anthropometric data (Table 1), maximal isometric muscle strength, or muscle CSA (mCSA: Table 2) at the inclusion of the study. No training-related complications were seen in any of the three groups.

Maximal isometric strength. Maximal isometric quadriceps strength increased by 24% in the ST group on the operated side 12 wk postsurgery compared with baseline (P < 0.05), whereas there was no increase in quadriceps strength in the two other training groups when 12-wk values were compared with baseline (Table 2). In the SR group, there was a decrease in peak torque from presurgery to 5 wk postsurgery (22%, P < 0.05), with a subsequent increase from 5 to 12 wk (27%, P < 0.05). A similar decrease in peak torque at 5 wk postsurgery was not observed in the two other groups. There was no change on the nonoperated side in any of the three groups (Table 2).

Although there was no difference in peak torque between groups at inclusion time, a significant difference in the relative change between the ST group and the SR group was observed at 5 (P < 0.005) and 12 wk (P < 0.001), and between the ST group and the ES group at 12 wk (P < 0.005). There were no statistically significant differences in the change in peak torque between the ES group and the SR group at any time point.

Quadriiceps CSA. Quadriceps mCSA in the SR group decreased 13% on the operated side at 5 wk (P < 0.05) and remained 9% below baseline values at 12 wk (P < 0.05, Table 2). In the ST group, mCSA of the operated leg was unchanged at 5 wk and increased 12% compared with baseline at 12 wk (P < 0.05). In ES, there was a 4% decrease in CSA on the operated side from baseline to 5 wk (P < 0.05) and a 7% increase from 5 to 12 wk (P < 0.05). There was no change on the nonoperated side in any of the three groups (Table 2). There were no differences in CSA between groups at inclusion but a significant difference in the relative change between the ST group and SR group after 12 wk of training (P < 0.05).

Contractile RFD and impulse. In the ST group, a steeper slope of the moment-time curve of the affected leg was observed after 12 wk of strength training (Fig. 2). Specifically, contractile RFD increased for peak RFD (21%, P < 0.005), and at time intervals of 0–30 ms (45%, P < 0.05), 0–50 ms (31%, P < 0.05), 0–100 ms (26%, P < 0.05), and 0–200 ms (30%, P < 0.005) of the affected side at the end of the 12-wk training period (Fig. 3A). When RFD was normalized to mCSA (RFD/CSA), there was a 25% increase (from 11.27 to 14.12 N·m·s⁻¹·cm⁻², P < 0.05) in the very initial part of the contraction phase (0–30 ms). In contrast, RFD/CSA remained unchanged in the intervals of 0–50 ms (15.28 vs. 17.33 N·m·s⁻¹·cm⁻², 0–100 ms (12.84 vs. 14.20 N·m·s⁻¹·cm⁻²), and 0–200 ms (8.96 vs. 10.22 N·m·s⁻¹·cm⁻²). RFD did not change in the two other training groups from preexercise to 12 wk (Fig. 3, B and C) or in the nonaffected side in any of the three groups (data not shown). Contractile impulse increased in the time intervals of 0–30 ms (32%, P < 0.05), 0–50 ms (32%, P < 0.05), 0–100 ms (28%, P < 0.05), and 0–200 ms (27%, P < 0.005) on the trained leg in the ST group (Fig. 4A). There were no change in impulse in the ES or SR group on the affected side (Fig. 4, B and C), and there were no changes on the nonaffected side in any of the three groups (data not shown).

Quadriiceps muscle EMG. In the ST group, MAV increased significantly for VL on the affected leg in the time intervals of 0–30 ms (36%, P < 0.05), 0–50 ms (40%, P < 0.05), 0–100 ms (38%, P < 0.05), and 0–200 ms (41%, P < 0.05), and for VM at 0–200 ms (21%, P < 0.05) from 5 to 12 wk of training (Fig. 5). In contrast, there were significant decreases in VL of the affected leg in the SR group from pretraining to 5 wk of training in the time intervals of 0–100 ms (45%, P < 0.05) and 0–200 ms (43%, P < 0.05) and a strong trend toward a decrease was observed in VM (0–200 ms) from pretraining to 5 wk of training (43%, P = 0.06) (Table 3). A subsequent increase in MAV (0–200 ms) was observed in VL (57%, P < 0.05) and VM (37%, P < 0.05) from 5 to 12 wks. In the ES group, there was no change in MAV on the affected side as

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<th>Table 1. Anthropometric data</th>
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<td>Age, yr</td>
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<td>Body weight, kg</td>
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<td>Height, cm</td>
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<td>BMI</td>
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Values are means ± SE (range). No significant differences were observed between groups at inclusion time (NS). ST, strength training; ES, electrical stimulation; SR, standard rehabilitation; F, female subjects; M, male subjects; BMI, body mass index.
well as on the nonaffected side in any of the three groups (Table 3). At the inclusion time, there was no difference in MAV between the three training groups; however, the above-mentioned changes led to significant differences between VL MAV (0–200 ms) in the ST and SR group at 5 wk (ST > SR, P < 0.05) and at 12 wk (ST > SR, P < 0.05), and a difference between ES and SR was observed at 5 wk (ES > SR, P < 0.05) (Fig. 5). For VM MAV (0–200 ms), there was only a tendency toward a difference between ST and SR (ST > SR, P = 0.09), whereas there were significant differences for the rectus femoris muscle at 5 wk (ST > SR, P < 0.05) and at 12 wk (ST > SR, P < 0.05) in the time intervals of 0–100 and 0–200 ms.

**DISCUSSION**

The present study examined specific neural adaptations to training, involving the CNS and peripheral muscle stimulation partly bypassing the CNS, by comparing the effects of 12 wk of strength training to electrical muscle stimulation (NMES) and conventional physiotherapy after unilateral hip replacement surgery.

For the first time, it was demonstrated that strength training is an effective way to increase muscle mass, muscle activation, and rapid muscle force characteristics (RFD) in elderly individuals rehabilitating after long-term disuse and surgery-related hospitalization. Importantly, the data show that strength training resulted in marked increases both in RFD and in contractile impulse in the time intervals of 0–30, 0–50, 0–100, and 0–200 ms, and in normalized RFD in the initial phase of muscle contraction (0–30 and 0–50 ms). In contrast, NMES and conventional rehabilitation did not produce such increases in these outcome measures.

Previous studies have demonstrated positive effects of strength training on mCSA and muscle strength in healthy elderly individuals (18, 37) and in very old subjects (16, 31). However, the use of strength training is seldomly used in elderly subjects rehabilitating from surgery, and the number of studies in this area are scarce. Only a few previous studies have investigated the effect of resistive exercises after hip surgery (32, 38, 45, 47) and reported significant increases in muscle strength, but none of these studies have reported results on muscle size or neuromuscular adaptations with training. In contrast to the above-mentioned studies, the baseline measures of the present study were obtained before the time of surgery, which enabled us to evaluate the effect of limb immobilization.

**Table 2. Isokinetic muscle strength and quadriceps muscle CSA**

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<tr>
<th></th>
<th>ST Op-leg</th>
<th>ST Con-leg</th>
<th>ES Op-leg</th>
<th>ES Con-leg</th>
<th>SR Op-leg</th>
<th>SR Con-leg</th>
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<tr>
<td>Quadriceps CSA, m²</td>
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<td>Pre</td>
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<td>5.08±0.15</td>
<td>5.09±0.16</td>
<td>5.03±0.15</td>
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<td>5 wk</td>
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<td>5.26±0.17</td>
<td>5.23±0.16</td>
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<td>12 wk</td>
<td>5.55±0.17</td>
<td>5.73±0.18</td>
<td>5.63±0.17</td>
<td>5.71±0.18</td>
<td>5.50±0.17</td>
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**Isometric strength, N·m**

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<th>ST Op-leg</th>
<th>ST Con-leg</th>
<th>ES Op-leg</th>
<th>ES Con-leg</th>
<th>SR Op-leg</th>
<th>SR Con-leg</th>
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<tr>
<td>Pre</td>
<td>122.9±7.2</td>
<td>156.2±20.9</td>
<td>125.2±13.9</td>
<td>147.9±15.7</td>
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<td>5 wk</td>
<td>130.8±12.7</td>
<td>152.0±20.9</td>
<td>121.1±15.1</td>
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<td>12 wk</td>
<td>151.9±17.8</td>
<td>157.8±19.1</td>
<td>132.9±15.8</td>
<td>148.7±16.3</td>
<td>117.4±13.8</td>
<td>143.2±18.3</td>
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**Table 3. EMG signal amplitudes**

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<tr>
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<th>ST VL</th>
<th>ST VM</th>
<th>ST RF</th>
<th>ES VL</th>
<th>ES VM</th>
<th>ES RF</th>
<th>SR VL</th>
<th>SR VM</th>
<th>SR RF</th>
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<td>0–30 ms, μV</td>
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<tr>
<td>Pre</td>
<td>72.8±11.3</td>
<td>73.4±19.6</td>
<td>38.7±8.1</td>
<td>70.7±22.0</td>
<td>41.7±7.8</td>
<td>29.4±3.4</td>
<td>76.1±20.5</td>
<td>49.3±12.6</td>
<td>30.5±4.1</td>
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<td>5 wk</td>
<td>47.8±5.8</td>
<td>67.7±16.2</td>
<td>43.1±5.3</td>
<td>55.4±18.8</td>
<td>44.3±10.3</td>
<td>44.9±22.5</td>
<td>47.1±11.1</td>
<td>48.8±9.6</td>
<td>31.8±5.4</td>
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<td>65.3±9.1*</td>
<td>68.0±13.1</td>
<td>28.3±4.5</td>
<td>41.1±7.9</td>
<td>46.9±7.7</td>
<td>24.1±3.8</td>
<td>50.5±7.2</td>
<td>49.3±9.0</td>
<td>28.7±6.1</td>
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<td>0–50 ms, μV</td>
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<tr>
<td>Pre</td>
<td>109.0±26.0</td>
<td>98.8±27.8</td>
<td>51.5±11.0</td>
<td>91.2±25.2</td>
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<td>70.8±18.2</td>
<td>54.3±21.0</td>
<td>55.4±11.1</td>
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<td>39.1±5.7</td>
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<tr>
<td>12 wk</td>
<td>88.3±11.0*</td>
<td>88.3±16.8</td>
<td>41.7±6.0</td>
<td>68.4±12.9</td>
<td>69.7±11.2</td>
<td>35.9±3.5</td>
<td>70.1±10.0</td>
<td>64.9±12.7</td>
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<td>0–100 ms, μV</td>
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<tr>
<td>Pre</td>
<td>127.4±31.8</td>
<td>117.8±34.3</td>
<td>77.4±13.9</td>
<td>134.1±31.7</td>
<td>103.8±32.7</td>
<td>64.5±10.9</td>
<td>123.2±23.0</td>
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<td>5 wk</td>
<td>91.6±7.3</td>
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<td>84.1±10.0</td>
<td>123.5±35.3</td>
<td>116.1±32.4</td>
<td>85.4±20.2</td>
<td>68.2±13.3*</td>
<td>67.4±14.9</td>
<td>49.3±7.1</td>
</tr>
<tr>
<td>12 wk</td>
<td>126.2±14.1*</td>
<td>124.1±21.8</td>
<td>83.1±8.1</td>
<td>109.4±19.0</td>
<td>103.6±14.4</td>
<td>63.3±7.2</td>
<td>106.0±14.5</td>
<td>90.5±18.3</td>
<td>60.8±15.9</td>
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<tr>
<td>0–200 ms, μV</td>
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</tr>
<tr>
<td>Pre</td>
<td>132.7±22.7</td>
<td>123.3±31.1</td>
<td>99.7±16.7</td>
<td>161.5±35.2</td>
<td>126.8±38.5</td>
<td>92.0±14.5</td>
<td>122.6±22.5</td>
<td>85.5±21.0</td>
<td>62.3±9.1</td>
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<td>5 wk</td>
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<td>112.9±19.6</td>
<td>104.5±13.0</td>
<td>144.8±28.9</td>
<td>126.9±28.6</td>
<td>99.6±18.2</td>
<td>70.2±13.8*</td>
<td>71.9±14.6</td>
<td>57.3±8.9</td>
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<tr>
<td>12 wk</td>
<td>157.0±17.5*</td>
<td>137.1±19.0*</td>
<td>112.1±12.2</td>
<td>128.8±21.2</td>
<td>117.3±15.8</td>
<td>84.8±10.3</td>
<td>110.6±13.3*</td>
<td>98.3±24.0*</td>
<td>75.0±16.9</td>
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</table>

Values are means ± SE. Mean integrated electromyogram (EMG) signal amplitudes from vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) from the trained leg in the 3 training groups (ST, ES, SR) at 3 time points (Pre, 5 wk, 12 wk). *P < 0.05, 12 wk significantly different from 5 wk. †P < 0.05 5 wk significantly different from baseline.
due to surgery 5 and 12 wk after the operation. Surprisingly, although the affected limb clearly had disuse-associated muscle atrophy, a further decline in muscle size (Table 2) was observed with conventional rehabilitation (SR group, 13%) 5 wk postsurgery, which was fully prevented with strength training and partly with electrical stimulation. Albeit not statistically significant, it appears that the muscle loss was less pronounced in the ES group (−4%) compared with the SR group (−13%) 5 wk after surgery.

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**Fig. 1.** Computer tomography images taken from the midthigh region of a female subject in the strength training (ST) group before and after training. The 2 images are shown at the same scale. Quadriceps muscle cross-sectional area of the operated side (op-leg) increased 32% in this subject; the nonoperated side (con-leg) did not change from pretraining to posttraining.

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**Fig. 2.** Average moment-time curves obtained for the ST group (n = 11) before (pre; solid line) and after 12 wk (post; dashed line) of training. Onset of contraction is denoted by a solid circle, and vertical lines indicate time intervals of 30, 50, 100, and 200 ms relative to the onset of contraction. Posttraining peak isometric torque increased significantly from 122.9 ± 17.2 to 151.9 ± 17.8 N·m in parallel with a steeper slope of the moment-time curve. The increase in slope was reflected by a significant increase in contractile rate of force development both in the initial (30 and 50 ms) and later (100 and 200 ms) phases of rising force.

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**Fig. 3.** Contractile rate of force development (RFD) at baseline and 5 and 12 wk posttraining in the trained leg of all 3 intervention groups [ST, electrical stimulation (ES), and standard rehabilitation (SR)]. Contractile RFD was derived as the average slope of the initial phase of the force-time curve (change in force/change in time) at 30, 50, 100, and 200 ms relative to the onset of contraction. In addition, peak RFD was determined in the time interval of 0–200 ms. Values are means ± SE. *Significant difference between 12-wk and baseline values (P < 0.05).
Moreover, there was no decrease in mCSA in the ES group 12 wk after surgery, in accordance with earlier studies in young anterior cruciate ligament patients (5, 19). However, it was not possible to detect any overall statistical difference in treatment outcome between these two intervention groups (SR and ES groups). In contrast, strength training not only prevented the postsurgery muscle atrophy at 5 wk but also augmented mCSA after 12 wk (12%), which resulted in a significant difference in treatment outcome between the ST group and the two other groups (Table 2).

With respect to isometric strength, similar changes were observed (Table 2) with a 22% decrease in the SR group 5 wk postsurgery, which was prevented in the ES and ST groups. Furthermore, maximal muscle strength increased 24% in the ST group from baseline to after 12 wk of training in contrast to the ES and SR groups. The observed improvements in the ST group corresponds to previous findings in elderly individuals.

![Graph A](image1.png)

**Fig. 4.** Contractile impulse at baseline and 5 and 12 wk postraining in the trained leg of all 3 intervention groups (ST, ES, and SR). Contractile impulse, defined as the area covered by the moment-time curve (f moment dt), was calculated in time intervals of 0–30, 50, 100, and 200 ms relative to the onset of contraction. In addition, peak RFD was determined in the time interval of 0–200 ms. Values are means ± SE. *Significant difference between 12-wk and baseline values (P < 0.05).

![Graph B](image2.png)

![Graph C](image3.png)

![Graph D](image4.png)

**Fig. 5.** Electromyogram (EMG) signal amplitudes at baseline (0), 5 wk (5), and 12 wk (12) postraining in the trained leg of all 3 intervention groups (ST, ES, and SR). Data presented were calculated as the mean integrated EMG divided by the integration time (200 ms) relative to onset of EMG integration for vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF). Values are means ± SE. MAV, mean average voltage. #Significant difference between 12-wk and 5-wk values (P < 0.05). *Significant difference between 5-wk and baseline values (P < 0.05). ST significantly different from SR (P < 0.05).
after prolonged strength training intervention regardless of age and gender (18, 20, 49).

Although the loading intensity of the three different training regimes was not directly comparable in the present study, the fact that neither electrical stimulation nor conventional rehabilitation induced increases in maximal muscle strength or muscle mass may reflect inadequate muscle activation with these training modalities and emphasizes the importance of loading intensity in rehabilitation programs.

The ability to develop force rapidly (i.e., contractile RFD) is an important performance characteristic, especially in older people, contributing to several tasks of daily life such as climbing stairs, walking, and attempting to avoid a fall (7, 17). At the same time, reduced muscle strength in older people, e.g., after a period of immobilization or disuse, may be associated with muscle atrophy, a lowered ability to produce force rapidly, and thereby an increased risk of falling (17). In healthy elderly individuals, it has been demonstrated that RFD is reduced compared with young individuals of both genders (12, 33, 50, 54), although when RFD is normalized to maximal voluntary contraction the results are conflicting (12, 50). Likewise, in healthy elderly individuals, Häkkinen and coworkers demonstrated significant increases in RFD and elevated EMG as a result of combined power/strength training performed for 12 wk (23), 21 wk (29), and 6 mo (24), whereas no effects on RFD could be demonstrated with a 10-wk mixed-methods training program in healthy elderly men (28). The strength training program used in the present study was designed as a progressively adjusted program. The aim was to avoid postoperative injuries while still ensuring a sufficiently high loading intensity (~8 RM) to induce adaptive changes in muscle size (15, 18) and muscle activation, as previously demonstrated in young individuals (2, 14, 46). In accordance with these studies, the present strength training regime resulted in marked increases in rapid force production, both in the very initial phase (30–50 ms, 31–45%) as well as the later part (100–200 ms, 26–30%) of the isometric force-time curve (Fig. 2). Similar changes occurred with respect to contractile impulse, which was determined as the integrated area under the force-time curve, both in the initial phase of contraction (30–50 ms, 32%) and in the later part (100–200 ms, 27%) (Fig. 4). Importantly, the present data are the first to demonstrate a 25% increase in the very initial phase of muscle contraction (30 ms) for RFD normalized to mCSA. This increase indicates that qualitative changes may have occurred in muscle contraction characteristics, such as increased maximal motor unit firing frequency (52) or changes in myosin heavy chain isoform composition toward an increased type II dominance (1). The importance of these rapid muscle force characteristics is stressed by the fact that a positive correlation was observed between RFD (0–30–50 ms) and maximal walking speed (data not presented) at baseline ($r = 0.51–0.55$, $P = 0.005$) but not between walking speed and maximal isometric muscle strength. Correspondingly, after 12 wk of strength training, maximal gait speed increased by $30\%$ ($P < 0.001$) and correlated to the increase in absolute RFD ($r = 0.79$, $P = 0.004$) and normalized RFD ($r = 0.86$, $P = 0.001$) in the very initial phase of muscle contraction (0–30 ms). In contrast, the change in maximal walking speed did not correlate to the adaptive change in maximal muscle strength or mCSA.

The fact that marked increases (36–41%) were observed in EMG signal amplitude, especially for VL, during the early (30–50 ms) and later (100–200 ms) phase of rising muscle force indicates that the increases in RFD and impulse at least partly was explained by adaptive changes in neural function. The lack of increased EMG with strength training in the early phase of training was somewhat surprising comparing with results from earlier studies (23, 39); however, it should be noted that the observed adaptations from preexercise to 5 wk of exercise reflect not only the training intervention but also the immobilization period due to surgery. Thus marked decreases in muscle activation (43–45%) were observed in the SR group from preexercise to 5 wk of exercise (Fig. 5), which seemed to be prevented in both the ST the ES groups.

In summary, the present study demonstrates that strength training is an effective way to induce marked increases in maximal muscle strength and enhanced rapid muscle force characteristics in elderly subjects after long-term unilateral limb disuse compared with rehabilitation regimes using electrical muscle stimulation or conventional physiotherapy. Furthermore, the gains in maximal muscle strength and rapid muscle force characteristics were accompanied by significant increases in EMG amplitudes and increased mCSA of the quadriceps muscles. Although the relative contribution to the observed changes in rapid muscle strength from neural vs. morphological adaptations could not be determined in the present study, the results underline the importance of training both aspects in elderly individuals. Furthermore, the observation that rapid muscle force capacity of the neuromuscular system remains trainable in elderly patients recovering from prolonged limb disuse may have important implications for future rehabilitation programs, especially when the importance of rapid muscle force capacity on postural balance, maximal walking speed, and other tasks of daily life actions are considered.

REFERENCES


