Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women

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ABSTRACT

The effects of a 6-month resistance training (2 day/week) designed to develop both strength and power on neural activation by electromyographic activity (EMG) of the agonist and antagonist knee extensors, muscle fibre proportion and areas of type I, IIa, and IIb of the vastus lateralis (VL) as well as maximal concentric one repetition maximum (1 RM) strength and maximal and explosive isometric strength of the knee extensors were examined. A total of 10 middle-aged men (M40; 42 ± 2), 11 middle-aged women (W40; 39 ± 3), 11 elderly men (M70; 72 ± 3) and 10 elderly women (W70; 67 ± 3) served as subjects. Maximal and explosive strength values remained unaltered during a 1-month control period. After the 6-month training maximal isometric and 1RM strength values increased in M40 by 28 ± 14 and 27 ± 7% (P < 0.001), in M70 by 27 ± 17 and 21 ± 9% (P < 0.001), in W40 by 27 ± 19 and 35 ± 14% (P < 0.001) and in W70 by 26 ± 14 and 31 ± 14% (P < 0.001), respectively. Explosive strength improved in M40 by 21 ± 41% (P < 0.05), in M70 by 21 ± 24% (P < 0.05), in W40 by 32 ± 45% (NS) and in W70 by 22 ± 28% (P < 0.05). The EMGs of the VL and vastus medialis (VM) muscles increased during the training in M40 (P < 0.001 and 0.05), in M70 (P < 0.001 and 0.05), in W40 (P < 0.001 and 0.05) and in W70 (P < 0.001 and 0.05). The antagonist biceps femoris (BF) activity during the isometric knee extension remained unaltered in M40, in W40, and in M70 but decreased in W70 (from 42 ± 34 to 32 ± 26%; P < 0.05) during the first 2 months of training. Significant increases occurred during the training in the mean fibre areas of type I in W70 (P < 0.05) and of overall type II along with a specific increase in IIa in both W40 (P < 0.05) and in W70 (P < 0.05), while the changes in the male groups were not statistically significant. The individual percentage values for type II fibres at pretraining correlated with the individual values for 1 RM strength in both W70 (r = 0.80; P < 0.05) and M70 (r = 0.61; P < 0.05) and also at post-training for maximal isometric torque in W70 (r = 0.77, P < 0.05). The findings support the concept of the important role of neural adaptations in strength and power development in middle-aged and older men and women. The muscle fibre distribution (percentage type II fibres) seems to be an important contributor on muscle strength in older people, especially older women. Women of both age groups appear to be hypertrophically responsive to the total body strength training protocol performed two times a week including heavier and lower (for fast movements) loads designed for both maximal strength and power development, while such a programme has limited effects on muscle hypertrophy in men.

Keywords: ageing, agonist-antagonist, hypertrophy, neural activation, power, resistance training, strength.

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Human muscle strength and the ability to develop explosive force or power are known to decrease with increasing age, especially at the onset of the sixth decade in both genders (Larsson 1978, Bosco & Komi 1980, Clarkson et al. 1981, Viitasalo et al. 1985, Vandervoort & McComas 1986, Porter et al. 1995, Häkkinen et al. 1998a, Jozsi et al. 1999). The decrease in strength characteristics can be explained to a large extent by the reduction in muscle mass, possibly related to age-related changes in hormone balance (Häkkinen & Pakarin 1993) and decline in the intensity of daily physical activities. The age-associated decline in muscle mass is thought to be mediated by a reduction in the size of individual muscle fibres (especially of type II fibres), and a loss of fibres (Lexell et al. 1988). Age-related declines in strength and power may also be in part because of decreased maximal voluntary activation of the agonist muscle as indicated by an age-related decrease in the firing rate of motor units (Kamen et al. 1995), although ageing may not necessarily impair the ability of a person to maximally activate some muscle groups (Enoka et al. 1992). In addition, there appears to be an age-related increase in antagonist coactivation, especially in dynamic multi-joint actions (Häkkinen et al. 1998a).

However, it has been shown beyond doubt that systematic strength training not only in young but also in older persons of both genders leads to substantial increases in strength performance. The initial increases in strength in older people may primarily result from considerable neural adaptations, particularly observed during the earlier weeks of resistance training as indicated by the increases in maximal electromyographic (EMG) activity of trained muscles (Moritani & DeVries 1980, Keen et al. 1994, Häkkinen & Häkkinen 1995, Häkkinen et al. 1998b,c). In addition to increased activation of the agonist muscles, training-induced learning effects (Rutherford & Jones 1986) in terms of reduced coactivation of the antagonist muscles are observed in older people especially (Häkkinen et al. 1998b) and/or an optimized activation of the synergists may also play an important role enhancing the net torque produced about the joint(s). The question remains how long the neural factors predominate over long-term training.

However, experimental data since the study by Frontera et al. (1988) have shown that strength development during progressive strength training may include a considerable contribution of muscle hypertrophy even in older men. Yet, power development was not an important feature of the strength training programme. The basic requirements for training-induced hypertrophy in older people of both genders are that the overall training intensity (in terms of the load in relation to the one repetition maximum (1 RM) action or maximum isometric force level) as well as the duration of the training period should be sufficient (Frontera et al. 1988, Fiatarone et al. 1990, Charette et al. 1991, Roman et al. 1993, Treuth et al. 1994, Häkkinen et al. 1998b). Training-induced hypertrophy in older men seems to take place in both fast and slow twitch muscle fibres. However, much less information is available on training-induced hypertrophy of individual muscle fibres in older women. Two studies have demonstrated significant increases in muscle fibre areas of type II or types II and I (Charette et al. 1991, Pyka et al. 1994), while other authors have reported no significant changes caused by resistance training (Lexell et al. 1995). Although conversion of the fast twitch-type subunits in human skeletal muscle following strength training may take place in both young subjects (Staron et al. 1989, 1991, 1994, Adams et al. 1993, Kraemer et al. 1995) and older men (Häkkinen et al. 1998e), it is improbable that such training would alter the proportions of type I and II fibres (MacDougall 1991). In addition to maximal strength of the muscles, the role of explosive strength characteristics, especially the leg extensor muscles, is also important for various functional physical activities in the elderly such as climbing stairs, walking actions such as crossing the road, and prevention of falls and/or trips (Bassey et al. 1992). It is likely that in order to induce increases in explosive strength capacity in older people, heavy resistance training should be combined with explosive types of exercises by emphasizing the higher action/movement velocities of the exercises performed (Häkkinen & Häkkinen 1995, Häkkinen et al. 1998b, Jozsi et al. 1999). To what extent this type of training stimuli, that is, lighter loads but faster movement speed, would cause muscle hypertrophy in older men and women which has not been investigated yet.

The purpose of the present study was to examine neuromuscular adaptations in middle-aged and older men and women during a resistance training period of 6 months utilizing a programme designed not only for maximal strength development (with heavier loads) but also including exercises of an explosive nature (with lighter loads but faster action velocities). We hypothesized that such a training programme for a prolonged period of time, although performed only two times a week, would lead to increased voluntary neural activation of the agonists contributing to strength and power gains. However, to what extent this type of training programme for both strength and power development cut into a 2 day/week format, the typically recommended frequency, would be adequate for muscle hypertrophy in men and women of both age groups was within our interest.
METHODS

Subjects

A total of 42 healthy men (M) and women (W) divided into two age groups of middle-aged M40 (42 ± 2; n = 10) (mean age ± SD years) and W40 (39 ± 3; n = 11) as well as older M70 (72 ± 3; n = 11) and W70 (67 ± 3; n = 10) volunteered for the study. The subjects were carefully informed about the design of the study with special information as to the possible risks and discomfort that might result. Thereafter, the subjects signed a written consent form prior to participation in the project. The study was conducted according to the declaration of Helsinki and was approved by the Ethics Committee of the University of Jyväskylä, Finland.

The subjects were healthy and habitually physically active. To keep themselves fit they had taken part in various recreational low-intensity physical activities such as walking, jogging, cross-country skiing, aerobics or biking but none of the subjects had any background in regular strength training or competitive sports of any kind. No medication was being taken by the subjects which would have been expected to affect physical performance.

This work was part of a larger research project. Some of the results obtained with these subjects from various other measurements conducted during the present follow-up have been published earlier (Häkkinen et al. 1998a,b, 2000) but all the muscle fibre data, isometric and concentric strength and EMG of the unilateral knee extensions are unique to this part of the investigation.

Experimental design

The experimental period of 7 months consisted of a 1-month control period followed by a 6-month resistance training period. The subjects were tested on five different occasions using identical protocols. The first month of the study (between the measurements at month –1 and at 0) served as a control period during which time no strength training was carried out but the subjects maintained their normal low-intensity recreational physical activities (e.g. walking, jogging, biking, swimming and aerobics). The subjects were tested before and after this control period. Thereafter, the subjects started a supervised experimental strength training period for 6 months. The measurements were repeated during the actual experimental training period at 2-month intervals (i.e. months 0, 2, 4 and 6).

Testing

The subjects were carefully familiarized with the testing procedures of voluntary force production of the unilateral knee extensor actions during several submaximal and maximal performances about 1 week before the measurements at month –1. Secondly, during the actual testing occasion several warm-up contractions were performed prior to the maximal test actions.

Isometric action

Isometric force-time curves and maximal isometric peak torque of the unilateral knee extension action of the right leg were measured on a David 200 dynamometer (David Fitness and Medical) (Häkkinen et al. 1998a,b). In this test the subjects were in a sitting position so that the knee and hip angles were 107 and 110° (180° refers to full extension), respectively. The subjects were instructed to exert their maximal force as fast as possible during a period of 2.5–4.0 s. A minimum of three trials were completed for each subject and the best performance trial with regard to maximal peak force was used for the subsequent statistical analysis.

Concentric action

The same David dynamometer was used to measure maximal unilateral concentric 1 RM strength force of the right knee extensors. The subject was in a seated position so that the hip angle was 110°. On verbal command the subject performed a concentric leg extension starting from a flexed position of 70° attempting to reach an extension position of 160° (at the minimum) against the resistance determined by the loads chosen on the weight stack. In the testing of the maximal load, separate 1 RM contractions were performed. After each repetition the load was increased (normally with 2.5–5.0 kg increments) until the subject was unable to extend the knee to the required position. The last acceptable extension with the highest possible load was determined as 1 RM.

The force signal was recorded on a computer (486 DX-100) and thereafter digitized and analysed with a Codas TM computer system (Data Instruments). Maximal peak force was defined as the highest value of the torque recorded during the unilateral isometric knee extension (Nm). The force-time analysis on the absolute scale included the calculation of average torque (Nm) produced during first 500 ms from the start of the action (Häkkinen et al. 1998a,b).

Electromyographic recording

The EMG activity during the unilateral extension actions of the knee muscles was recorded from the agonist muscles vastus lateralis (VL) and vastus medialis (VM) and from the antagonist muscle biceps femoris (BF; long head) of the right leg. Bipolar (20 mm
interelectrode distance) surface EMG recording (Beckman miniature-sized skin electrodes 650437, Illinois, USA) was employed. The electrodes were placed longitudinally on the motor point areas determined by an electrical stimulator (using also the anatomical landmarks). The EMG signals were recorded telemetrically (Glonner, Biomes 2000). The positions of the electrodes were marked on the skin by small ink tattoos (Häkkinen et al. 1998b) which ensured the same electrode positioning in each test over the 7-month experimental period. The EMG signal was amplified (by a multiplication factor of 200; low pass cut-off frequency of 360 Hz/3dB⁻¹) and digitized at a sampling frequency of 1000 Hz by an on-line computer system. The EMG was full wave rectified, integrated electromyographic activity (IEMG in mV · s) and time normalized for 1 s in the following phases: (1) in the isometric actions for the initial 500 ms period from the start of the contraction; (2) for the maximal peak force phase of the isometric contractions (500–1500 ms) to calculate maximal IEMG (Häkkinen et al. 1998a,b); and (3) in the concentric action of the 1 RM for the entire range of motion. EMG of the biceps femoris muscles acting as an agonist was recorded during maximal unilateral isometric knee flexion of the right leg (with the hip and knee angles 110 and 90°, respectively) using the David 200 dynamometer (Häkkinen et al. 1998a,b). The EMG of BF during the knee flexion was analysed in a similar manner as were the VL and VM muscles during the isometric knee extensions. The maximum IEMG value recorded for the right BF muscle was used to calculate the antagonist BF activity recorded during the maximal isometric and concentric knee extension actions by expressing the activity relative to maximum agonist values of the BF.

Muscle biopsies

The muscle biopsies were obtained before and after the experimental training period. The samples were obtained from the superficial portion of the VL muscle of the right leg utilizing the percutaneous needle biopsy technique of Bergström (1962). Special care was taken to extract tissue from the same location (close to the prebiopsy scar) and depth each time. Muscle tissue samples were frozen in isopentane cooled with liquid nitrogen and stored at −80 °C until analysed. Serial cross-sections (10 µm thick) were cut on a cryostat at −20 °C for histochemical analyses. Histochemical staining for myofibrillar adenosine triphosphatase (ATPase) was used to classify the fibres as I, IIa, IIb and IIC (based on the stability of their ATPase activity at pH 4.2, 4.6 and 10.3 in the pre-incubation medium) according to Brooke & Kaiser (1970). The IIC fibres were, however, so rare that they were not included in the final statistical analyses. Fibre type percentage values were calculated from the mean number of fibres (at pre and post-training) of 348 ± 171 and 358 ± 118 recorded for M40, 345 ± 205 and 270 ± 81 for W40, 315 ± 120 and 317 ± 156 for M70 and 476 ± 200 and 326 ± 72 for W70, respectively. For the calculation of mean fibre areas, an average number of fibres analysed were 45 and 44 for M40, 36 and 30 for N40, 58 and 28 for M70 and 48 and 24 for W70, respectively. A loaded image of stained cross-sections was analyzed by Tema Image-Analysis System (Scan Beam, Denmark). A videoscope consisting of a microscope (Olympus BX 50) and colour video camera (Sanyo High Resolution CCD) was used to calculate the mean fibre area values of each fibre type.

The percentage of fat in the body was estimated from the measurements of skinfold thickness from four different sites (Durnin & Womersley 1967).

Experimental strength training

The supervised 6 months periodized strength training programme of the subjects was a total body (low-volume) programme cut into a 2 day/week format. In addition, we attempted to address two major programme components each week (i.e. maximal 1 RM strength and power) for the leg extensor muscles. Each training session included two exercises for the leg extensor muscles (the bilateral leg press exercise and the bilateral and/or unilateral knee extension exercise on the David 200 machine) and four to five exercises for the other main muscle groups of the body (the bench press and/or the seated press and/or lateral pull down exercise for the upper body; the sit-up exercise for the trunk flexors and/or another exercise for the trunk extensors; and the bilateral elbow and/or knee flexion exercise). All the exercises were performed using concentric muscle actions followed by eccentric actions during the ‘lowering’ phase of the movement. The loads were determined during the training sessions throughout the 6-month training period according to the maximum-repetition method.

During the first two months of the training the subjects were trained with loads of 50–70% of the 1RM. The subjects performed 10–15 repetitions per set and performed 3–4 sets of each exercise. The loads were 50–60% and 60–70% of the maximum by month 3 and 50–60% and 70–80% by month 4. In the two exercises for the leg extensor muscles the subjects now performed either 8–12 repetitions per set (at lower loads) or 5–6 repetitions per set (higher loads) and performed 3–5 sets. In the other four exercises the subjects performed 10–12 repetitions per set and performed 3–5 sets. During the last two months of training (months 5–6) the subjects performed in the two exercises for the leg...
extensor muscles 3–6 repetitions per set with the loads of 70–80% of the maximum and 8–12 repetitions per set with the loads of 50–60% and performed 4–6 sets. In the other four exercises 8–12 repetitions per set were performed for 3–5 sets altogether.

The strength training utilized was a combination of heavy and explosive resistance training programmes so that a volume of about 25% of the total volume of the leg extensor exercises (leg press and knee extension) with light loads (50–60% of the maximum) was performed according to the principle of explosive strength training. These repetitions were executed as explosively as possible (rapid muscle actions) throughout the range of motion. The overall amount of training was progressively increased until the fifth month at which point it was slightly reduced for the final month of the 6-month training period. During the 6-month experimental training period the subjects continued taking part in recreational low-intensity physical activities such as walking, jogging, swimming, biking or gymnastics 1–3 times per week in a similar manner to what they were accustomed to before this experiment.

Statistical methods

Standard statistical methods were used for the calculation of mean values, standard deviations (SD), standard errors (SE), and Pearson product moment correlation coefficients. The data were then analysed utilizing multivariate analysis of variance (ANOVA) with repeated measures. Probability adjusted t-tests were used for pairwise comparisons when appropriate. The $P < 0.05$ criterion was used for establishing statistical significance.

RESULTS

Physical characteristics

As reported earlier (Häkkinen et al. 1998b) body mass and the percentage of body fat remained statistically unaltered during the 6-month training period with the pre- and post-training values of 83 ± 14 kg (mean and SD) and 84 ± 15 kg and 19 ± 4% and 19 ± 5% (and of 178 ± 7 cm for body height) in M40, 80 ± 10 kg and 80 ± 10 kg and 24 ± 4% and 23 ± 5% (172 ± 7 cm) in M70, 62 ± 8 kg and 62 ± 8 kg and 26 ± 6% and 26 ± 6% (163 ± 5 cm) in W40 and 66 ± 7 kg and 66 ± 7 kg and 34 ± 3% 34 ± 5% (159 ± 6 cm) in W70, respectively.

Maximal isometric unilateral knee extension torque, force-time 500 ms and IEMGs

Maximal isometric unilateral peak torques at month -1 were in M40 larger ($P < 0.001$) than in M70 and in W40 larger ($P < 0.001$) than in W70 (Fig. 1). The torque values remained statistically unaltered in all groups during the 1-month control period. During the 6 month training the torque values improved in M40 by 28 ± 14% (mean and SD) ($P < 0.001$), in M70 by 27 ± 17% ($P < 0.001$), in W40 by 27 ± 19% (P < 0.001) and in W70 by 26 ± 14% ($P < 0.001$). The IEMG values remained unaltered during the 1-month control period but during the course of the 6-month training the maximum IEMGs of the VL and/or VM muscles (and/or the mean of the two muscles) of the right leg (Fig. 2) of the isometric action increased in M40 (P-values between 0.001 and 0.05), in M70 (P-values between 0.01 and 0.05), in W40 (P-values between 0.01 and 0.05) and in W70 (P-values between 0.01 and 0.05). The antagonist BF activity (relative to maximum agonist values of the BF) during the isometric knee extension remained unaltered during the 1-month control period in all groups. During the 6-month training it remained statistically unaltered in M40 (from 23 ± 12 to 22 ± 16%), in W40 (from 28 ± 15 to 25 ± 17%), and in M70 (from 29 ± 6 to 34 ± 17%) but decreased in W70 (from 42 ± 34 to 32 ± 26%; $P < 0.05$) during the first 2 months of the training.
The average knee extension torques produced in 500 ms of 180 ± 34 Nm (mean ± SD) in M40, 120 ± 23 Nm in M70, 105 ± 30 Nm in W40 and 79 ± 21 Nm in W70 recorded at month −1 remained statistically unaltered in all groups during control period. During the 6-month training these torque values improved in M40 by 21 ± 41% (mean and SD) (P < 0.05), in M70 by 21 ± 24% (P < 0.05), in W40 by 32 ± 45% (NS) and in W70 by 22 ± 28% (P < 0.05). The IEMG values produced during the initial 500-ms period remained unaltered during the 1-month control period but during the course of the 6-month training the IEMGs of the VL and/or VM muscles (and/or the mean of the two muscles) of the right leg increased in M40 (P-values between 0.01 and 0.05), in M70 (P-values between 0.001 and 0.01), in W40 (P-values between 0.001 and 0.05) and in W70 (P-values between 0.001 and 0.05). The antagonist BF activity during the concentric 1RM knee extension remained unaltered during the 1-month control period but during the course of the 6-month training it remained statistically unaltered in M40 (from 28 ± 12 to 34 ± 22%), in W40 (from 33 ± 20 to 31 ± 17%), in M70 (from 35 ± 19 to 37 ± 21%) but decreased slightly (NS) in W70 (from 44 ± 39 to 37 ± 28%).

Maximal 1 RM strength and IEMGs

The 1RM knee extensions at month −1 were in M40 larger (P < 0.001) than in M70 and in W40 larger (P < 0.001) than in W70 and remained unaltered in all groups during the control period (Fig. 3). During the 6-month training the 1 RM values improved in M40 by 27 ± 7% (mean and SD) (P < 0.001), in M70 by 21 ± 9% (P < 0.001), in W40 by 35 ± 14% (P < 0.001) and in W70 by 31 ± 14% (P < 0.001). The IEMG values remained unaltered during the 1-month control period but during the course of the 6-month training the maximum IEMGs of the VL and/or VM muscles (and/or the mean of the two muscles) of the right leg (Fig. 4) of the 1 RM action increased in M40 (P-values between 0.01 and 0.05), in M70 (P-values between 0.001 and 0.01), in W40 (P-values between 0.001 and 0.05) and in W70 (P-values between 0.001 and 0.05). The antagonist BF activity during the concentric 1RM knee extension remained unaltered during the 1-month control period in all groups. During the 6-month training it remained statistically unaltered in M40 (from 28 ± 12 to 33 ± 20), in W40 (from 33 ± 20 to 31 ± 17%), in M70 (from 35 ± 19 to 37 ± 21%) but decreased slightly (NS) in W70 (from 44 ± 39 to 37 ± 28%).

Muscle fibre characteristics

The percentage values for the muscle fibre distribution of the VL muscle did not differ significantly
between the subject groups either before or after the training period (Table 1). No statistically significant changes took place in the muscle fibre distribution during the 6-month training period in any of the subject groups.

The mean fibre area of type I did not differ significantly between the subject groups at pretraining (Fig. 5a). However, both male subject groups demonstrated larger mean fibre areas of type II (M40 vs. W40, \( P < 0.01 \), M70 vs. W70, \( P < 0.05 \), Fig. 5b), type IIa and IIb (M40 vs. W40, \( P < 0.01 \), M70 vs. W70, \( P < 0.05 \), Figs 6a,b) than the female groups. The mean fibre area ratio of type II/I of 1.34 ± 0.40 in M40 was larger (\( P < 0.05 \)) than those of 0.79 ± 0.25, 0.69 ± 0.14 and 0.65 ± 0.18 recorded for M70, W40

<table>
<thead>
<tr>
<th>Type</th>
<th>M40 (n = 10)</th>
<th>M70 (n = 9)</th>
<th>W40 (n = 9)</th>
<th>W70 (n = 8)</th>
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<tr>
<td>Pre</td>
<td>Post</td>
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<tr>
<td>Type I (%)</td>
<td>53 ± 20</td>
<td>55 ± 9</td>
<td>57 ± 14</td>
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<tr>
<td>Type IIa (%)</td>
<td>42 ± 18</td>
<td>43 ± 9</td>
<td>35 ± 12</td>
<td>39 ± 6</td>
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<tr>
<td>Type IIb (%)*</td>
<td>5 ± 4</td>
<td>3 ± 1</td>
<td>8 ± 5</td>
<td>3 ± 2</td>
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</tbody>
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* M40, n = 9 and 6; M70, n = 8 and 3; W40, n = 7 and 2; W70, n = 7 and 3.
and W70, respectively. The 6-month training period resulted in significant increases in the mean fibre areas of type I in W70 ($P < 0.05$) and of type II and IIa in both W40 ($P < 0.05$) and in W70 ($P < 0.05$), while the changes in the male groups were not statistically significant.

The individual percentage values for type II fibres at pretraining correlated significantly with the individual values for maximal concentric 1 RM strength in both W70 ($r = 0.80; P < 0.05$) and M70 ($r = 0.61; P < 0.05$). The individual percentage values for type II fibres correlated significantly with the individual values for maximal isometric strength in W70 both at pre- and post-training ($r = 0.74, P < 0.05$, Fig. 7a) and post-training ($r = 0.77, P < 0.05$) (Fig. 7b).

**DISCUSSION**

The present total body heavy resistance training programme combined with explosive types of exercises performed two times a week led to large gains in both maximal isometric and dynamic strength as well as in explosive force production characteristics of the knee extensor muscles in both middle-aged and elderly men and women. The maximal strength gains were accompanied by significant increases in the voluntary neural activation of the agonist muscles recorded in both isometric and concentric actions with significant reductions taking place during the initial training phases in the antagonist coactivation of the maximal knee extension action in elderly women. The training programme also led to significant increases in the mean fibre areas of type I in elderly women and of type II in women of both age groups, while the changes in the male groups did not reach a statistical significance. The individual percentage values for type II fibres correlated significantly with the individual values for maximal
strength recorded at pretraining in elderly groups of both genders and remained significant also at post-training in elderly women.

The 6-month progressive strength training, although performed only twice a week, led to large gains in maximal strength recorded in both isometric and concentric unilateral actions of the knee extensors in middle-aged and elderly subjects of both genders. Moreover, the relative magnitudes of the increases in maximal strength values were very similar in our subject groups differing with regard to age and gender. The results are thus well in line with several previous observations that maximal muscle strength in previously untrained healthy subjects can be increased during progressive strength training independently of age and gender. This seems to be true independently of the muscle group in question and also taking place in ‘any’ type of actions whether isometric or dynamic and whether unilateral or bilateral (Frontera et al. 1988, Fiatarone et al. 1990, Charette et al. 1991, Häkkinen & Häkkinen 1995, Lexell et al. 1995, Morganti et al. 1995, McCartney et al. 1996, Häkkinen et al. 1998b,c, Kraemer et al. 1999). Thus, an important conclusion from the practical standpoint is the fact that the frequency of strength training in previously untrained middle-aged and elderly subjects can be as low as twice a week, when the loading intensity of training is sufficient and increased progressively (i.e. periodized) throughout the training period.

The strength training performed twice a week led to large increases in the maximal voluntary activation of the agonist muscles recorded during both isometric and concentric knee extension actions in all groups. The magnitudes and the time courses of these EMG increases were rather similar to those changes recorded for the isometric and concentric strength of the same muscle groups. This finding indicates that the contributing role of the nervous system for strength development during the present heavy resistance training combined with explosive exercises may have been of great importance. The largest increases in the IEMGs were noted during the first two months of training (Figs 2 and 4) supporting the concept that in previously untrained subjects, not only in younger adults but also in both middle-aged and older persons of both genders, large initial increases in maximal strength observed during the initial weeks of strength training can be attributed largely to the increased motor unit activation of the trained agonist muscles (Moritani & DeVries 1980, Sale 1991, Higbie et al. 1996, Häkkinen et al. 1998b,c). Strength training-induced increases in the magnitude of EMG could result from the increased number of active motor units and/or increase in their firing frequency (Sale 1991). Increases in net excitation of the motor neurones may result from increased excitatory input, reduced inhibitory input or both (Sale 1991). The present EMG data additionally showed that the increases in the maximal IEMGs, especially those recorded during the concentric actions, took place in men and women of both age groups not only during the initial phases of training but also to some degree during the entire course of the 6-month training period. This may be explained by the fact that the training loads of the exercises were progressively increased in a periodized manner and that the subjects activated their muscles also during the explosive actions highly throughout the training. Although the actual nature of adaptations in the nervous system is difficult to determine, progressive strength training can lead not only to increased activation of the agonists but training-induced learning effects in terms of reduced coactivation of the antagonist muscles may also play a contributive role. The latter phenomenon can also enhance the net strength production of the agonists in both younger adults (Carolan & Cafarelli 1992) and, maybe even more importantly in older subjects especially during multi-joint actions (Häkkinen et al. 1998b). The present data showed that significant reductions took place in the elderly women during the initial 2 months of the training in the antagonist coactivation, even during the single joint maximal knee extension action. Actually, the magnitude and the time course of the changes in the antagonist coactivation may be related to the type of actions used, to the exercises utilized in the training and to the initial physical status of the subjects in terms of experience and skill in strength training as well as to the age and/or gender of the subjects (Carolan & Cafarelli 1992, Häkkinen et al. 1998a,b). To what extent reduced coactivation of the antagonists is mediated by mechanisms in the central nervous system (Carolan & Cafarelli 1992) or associated also with peripheral neural control is difficult to interpret.

When sensitive techniques such as fibre area determination by muscle biopsy or muscle cross-sectional area determination by CT or MRI have been utilized, skeletal muscles of older people of both genders do retain the capacity to undergo training-induced hypertrophy provided the volume, intensity and the duration of the training period are sufficient (Frontera et al. 1988, Fiatarone et al. 1990, Charette et al. 1991, Häkkinen et al. 1998c). The present heavy resistance training program combined with explosive exercises performed only twice a week did lead to significant increases in the mean fibre areas of type I in our elderly women and of type II in our women of both age groups. The relative magnitude of muscle hypertrophy was similar between the middle-aged and elderly women. Also both of our male groups did show some training-induced increases in the mean fibre areas of type II but the changes did not reach a statistical significance. This

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was most likely caused by a low number of subjects in the groups included in the statistical analysis for fibre area determination as well as because of large individual variation in adaptation to the present training stimuli. Secondly, it is possible that the nature of our training programme composed not only of heavy resistance loading but included a considerable portion of explosive exercises using light loads could in part explain the finding that the enlargements in the mean fibre areas of the trained muscles in men remained smaller in magnitude than those recorded in women of the same age groups. Although neural activation of the muscles during the lighter load exercises used in power training can be rather high even in elderly subjects of both genders (Häkkinen et al. 1998a), the duration of this activation during each single muscle action remains much shorter than that of a typical heavy resistance training programme suggested to be crucial for training-induced hypertrophy (MacDougall 1991). The present training stimuli may be sufficient to produce significant muscle hypertrophy in middle-aged and older women showing at pretraining smaller initial mean fibre areas of type II than those recorded for men of the same age groups. However, some caution must be exercised when interpreting the present muscle fibre data with a relative low number of fibres analysed and the biopsy obtained only at one particular portion of the thigh, as training-induced muscle hypertrophy can also be non-uniform along the belly of the muscle (Narici et al. 1996).

Age-associated decline in muscle mass is thought to be mediated by a reduction in the size of individual muscle fibres, especially of type II fibres, and a loss of these fibres (Lexell et al. 1988) accounting largely for the age-related decrease in strength characteristics of the same muscles. The present data recorded at pretraining actually showed that the individual percentage values for type II fibres correlated significantly with the individual values for maximal concentric 1 RM strength in older subjects of both genders. Moreover, the relationship with regard to maximal isometric force remained significant in older women also after the 6-month training period. The data indicate the important role of muscle fibre distribution (percentage type II fibres) on muscle strength in older people, especially older women. However, the true role of muscle fibre distribution on training-induced increases in strength or the degree of muscle hypertrophy during strength training remains to be determined. During strength training with a higher volume of training (performed three times a week) and with a larger number of younger and older male subjects, the subjects with a higher relative proportion of type II fibres have shown greater increases in the CSA of the trained muscle than those subjects possessing a lower proportion of type II in their muscles (Häkkinen et al. 1998c). Further research work has to be performed using experimental designs with longer durations of training, a larger number of subjects, and a larger variability in the age of subjects under investigation.

No transformation of type II muscle fibre subtypes or changes in the percentage of type I fibres were observed pre- to post-training for any of the present subject groups. The type II subtype transformation going from type IIB to IAB to IIA has been previously observed in younger (Staron et al. 1991, 1994, Adams et al. 1993, Kraemer et al. 1995) and older men (Häkkinen et al. 1998c). The present subject groups did show some decreases in the percentage of type IIB during the training period but because of a very low number of subjects per group the changes did not reach statistically significant levels. Prior studies in younger men with long training periods have typically demonstrated the absence or very low percentages values (<2%) of type IIB muscle fibres after a heavy resistance training programme (Staron et al. 1991, Adams et al. 1993, Kraemer et al. 1995). The roles of duration and mode of resistance training as well as that of age in muscle fibre transformation in the type IIB fibre population needs further examination.

Muscle strength and the ability of the leg extensor muscles to develop force rapidly are important performance characteristics, especially in older people, contributing to several tasks of daily life such as climbing stairs, walking actions such as crossing the road, or even prevention of falls and/or trips (Bassey et al. 1992). A very low level of maximal strength in older people may also be associated with a lowered ability to produce force rapidly in both dynamic and isometric actions (Häkkinen et al. 1998a). The present heavy resistance training programme combined with explosive exercises did lead to significant increases in both maximal strength and rapid force production in the earlier portions of the isometric force-time curve of the unilateral knee extension action. These results are in line with earlier training-induced observations in both middle-aged and older subjects of both genders recorded during both isometric and dynamic actions of the leg extensors (hip, knee and ankle extensors) (Häkkinen & Häkkinen 1995, Häkkinen et al. 1998b). The significant increases observed in the IEMGs of the agonists during the early phase of the isometric knee extension action indicate that the increases in explosive force of the trained muscles might have been explained largely by training-induced increases in the rapid neural activation of the motor units (Van Cutsem et al. 1998) not only in middle-aged but also in older subjects of both genders. The observation that explosive force production capacity of the neuromuscular system remains trainable even in older subjects should also be of
practical value, for example, in primary and secondary prevention of frailty and in physical rehabilitation programmes for ageing men and women.

In summary, the present total body heavy resistance training programme combined with lower load explosive exercises performed only two times a week led to large gains in both maximal isometric and dynamic strength as well as in explosive force production characteristics of the knee extensor muscles in both middle-aged and elderly men and women. The maximal strength gains were accompanied by significant increases in the voluntary neural activation of the agonists in all subject groups with significant reductions taking place during the initial training phases in elderly women in the antagonist coactivation, even during the simple single joint knee extension action. The findings support the concept of the important role of neural adaptations in strength and power development in middle-aged and older men and women. The muscle fibre distribution (percentage type II fibres) seems to be an important contributor on muscle strength in older people, especially older women. The training programme also led to significant increases in the mean fibre areas of type I in elderly women and of type II in women of both age groups, while the changes in the male groups did not reach statistically significant levels. Women of both age groups appear to be hypertrophically responsive to the total body strength training protocol performed only two times a week including heavier and lighter loads (for fast actions) designed for both maximal strength and power development, while such a programme has limited effects on muscle hypertrophy in men.

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REFERENCES


Strength training in middle-aged and older men and women

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