Basal Concentrations and Acute Responses of Serum Hormones and Strength Development During Heavy Resistance Training in Middle-Aged and Elderly Men and Women

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Effects of 6 months of heavy resistance training combined with explosive exercises on both basal concentrations and acute responses of total and free testosterone, growth hormone (GH), dehydroepiandrosterone (DHEA), dehydroepiandrosterone sulfate (DHEAS), cortisol and sex hormone-binding globulin (SHBG), as well as voluntary neural activation and maximal strength of knee extensors were examined in 10 middle-aged men (M40; 42 ± 2 years), 11 middle-aged women (W40; 39 ± 3 years), 11 elderly men (M70; 72 ± 3 years), and 10 elderly women (W70; 67 ± 3 years). The maximal integrated electromyographic (iEMG) and 1 repetition maximum (1RM) knee-extension values remained unaltered in all groups during a 1-month control period with no strength training. During the 6-month training the 1RM values increased in M40 by 27 ± 9% (p < .001), in M70 by 16 ± 6% (p < .001), in W40 by 28 ± 11% (p < .001), and in W70 by 24 ± 10% (p < .001). The iEMGs of the vastus lateralis and medialis muscles increased (p < .05-.001) in M40, W70, W40, and W70. No systematic changes occurred during the experimental period in the mean concentrations of serum total and free testosterone, DHEA, DHEAS, GH, cortisol, or SHBG. However, the mean levels of individual serum free testosterone in W70 and serum testosterone in the total group of women correlated with the individual changes recorded in strength during the training (r = .55, p < .05; and r = .33, p < .05). The single exercise session both before and after the training resulted in significant responses in serum total and free testosterone concentrations in both male groups (p < .05-.01), but not in the female groups, as well as in serum GH levels in all groups (p < .05-.01) except W70 (ns). In summary, the present strength training led to great increases in maximal strength not only in middle-aged but also in elderly men and women. The strength gains were accompanied by large increases in the maximal voluntary activation of the trained muscles. None of the groups showed systematic changes in the mean serum concentrations of hormones examined. However, a low level of testosterone, especially in older women, may be a limiting factor in strength development and testosterone could mediate interactions with the nervous system contributing to strength development. The physiological significance of the lack of acute responsiveness of serum GH to heavy resistance exercise in older women for their trainability during prolonged strength training requires further examination.

HUMAN muscle mass, strength and power decrease during aging, especially from the sixth decade on in both men and women (1-3). The decline in muscle mass is thought to be mediated by a reduction in the size and/or number of individual muscle fibres, especially of fast-twitch fibres (1). Age-related declines in strength may also be due to decreased maximal voluntary activation of the agonist muscle and/or changes in antagonist coactivation (4,5), although these neural and associated strength changes may vary between different muscles in relation to their decreased use in daily physical activities (2,6,7). The age-related decreases in muscle mass and strength are not surprising, because aging is very often associated with a decline in the quantity and especially intensity of daily physical activities (8). Further, with aging blood concentrations of circulating anabolic hormones and growth factors, e.g., testosterone, growth hormone (GH), and insulin-like growth factor-1 are diminished (9-14). The correlations observed between serum testosterone concentrations, muscle cross-sectional area and strength in middle-aged and older women (11) suggest that the decreasing basal level of blood testosterone in aging females over the years may lead to decreasing anabolic effects on muscles associated possibly with muscle atrophy and decreased strength.

However, progressive strength training not only in middle-aged but also in elderly people can lead to substantial increases in strength performance. This might primarily result from considerable neural adaptations observed especially during the earlier weeks of training (15-17), as indicated by large increases in maximal electromyographic (EMG) activity of trained muscles. In addition to the increased activation of the agonists, strength training can lead to decreases in the coactivation of the antagonists, especially in elderly subjects of both genders (17). It has also been shown with sensitive techniques such as fibre area determination by muscle biopsy, or muscle cross-sectional area
determination by computed tomography (CT), magnetic resonance imaging (MRI), or ultrasound scan, that muscle hypertrophy accounts for the strength gains not only in young but also to some extent in elderly persons (16,18,19).

Heavy resistance exercise is known to be a potent stimulus for acute increases in circulating anabolic hormones in young men, although it has not been shown to elicit the same magnitude of hormonal responses in older men (14,20–22), and very minor or no response in older women (21). No systematic changes have been reported to take place in basal blood concentrations of circulating hormones during strength training for 12 to 16 weeks in older men (20,22,23) or in older women (23). Similarly, the acute exercise-induced minor GH response in 60–62-year-old men has not changed after 12 to 16 weeks of strength training compared to that recorded before the training (20,22). No experimental results about the effects of strength training on possible changes in acute hormone responsiveness in older women have been reported. Because blood concentrations of circulating anabolic hormones and growth factors are also diminished with aging, it was our purpose to examine not only in middle-aged and older men but also in middle-aged and older women the possible effects of strength training on basal concentrations and acute responses of serum hormones and their possible interrelationships with strength gains during a prolonged strength training period of 6 months.

**METHODS**

**Subjects**

The subjects who volunteered for the study were 42 healthy men (M) and women (W). They were divided into two age groups of middle-aged and elderly as follows: M40 (42 ± 2; mean age ± SD years, n = 10), M70 (72 ± 3, n = 11), W40 (39 ± 3; n = 11), and W70 (67 ± 3; n = 10). The percentage of fat in the body was estimated from the measurements of skinfold thickness (24). The subjects were carefully informed about possible risks and discomfort that might result and they 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 living independently in the town of Jyväskylä, Finland. They were habitually physically active. To keep themselves fit and as recreation, they took part in various physical activities such as walking, jogging, swimming, biking, and aerobics for one to two times a week, but they had no background in regular strength training. No medication was being taken by the subjects which would have been expected to affect physical performance or endocrine profile.

This work was a 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 (17), but all the hormonal, strength, and EMG data presented are unique to this part of the investigation.

**Experimental Design**

The duration of the present study was 7 months. The first month of the study (between the measurements at month 1 and at month 0) was used as a control period during which no strength training was carried out but the subjects maintained their normal 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 program for 6 months. The measurements were repeated during the actual 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 knee extensor muscles during bilateral extension actions about 1 week before the measurements at month 1. Secondly, during the actual testing, warm-up actions were performed prior to the measurement of the maximal 1 RM (repetition maximum) knee-extension performance.

A David 200 dynamometer (David Fitness and Medical Ltd., Finland) was used to measure maximal bilateral concentric force production of the knee extensors (16). The subject was in a seated position so that the hip angle was 110 degrees. On verbal command the subject performed a concentric knee extension starting from a flexed position of 70 degrees, trying to reach an extension of 160 degrees (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 until the subject was unable to extend the legs to the required position. The last acceptable extension with the highest possible load was determined as 1 RM. In all test conditions the time period of rest between the maximal contractions was always 1.5 minutes. External verbal encouragement was given for each subject.

EMG activity during the bilateral knee-extension actions was recorded from the agonist muscles vastus lateralis (VL) and vastus medialis (VM) of the right and left leg separately. 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. EMG signals were recorded telemetrically (Glonner, Biomes 2000). The positions of the electrodes were marked on the skin by small ink tattoos (25). These dots 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) and digitized at a sampling frequency of 1000 Hz by an on-line computer system. EMG was full-wave rectified, integrated (iEMG in mV·s) and time-normalized for 1 s in the concentric action of the 1 RM for the entire range of motion. The iEMG values of the right and the left muscles recorded during the maximal 1 RM action were taken for further analysis.

**Heavy-Resistance Protocol**

The heavy-resistance protocol at month 0 before the training period as well as at month 6 after the 6-month training period included the bilateral leg-press exercise on a machine (David 210, David Fitness and Medical Ltd, Finland). In the exercise the subject started from the flexed knee position (70 degrees) and extended the knees concentrically to a full extension (180 degrees) and thereafter lowered the load eccentrically back to the starting position. The actual loads were always the RM for each subject so that the subjects performed 10 repetitions per
set with the maximal load possible for a total of 5 sets (5 × 10 RM). The recovery time between the sets was 3 minutes for all groups. The loads were adjusted during the course of the session due to fatigue so that each subject would be able to perform 10 repetitions at each set. If the load happened to become too heavy, the subject was assisted slightly during the last one to three repetitions of the set, while she/he maintained her/his maximum performance so that the required number of repetitions could be reached and the subjects would also maintain the same contraction time.

**Blood Samples During the Heavy-Resistance Loading Protocol**

To examine acute hormone responses to the heavy-resistance loading, blood samples were drawn twice (within 1 hour) during the control day at month 0 and twice (within 1 hour) during the 2nd control day after the training at month 6 from the antecubital vein of each subject. Blood samples were also drawn twice during the 2 heavy-resistance exercise days (pre- and postloading samples within about 1 hour) at month 0 and at month 6. The heavy-resistance protocol was performed between 9.00 AM and 6.00 PM, always at the same time of day for each subject (at the corresponding time of the day as the blood sampling during the controls days) before and after the 6-month training period. The subjects were instructed to maintain their normal food intake prior to the heavy-resistance exercise protocol and to have their last light meal during that day no later than 2 hours before the session.

**Basal Blood Samples During the 1-Month Control Period and 6-Month Strength Training**

To examine the basal concentrations of serum hormones, blood samples were drawn from the antecubital vein of each subject after 12 hours of fasting and approximately 8 hours of sleep in the mornings (between 7.30 AM and 8.30 AM) during the 1-month control period (at month -1 and month 0) as well as during the 6-month training period (at months 0, 2, 4, and 6).

**Analytical Methods**

Serum samples for the hormonal analyses were kept frozen at -20°C until assayed. Serum testosterone concentrations were measured by the Chiron Diagnostics ACS:180 automated chemiluminescence system using ACS:180 analyzer. The sensitivity of the testosterone assay was 0.42 nmol·L⁻¹, and the intra-assay coefficient of variation was 6.7%. The concentrations of serum free testosterone, dehydroepiandrosterone (DHEA), and dehydroepiandrosterone sulfate (DHEAS) were measured by radioimmunoassays using kits obtained from Diagnostic Products Corp. (Los Angeles, CA). Prior to the DHEA assays, serum samples were extracted with dichloromethane. The sensitivity of the free testosterone assay was 0.52 pmol·L⁻¹ and the intra-assay variation was 3.8%. The respective values were 0.10 nmol·L⁻¹ and 5.2% for the DHEA assay and 0.06 µmol·L⁻¹ and 4.5% for the DHEAS assay. The assays of serum cortisol were carried out by radioimmunoassays. The sensitivity of cortisol assay was 0.05 µmol·L⁻¹ and the coefficient of the intra-assay variation was 4.0%. Serum sex hormone–binding globulin (SHBG) concentrations were measured by two-site fluoroimmunometric methods with kits obtained from Wallac (Turku, Finland) using the 1235 AutoDELFIA automatic immunoassay system. The sensitivity of the SHBG assay was 0.5 nmol·L⁻¹ and the intra-assay variation was 4.4%. Concentrations of growth hormone (GH) were measured using radioimmunoassay kits from Pharmacia Diagnostics (Uppsala, Sweden). The sensitivity of the GH assay was 0.2 µg·L⁻¹ and the intra-assay variation was 2.5–5.1%. All samples for each test subject were analyzed in the same assay for each hormone. Blood lactate concentrations were determined using a lactate analyzer (model 640, Roche, Switzerland).

**Experimental Strength Training Program**

The subjects participated in a supervised 6-month strength-training period. Each training session included two exercises for the knee-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 other 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).

During the first 2 months of the training the subjects trained twice a week with loads of 50 to 70% of the 1 RM. The subjects performed 10 to 15 repetitions per set and performed three to four sets of each exercise. During the 3rd and 4th months of training the subjects still trained twice a week. The loads were 50 to 60% and 60 to 70% of the maximum by month 3 and 50 to 60% and 70 to 80% by month 4. In the two exercises for the leg-extensor muscles, the subjects now performed either 8 to 12 repetitions per set (at lower loads) or 5 to 6 repetitions per set (higher loads) and performed three to five sets. In the other four exercises the subjects performed 10 to 12 repetitions per set and performed three to five sets. During the last 2 months of training (months 5–6), two different load ranges were used in the two exercises for the leg extensors so that the subjects completed three to six repetitions per set with the loads of 70 to 80% of the maximum and 8 to 12 repetitions per set with the loads of 50 to 60%. The total number of sets varied between four and six. In the other four exercises the subjects performed 8 to 12 repetitions per set and performed three to five sets altogether. The strength-training program was a combination of heavy resistance and "explosive" strength training. A major part of the knee-extension exercises was performed using the basic principles of heavy resistance training, but a part (20%) of these exercises with light loads (50 to 60% of the maximum) was performed so that each repetition of each set was executed as "explosively" as possible (rapid muscle actions). The overall amount of training was progressively increased until the 5th 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 physical activities such as walking, jogging, swimming, biking, or gymnastics one to two times per week in a similar manner to what they were accustomed to before this experiment.

**Statistical Analyses**

Standard statistical methods were used for the calculation of means, standard deviations (SD), standard errors (SE), and Pearson product moment correlation coefficients. The data were then analyzed utilizing multivariate analysis of variance...
(MANOVA) with repeated measures. Probability-adjusted t tests were used for pairwise comparisons when appropriate. The p < .05 criterion was used for establishing statistical significance.

RESULTS

Physical Characteristics

Body mass and the percentage of body fat remained statistically unaltered during the 6-month strength-training period in all subject groups with 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% and 34 ± 5% (159 ± 6 cm) in W70, respectively.

Maximal Strength and iEMGs

The 1 RM bilateral knee-extension values remained statistically unaltered in all groups during the 1-month control period (Figure 1). During the 6-month training the 1 RM values improved in M40 by 27 ± 9% (mean and SD) (p < .001), in M70 by 16 ± 6% (p < .001), in W40 by 28 ± 11% (p < .001), and in W70 by 24 ± 10% (p < .001). The iEMG values remained unaltered during the 1-month control period, but during the 6-month training the maximum iEMGs of the VL and VM muscles of the right and left leg (Figure 2) of the 1 RM action increased in M40 (p values between .01 and .05), in M70 (p values between .001 and .05), W40 (p values between .01 and .05), and W70 (p values between .001 and .05).

Basal Serum Hormone Concentrations

No statistically significant changes took place either during the 1-month control period or the 6-month training in mean serum testosterone concentrations from their initial values of 16.8 ± 4.1 (mean and SD) nmol·L⁻¹ in M40, of 18.1 ± 4.5 nmol·L⁻¹ in M70, of 1.7 ± 0.6 nmol·L⁻¹ in W40, and of 1.2 ± 0.6 nmol·L⁻¹ in W70 (Figure 3). Mean serum concentrations of free testosterone in M40 were higher (p < .05) than in M70 as well as higher in W40 (p < .05) than in W70 (averaged for the experimental period), but remained statistically unaltered in all groups during the entire experimental period (Figure 4).

The mean level of individual serum free testosterone concentrations (averaged for the entire experimental period) and the individual changes in maximal strength of the knee-extensor muscles during the 6-month training correlated significantly in W70 (r = .55; p < .05) (Figure 5). The respective correlation coefficient between the mean level of individual serum testosterone/cortisol ratio and the individual changes in maximal strength in W40 was also significant (r = .60; p < .05). In the total group of women (W40 + W70), the same was true for individual serum testosterone concentrations and strength development (r = .43; p < .05) (Figure 5) as well as for individual serum testosterone/cortisol ratios and strength development (r = .55; p < .01). In the two groups of men no significant positive correlations were observed between the individual hormone concentrations and the changes in strength during the training period.

The initial mean serum concentrations of SHBG of 29.6 ± 10.1 nmol·L⁻¹ in M40 was lower (p < .05) than that of 56.3 ± 11.8 nmol·L⁻¹ in M70, and of 55.2 ± 16.8 nmol·L⁻¹ in W40 was...
Figure 3. Mean (± SD) serum total testosterone concentration during the 1-month control period and the 6-month strength training period in middle-aged and elderly men (M40, n = 10; M70, n = 11) and women (W40, n = 11; W70, n = 10).

Figure 4. Mean (± SD) serum free testosterone concentration during the 1-month control period and the 6-month strength training period in middle-aged and elderly men (M40, n = 10; M70, n = 11) and women (W40, n = 11; W70, n = 10).

Figure 5. The relationships (top) between serum free testosterone concentration (averaged for the entire experimental period) and the individual changes in maximal strength (1 RM) of the knee extensor muscles during the 6-month strength training in elderly women (W70) and (bottom) between the serum testosterone concentration (averaged for the entire experimental period) and the individual changes in maximal strength (1 RM) of the knee extensor muscles during the 6-month strength training in a total group of middle-aged (W40) and elderly women (W70).

slightly (ns) lower than that of 60.5 ± 19.3 nmol-L⁻¹ in W70, with no significant changes taking place during the experiment in any of the subject groups. The initial serum testosterone/SHBG ratio of 0.59 ± 0.12 in M40 was higher (p < .05) than that of 0.33 ± 0.07 in M70, and that of 0.03 ± 0.01 in W40 was slightly (ns) higher than that of 0.02 ± 0.01 in W70 with no significant changes taking place during the experimental period. The initial concentrations of GH of 0.42 ± 1.02 µg·L⁻¹ in M40, of 0.72 ± 1.48 µg·L⁻¹ in M70, of 2.66 ± 3.40 µg·L⁻¹ in W40, and of 1.54 ± 1.77 µg·L⁻¹ in W70 remained statistically unaltered during the study period. The initial concentrations of serum cortisol of 0.54 ± 0.11 µmol·L⁻¹ in M40, of 0.42 ± 0.11 µmol·L⁻¹ in M70, of 0.51 ± 0.15 µmol·L⁻¹ in W40, and of 0.59 ± 0.10 µmol·L⁻¹ in W70 remained statistically unaltered during the experiment in all groups. The mean concentrations of DHEA (data not shown) and DHEAS (Figure 6) were higher in M40 (p < .05) than in M70 and higher in W40 (p < .05) than in W70, whereas no significant changes took place during the control or training periods in any of the groups.

Acute Hormone Responses to Exercise

Serum hormone concentrations (mean and SD) of testosterone, free testosterone, and GH in the different subject groups remained either unaltered or decreased during the control days (pre- and postsamples within 1 hour) at month 0 (before training) and at month 6 (after 6 months of strength training) (Table 1).
The mean concentration of serum testosterone increased during the heavy resistance loading protocol in M40 at both pre- \((p < .01)\) and post-training \((p < .05)\), in M70 at both pre- \((p < .05)\) and post-training \((p < .01)\), whereas the concentrations remained statistically unchanged in both W40 and W70 at both pre- and post-training (Figure 7). The mean concentration of serum free testosterone increased during the exercise in M40 at both pre- \((p < .05)\) and post-training \((p < .01)\), in M70 at both pre- \((p < .05)\) and post-training \((p < .01)\), whereas in W40 and W70 the changes were significant only at post-training \((p < .05)\) (Figure 8). The mean concentration of serum GH increased during the exercise session in M40 at both pre- \((p < .05)\) and post-training \((p < .05)\), in M70 at both pre- \((p < .05)\) and post-training \((p < .05)\), in W40 at both pre- \((p < .05)\) and post-training \((p < .01)\), whereas W70 demonstrated no significant changes at all neither at pre- nor post-training (Figure 9).

### Blood Lactate

The mean blood lactate concentration increased significantly during the exercise session at pretraining up to \(5.5 \pm 1.6\) mmol-L\(^{-1}\) (mean and SD) \((p < .001)\), \(4.5 \pm 1.9\) mmol-L\(^{-1}\) \((p < .001)\), \(4.2 \pm 0.9\) mmol-L\(^{-1}\) \((p < .001)\), and \(3.4 \pm 1.0\) mmol-L\(^{-1}\) \((p < .01)\) in M40, M70, W40, and W70, respectively. At post-training, the corresponding increases were up to \(6.3 \pm 1.6\) mmol-L\(^{-1}\) \((p < .001)\), \(3.8 \pm 2.0\) mmol-L\(^{-1}\) \((p < .01)\), \(5.2 \pm 1.4\) mmol-L\(^{-1}\) \((p < .001)\), and \(2.5 \pm 0.8\) mmol-L\(^{-1}\) \((p < .001)\) in M40, M70, W40, and W70, respectively. The post value at pre-training in M40 was higher \((p < .05)\) than in W40 and higher in W40 \((p < .05)\) than in W70. The post value at post-training was higher in M40 \((p < .05)\) than in M70 and higher in W40 \((p < .05)\) than in W70.

### Discussion

The primary findings of the present study showed that the progressive strength training program resulted in (i) great gains in maximal strength of the trained muscle groups with the same relative increases in the middle-aged and elderly subjects of both genders. (ii) The strength gains were accompanied by large increases in the maximal voluntary neural activation of the trained muscles in all subject groups. (iii) None of the subject groups demonstrated systematic changes during the 6-month strength-training period in mean serum concentrations of testosterone, DHEA, DHEAS, GH, cortisol, or SHBG. (iv) The mean levels of individual serum testosterone and free testosterone correlated significantly with the individual changes recorded during the 6-month training period in maximal strength in women, especially in older women. (v) The single heavy-resistance exercise session both before and after the 6-month training period resulted in significant responses in serum testosterone concentrations in both male groups but not in the female groups, and in serum GH levels in all groups with the exception of the group of elderly women.

The present progressive strength training led to great gains in the concentric 1 RM strength in the middle-aged and elderly subjects of both genders (Figure 1). The relative magnitudes of the increases in maximal strength did not differ significantly between the four subject groups differing with regard to age.
Figure 7. Mean (± SE) values for serum testosterone concentrations before (pre) and immediately after the heavy resistance loading sessions (post) both before (pretraining) and after the 6-month strength training (post-training) in middle-aged and elderly men (M40, n = 10; M70, n = 11) and women (W40, n = 11; W70, n = 10). *p < .05; **p < .01.

Figure 8. Mean (± SE) values for serum free testosterone concentrations before (pre) and immediately after the heavy resistance loading sessions (post) both before (pretraining) and after the 6-month strength training (post-training) in middle-aged and elderly men (M40, n = 10; M70, n = 11) and women (W40, n = 11; W70, n = 10). *p < .05; **p < .01.
and gender. The results are thus well in line with the previous observations that maximal muscle strength of the leg extensors can be increased during progressive strength training independently of age and gender (16–19,26–29). It is of some importance to point out that the present increases in maximal strength were as large as 16–28%, although the subjects trained only two times a week. Thus, it seems that the frequency of strength training, at least in previously untrained middle-aged and elderly subjects, can be rather low, such as twice a week, when the loading intensity of training was relatively high and increased progressively throughout the training period.

It has been shown that in previously untrained young and older subjects, great initial gains in maximal strength can be attributed largely to the increased motor unit activation of the trained muscles (15–17,25,28,30,31). The significant increases observed in the maximal voluntary activation of the agonist muscles, especially during the first 2 to 4 months of training (Figure 2) support strongly this suggestion in both genders. The magnitude of the increase in EMG during strength training could result from the increased number of active motor units and/or the increase in their firing frequency in both younger and older subjects of both genders. The actual nature of adaptations in the nervous system is difficult to determine. However, changes in the facilitatory and/or inhibitory pathways may take place (2,6,32) so that progressive strength training can lead to not only increased activation of the agonist muscles, but training-induced learning effects in terms of reduced co-activation of the antagonist muscles may also play an important role. The latter phenomenon can also enhance the net strength production of the agonists in both young (33) and, especially, in older subjects (17). Because our data indicate that the subject groups showed none or only minor increases in muscle mass during the present training period, the contributing role of the nervous system may have been of great importance for the strength gains. However, great caution must be exercised with regard to the possible role of muscle hypertrophy in the present study, because no sensitive techniques such as muscle fibre area determination by muscle biopsy, or muscle cross-sectional area determination of the leg extensors by CT, MRI, or ultrasound scans were performed. Second, it is likely that the specific nature of the training program, which was composed of both heavy resistance and explosive types of exercises, could in part explain why muscle hypertrophy may have actually been rather minor in all subject groups of the present study. It has been shown that although neural activation during explosive exercises can be quite high even in older subjects (5), the duration of the activation during each single muscle action remains much shorter than that of a typical heavy-resistance training program. This has been suggested to be crucial for training-induced muscle hypertrophy in both younger and older subjects of both genders (2,34). Therefore, skeletal muscles of elderly men and women retain the capacity to undergo hypertrophy, when both the type, volume (and frequency), and intensity of heavy-resistance loading as well as the duration of training period are optimized for hypertrophic purposes (16,18).

No systematic changes were observed during the present 6-month strength-training period in the concentrations of serum testosterone, free testosterone, DHEA(S), GH, cortisol, nor in the testosterone/cortisol or testosterone/SHBG ratios. In general, these observations are rather similar to those found earlier in young men and women (35–38), and in both middle-aged and elderly subjects of both genders, utilizing a more typical
strength-training program over a period of a few months (22,23). The overall loading of the present strength training program, which was a combination of heavy resistance and explosive types of exercises, may have been within normal physiological range, because maximal strength increased throughout the 6-month training period with no systematic changes in the concentrations of anabolic and catabolic hormones. It is likely that the present type of strength training stimulus may not lead to systematic long-term changes in circulating concentrations of testosterone, despite the potential for short-term homeostatic increases in various phases of training (39,40). As expected, resting free testosterone concentrations were higher in M40 than in M70 and higher in W40 than in W70 throughout the experimental period (Figure 4). The data further showed that in women, especially in older women who demonstrated low basal testosterone levels, a significant correlation was observed between the individual serum testosterone concentration and the individual changes in maximal strength during the strength training period (Figure 5). This observation suggests that a low level of the anabolic hormone testosterone, especially in older women, may be a limiting factor in strength development and muscle hypertrophy, although the magnitudes of strength gains between the groups remained the same, utilizing the present low-volume training protocol over the 6-month period. Because no observable changes occurred in body mass, most likely due to the specific training program, the correlation observed suggests that testosterone could mediate interactions with the nervous system, e.g., increased neurotransmitter synthesis (41,42) contributing to strength development. The present training program did lead to increased EMGs of the trained muscles (Figure 2). Nevertheless, the findings are well in line with previous observations that basal concentrations of blood testosterone may be of great importance in both young women (38) and older women (23) for strength development and muscle hypertrophy, when typical heavy-resistance training programs with higher volumes are utilized, even for shorter training periods such as a few weeks or months. In this study only the serum levels of testosterone were measured. It is possible that even though the blood testosterone levels would remain unaltered, strength training can induce changes, e.g., at the receptor level.

DHEA and its conjugated form DHEAS are androgens secreted from adrenal cortex (43). It has been reported earlier that the serum DHEA(S) levels are somewhat lower in females compared with males and that the serum levels decrease with aging after the age of 20-30 years (44–46). The basal concentrations of serum DHEA(S) presented in Figure 6 are well in accordance with these age- and gender-related differences. As in the case of testosterone no systematic training-induced changes were observed in the circulating levels of this androgen in any of the present subject groups during the entire experimental training period.

In addition to the basal levels of the hormones, serum total and free testosterone as well as GH concentrations were measured in the present study during the single heavy-resistance exercise session before and after the 6-month strength training period. It has been reported earlier that serum testosterone concentration may increase during typical heavy-resistance exercise in young men, whereas the response in women may be minor (21,47–49). The acute exercise-induced testosterone response is usually lower in older than in younger men, depending also on the type of loading protocol (14,20,21). The loading used in this study at the pretraining condition resulted in significant increases in serum total and free testosterone concentrations, not only in middle-aged men but also in our older men, even at their age of 72 years, whereas no significant responses were recorded in women. The relative intensity of the loading at the post-training condition was the same as before the training period, but the overall absolute volume of the loading was naturally greater, due to the increased strength level of each subject. Under these conditions the post-training loading responses in men of both age groups were significant and did not differ from those responses recorded at the pretraining. In women no significant responses were observed in serum testosterone levels during the post-training loading conditions, as was the case before the training. However, a significant response was observed in serum free testosterone levels under the post-training loading conditions in women of both age groups. The results in men indicate that although the absolute loading is increased due to strength training, the acute testosterone response remains the same, when the relative intensity is kept the same. However, it is difficult to conclude the physiological significance of the difference in serum free testosterone responses between the pre- and post-training loading conditions observed in women. It is unclear whether the lack of serum total testosterone response in older women in both loading conditions is a limiting factor in strength development and muscle hypertrophy, as it seems to be the case for the low basal serum testosterone level (Figure 5).

The results presented in Figure 9 clearly show that the present loading resulted in significant increases in serum GH concentrations in both pre- and post-training conditions in all subject groups, with the exception of older women. This finding is well in accordance with previous observations about the lowered GH response with increasing age, especially in women (21). The older men produced a lower lactate response to the loading protocol than middle-aged men using the same relative intensity. The same was true for older women compared to middle-aged women. Actually, the lowest blood lactate response during both pre- and post-training loading conditions was observed in the group of elderly women who demonstrated no GH response at all. Due to the pulsatile nature of GH secretion, the interpretation of single measures must be done cautiously. However, the present data indicate that the response of GH to the same relative heavy-resistance work load was greatly lowered in older women and they remained nonresponsive also after the 6-month training period. The physiological significance of this lack of acute responsiveness of serum GH to heavy resistance exercise in older women for their trainability during more prolonged strength training periods requires further examination.

In summary, the present results show that the specific strength training with heavy and explosive exercises leads to great increases in maximal concentric strength of the leg extensors not only in middle-aged but also in elderly men and women. The increases in strength were accompanied by large increases in the maximal voluntary activation of the agonist muscles in all groups, although no observable changes occurred in body mass. None of the groups showed systematic changes in the mean serum concentrations of testosterone, DHEA(S), GH, cortisol, or SHBG, but a low level of testosterone, especially in older women, may be a limiting factor in strength de-
velopment in that testosterone could mediate interactions with the nervous system contributing to strength development. The physiological significance of the lack of acute responsiveness of serum GH to heavy-resistance exercise in older women for their trainability during prolonged strength training requires further examination.

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