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Effects of strength training on muscle power and serum hormones in middle-aged and older men

M. IZQUIERDO,¹ K. HÄKKINEN,² J. IBAÑEZ,¹ M. GARRUES,¹ A. ANTÓN,¹
A. ZÚNIGA,¹ J. L. LARRIÓN,³ AND E. M. GOROSTIAGA¹

¹Centro de Investigación y Medicina del Deporte de Navarra, Gobierno de Navarra,
and ³Servicio Navarra de Salud, Hospital de Navarra, 31002 Pamplona, Navarra, Spain;
and ²Department of Biology of Physical Activity and Neuromuscular Research Center,
University of Jyväskylä, FIN-40351 Jyväskylä, Finland

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Izquierdo, M., K. Häkkinen, J. Ibañez, M. Garrues, A. Antón, A. Zúñiga, J. L. Larrión, and E. M. Gorostiaga. Effects of strength training on muscle power and serum hormones in middle-aged and older men. *J Appl Physiol* 90: 1497–1507, 2001.—Effects of 16-wk strength training on maximal strength and power performance of the arm and leg muscles and serum concentrations [testosterone (T), free testosterone (FT), and cortisol] were examined in 11 middle-aged (M46; 46 ± 2 yr) and 11 older men (M64; 64 ± 2 yr). During the 16-wk training, the relative increases in maximal strength and muscle power output of the arm and leg muscles were significant in both groups ($P < 0.05$ – 0.001), with no significant differences between the two groups. The absolute increases were higher ($P < 0.01$ – 0.05) in M46 than in M64 mainly during the last 8 wk of training. No significant changes were observed for serum T and FT concentrations. Analysis of covariance showed that, during the 16-wk training period, serum FT concentrations tended to decrease in M64 and increase in M46 ($P < 0.05$). However, significant correlations between the mean level of individual serum T and FT concentrations and the individual changes in maximal strength were observed in a combined group during the 16-wk training ($r = 0.49$ and 0.5 , respectively; $P < 0.05$). These data indicate that a prolonged total strength-training program would lead to large gains in maximal strength and power load characteristics of the upper and lower extremity muscles, but the pattern of maximal and power development seemed to differ between the upper and lower extremities in both groups, possibly limited in magnitude because of neuromuscular and/or age-related endocrine impairments.

aging; maximal strength; muscle power; testosterone

NORMAL BIOLOGICAL AGING IS associated with declines in the functional capacity of the neuromuscular and neuroendocrine systems, resulting in decreases in maximal strength and muscle power output. However, it has also been suggested that muscular performance may vary between the upper and lower extremity muscles in relation to differences in age-related declines in the quantity and/or intensity of daily physical activities throughout the life span (4, 7, 18, 27). Age-related

decreases in strength and power result from a reduction in muscle mass mediated by both a loss and a decrease in the size of the individual fibers, especially of type II fibers (25, 26), and in part from a decrease in maximal voluntary neural drive of the agonist muscle and/or changes in the degree of antagonist coactivation (8). Several aging studies have also observed decreases in blood concentrations of circulating anabolic and androgenic hormones in elderly men (6, 14, 23) accompanied by an increase in diurnal concentrations of serum basal cortisol (C) secretion (6). Furthermore, correlations observed among the individual values of circulating levels of serum testosterone (T)-to-C ratio, muscle cross-sectional area (CSA), and strength in middle-aged and older men (14) suggest that the balance between anabolic and catabolic hormones in aging men over the years has a plausible association with muscle atrophy and decreased voluntary force production.

Several studies have shown that strength training of the lower extremity muscles improves maximal strength not only in middle-aged, but also in older subjects of both genders (5, 9, 11, 28, 29). The primary mechanisms responsible for the strength performance improvements after resistance training are the increased neural activation of the trained agonist muscles (11, 28, 32) accompanied by gradually increasing muscle hypertrophy during the later stages of training. This seems to hold true even in older people, when both the overall training intensity and the duration of the training period are sufficient. However, little experimental information is available about total body resistance training-induced changes in maximal strength between the lower and upper extremity muscles in middle-aged and older men. Second, human muscle metabolism is under homeostatic hormonal control, and strength-training-related changes in resting anabolic environment have been thought to play an important role in protein accretion, increased neurotransmitter synthesis, and strength development (6, 14, 24), attenuating the known sarcopenia and loss of strength

Address for reprint requests and other correspondence: M. Izquierdo, Centro de Investigación y Medicina del Deporte de Navarra, Gobierno de Navarra, C/ Paulino Caballero, 13, 31002 Pamplona (Navarra) Spain (E-mail: mizquierdo@jet.es).

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with aging (14, 15, 23, 24). However, there is a lack of data with regard to possible interrelationships between training-induced strength and power changes and circulating levels of anabolic and catabolic hormones in older men.

Age-related reductions in muscle power output and the ability to develop force rapidly, especially in the lower extremity muscles, are maybe more important than the role of the maximal strength of the muscles. This is crucial for various activities of daily living, especially among individuals close to the threshold of dependency (2, 17, 34). Traditional heavy-resistance training utilizing high loads performed with slow-movement velocities leads to improved maximal strength with only minor changes in explosive characteristics of the trained muscles in both middle-aged and older subjects (5). Because performance of daily activities requires both strength and muscle power, heavy-resistance training might be combined with explosive types of exercises by also emphasizing higher action velocities of the exercises performed. Thus several previous studies combining exercises for maximal and explosive strength development have shown improvements in older people in both maximal and rapid isometric force production (10, 11), as well as in explosive jumping actions (9, 11) and muscle power output on pneumatic resistance machines (20). However, much fewer data are available on training-induced changes in maximal strength and muscle power performances between the lower and upper extremity muscles by using a total body training program for the main upper and lower extremity muscle groups with a combination of heavy-resistance and high-velocity exercises. Therefore, we hypothesized that the prolonged total strength-training program would lead to different maximal strength and power enhancements between upper and lower extremity muscles in middle-aged and older men, possibly limited in magnitude because of neuromuscular and/or age-related endocrine impairments.

Therefore, the purpose of the present study was to examine the effects of 16-wk progressive, heavy-resistance training on 1) maximal strength and muscle power performance of the lower and upper extremity muscles; 2) serum concentrations of T, free testosterone (FT), and C; and 3) possible interrelationships between the strength and power changes and serum hormone concentrations.

Table 1. Physical characteristics of middle-aged and elderly men before (week 0) and after 8 and 16 wk of strength training

	Age, yr	Height, cm	Energy Cost, MET min/day	Body Mass, kg			Body Fat, %			Fat-free Mass, kg			Cross-sectional Area of Quadriceps Femoris, cm ²	
				Week 0	Week 8	Week 16	Week 0	Week 8	Week 16	Week 0	Week 8	Week 16	Week 0	Week 16
M46	46 ± 3	175 ± 3	1,247 ± 796	86 ± 11	85 ± 11	84 ± 12	23 ± 1	22 ± 4	21 ± 4*	65 ± 5	66 ± 6	66 ± 6	48 ± 8	54 ± 9*
M64	64 ± 2	167 ± 4	877 ± 380	81 ± 10	81 ± 3	80 ± 11	24 ± 5	24 ± 5	22 ± 4*	61 ± 3	61 ± 4	62 ± 5	46 ± 13	51 ± 16*

Values are means ± SD; *n* = 11 subjects/group. MET, metabolic equivalent [1 MET = energy expenditure of 3.5 ml·kg⁻¹·min⁻¹ (oxygen consumption at rest)]; M46, 46-yr-old middle-aged subjects; M64, 64-yr-old elderly subjects. *Significantly different (*P* < 0.05) from corresponding value at week 0.

METHODS

Subjects

Eleven middle-aged (46-yr-old; M46) and eleven older men (64-yr-old; M64) volunteered to participate in the present study. They were recruited through advertisement and personal letter from a private recreational and physical fitness club. All subjects were carefully informed about the possible risks and benefits of the project, which was approved by the Ethics Committee of the Health Department. Thereafter, the subjects signed a written consent form before participation in the study. Before inclusion in the study, all candidates were thoroughly screened using an extensive medical history (including current medication information) and resting and maximal exercise electrocardiogram and blood pressure measurements. Cardiovascular, neuromuscular, arthritic, pulmonary, or other debilitating diseases, as determined via one or all of the screening tools, were reasons for exclusion from the study. All subjects were healthy, and none was taking cardiovascular medications. A physical activity questionnaire was used to quantify 4-wk physical activity energy cost (Minnesota Leisure Time Physical Activity questionnaire) (31), and it revealed that all subjects were physically active. To keep themselves fit, they had taken part in various recreational physical activities, such as walking, biking, cross-country hiking, and to a lesser extent swimming and soccer. However, none of the subjects had any background in regular strength and/or endurance training or competitive sports of any kind. All lived at home and were able to perform activities of natural daily life independently. No medication was being taken by the subjects that would have been expected to affect physical performance. The physical characteristics of the two subject groups are presented in Table 1.

This work is part of a larger research project. Some of the results obtained for these subjects from the first measurement of the follow-up design have been used earlier for various cross-sectional comparative purposes between the two different age groups (18).

Experimental Design

The total duration of the present study was 20 wk. The subjects were tested on four different occasions using identical protocols. Baseline testing was completed during the first 4 wk of the study (between the measurements at weeks -4 and 0) during which time no strength training was carried out, but the subjects maintained their customary recreational physical activities (e.g., walking, biking, and swimming). This was followed by a 16-wk period of supervised experimental strength training. The measurements were repeated during the actual experimental training period at 8-wk intervals (i.e., weeks 8 and 16).

Testing Schedule

Before testing and training, each subject was carefully familiarized with the testing procedure of voluntary force production during several submaximal and maximal actions. In addition, several warm-up contractions were recorded before the actual maximal test actions. Strength and muscle power testing was conducted over two different sessions separated by 5 days. During the first testing occasion, each subject was tested for the low-extremity muscles in one-repetition concentric maximum (1 RM) from a half-squat position (1 RM_{HS}) and for the load-velocity and power-load relationships of the leg extensor muscles by using the loads of 0 (no load), 15, 30, 45, 60, and 70% of 1 RM_{HS}. In the second test session, each subject was tested for the maximal unilateral concentric 1 RM (kg) and unilateral isometric torque (maximal isometric force; N·m) of the knee extensor muscles (MIF_{KE}), as well as for his maximal concentric 1-RM bench press (1 RM_{BP}) and for the velocity and power during the concentric actions with the loads of 0 (no load), 30, 45, 60, and 70% of the maximal 1 RM_{BP}. Muscle strength tests took place for a given subject at the same time of day throughout the experiment. Training was integrated into the test-week schedules, and a minimum of 48 h of rest was allowed after the last training session before the tests were conducted.

Strength and Power Testing

Lower and upper body maximal strength was assessed by using 1-RM actions. In the half squat (1 RM_{HS}), the shoulders were in contact with a bar, and the starting knee angle was 90°. On command, the subject performed a concentric extension (as fast as possible) of the leg muscles (hip, knee, and ankle extensor muscles) starting from the flexed position to reach the full extension of 180° against the resistance determined by the weight plates added to both ends of the bar. The trunk was kept as straight as possible. A security belt was used by all subjects. All of the tests were performed in a squatting apparatus in which the barbell was attached to both ends, with linear bearings on two vertical bars allowing only vertical movements. Warm-up consisted of a set of five repetitions at the loads of 40–60% of the perceived maximum. Thereafter, four to five separate, single attempts were performed until the subject was unable to extend his legs to the required position. The last acceptable extension with the highest possible load was determined as 1 RM. In the concentric bench press (1 RM_{BP}), the bar was positioned 1 cm above the subject's chest and was supported by the bottom stops of the measurement device. The subject was instructed to perform from the starting position a purely concentric action maintaining the shoulders in a 90° abducted position to ensure consistency of the shoulder and elbow joints throughout the testing movement (30). Three to four trials were performed until the subject was unable to reach the full extension position of the arms. The last acceptable extension with the highest possible load was determined as 1 RM.

The power-load relationship of the leg and arm extensor muscles was also tested at *weeks* -4, 0, 8, and 16 concentrically in a half-squat position using the relative loads of 0, 15, 30, 45, 60, and 70% of 1 RM and in the bench-press position using the relative loads of 30, 45, 60, and 70% of 1 RM. In this case, the subjects were instructed to move the load as fast as possible. Two testing actions were recorded, and the best reading (with the best velocity) was taken for further analyses.

During lower extremity test actions, bar displacement, maximal average velocity (m/s), and power (W) were recorded by linking a shuttle to the end part of the bar locked to an

infrared sensor. The accuracy of the electronic device reached the 10- μ s time resolution with an optical transducer interruption each 3 mm of displacement (3). The calculation of instantaneous velocity and power was performed, and it has been described elsewhere (3, 18). Average velocity and power were calculated through the whole range of motion utilized to perform a complete repetition. Power curves were plotted using average power over the whole range of movement as a most representative mechanical parameter associated with a contraction cycle of each muscle group. For comparison purposes, an averaged index of muscle power output with all absolute loads examined was calculated in M46 and M64 separately. Power curves were plotted by using average power over the whole range of movement.

A David Rehab 2200 dynamometer (David Fitness and Medical) was used to measure MIF_{KE} (N·m). The subject was in a seated position so that the hip and knee angles were 110 and 90°, respectively. On verbal command, the subject performed a maximum isometric knee extension or flexion for the right leg. A minimum of three maximal actions was recorded for the extension and flexion action, and the best maximum was taken for further analysis. Maximal unilateral concentric 1 RM (kg) of the knee extensor muscles was also assessed with the David 2200. In this test, the subject performed a concentric knee extension from a flexed position of 70° to reach a required extension of a minimum 170° (full extension 180°) against the resistance determined by the loads chosen on the weight stacks. In testing the maximal load, separate 1-RM contractions were performed. After each repetition, the load was increased until the subject was unable to extend his leg to the required position. The last acceptable extension with the highest possible load was determined as 1 RM. Maximal strength and muscle power variables showed reliability coefficients ranging from 0.80 to 0.99, and the coefficients of variation ranged from 2 to 7%.

In all tests of neuromuscular performance, strong verbal encouragement was given to each subject to motivate him to perform each test action as maximally and as rapidly as possible. The time period of rest between the actions was always 1.5 min.

Muscle CSA and Body Composition

Thigh bone-free muscle CSA of the quadriceps femoris (QF) muscle group (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedialis; CSA_{QF}) was measured at *week 0* and after the experimental period (*week 16*) with a compound ultrasonic scanner (Toshiba SSA-250) and a 5-MHz convex transducer. The CSA was measured at the lower one-third portion between the greater trochanter and lateral joint line of the knee. Two consecutive measurements were taken from the right thigh and then averaged for further analyses. The CSA was then calculated from the image by the computerized system of the apparatus. The percentage of fat in the body was estimated from the measurements of skinfold thickness (19). Muscle mass variables showed reliability coefficients >0.74. The coefficient of variation ranged from 1.4 to 4.3% for the measured circumference and CSA_{QF} muscle group.

Analytic methods. Resting blood samples were drawn at *week* -4 (4 wk before the start of training) and at *weeks* 0, 8, and 16 during the training period. The subjects reported to the laboratory and were sitting quietly for 10–15 min before giving a blood sample. Venous blood samples were obtained at rest between 8 and 9 AM from the antecubital vein to determine concentrations of serum total T, FT, and C. Blood samples were taken at the same time of day to reduce the

effects of diurnal variation on hormonal concentrations. Blood was drawn after 12 h of fasting and 1 day of minimal physical activity. The samples for the analyses of hormones were centrifuged, and the serum was removed and frozen at -20°C for later analysis. The assays of serum C and T were performed by radioimmunoassays. Serum total T, FT, and C concentrations were measured by using reagent kits from Diagnostic Product and INCSTAR (Coat-A-Count total/free testosterone TKTT11CS, Los Angeles, CA; and GammaCoat C radioimmunoassay kit, respectively). The sensitivity of the total T and FT assay was 0.14 nmol/l and 0.15 pmol/l, respectively. The sensitivity of the C assay was 0.21 $\mu\text{g}/\text{dl}$. The coefficient of intra-assay variation was 5 and 4%, and that of interassay variation was 5.9 and 3.7%, for the total T and FT, respectively. The respective values were 6.6 and 8.8% for the C assay. All samples were analyzed in the same assay for each hormone, according to the instructions of the manufacturer.

Periodized Heavy- and Explosive Resistance Training Program

The subjects were required to participate in a supervised 16-wk period of strength training with a training frequency of 2 days/wk. Each training session included two exercises for the leg extensor muscles (bilateral leg press and bilateral knee extension exercises), one exercise for the arm extensor muscle (the bench press), and four to five exercises for the main muscle groups of the body (chest press, lateral pull-down, and/or shoulder press for the upper body; abdominal crunch and/or rotary torso and/or another exercise for the trunk extensors; and the standing leg curl and/or adductor-abductor exercises). Only the machine exercises were used throughout the training period. All of the exercises were performed by using concentric muscle actions followed by eccentric actions during the “lowering” phase of the movement. The subjects performed both concentric and eccentric muscle actions, but the loads were based on the concentric performance. Resistance used in this study was determined during the training sessions every week for the 16-wk training period using a repetition maximum approach.

During the first 8 wk of the training period, the subjects trained with the loads of 50–70% of their individual 1 RM. The subjects performed 10–15 repetitions per set and 3–4 sets of each exercise. During the last 8 wk of the training, the loads were 50–60 and 60–70% of the maximum by weeks 9–12 and 50–60 and 70–80% by week 13–16. In the two exercises for the leg extensor muscles and in the exercise of the bench press for the upper extremity, 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 five exercises, the subjects performed 10–12 repetitions per set and performed 3–5 sets. The strength-training program utilized in the present study was similar to that reported previously (11) and was a combination of heavy-resistance and “explosive” strength training. Therefore, in addition to the heavy-resistance training design, the basic requirements for the development of explosive strength were taken into consideration during the last 8 wk of the training period (from week 8 to week 16) by instructing the subjects to perform a part (20%) of the leg extensor and bench-press sets with the loads ranging from 30–50 and 30–40% of the maximum, respectively. In these training occasions, the subjects now performed six to eight repetitions per set and three to four sets of each exercise but executed all of these repetitions as rapidly as possible. A trained researcher supervised each workout session to verify that

proper training procedures were followed. The researcher also recorded the compliance and individual workout data during each exercise session.

During the 16-wk experimental training period, the subjects continued taking part in physical activities such as walking or swimming one to two times per week in a manner similar to what they were accustomed to doing before this experiment.

Statistical Methods

Standard statistical methods were used for the calculation of the means, SD, SE, and Pearson product-moment correlation coefficient. Statistical comparison during the control period (from week -4 to week 0) was performed by Student's paired *t*-test. A *t*-test for independent samples determined any differences among the two groups' initial strength, endurance, and hormones measures. A repeated-measures multivariate analysis of variance was used to assess training-related effect, within-subject analysis. When appropriate, post hoc comparisons were accomplished via Scheffé's test. Analyses of covariance (ANCOVAs) were used to adjust post-training values to compare the data between the groups. For this purpose, pretraining values were used as covariates so that the effects of the covariance could be observed. Statistical power calculations for this study ranged from 0.75 to 0.80. The $P \leq 0.05$ criterion was used for establishing statistical significance.

RESULTS

Muscle CSA and Anthropometry

The CSA_{QF} increased during the 16-wk training period in M46 by $13 \pm 10\%$ (from 48.3 ± 8 to $54.7 \pm 7 \text{ cm}^2$; $P < 0.01$) and in M64 by $11 \pm 9\%$ (from 46 ± 13 to $51.2 \pm 16 \text{ cm}^2$; $P < 0.01$). The relative increases in the CSA_{QF} during the course of the training did not differ significantly between the subject groups. Percentage of body fat decreased significantly ($P < 0.05$) during the 16-wk training period in both groups, whereas no significant changes were observed for body mass after the training for either group (Table 1).

Maximal concentric 1 RM_{HS}, 1-RM knee extension, and bench-press strength. Maximal 1 RM_{HS} increased slightly ($P < 0.03$) during the 4-wk control period (from week -4 to week 0) in both age groups. No significant differences were observed between the groups in the pretraining strength level for the 1 RM_{HS}. During the 16 wk of training, significant increases took place in maximal concentric 1 RM_{HS} in M46 by $45 \pm 6\%$ (from 113 ± 26 to $163 \pm 27 \text{ kg}$; $P < 0.001$) and in M64 by $41 \pm 16\%$ (from 100 ± 24 to $136 \pm 28 \text{ kg}$; $P < 0.001$) (Fig. 1A). The increase in maximal concentric 1 RM was already significant during the first 8 wk of training in M46 by $24 \pm 6\%$ (from 113 ± 26 to $140 \pm 25 \text{ kg}$; $P < 0.001$) and in M64 by $27 \pm 6\%$ (from 100 ± 24 to $126 \pm 28 \text{ kg}$; $P < 0.001$). The relative increases did not differ between the two groups. ANCOVA showed that the increase in maximal concentric 1 RM_{HS} observed during the 16-wk training period was significantly higher ($P < 0.05$) in M46 than in M64 (Fig. 1A). This difference occurred mainly during the last 8 wk of training ($P < 0.02$ between weeks 8 and 16), because, in the

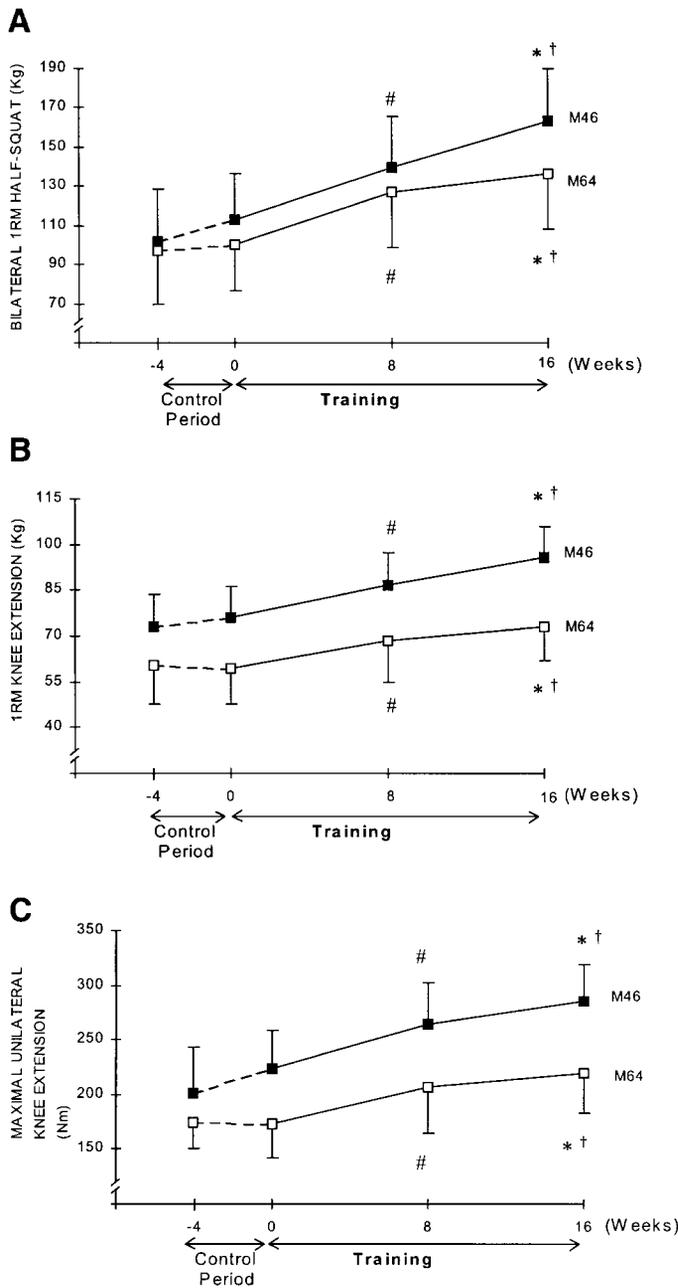


Fig. 1. Maximal bilateral concentric one-repetition maximum (1-RM) half squat (A), maximal unilateral concentric 1-RM knee extension (B), and maximal unilateral isometric knee extension (C) in middle-aged men (46 yr; M46) and elderly men (64 yr; M64) during 4-wk control period and 16-wk strength-training period. Values are means \pm SD. Significant difference ($P < 0.05$) between #weeks 0 and 8, *weeks 0 and 16, and †weeks 8 and 16.

early phase of training (from week 0 to week 8), the increase in 1 RM_{HS} was similar in both groups.

Maximal 1-RM knee extension remained unaltered during the 4-wk control period (from week -4 to week 0) in both groups. Significant differences ($P < 0.01$) were observed between the groups in pretraining 1-RM knee extension (Fig. 1B). The strength-training program resulted in significant increases ($P < 0.001$) in maximal 1-RM concentric knee extension force during the 16-wk training period in M46 by $29 \pm 13\%$ (from

75 ± 10 to 95 ± 10 kg; $P < 0.001$) and in M64 by $25 \pm 18\%$ (from 59 ± 11 to 73 ± 11 kg; $P < 0.001$). When the data were analyzed by ANCOVA using the pretraining strength values as the covariate, it was shown that, during the early phase of training (from week 0 to week 8), the increase in 1-RM knee extension was similar in both groups (by 19 ± 9 and $15 \pm 5\%$ in M46 and M64, respectively). However, the increase in maximal concentric 1-RM knee extension observed during the last 8 wk of training (between weeks 8 and 16) was significantly higher ($P < 0.001$) in M46 than in M64 but was not significant between weeks 0 and 16 (Fig. 1B).

MIF_{KE} increased slightly during the 4-wk control period (from week -4 to week 0) in M46, whereas it remained unaltered in M64 (Fig. 1C). Large increases took place in MIF_{KE} during the 16-wk training period in M46 by $27 \pm 7\%$ (from 224 ± 36 to 285 ± 33 N·m; $P < 0.001$) and in M64 by $26 \pm 15\%$ (from 173 ± 31 to 220 ± 37 N·m; $P < 0.001$). ANCOVA showed that, during the early phase of training (from week 0 to week 8), the increase in MIF_{KE} was similar in both groups (by 15 ± 6 and $15 \pm 7\%$ in M46 and M64, respectively). However, the increase in MIF_{KE} knee extension observed during the last 8 wk of training (between weeks 8 and 16) was significantly higher ($P < 0.05$) in M46 than in M64 but was not significant between weeks 0 and 16 (Fig. 1C).

Maximal 1-RM_{BP} strength remained unaltered during the 4-wk control period. Significant differences ($P < 0.05$) were observed between the groups in the pretraining 1 RM_{BP}. During the 16-wk training period, maximal concentric 1 RM_{BP} improved in M46 by $36 \pm 13\%$ (from 58 ± 16 to 80 ± 10 kg; $P < 0.001$) and in M64 by $36 \pm 11\%$ (from 47 ± 10 to 64 ± 9 kg; $P < 0.001$). When the data were analyzed by ANCOVA, the increase in maximal concentric 1 RM_{BP} during the observed 16-wk training period was significantly higher ($P < 0.01$) in M46 than in M64 (Fig. 2). This difference occurred mainly during the last 8 wk of training ($P < 0.01$; between weeks 8 and 16), because, in the early phase of training (from week 0 to week 8), the increase in 1 RM_{BP} was similar in both groups.

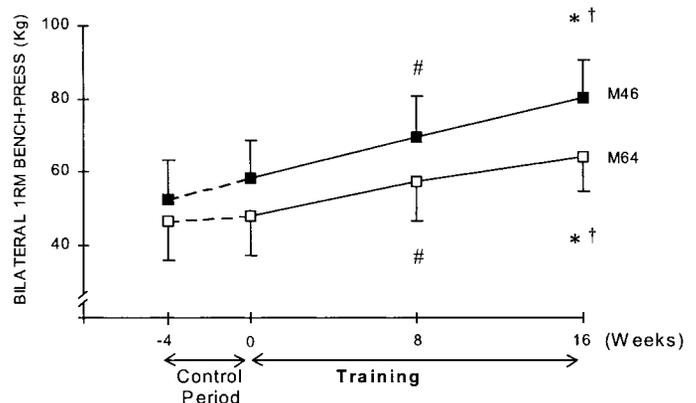


Fig. 2. Maximal unilateral concentric 1-RM bench press in M46 and M64 during 4-wk control period and 16-wk strength-training period. Values are means \pm SD. Significant difference ($P < 0.05$) between #weeks 0 and 8, *weeks 0 and 16, and †weeks 8 and 16.

In both age groups, the individual initial values of maximal bilateral concentric 1 RM_{HS} and 1 RM_{BP} at *week 0* correlated (from $r = -0.58$ to -0.75 ; $P < 0.05-0.01$) with the individual changes in 1 RM_{HS} and 1 RM_{BP} during the 16-wk training period.

Muscle power output. The data for the shapes of the average bilateral concentric half-squat and bench-press power-load curve in absolute values during the 16-wk training period are presented in Figs. 3 and 4, respectively. Muscle power output of the lower extremities at all loads examined remained unaltered during the 4-wk control period in M46 (however, $P < 0.05-0.01$ at 0 and 70% of 1 RM_{HS}) and in M64 ($P < 0.05-0.01$ at the load of 0–45% of 1 RM_{HS}). During the first 8 wk of training, the average bilateral concentric half-squat power-load curve increased significantly at loads ranging from 0 to 70% of 1 RM_{HS} in M46 ($P <$

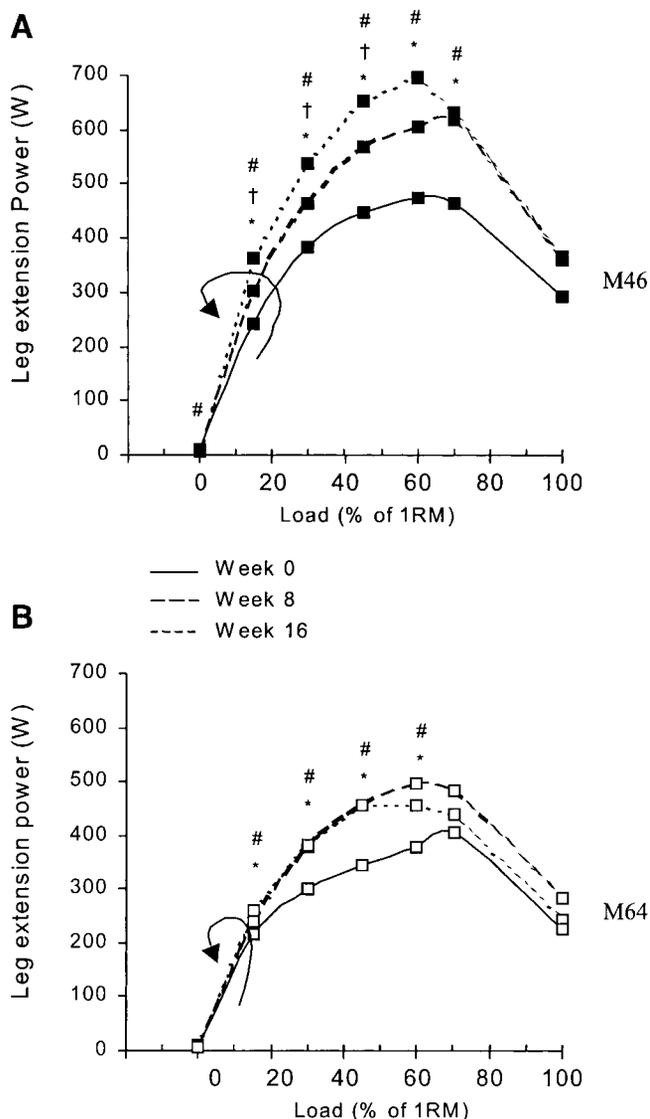


Fig. 3. Average power-load curve in the concentric half-squat extension in M46 (A) and M64 (B) at *weeks 0, 8, and 16* during the 16-wk strength-training period. Significant difference ($P < 0.05$) between #*weeks 0 and 8*, **weeks 0 and 16*, and †*weeks 8 and 16*. Arrows denote time course of power gain.

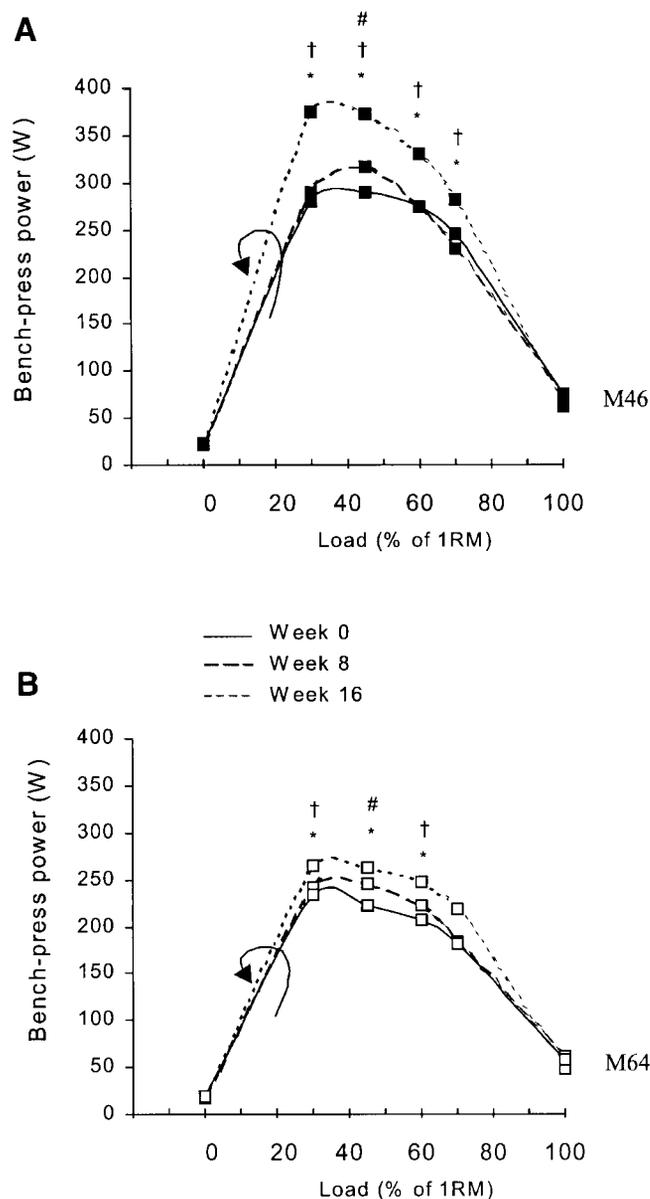


Fig. 4. Average power-load curve in the bench-press action in M46 (A) and M64 (B) at *weeks 0, 8, and 16* during the 16-wk strength-training period. Significant difference ($P < 0.05$) between #*weeks 0 and 8*, **weeks 0 and 16*, and †*weeks 8 and 16*. Arrows denote time course of power gain.

0.01–0.001) and from 15 to 60% of 1 RM_{HS} in M64 ($P < 0.01-0.001$) (Fig. 3). During the next 8 wk of training, no significant increase in power took place at any load in M64, whereas a further increase was observed in M46 at loads ranging from 15 to 45% of 1 RM_{HS} ($P < 0.01-0.001$). When the data were analyzed by ANCOVA using the pretraining strength values as the covariate, it showed that, during the early phase of training (from *week 0* to *week 8*), the muscle power output increases with the relative load of 60% of 1 RM_{HS} were similar in both groups (by 29 ± 18 and $36 \pm 22\%$ for M46 and M64, respectively). During the last 8 wk of training (between *weeks 8* and *16*), it was significantly higher (by 15 ± 18 and $-2 \pm 21\%$ for M46 and

Table 2. Serum hormone concentrations in middle-aged and elderly men during the control period (weeks -4 to 0) and after the 16-wk strength-training period (weeks 0 to 16)

	Week -1	Week 0	Week 8	Week 16
M46				
Total testosterone, nmol/l	19.1 ± 8	18.6 ± 5	18.5 ± 5	19.4 ± 6
Free testosterone, pmol/l	63.5 ± 12	63.4 ± 15	63 ± 13	67 ± 13
Cortisol, nmol/l	578 ± 128	564 ± 156	551 ± 176	538 ± 137
M64				
Total testosterone, nmol/l	17.4 ± 4	18.8 ± 5	19 ± 6	17.8 ± 5
Free testosterone, pmol/l	52.8 ± 13	53 ± 13	54 ± 15	50.3 ± 14
Cortisol, nmol/l	541 ± 128	552 ± 118	611 ± 84	517 ± 90*

Values are means ± SD. *Significantly different ($P < 0.05$) from corresponding value at week 8.

M64, respectively; $P < 0.01$) in M46 than in M64 ($P < 0.05$ from week 0 to week 8) (Fig. 3). During the 16-wk training period, muscle power output with the relative load of 60% of 1 RM_{HS} improved in M46 by 46 ± 30% ($P < 0.001$) and in M64 by 37 ± 29% ($P < 0.001$).

Bench-press power output at all loads examined remained unaltered during the 4-wk control period in M46 (however, $P < 0.05$ at 45 and 60% of 1 RM_{BP}) and in M64 ($P < 0.05$ at 45% of 1 RM_{BP}). During the 16 wk of training, bench-press power output increased significantly ($P < 0.001$) at loads ranging from 30 to 70% of 1 RM_{BP} in M46 and from 30 to 60% in M64 (Fig. 4). When the data were analyzed by ANCOVA, the increase in muscle power at the loads of 30 and 45% of 1 RM_{BP} during the 16-wk training period was significantly higher ($P < 0.01$) in M46 (26 ± 14%) than in M64 (by 21 ± 19%) (Fig. 4). This difference occurred mainly during the last 8 wk of training ($P < 0.01$ between weeks 8 and 16), because, in the early phase of training (from week 0 to week 8), the increase in muscle power output at the loads of 30 and 45% was similar in both groups.

Serum hormone concentrations. Table 2 presents serum concentrations of T, FT, and C at weeks -4, 0, 8, and 16. No significant differences were observed in pretraining serum hormone concentrations between the groups. Serum hormone concentrations of T, FT, and C remained unaltered during the 4-wk control period in both groups. During the 16-wk training period, no significant changes were observed for T in either of the age groups. For C, a significant decrease ($P < 0.05$) was observed in M64 during the last 8 wk of training, whereas in M46 it remained unchanged throughout the training. ANCOVA showed that, during the 16-wk training period, serum FT concentrations decreased in M64 and increased in M46 ($P < 0.05$). This occurred mainly during the last 8 wk of training.

Statistically significant correlations were observed in a combined group of M46 plus M64 between the mean level of individual serum FT and total T concentration (averaged for the entire training period) and the individual changes in maximal unilateral isometric force during the 16-wk training period ($r = 0.5$ and 0.49; $P < 0.05$; Fig. 5, A and B, respectively). The corresponding correlation coefficients between the mean level of individual serum total T and FT concen-

tration averaged for the last 8 wk of the 16-wk training period and the individual changes in maximal unilateral isometric force during the same training period (from week 8 to week 16) were also significant ($r = 0.45$ and 0.44, respectively; $P < 0.05$). No significant correlations during the first 8 wk of the 16-wk (from week 0 to week 8) training period were observed. In the M46

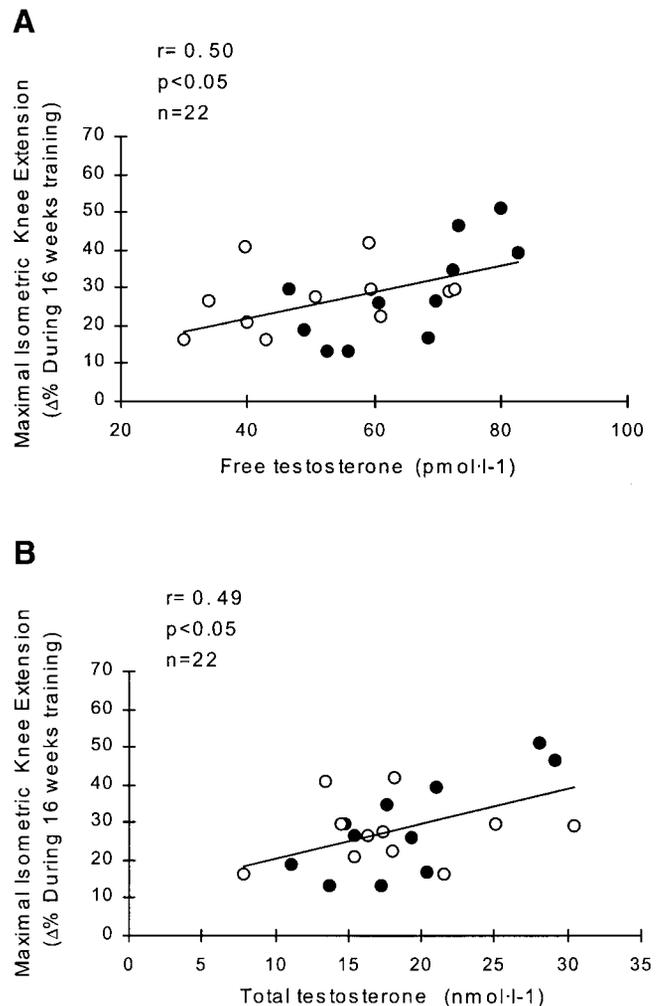


Fig. 5. Relationships between the mean level of individual serum total (B) and free testosterone (A) concentration (averaged for the 16-wk training period) and the individual changes in maximal unilateral isometric force during the 16-wk training period in a combined group of M46 (●) and M64 (○). n, No. of subjects.

group, significant correlations were observed between the mean level of individual serum total T and FT concentration and the individual changes in maximal unilateral isometric force averaged both for the entire training period ($r = 0.78$ and 0.71 ; $P < 0.01$ and 0.05 , respectively) or for the last 8 wk of the 16-wk training period ($r = 0.74$; $P < 0.01$, for total T).

DISCUSSION

The present progressive heavy-resistance training program combined with explosive types of exercises led to great gains in maximal dynamic strength and power-load characteristics of the leg and arm extensors muscles in both M46 and M64 with only two sessions a week. The relative gains in maximal strength were similar in both groups, but the absolute gains in maximal strength and power were greater in M46 compared with M64, occurring mainly during the last 8 wk of training. The gains in strength were associated in both groups with considerable (and of similar magnitude) enlargements in the CSA_{QF} . No systematic changes were observed during the present 16-wk strength-training period in the basal concentrations of serum T and FT. However, during the last 8 more intensive training weeks, ANCOVA showed a significant decrease in serum FT concentrations in M64, whereas it remained unaltered in M46. It was also interesting to observe that, in a combined group of M46 and M64, the mean levels of individual serum total T and FT concentrations and the individual changes in maximal unilateral isometric force correlated significantly during the entire 16-wk training period, as well as during the last 8 most stressful weeks of the training period.

The primary results of the present study demonstrated that a progressive 16-wk strength-training program led to similar relative and absolute gains in maximal strength of the arms and legs during the first 8 wk of training in the M46 and M64. However, during the last 8 most intensive training weeks of the 16-wk training period, maximal strength increased at a greatly diminished absolute rate in the M64 compared with the M46 group. Several previous investigations have reported that, in previously untrained young and older subjects, great initial increases in maximal strength may occur after a few weeks of strength training (5, 7, 11, 13, 20, 22, 28, 29). Thus during the first weeks of training it would appear that older subjects are equally trainable for maximal strength as are the younger counterparts. However, it is possible that, after the initial 8–10 wk of strength training, when the resistance (70–80% 1 RM) and/or the frequency of training (2–3 times per week) are increased, a tendency toward diminished absolute rate of improvement in maximal strength may be observed in older men compared with young or middle-aged men (9, 14). It is also possible that the power training performed during the latter 8-wk training period could have interfered more with optimal maximal strength development in M64 men than in M46 men. It is also likely that

slightly different training protocols with increased frequency of training and/or more periodization in the training program are needed to optimize training-induced increases in maximal strength and muscle power output in middle-aged and older men.

Training-induced increases in muscle strength of previously untrained young and older men has been shown to result primarily from the increased motor unit activation of the trained muscles (9, 11, 28, 32). Gradually increasing muscle hypertrophy contributes to strength development during the later stages of progressive heavy-resistance training (1, 5, 10, 12, 28, 33). In the present study, the strength-training program was planned to promote muscle hypertrophy and power. Accordingly, significant enlargements occurred in the CSA_{QF} in both age groups, supporting the earlier observations that skeletal muscle of older people seems to retain the capacity to undergo training-induced hypertrophy when the volume, intensity, and duration of the training period are sufficient (5, 10, 12, 21). It is also likely that initial increases in strength may also be related in part by transformation of type II muscle-fiber subtypes (i.e., alterations in myosin ATPase isoform and myosin heavy chains) (13). Nevertheless, as suggested earlier, neural adaptations may have been a more important contributing factor in the present study than that of muscle hypertrophy for strength development (11, 14, 28, 32). This was indicated by the significant but rather minor enlargements in the CSA of the trained muscles over the 16-wk training period compared with the increases recorded in maximal strength of the subject groups. Because no electromyogram data were recorded, the magnitude and time course of neural adaptations could not be evaluated, as reported previously in middle-aged and older subjects (10, 11).

The heavy-resistance strength training for the leg and arm extensor muscles was combined with the exercises performed as explosively as possible, according to the basic principle of the training protocol utilized for explosive strength development. The present results demonstrate that, in addition to great increases obtained in maximal dynamic strength of the leg extensor muscles, the present training program led to even greater increases in muscle power output during the bilateral concentric half-squat actions performed with submaximal loads in both M46 and M64. Jozsi et al. (20) also observed this similar response in muscle power measured on a pneumatic resistance machine after 12 wk of training in men aged 56–66 yr. The greatest increase in power with training was observed with the loads more frequently employed during the strength-training sessions (60% of 1 RM). This agrees well with the principle of the specificity of the training and seems to be true also in older people. The great increase observed in explosive strength indicates that considerable training-induced changes may have taken place in the voluntary and/or reflex-induced rapid neural activation of motor units and/or selective hypertrophy of type II muscle fibers in both age groups (10, 11, 13).

Similarly to that observed with maximal strength, the present resistance training program led to different age-related increases in the magnitude of power improvement during the last 8 wk of the training. Thus it was interesting to observe that the increases achieved by the M64 group peaked at 8 wk, whereas in the M46 group a gradual and higher increase was observed throughout the training period. However, it was also interesting that the muscle power output differences observed between our M46 and M64 men were more marked than the differences observed in maximal strength, because during the last 8 wk of training the M64 group had already peaked in muscle power, whereas they improved in maximal strength, although at a greatly diminished rate compared with the M46 men. It is possible that M64 subjects are more sensitive to the duration and/or the intensity of training than are the M46 subjects for muscle power development than for maximal strength development and/or that the training regimens should be modified in a different way.

The first 8 wk of strength training resulted in rather minor increases in power of the upper extremities in both age groups. In contrast to the further significant increases observed in both groups in the muscle power output of the arm extensor muscle during the last 8 wk of training (with heavy and explosive exercises), no further increases were observed in the M64 group in muscle power output of the leg extensor muscles. The different pattern of strength-training-induced adaptation in muscle power between the lower and upper extremity muscles could be explained to some extent by differences in the initial conditioning status between the leg extensor and upper body muscles (27), which may be related, in part, to differences between the muscle groups in the pattern of quantity and/or intensity of daily physical activities throughout life. Therefore, further experimental data collection on training frequency and protocols are needed to optimize maximal strength and muscle power development of the arm and leg extension actions in both younger and older subjects.

No systematic changes were observed in the basal concentrations of serum T and FT in this study during the present 16-wk strength-training period. These observations are in agreement with prior studies in middle-aged and older men (14, 15), who also failed to show changes in resting serum T utilizing a strength-training program over a period of few months. Kraemer et al. (24) also observed this similar nonresponse in 62-yr-old men with 10 wk of training, despite the enhanced adaptational ability to acute exercise-induced response after resistance exercise. In this study, the mean value for serum total T and FT for the younger and older men may have been within the normal physiological range, which may explain the lack of changes in hormonal concentrations, as none were hypogonadal. However, during the last 8 more intensive training weeks, the serum FT concentration tended to decrease in M64, whereas it remained unaltered in M46. The decrease in the concentration of anabolic hor-

mones as well as the diminished rate of increase in maximal dynamic strength and muscle power observed during the last 8-wk training period in M64 compared with M46 suggests that, in the M64 group, the overall loading of the training program during the last 8 wk of training may have been near to the limit of the physiological range. It is possible that the increase in the overall intensity of the training during the last 8 experimental weeks (the loads between 50 and 80% of the maximum) and/or the target for both maximal strength and power development became too stressful for the M64 men and led to the diminished anabolic environment. Thus lower FT in the blood appears to indicate a decreased "bioactivity status" for the M64 men during the last 8 wk of training (23, 24), as also noted especially for older women during the latter weeks of a prolonged strength-training period (15). Therefore, one might speculate that the lower androgenic environment, despite some reduction in the concentration of C during the last 8 wk of training in the M64 men, appears to support a lower overall absolute magnitude of the training-related increase in maximal dynamic strength and muscle power output.

It was also interesting to observe that, in a combined group of M46 and M64 men, the mean levels of individual serum total T and FT concentrations and the individual changes in maximal unilateral isometric force correlated significantly during the 16-wk training period, as well as during the last 8 most stressful weeks (from *week 8* to *week 16*) of the 16-wk training period (Fig. 5, A and B). This kind of correlation is similar to that observed previously in older men and older women during prolonged heavy-resistance strength training (14, 15). It indicates that those subjects with lower levels of anabolic hormones may be able to produce minor strength gains vs. those with higher levels, especially during the last 8 wk of the training period when the overall intensity and volume of the training were greatly increased. This observation suggests that a low level of the anabolic hormone T may be a limiting factor in strength development during prolonged strength and/or power training in both middle-aged and older people of both genders. Nevertheless, one might speculate on the importance of the basal concentration of T in middle-aged and older men by the potent influence on neuromuscular adaptations (e.g., in muscle hypertrophy and/or increased neurotransmitter synthesis) for strength development (6, 14, 24). It is possible that, even though the blood T levels would remain unaltered, strength and power training can induce changes, e.g., at the receptor level (16).

In summary, the present progressive heavy-resistance training program combined with explosive exercises led to large gains in maximal dynamic strength and power-load characteristics of the leg extensor muscles in both M46 and M64 men with only two sessions a week. The relative gains in maximal strength were similar in both groups, but the absolute gains in maximal strength and power were greater in M46 men, occurring mainly during the last 8 wk of training. The



gains in strength were associated in both groups with considerable muscular hypertrophy, although to a lesser degree compared with the gains obtained in maximal strength. The pattern of power development seemed to differ between the upper and lower extremities in both groups. Neither of the groups showed systematic changes in the mean serum concentrations of total T and FT, but a low level of T may be a limiting factor in strength development, especially during prolonged and intensive strength and/or power training periods of several months. Because both muscle strength and the ability to develop force rapidly, or power, are important performance characteristics contributing to several tasks of daily life, alternate training strategies may be needed to improve human performance of dynamic activities of the lower and upper extremities that require both maximal strength and high-power output in middle-aged and especially in older men.

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