

Maximal strength and power, endurance performance, and serum hormones in middle-aged and elderly men

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ABSTRACT

IZQUIERDO, M., K. HÄKKINEN, A. ANTÓN, M. GARRUES, J. IBAÑEZ, M. RUESTA, and E. M. GOROSTIAGA. Maximal strength and power, endurance performance, and serum hormones in middle-aged and elderly men. *Med. Sci. Sports Exerc.*, Vol. 33, No. 9, 2001, pp. 1577–1587. **Purpose:** To examine maximal strength, power and muscle cross-sectional area, maximal and submaximal cycling endurance characteristics, and serum hormone concentrations of testosterone (T), free testosterone (FT), and cortisol (C) in middle-aged and elderly men. **Methods:** Maximal knee extension force (isometric; MIF_{KE}), power-load curves during concentric actions with loads ranging from 15% to 70% of 1 RM half-squat (1RM_{HS}), muscle cross-sectional area of quadriceps femoris (CSA_{QF}), workload, heart rate and lactate accumulation during incremental cycling, and serum hormone concentrations were measured in 26 middle-aged (M42 yr) and 21 elderly men (M65 yr). **Results:** The 1RM_{HS} (14%), MIF_{KE} (24%) and CSA_{QF} (13%) were lower in M65 than in M42 ($P < 0.05$ – 0.01). Power during submaximal actions was lower ($P < 0.05$ – 0.001) in M65 than in M42, but the differences disappeared when expressed relative to CSA_{QF}. Serum FT was in M42 higher ($P < 0.05$) than in M65. Maximal workload, maximal heart rate and peak blood lactate during cycling in M65 were 31%, 11%, and 20% lower than in M42 ($P < 0.01$). During submaximal cycling blood lactate rose more rapidly with increasing workload in M65 than in M42 ($P < 0.05$ – 0.01), but the differences disappeared when expressed relative to CSA_{QF}. Significant correlations existed between individual values of serum FT:C ratio, C and T, and those of muscle strength and maximal workload. **Conclusion:** Declines in maximal strength, muscle mass, and endurance performance seem to take place with increasing age, although muscle power and demand for aerobic energy per unit of muscle tissue during submaximal loads remain similar. The balance between anabolic and catabolic hormones in aging people over the years may be associated with age-related decreased strength and declines in maximal cycling workload. **Key Words:** AGING, MUSCLE STRENGTH, FORCE-VELOCITY, MUSCLE POWER, MAXIMAL AEROBIC POWER, TESTOSTERONE, CORTISOL

Functional capacity of the neuromuscular, cardiovascular, and respiratory systems declines in average from 0.5 to 3.5% per year with aging, resulting in decreases in maximal and explosive strength (14,30) and maximal aerobic power ($\dot{V}O_{2max}$) (3). The declines in maximal and explosive strength with aging have been in part associated with the reduction in muscle mass (13,14,30) and with alterations in maximal voluntary neural activation of the agonist muscles and/or changes in the degree of agonist/antagonist coactivation (14). The decline in maximal aerobic power with aging has been primarily associated with the decline of maximal cardiac output mediated by a decrease in maximal stroke volume and maximal heart rate with minor changes in arteriovenous O_2 differences (2,3). However, it is not known to what extent the decrease in force production capacity observed with aging may also contribute to the decrease in maximal aerobic power.

Examination of the blood lactate accumulation kinetics during exercise has been postulated to be an important physiologic determinant accounting for the ability to sustain a high $\dot{V}O_2$ during submaximal exercise, because it changes independently and is more closely related to endurance performance than maximum aerobic power (9,25). However, there are relatively little data concerning the lactate accumulation during progressive exercise in elderly people and to what extent the age-related decline in strength and muscle mass might influence the lactate responses during cycling.

Several aging studies have also observed androgenic and anabolic hormonal deficits in elderly men (12,13) accompanied by an increase in diurnal concentrations of serum basal cortisol secretion (12,29). It is also well known that human skeletal muscle metabolism is under hormonal control and that the androgens play an important role in muscle hypertrophy and strength development. Age-related changes observed in muscle mass, maximal and explosive strength production, as well as in maximal aerobic power could be associated with the alterations in hormone balance and to some extent with age-related changes in the intensity/quantity of daily normal physical activities. However, there are few reports in the literature to indicate to what extent

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strength output characteristics (13) and endurance characteristics could be related to serum levels of circulating hormones in middle-aged and elderly men. Therefore, it should be within both scientific and practical interests to examine the extent to which age-related decreases in maximal strength/power characteristics and muscle mass may also contribute to changes in maximal and submaximal endurance cycling exercise and whether these decreases are related with alterations in hormone balance with increasing age.

The purposes of the present study were to examine the differences in 1) maximal strength and muscle power output, muscle cross-sectional area and in 2) maximal and submaximal cycling endurance characteristics between middle-aged and elderly men, as well as 3) the relationship between maximal strength and power characteristics and maximal aerobic power. Second, our interest was also in the examination of possible relationships between serum hormone concentrations (total testosterone, free testosterone, and cortisol) and muscle strength and power characteristics and maximal aerobic power in these men at two age groups.

METHODS

Subjects. Fifty-six male volunteered subjects were recruited through advertisement and personal letter from a private recreational and physical fitness club. All potential candidates were thoroughly screened by using an extensive medical history (including current medication information), 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. From the screening we obtained a sample of 47 subjects. They were divided into two groups according to age: 26 middle-aged men in the 42-yr-old age group (M42) (mean age 42, range 35–46) and 21 elderly men in the 65-yr-old age group (M65) (mean age 65, range 60–74). All subjects were healthy and none was taking cardiovascular medications. The Minnesota Leisure Time Physical Activity Questionnaire (LTPA) was used to quantify a 4-wk physical activity energy expenditure in both age groups (27). Most of the subjects performed 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. None had been involved in any structured physical fitness program within the last 3 months. In the M65 group, all lived at home and were able to independently perform activities of natural daily life. No medication was being taken by the subjects that would have been expected to affect physical performance. Each subject signed a written informed consent form before participation in the study. The study was approved by the ethics committee of the Health Department of the Gobierno de Navarra (Spain).

This work is a part of a larger research project. Maximal strength, muscle cross-sectional area, and absolute power

values have been used earlier for various cross-sectional comparative purposes between the two age groups (17). In the present study, these data were repeated in connection with original data of relative muscle power output, maximal and submaximal cycling endurance characteristics, and serum concentrations of testosterone, free testosterone, and cortisol in middle-aged and elderly men.

Testing procedures. The subjects were carefully familiarized with the testing procedure of voluntary force production during several submaximal and maximal actions a few days before the measurements. The subject also completed several explosive type of actions to become familiar with the action to rapidly move different loads. In addition, several warm-up muscle actions were recorded before the actual maximal and explosive test actions. Testing was conducted over three different sessions separated by 5 d.

Maximal strength and muscle power testing. During the first testing occasion, each subject was tested for his concentric one repetition maximum (1RM) from a half-squat position ($1RM_{HS}$). The shoulders were in contact with a bar and the starting knee angle was 90° . The 90° position was measured initially with a goniometer and the marker was used for subsequent trials. On command, the subject performed a concentric leg extension (as fast as possible) starting from the flexed position to reach the full extension of 180° against the resistance provided by the weight plates added to both ends of the bar. The trunk was kept as straight as possible, and the trial was rejected if the subject bounced the bar off his shoulders at the bottom position of the half-squat. Security belts were used by all subjects. All the tests were performed in a squatting apparatus in which the barbell was attached at both ends with linear bearings on two vertical bars, allowing only vertical movements. Four to five separate attempts were performed 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 1RM.

The load-power relationship of the leg extensor muscles were also tested concentrically in a half-squat position by using the loads of 15%, 30%, 45%, 60% and 70% of $1RM_{HS}$. 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 ($m \cdot s^{-1}$) 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 $10\text{-}\mu s$ time resolution with an optical transducer interruption each 3 mm of displacement (5). The calculation of instantaneous velocity and power was calculated and has been described elsewhere (5,17). Average velocity and power were calculated through the whole the 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 middle-aged and elderly men separately.

During the second test occasion, a David Rehab 2200 dynamometer (David Fitness and Medical, Ltd. Vantaa, Finland) was used to measure maximal isometric torque (MIF; Nm) of the knee extensor (K_E) muscles. 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 maximal isometric knee extension of the right leg. A minimum of three maximal actions were recorded, and the best maximum was taken for further analysis. The testing session began with a warm-up including one set of 6 repetitions at a submaximal load of 50% of 1RM and two sets of isometric contractions during 5 s at a self-adjusted progressive increasing intensity.

In all tests of neuromuscular performance, strong verbal encouragement was given for each subject to motivate them to perform each test action as maximally and as rapidly as possible. The time period of rest between each trial and set was always 1.5 and 3 min, respectively. These time periods of rest have been utilized with good success in elderly men in order to reduce any possible effects of fatigue during the maximal and explosive efforts (14,17).

Muscle cross-sectional area. A day before the isometric testing, the cross-sectional area (CSA) of the quadriceps femoris (QF) muscle group (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedialis; CSA_{QF}) was measured with a compound ultrasonic scanner (Toshiba SSA-250, Tokyo, Japan) and a 5-MHz convex transducer. The CSA was measured at the lower 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 skin-fold thickness (18). Muscle mass variables showed reliability coefficients greater than 0.74. The coefficient of variation (CV) ranged from 1.4% to 4.3% for the measured circumference and cross-sectional area of the quadriceps femoris (CSA_{QF}) muscle group, respectively.

Cycling exercise test. In the third test session, each subject performed a maximal multistage discontinuous incremental cycling test on a mechanically braked cycloergometer (Monark Ergonomic 818E, Varberg, Sweden), fitted with toe clips, at a constant pedaling rate of 60 rpm, while blood pressure and a 12-lead electrocardiogram were monitored. Each subject started with unloaded cycling during 3 min, and the load was increased by 30 W every 3 min until volitional exhaustion or the required pedaling frequency of 60 rpm could not be maintained. After each workload, the test was interrupted for 60 s before initiating the next workload.

Heart rate was monitored continuously from a cardiotelemetry (Sportster Polar, Kempele, Finland) and determined during the last 60 s of each stage. Subjects were verbally encouraged during the test.

Before exercise and immediately after each exercise stage, capillary blood samples for the determination of lactate concentrations were obtained from a hyperemic earlobe. Samples for the whole blood lactate determination ($100 \mu\text{L}$) were deproteinized, stored at 4°C , and analyzed (YSI 1500, Yellow Springs, OH) within 5 d after completing the test. The blood lactate analyzer was calibrated after every fifth blood sample dosage with three known controls (5, 15, and $30 \text{ mmol}\cdot\text{L}^{-1}$). Individual data points for the exercise blood lactate values were plotted as a continuous function against time. The exercise lactate curve was fitted with a second degree polynomial function. The range of the individual correlation coefficient with the use of the mathematical function describe above was $r = 0.98\text{--}0.99$ ($P < 0.001$). From the equation describing the exercise blood lactate curve, the workloads associated with a blood lactate concentration of $2 \text{ mmol}\cdot\text{L}^{-1}$ (W_2) and $4 \text{ mmol}\cdot\text{L}^{-1}$ (W_4) were interpolated. W_2 and W_4 have been called the aerobic and anaerobic threshold, respectively, by some researchers and have been shown to be important determinants of endurance performance capacity (34). This definition has the advantage of being objective and, therefore, not subject to bias or variability introduced by different researchers (1).

The maximal workload of each cycling test (W_{max}) was calculated with the following formula:

$$W_{\text{max}} = W_{\text{com}} + [(t-180)^{-1}]\Delta W$$

in which W_{com} is the last workload completed, t the number of seconds the final and incomplete stage was sustained, and ΔW the final load increment (30 W) (20). To be able to compare the workloads between, as well as within, the individuals, the workloads in each stage were normalized by converting the absolute workloads to relative workloads. This was done by expressing the workloads of each stage as the percentage of the W_{max} value attained in the corresponding test. The criteria used to define a true W_{max} in M42 were as follows: a) a final heart rate of within 10 beats per minute of age-predicted maximum ($220 \text{ beats}\cdot\text{min}^{-1}$ minus age), and b) a peak blood lactate concentration value of greater than $8 \text{ mmol}\cdot\text{L}^{-1}$ (4). All the subjects in the M42 group reached a peak blood lactate concentration value of greater than $8 \text{ mmol}\cdot\text{L}^{-1}$, and 21 of the whole group of middle-aged subjects reached a final heart rate of within 10 beats per minute of the age-predicted maximum. The criteria of a peak blood lactate concentration value of greater than $8 \text{ mmol}\cdot\text{L}^{-1}$ is not valid in M65, because it is known that peak blood lactate value is lower in this population (4). However, the fact that in M65 19 of the whole elderly group reached a final heart rate of within 10 beats per minute of age-predicted maximum suggests that true W_{max} was achieved (4). Maximal workload was chosen because it has been shown that in healthy sedentary men aged 20–70 yr old, $\dot{V}O_{2\text{max}}$ can be accurately predicted from maximal work rate attained during a cycloergometer graded exercise test (31). In addition, Kuipers et al. (20) have found that the day to day variation of $\dot{V}O_{2\text{max}}$ (4–11%) exceeds that of the maximal workload (W_{max}) (3–7%), suggesting that W_{max} might

be a better sensitive parameter than $\dot{V}O_{2\max}$ to detect differences in maximal aerobic power.

Analytical methods. After 12 h of fasting and 1 d of minimal physical activity, venous blood samples were obtained at rest between 8 and 9 a.m. from the antecubital vein to determine concentrations of serum total testosterone, free testosterone, and cortisol. The samples were centrifuged and the serum removed and frozen at -20°C for later analysis. The assays of serum cortisol and testosterone were performed by radioimmunoassays. Serum testosterone (T) and cortisol (C) concentrations were measured using reagent kits from Diagnostic Product Corporation and INCSTAR corporation (Coat-A-Count Total testosterone TKTT11CS, Los Angeles, CA, and GammaCoat Cortisol Radioimmunoassay Kit, Los Angeles, CA). The sensitivity of the total testosterone and free testosterone (FT) assay was $0.14\text{ nmol}\cdot\text{L}^{-1}$ and $0.15\text{ pg}\cdot\text{mL}^{-1}$, respectively. The sensitivity of the cortisol assay was $0.21\text{ }\mu\text{g}\cdot\text{dL}^{-1}$. The coefficient of intra-assay variation was 5% and 4%, and that of interassay variation was 5.9% and 3.7%, for the total and free testosterone, respectively. The respective values were 6.6% and 8.8% for the cortisol assay. All samples were analyzed in the same assay for each hormone according to the instructions of the manufacturer.

Statistical methods. Standard statistical methods were used for the calculation of the means and standard deviations (SD), standard errors (SE), and Pearson product moment correlation coefficients. In addition, a stepwise multiple linear regression analysis was used to predict maximal workload (W_{\max}) and maximal strength (1RM_{HS} , 1RM_{KE} , and MIF_{KE}). The independent variables (1RM_{HS} , $30\text{--}60\%$, CSA_{QF} , T, FT, C, T:C, and FT:C) that correlated most significantly with the W_{\max} and maximal strength variables were entered into stepwise procedure. The results for the average power index and for the exercise blood lactate values were compared using probability adjusted *t*-test (two tailed hypothesis). The power and blood lactate values at each load were compared using a one-way analysis of variance (ANOVA), using Scheffe *post hoc* comparison to determine differences within loads. The $P \leq 0.05$ criterion was used for establishing statistical significance.

RESULTS

Physical characteristics. The mean (\pm SD) body height, body mass, and percent of body fat of M42 and M65 were 173.7 ± 0.06 and $165.3 \pm 0.04\text{ cm}$ ($P < 0.01$), 84 ± 9.6 and $78 \pm 9.3\text{ kg}$ ($P < 0.01$), and 22.6 ± 3.9 and $22.7 \pm 4.3\%$, respectively. The physical activity energy expenditure of M42 and M65 were 1392 ± 920 and $893 \pm 404\text{ MET}\cdot\text{d}^{-1}$ ($P < 0.05$), respectively.

Maximal strength, muscle CSA, and power output. The maximal bilateral concentric 1RM_{HS} (mean \pm SD) of $117.5 \pm 3.9\text{ kg}$ recorded in M42 was greater ($P < 0.05\text{--}0.001$) than that of $101.0 \pm 5.1\text{ kg}$ recorded for M65, respectively. The maximal unilateral isometric force (right leg) of the knee extensor muscles differed also between the groups so that the mean value of $217.7 \pm 40.2\text{ Nm}$ in M42

was greater ($P < 0.01$) than the mean value of $165.7 \pm 23.7\text{ Nm}$ recorded in M65. The mean (\pm SD) value of $48.2 \pm 1.3\text{ cm}^2$ for the CSA of the QF in M42 was greater ($P < 0.01$) than that of $42.1 \pm 2.2\text{ cm}^2$ in M65.

At all absolute loads examined, power output of the lower extremities was higher in M42 ($P < 0.05\text{--}0.001$) than in M65 (Fig. 1A). Maximal power output was produced at the loads of 60% ($486 \pm 20\text{ W}$) and 70% ($391 \pm 28\text{ W}$) for M42 and M65, respectively. Absolute average power output produced with the maximal concentric strength (1RM_{HS}) in M42 was 28% higher ($P < 0.001$) than in M65. When power output was expressed relative to kilogram of body weight ($\text{W}\cdot\text{kg}^{-1}$), the difference was reduced to 22% ($P < 0.05$) (Fig. 1B). When muscle power output was expressed relative to muscle CSA of the QF muscle group, the differences between the young and the elderly subjects in submaximal loads disappeared (Fig. 1C), except for those of the maximal loads where M42 ($6.11 \pm 1.8\text{ W}\cdot\text{cm}^{-2}$) showed a higher ($P < 0.05$) value than M65 ($4.98 \pm 1.6\text{ W}\cdot\text{cm}^{-2}$). Averaged power output index at all loads in M42 ($411 \pm 89\text{ W}$) was higher ($P < 0.01$) than in M65 ($324 \pm 107\text{ W}$). The difference was minor but was still significant ($P < 0.05$) when averaged power output index was expressed relative to kilogram of body weight ($4.9 \pm 1\text{ W}\cdot\text{kg}^{-1}$ and $4.1 \pm 1\text{ W}\cdot\text{kg}^{-1}$ for M42 and M65, respectively). When averaged muscle power output index was expressed relative to muscle CSA of the QF muscle group, the difference between the young and the elderly subjects disappeared (Fig. 1C).

Cycling exercise test. The maximal workload (W_{\max}) attained during the cycling test was 31% higher in M42 ($210 \pm 32\text{ W}$; $P < 0.001$) than that recorded in M65 ($161.4 \pm 32\text{ W}$). When W_{\max} was related to body mass, the difference was reduced (19%) but remained statistically significant ($P < 0.01$). The maximal values of blood lactate concentration (LA_{\max}) and heart rate (HR_{\max}) of $9.7 \pm 1.6\text{ mmol}\cdot\text{L}^{-1}$ and $180 \pm 11\text{ beats}\cdot\text{min}^{-1}$ recorded in M42 were 20% and 11% higher ($P < 0.001$), respectively, than those of $8.05 \pm 1.7\text{ mmol}\cdot\text{L}^{-1}$ and $163 \pm 15\text{ beats}\cdot\text{min}^{-1}$ recorded in M65.

The shapes of the average blood lactate concentration-workload and heart rate-workload curves in absolute values differed also between the groups. Figure 2A shows that during submaximal cycling exercise, blood lactate concentration, and heart rate rose more rapidly with increasing workload in M65 than in M42 ($P < 0.05\text{--}0.01$). The workloads expressed in W which elicited a blood lactate concentration of $2\text{ mmol}\cdot\text{L}^{-1}$ (W_2) and $4\text{ mmol}\cdot\text{L}^{-1}$ (W_4) were 21% lower ($P < 0.05$) in M65 than in M42 (115.5 ± 24.8 , 139.5 ± 25.6 and 74.7 ± 26.5 , 91.8 ± 22.64 , respectively).

When the workload was expressed relative to body weight ($\text{W}\cdot\text{kg}^{-1}$), the differences observed between M65 and M42 were reduced but remained statistically significant (Fig. 2B). Thus, maximal workload relative to body weight in M42 was 23% higher ($P < 0.001$) than in M65, whereas W_2 and W_4 were 15% (NS) and 14% ($P < 0.01$) higher, respectively, in M42 than in M65 (Fig. 2B). When workload was expressed relative to muscle cross-sectional area of the quadriceps femoris ($\text{W}\cdot\text{cm}^{-2}$) muscle group, differences between the young and the elderly subjects in

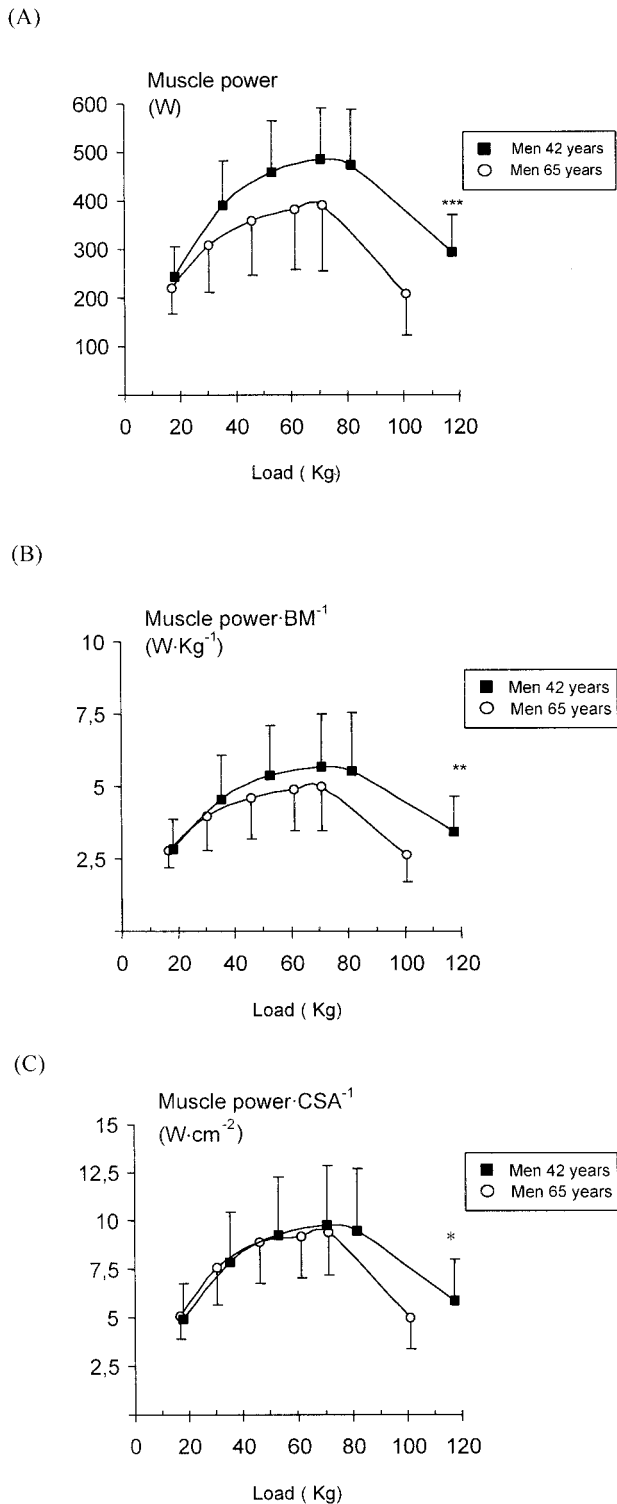


FIGURE 1—Mean (\pm SD) muscle power output of the lower extremity muscles during a half-squat execution at different loads corresponding to the 15%, 30%, 45%, 60%, 70%, and 100% of one individual repetition maximum from a half-squat position in absolute value (A), normalized for kilogram of body mass (B), and normalized for cross-sectional area of the quadriceps femoris muscle group (C) (* $P < 0.05$; *** $P < 0.001$).

the submaximal blood lactate response to cycling exercise disappeared (Fig. 2C). However, when maximal workload was expressed relative to muscle cross-sectional area of quadriceps femoris muscle group, there was a nonsignificant tendency ($P = 0.07$) toward higher values in M42 ($4.4 \pm 1.7 \text{ W}\cdot\text{cm}^{-2}$) than in M65 ($3.91 \pm 1.8 \text{ W}\cdot\text{cm}^{-2}$).

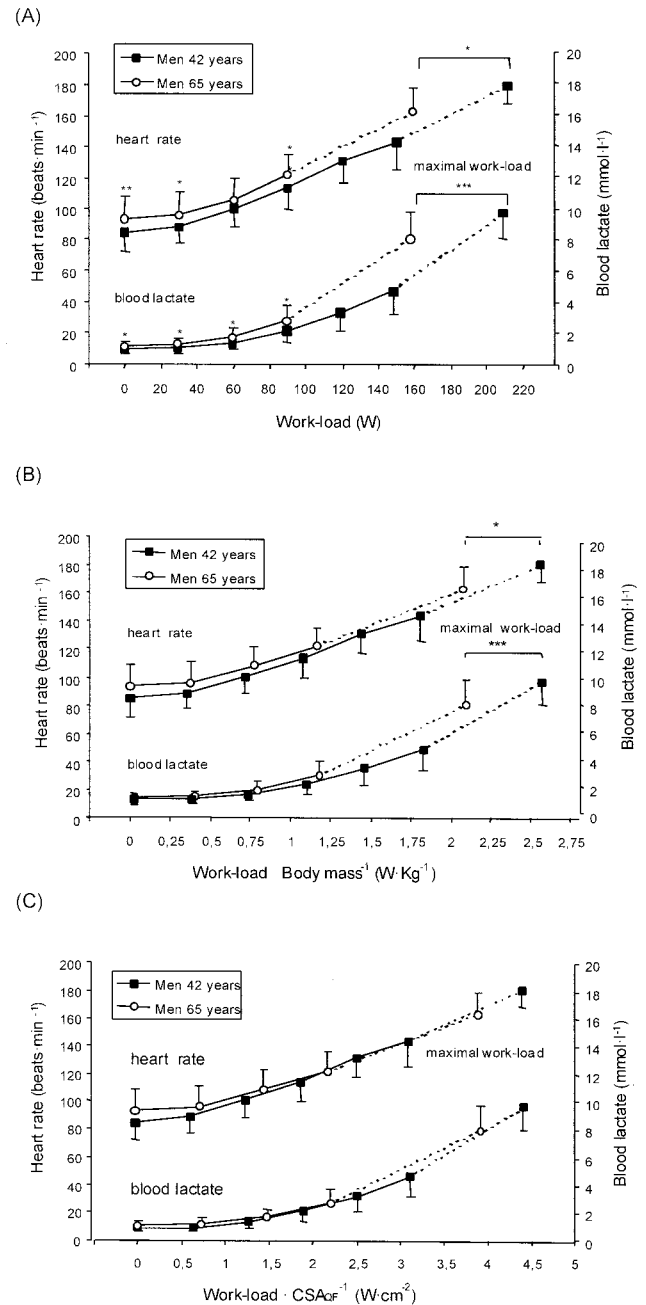
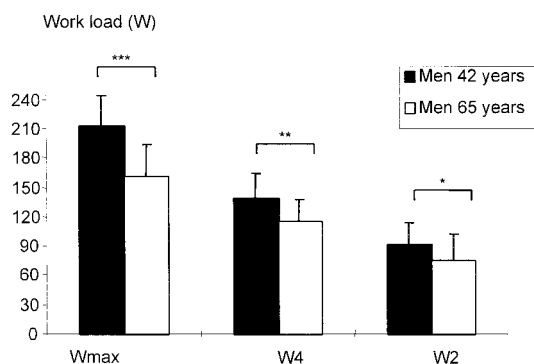


FIGURE 2—Mean (\pm SD) heart rate and blood lactate concentrations during a maximal multistage discontinuous incremental cycling test at submaximal and maximal workload in absolute values (A), normalized to body mass (B), and normalized to cross-sectional area of the quadriceps femoris muscle group (C) (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$).

When workloads at W_2 and W_4 were expressed relative to maximal workload, the elderly subjects were able to exercise at a higher percentage of maximal workload (W_{\max}) before reaching a blood lactate concentration of 4 and 2 $\text{mmol}\cdot\text{L}^{-1}$ ($71.6 \pm 8.0\% W_{\max}$, and $45.1 \pm 10.67\% W_{\max}$, respectively) than the younger group ($66.04 \pm 5.53\% W_{\max}$, and $42.8 \pm 6.53\% W_{\max}$, respectively) (Fig. 3).

(A)



(B)

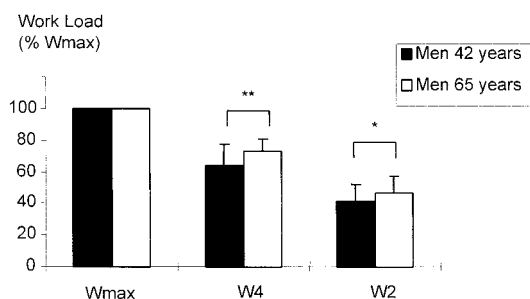


FIGURE 3—Mean (\pm SD) maximal workload (W_{\max}), workload at a blood lactate concentration of $4 \text{ mmol}\cdot\text{L}^{-1}$ (W_4), and of $2 \text{ mmol}\cdot\text{L}^{-1}$ (W_2) expressed in absolute values (A) and relative to the maximal workload (B) attained during a maximal multistage discontinuous incremental cycling test (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$).

Serum hormones concentrations. No statistically significant differences were observed in the mean serum total testosterone concentrations between M42 ($18.2 \pm 5 \text{ nmol}\cdot\text{L}^{-1}$) and M65 ($18.0 \pm 5 \text{ nmol}\cdot\text{L}^{-1}$). The concentration of mean serum free testosterone of $66.5 \pm 19 \text{ pmol}\cdot\text{L}^{-1}$ in M42 was higher ($P < 0.05$) than that of $55.3 \pm 13 \text{ pmol}\cdot\text{L}^{-1}$ recorded in M65. No significant differences were observed in serum cortisol concentration between M42 ($574 \pm 160 \text{ nmol}\cdot\text{L}^{-1}$) and M65 ($578 \pm 149 \text{ nmol}\cdot\text{L}^{-1}$). The testosterone/cortisol and the free testosterone/cortisol ratios did not differ between the two age groups.

One subject in the M42 group and one subject in the M65 group had serum total and free testosterone circulating levels under the lower limit of normality for the assay ($9.85 \text{ nmol}\cdot\text{L}^{-1}$ and $23.25 \text{ pmol}\cdot\text{L}^{-1}$, respectively). In the cortisol determination, six subjects in the M42 group and seven subjects in the M65 group had higher levels than the limit of normality for the assay ($687.5 \text{ nmol}\cdot\text{L}^{-1}$).

Relationships between serum hormone concentrations, muscle mass, and maximal strength/power. In both age groups, the individual values in serum cortisol concentration correlated negatively with the individual values of maximal unilateral isometric force ($r = -0.42$ and -0.63 ; $P < 0.05$ – 0.01 , for M42 and M65, respectively), as well as with the CSA of the QF ($r = -0.49$; $P < 0.05$) in M65 (Table 1). In both age groups, the

TABLE 1. Correlation coefficients between various indices of muscle power output, maximal concentric force production, muscle mass, and serum hormone concentrations.

	1RM_{HS}	MIF_{ke}	CSA_{QF}
M42			
T	-0.27	-0.03	-0.23
FT	0.06	0.20	-0.07
C	0.36	-0.42*	0.09
T:C	-0.32	0.24	-0.19
FT:C	-0.10	0.43*	-0.09
M65			
T	0.11	0.10	0.09
FT	0.41	0.07	-0.03
C	-0.41	-0.63**	-0.49*
T:C	0.37	0.49*	0.47*
FT:C	0.59**	0.52*	0.38

* $P < 0.05$; ** $P < 0.01$.

(1RM_{HS}) concentric one repetition maximum from a half-squat position, (MIF_{ke}) maximal isometric torque of knee extensor, (CSA_{QF}) cross-sectional area of quadriceps femoris muscle group, (T) serum testosterone concentration, (FT) serum free testosterone concentration, (C) serum cortisol concentration, (T:C) ratio testosterone-cortisol, (FT:C) ratio free testosterone-cortisol.

stepwise multiple regression analyses using MIF_{KE} performance as the dependent variable and values CSA of the QF of serum testosterone, free testosterone, and cortisol as independent variables showed that the serum cortisol ($R^2 = 0.18$ and 0.4 for M42 and M65, respectively) as a single predictor accounted for 18% and 40% on the variance in maximal isometric knee extension strength ($P < 0.05$ – 0.01) in M42 and M65, respectively.

In both age groups, the individual values of the free testosterone/cortisol ratio correlated significantly with the individual values of maximal unilateral isometric force ($r = 0.43$ and 0.52 ; $P < 0.05$ for M42 and M65, respectively) (Fig. 4A). In the elderly group, the individual values in the serum total testosterone/cortisol ratio also correlated significantly with the individual values of maximal unilateral isometric knee extension force ($r = 0.49$; $P < 0.05$) and with the individual values of the CSA of QF ($r = 0.47$; $P < 0.05$). In M65, the individual values of the serum free testosterone/cortisol ratios correlated significantly with the maximal bilateral concentric 1RM_{HS} ($r = 0.59$; $P < 0.01$). Multiple correlation with maximal isometric strength as dependent variable and the individual values of CSA of QF and serum free and total testosterone/cortisol ratios as independent variables showed that free testosterone/cortisol ratio as a single predictor accounted for 19% and 36% of the total variance (R^2) ($P < 0.05$ – 0.01) for M42 and M65, respectively.

Relationship between serum hormone concentrations and cycling exercise test. In the middle-aged group, no significant correlations were found between the individual values of serum testosterone (free and total) and cortisol and various indices of cycling exercise testing. In the elderly group, the individual values of mean total and free testosterone correlated significantly with the individual values of maximal workload (W_{\max}) ($r = 0.59$ and $r = 0.50$; $P < 0.01$), respectively. In M65, multiple correlation with maximal workload as dependent variable and the individual values of CSA of QF, maximal heart rate, peak blood lactate, serum free and total testosterone, and serum cortisol as independent variables showed total testosterone as a

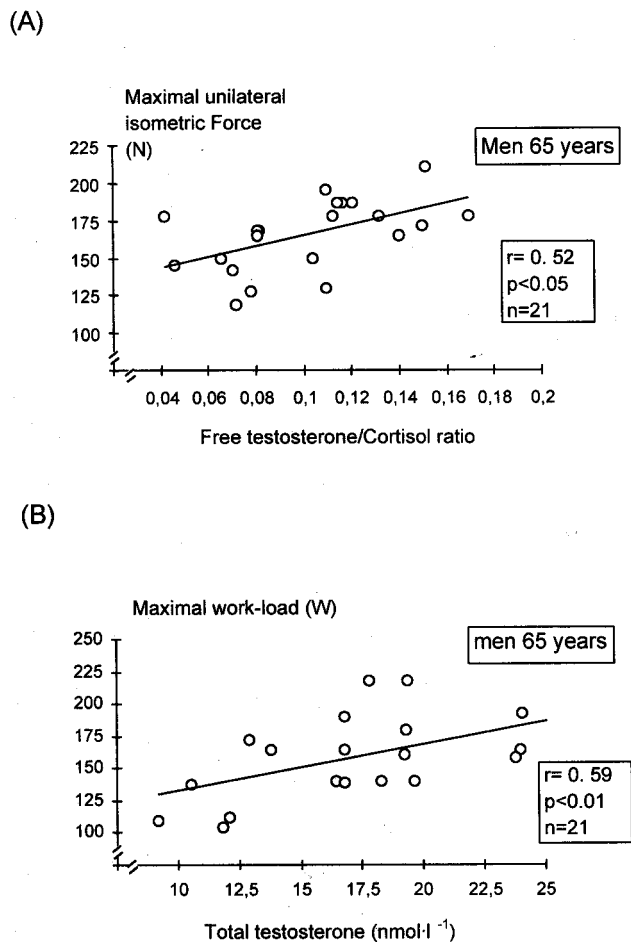


FIGURE 4—The relationships between the maximal unilateral isometric force of the knee extensor muscles (right leg) and serum free testosterone/cortisol ratio (A) and between maximal workload during cycling (W_{\max}) and serum total testosterone (B) in elderly (M65) men.

single independent variable accounting for 35% of the total variance (R^2) ($P < 0.01$) (Fig. 4B).

Relationships between maximal strength/power and cycling exercise test. In the elderly group, the individual maximal and submaximal workloads attained in the cycling exercise test correlated (from $r = 0.44$ to 0.55 ; $P < 0.05$ – 0.01) with the individual values of maximal bilateral concentric $1RM_{HS}$, whereas in M42 the corresponding correlation coefficients were not statistically significant (Table 2). However, in the younger group, the individual values in maximal and submaximal workloads attained in the cycling exercise test correlated with the individual values of concentric power production at the loads ranging from 30% to 60% (from $r = 0.44$ to 0.56 ; $P < 0.05$ – 0.001) of $1RM_{HS}$. In this group, the highest correlation observed in the cycling test was with the individual values of concentric power production at the load of 30% of $1RM_{HS}$ (from $r = 0.46$ to 0.56 ; $P < 0.05$ – 0.01). In the younger group, the stepwise multiple regression analyses using maximal workload attained during cycling (W_{\max}) as the dependent variable and the individual values of maximal bilateral concentric ($1RM_{HS}$), concentric power production,

CSA of the QF, and serum hormones as independent variables showed that only the concentric power production at the load of 30% of $1RM_{HS}$ ($R^2 = 0.32$) as a single independent variable accounted for 32% of the variance in W_{\max} ($P < 0.01$). However, the same multiple correlation performed in M65 with W_{\max} as dependent variable showed that $1RM_{HS}$ and serum total testosterone ($R^2 = 0.5$) accounted for 50% of the total variance in W_{\max} demand ($P < 0.01$).

DISCUSSION

The present findings well support several previous observations that in normal biological aging process, especially at the onset of sixth decade, not only maximal strength and muscle mass but also muscle power and explosive force decrease greatly (2,14,22). However, the ability to develop muscle power and explosive force calculated in absolute values may decline with increasing age probably even more than maximal strength (14). Although an age-related difference of 13% in muscle mass was associated with differences of 14% recorded for maximal concentric $1RM_{HS}$ strength between M42 and M65, respectively, the differences observed in power output at all absolute loads were as much as 21–28% (Fig. 1A). Decreases in maximal and explosive strength with increasing age could be due to a loss of muscle mass mediated by both a loss and a decrease in the size of the individual fibers, especially of fast-twitch fibers (22,23). This age-related decrease in force production capacity may be also explained in part by a decrease in maximal voluntary neural drive to muscles (14) and/or qualitative characteristics of the muscle tissue itself (23).

When muscle power output at submaximal loads was expressed relative to kilogram of body mass (Fig. 1B) and relative to muscle cross-sectional area of the QF muscle group (Fig. 1C), the differences observed between the age groups in the ability to rapidly move different absolute loads were diminished (Fig. 1B) or even disappeared (Fig. 1C). This suggests that neural activation patterns and/or twitch tension per cross-sectional area of muscle (7) under submaximal concentric half-squat actions (typical leg extension actions also in normal daily activities) could be rather similar between the middle-aged and elderly subjects examined. However, the age-related decreases in muscle power output response under the maximal loading seemed to be slightly different than those observed for the submaximal loads. Thus, when the individual values of maximal strength and muscle power output in the maximal half-squat concentric strength ($1RM_{HS}$) were expressed relative to body mass and to the individual values of CSA of the quadriceps femoris muscle, the force (kg and Nm) and/or power (W) (Fig. 1, B and C) per unit of CSA in M65 was still significantly lower than in M42. Although some findings suggest that aging does not necessarily impair a person's ability to generate muscle power per unit of active muscle (7), there are some other studies indicating that aging may lead to some decrease in maximal voluntary neural drive (14). Our data suggest that muscle response in young and elderly men may

TABLE 2. Correlation coefficients between various indices of muscle power output, maximal concentric force production, muscle mass, and various indices of bicycling testing.

	1RM _{HS}	1RM _{HS30%}	1RM _{HS45%}	1RM _{HS60%}	CSA _{qF}
M42					
W _{max}	0.34	0.56**	0.54**	0.44*	0.07
W ₄	0.25	0.46*	0.38	0.23	0.10
W ₂	0.21	0.34	0.29	0.11	0.11
M65					
W _{max}	0.44*	0.29	0.29	0.28	0.16
W ₄	0.50*	0.37	0.38	0.36	0.16
W ₂	0.55**	0.48*	0.48*	0.48*	0.23

* $P < 0.05$; ** $P < 0.01$.

(W_{max}) maximal workload, (W₄) workload at blood lactate concentration 4 mmol·L⁻¹, (W₂) workload at blood lactate concentration 2 mmol·L⁻¹, (1RM_{HS 30%, 45%, 60%}) concentric force production at different loads of 1RM_{HS}; for more details see Table 1.

differ depending on the type of muscle action, the complexity of motion, the time/velocity, and force requirements of the action. However, the present results should be treated with caution, because the CSA measurement was taken only for the right leg and it does not represent the exact muscle contribution involved in the bilateral half-squat extension actions of the lower extremities. Nevertheless, the results do not exclude the possibility that the age-related declines observed in maximal strength and power output with the maximal load may be accounted to some extent by a decrease in maximal voluntary neural drive (14) and/or with declines in the specific tension of the involved muscles related to different myofibrillar packing density and muscle fiber composition (22,23).

Maximal workload (W_{max}), an accurate predictor of $\dot{V}O_{2max}$ (31), maximal heart rate, and peak blood lactate during the cycling test were lower in M65 than those recorded for M42. This agrees with previous studies showing that maximal aerobic power ($\dot{V}O_{2max}$) declines 6–10% per decade after the age of 25 yr in normal healthy men (3) and that peak blood lactate is reduced with advancing age (3). The impairment of the oxygen transporting system with age is related to the decline of maximal cardiac output due to a decreased maximal stroke volume and maximal heart rate with minor changes in arteriovenous O₂ difference (2,3,11). The decrease observed with advancing age in the peak blood lactate has been related to a reduction in muscle glycolytic capacity, due to a selective muscle atrophy of high glycolytic Type IIb fibers, a reduced muscle lactate dehydrogenase activity (22), and a loss of sensitivity to adrenaline (26).

There is a paucity of information about the blood lactate accumulation during a progressive cycling exercise in aging people. In the present study, blood lactate accumulation rose more rapidly with increasing workload in M65 than in M42 during the submaximal cycling exercise. It has been suggested that the blood lactate concentration response during submaximal exercise is more closely related to endurance performance than maximum oxygen uptake because it is dependent on peripheral factors, such as enzyme activities of skeletal muscle (28) or the numbers of mitochondria (25). Therefore, the higher blood lactate values for a given workload observed in M65 than in M42 suggest that endurance performance is decreased with age. This decrease is minor when the workload is expressed relative to body weight, but it remains statistically significant.

One of the major findings in this study was the observation that when workload was expressed relative to muscle cross-sectional area of the quadriceps femoris muscle group, the differences between the young and elderly subjects in the blood lactate response to submaximal cycling exercise disappeared. This suggests that the age-associated impairment in the blood lactate response during submaximal cycling exercise is mainly due to loss of muscle mass. It has been shown that the submaximal blood lactate response to exercise is mainly determined by peripheral factors such as capillary density or enzyme activities of skeletal muscle (31). Therefore, the similar response found in this study in M42 and M65 in the blood lactate accumulation during submaximal cycling exercise when the workload was expressed relative to the muscle cross-sectional area suggests that the demand for aerobic energy per unit of muscle tissue is probably similar in elderly compared with middle-aged men. This agrees with previous studies that have shown that muscle oxidative enzyme activities and capillarization are similar or higher in elderly compared with young men (22).

When maximal workload attained during cycling exercise was expressed relative to the muscle cross-sectional area of the quadriceps femoris muscle, there was a nonsignificant tendency ($P = 0.07$) toward higher values in M42 than in M65. A reduction with age in maximal aerobic power ($\dot{V}O_{2max}$) per kilogram of limb muscle or per index of muscle mass (i.e., 24-h urinary creatinine excretion) has been found by others in healthy subjects (10), and it has been associated with a modest decrease in central cardiocirculatory factors. Taking together, the observed submaximal and maximal blood lactate responses per unit muscle mass during cycling exercise it can be suggested that, with age, the peripheral factors per unit active mass are similar in elderly compared with middle-aged men. It is also likely that the modest reduction in maximal aerobic power per unit active muscle could be also associated with a decline in central cardiocirculatory factors.

The workload that elicits a blood lactate concentration level of 4 and 2 mmol·L⁻¹ (W₄ and W₂, respectively) occurred at a higher percentage of maximal workload in M65 than in M42. This indicates that the members of the M65 group do not accumulate lactate in their blood until they are at a higher percentage of their maximal workload (W_{max}). This finding agrees with other authors who measured ventilatory threshold (1,25,32) or submaximal blood lactate concentrations (1,25) in elderly subjects (32) and

athletes (1). Some authors have proposed that the higher workload, in percentage of maximal workload, observed in W_4 and W_2 in the elderly populations could be the result of a greater decrease with age in central cardiocirculatory factors (i.e., decrease in maximal heart rate and in maximal stroke volume) than in peripheral factors (i.e., muscle capillarization and oxidative enzyme levels) (1,22). However, several authors suggest that the mechanisms accounting for the differing rates of decline in W_{max} and W_4 - W_2 with age can be also related to age-associated changes in skeletal muscle (25). Thus, some authors suggest that the reduction in muscle mass with age is characterized by a selective loss in the number and reduction in the size of Type II fibers (with high anaerobic muscle enzyme activity) with preservation of Type I fibers (with high aerobic muscle enzyme activity) (22,23). Because at W_4 and W_2 , energy metabolism is primarily aerobic, and above W_4 work becomes increasingly anaerobic, the relative increase in the percent of the "aerobic" Type I fibers with age could explain why W_2 and W_4 occurred at a higher percentage of maximal workload in M65 than in M42.

Serum free testosterone concentrations were lower ($P < 0.05$) in M65 than in M42, whereas no differences were observed in serum total testosterone concentrations between the groups. The decrease in serum free testosterone or in the testosterone/SHBG ratio with age is in agreement with previous findings (12,13,19) suggesting that androgen activity is lowered in older men. Mechanisms proposed to explain the age-related reduction in circulating levels of free testosterone include a failure of the hypothalamic-pituitary axis, testicular dysfunction, an increase in sex hormone-binding globulin levels (SHBG) and/or increased sensitivity of gonadotropin secretion to androgen negative-feedback inhibition (33). Lower androgenic activity may be related to the decreased anabolic effects observed with age on muscle mass and strength in both men and women (12,13). The low magnitude of decline in serum total testosterone with age and its high biological variability may explain the absence of differences between the age groups, when a low number of subjects is used. Although some researchers using a high number of subjects and/or wide age ranges have observed a reduction in total and free testosterone level with age (12), others have observed no changes (13,19). Indeed, discrepancies in the results of these studies may be attributable to the differences in study design, number of subjects, range of age, biological variability, assay techniques, and inclusion criteria for the definition of middle-aged and older subjects (13,19). Thus, cross-sectional studies using a lower number of subjects and/or narrow age ranges have found decreases in serum free testosterone but not necessarily significant changes in serum total testosterone level with advancing age (13,19). The present data of serum cortisol concentrations indicated no age-related changes. These results are in agreement with previous findings (12,13,19) and suggest that in the age range studied, aging *per se* is probably not associated with an impairment in the basal hypothalamic-pituitary-adrenal axis function.

Due to the cross-sectional design of the study, the interpretation based on the results of serum hormone concentrations should be treated with great caution. However, in the present subject population, significant correlations were observed between the individual values of free and total testosterone/cortisol ratios and the individual values of maximal strength. In addition, in both groups, and especially in the elderly group, the stepwise multiple regression analyses showed the significant negative correlation between the individual values of serum cortisol concentrations and the maximal isometric knee extension strength. It is known that testosterone activates the anabolic phase of skeletal muscle protein metabolism acting against the proteolytic effect of cortisol (21). Several studies have shown that increased adrenal glucocorticoid secretion in aging individuals could be associated with an impaired cognitive development, hippocampal neuronal loss (29), and muscle weakness (24). Actually, the ratio between serum testosterone and cortisol has been suggested to be an indicator of the balance between anabolic and catabolic metabolism in muscle (21). Therefore, despite the limitations of the study design, the significant correlations observed between the individual values of serum total and free testosterone/cortisol ratios, cortisol, and the individual values of maximal isometric and concentric strength performances suggest that the balance between anabolic and catabolic hormones in aging people over the years has a plausible association with the voluntary force production of the neuromuscular system (13).

In the present study, the correlation coefficients between the serum hormone concentrations and aerobic performance variables were also examined. The results of the correlation and regression analyses showed significant correlations in M65, but not in M42, between the individual values of serum total and free testosterone concentrations and the individual values of maximal workload. Significant correlations in elderly males between serum testosterone and maximal aerobic power have been found in other studies (8) suggesting that the androgenic activity plays a significant role in aerobic cycling performance in elderly healthy men.

One of the purposes of this study was also to examine the relationships between strength/power characteristics and various indices of the cycling testing in middle-aged and elderly men. The results showed significant positive correlations in M65, but not in M42, between the individual values of the 1RM concentric action from a half squat position ($1RM_{HS}$) and various indices of cycling testing (W_{max} , W_4 and W_2). This finding suggests that the reduction observed on maximal work rate with aging during a cycling test can be explained in part by a reduction in maximal dynamic strength of the leg extensor muscles. The assumption that maximal dynamic leg extension strength plays an important role in the maximal work rate attained during a progressive cycling test in elderly subjects is supported by the finding that an increase in maximal strength of the leg muscles produced by heavy resistance strength training led to an improvement in maximal cycling workload in elderly men (11) but not in young or middle-aged men (15,16). Therefore, the significant correlations observed in

M65 between the individual values of cycling performance with the individual values of leg strength, and those of serum testosterone suggest that the age-related decline in maximal cycling workload may be explained in part by a decrease in leg muscle strength mediated by a lowered androgen activity. Furthermore, in accordance with previous studies M65 showed a 35% lower energy expenditure than M42, indicating an age-related decline in the quantity and intensity of daily physical activities.

In contrast to M65, no significant correlations were observed in M42 between individual maximal dynamic leg strength and various indices of cycling testing. However, an interesting finding was that in M42 the individual values of concentric power production at the loads ranging from 30% to 60% of $1RM_{HS}$ were a good predictor of various indices of cycling testing (W_{max} , W_4 , and W_2). The highest correlation and regression coefficients were observed at the loads of 30% of $1RM_{HS}$. A plausible explanation of these relationships could be related to the similar average time of force applied during the concentric actions and the downstroke portion of pedal stroke at a pedaling rate of 60 rpm (for example, at the load of 30% of $1RM_{HS}$ it was 475 ms) (6). Therefore, it seems that the capacity to generate high muscle power values during submaximal dynamic leg extension actions appears to play a significant role in cycling performance in middle-aged men.

In summary, the results of this study indicate that elderly men showed decreased values of maximal strength, muscle cross-sectional area, muscle power, and maximal workload during cycling exercise as well as lower serum free testosterone concentrations than middle-aged men. In the elderly group, the stepwise multiple regression analyses showed significant correlations between the individual values of

serum free testosterone/cortisol ratio, cortisol, and those of maximal strength, as well as between the individual concentrations of serum total testosterone and maximal workload. When muscle power output attained by the leg extensors muscles in a half-squat action and workload reached during cycling exercise under submaximal loading were expressed relative to the muscle cross-sectional area of quadriceps femoris, the differences between the middle-aged and elderly men disappeared. This suggests that per unit of muscle tissue the generation of muscle power and the demand for aerobic energy is similar in elderly compared with middle-aged men under submaximal concentric actions and submaximal cycling workload but that the differences still remain significant under the respective concentric maximal strength performance and maximal cycling workload. Within the limitations of the study design, the present data also suggest that the balance between anabolic and catabolic hormones in aging people over the years may have a possible association with force production of the neuromuscular system. The decline in cycling maximal aerobic power observed in elderly males was related in part to quantitative peripheral factors (e.g., the reduction in maximal dynamic strength and muscle mass) probably mediated by age-related alterations in the balance between anabolic and catabolic hormones.

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