

Effects of Strength Training on Submaximal and Maximal Endurance Performance Capacity in Middle-Aged and Older Men

MIKEL IZQUIERDO,¹ KEIJO HÄKKINEN,² JAVIER IBAÑEZ,¹ ALAZNE ANTÓN,¹ MIRIAM GARRUÉS,¹ MAITE RUESTA,¹ AND ESTEBAN M. GOROSTIAGA¹

¹Centro de Investigación y Medicina del Deporte de Navarra, Gobierno de Navarra, Navarra, Spain 31002;

²Department of Biology of Physical Activity and Neuromuscular Research Center, University of Jyväskylä, Jyväskylä, Finland 40014.

ABSTRACT

Effects of a 16-week progressive strength-training program on blood lactate accumulation (LA), maximal workload (W_{\max}) attained during progressive cycling exercise, maximum half-squat ($1RM_{HS}$), muscle cross-sectional area of the quadriceps femoris muscle group (CSA_{QF}), and serum hormone concentrations were examined in 11 middle-aged (46 year old [M46]) and 11 older (64 year old [M64]) men. During the 16 weeks of training, significant increases were observed in $1RM_{HS}$ in M46 and M64 (41–45%; $p < 0.001$). The muscle CSA_{QF} increased (13–11%; $p > 0.01$) for both groups. The first 8 weeks of training led to significant increases in W_{\max} (6–11%; $p < 0.001$) and decreases in submaximal (LA) in both groups, but no further training-induced changes were observed during the subsequent 8 weeks of training. Statistically significant relationships were observed in M64 and in the combined group M46 + M64 between the training-induced changes observed in W_{\max} and serum testosterone-cortisol and free-testosterone-cortisol ratios, whereas in M46 the respective correlations values did not reach statistically significant levels. These data indicate that strength training results in a significant improvement in maximal and submaximal endurance during the first 8 weeks of strength training in both age groups, related in part to the intensity and the volume of resistance training used and to the training status of the subjects. The relationships found in this study between various indices of cycling testing and serum hormone concentrations after strength training suggest that maximal incremental cycling might be used as an additional test to detect anabolic-catabolic responses to prolonged strength training in middle-aged and older men.

Key Words: lactate, maximal workload, testosterone, strength, cortisol, aging

Reference Data: Izquierdo, M., K. Häkkinen, J. Ibañez, A. Antón, M. Garrués, M. Ruesta, and E.M. Gorostiaga. Effects of strength training on submaximal and maximal endurance performance capacity in middle-

aged and older men. *J. Strength Cond. Res.* 17(1):129–139. 2003.

Introduction

Normal biological aging is associated with declines in the functional capacity of the neuromuscular, neuroendocrine, cardiovascular, and respiratory systems resulting in decreases in maximal strength and maximal aerobic power (4, 16, 18, 41). Declines in muscle strength have been associated with muscle atrophy (33, 35), a decrease in maximal voluntary neural drive of the agonist muscle, or changes in the degree of agonist-antagonist coactivation (16), probably mediated by age-related alterations in plasma concentrations of circulating anabolic and catabolic hormones (7, 18, 30). The functional capacity of the cardiovascular and respiratory systems declines by about 0.5–3.5% per year, after the third decade of life, resulting in decreases in maximal aerobic power ($\dot{V}O_{2\max}$) (4, 43). Declines in maximal aerobic power with aging have primarily been associated with the decline in maximal cardiac output (3, 4), but it also has been attributed, in part, to the reduction in maximal dynamic strength and muscle mass (10, 25), probably mediated by age-related alterations in the balance between anabolic and catabolic hormones (7, 18, 30). This has led some authors to suggest that an increase in the strength and muscle mass of the lower-extremity muscle could improve maximal aerobic power (11) and submaximal endurance performance (i.e., submaximal blood lactate accumulation [LA]) (23) after strength training.

Previous studies on the effect of strength training on maximal oxygen uptake or maximal aerobic power have produced conflicting results (1, 11, 21, 24, 45). Traditional strength training (i.e., 60–80% of 1 repetition maximum [1RM] for 6–15 repetitions) generally

does not increase $\dot{V}O_{2\max}$ (1, 20, 22–24, 31, 36), whereas circuit weight training (i.e., 40–60% 1RM for 10–20 repetitions) may lead to slight improvements in $\dot{V}O_{2\max}$ (11–13, 21, 29, 45). Examination of blood LA during exercise has been postulated to be an important physiologic determinant of the ability to sustain a high $\dot{V}O_{2\max}$ during submaximal exercise because it changes independently and it is more closely related to endurance performance than is $\dot{V}O_{2\max}$ (38). Because it has been suggested that this factor might explain better than $\dot{V}O_{2\max}$ the improved endurance performance observed in several studies after strength training (22, 23, 36, 45), examination of submaximal endurance performance would seem to be warranted. Several studies also have reported that improvements in strength and muscle hypertrophy may improve submaximal endurance performance after strength training (22, 23). However, much fewer data are available on the long-term effects (i.e., >14 weeks) of strength training on blood LA during cycling exercise, and the same has received only little attention in middle-aged and older men. This is crucial to perform activities of daily life that require submaximal efforts, especially among individuals who are close to the threshold of dependency.

It has been thought that strength training–related changes in resting, circulating anabolic and catabolic hormones (i.e., total testosterone [T] and cortisol [C]) have a potent influence on neuromuscular adaptations (e.g., in muscle hypertrophy or increased neurotransmitter synthesis, or both) for strength development (18, 30), attenuating sarcopenia and loss of strength with aging (18, 30, 31, 33). The magnitude of hormonal responses is lowered in older men (18, 30), and it may be a limiting factor in strength and endurance development during prolonged strength training. Therefore, it also was within the interest of this study to examine the possible effects of a 16-week progressive heavy resistance training on basal serum concentrations of T, free testosterone (FT), and C and their possible interrelationships with various indices of maximal and submaximal endurance performance changes not only in middle-aged but also in older men.

Considering the paucity of data examining the effects of resistance training on endurance performance in aging populations, this study examines the effects of a 16-week progressive heavy resistance training on workload and blood LA during submaximal and maximal cycling exercise as well as on maximal strength and serum hormone concentrations in middle-aged and older men. It was hypothesized that strength training would lead to different enhancements in various submaximal and maximal indices of cycling testing in middle-aged and older men, which is possibly limited in magnitude due to neuromuscular or age-related endocrine impairments, or both.

Methods

Experimental Approach to the Problem

This study was undertaken to determine the effect of strength training on maximal workload (W_{\max}) and submaximal indices (i.e., blood LA and heart rate) during cycling exercise and on serum hormone concentrations, and further to elucidate the role of strength training and serum hormone concentration on endurance performance in middle-aged and older men. To examine a long-term training scenario, we used a period of 16 weeks of training under carefully monitored conditions. The total duration of this study was 20 weeks. The subjects were tested on 4 different occasions using identical protocols. Baseline testing was completed during the first 4 weeks of the study (between the measurements at week 4 and at week 0) during which time no strength or endurance 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-week period of supervised experimental strength training. The strength-training program used in this study was similar to that reported previously (17, 26) and was a combination of heavy resistance and “explosive” strength training. The measurements were repeated during the actual experimental training period at 8-week intervals (i.e., weeks 8 and 16). Maximal strength, blood LA, W_{\max} attained during progressive cycling exercise, and muscle cross-sectional area (CSA) of the quadriceps femoris muscle group (CSA_{QF}) were assessed. Serum resting concentrations of T, FT, and C were used to examine the anabolic and catabolic hormonal adaptations to strength training. The results of this study provide additional support for the need for strength training in middle-aged and older men for long-term improvements in muscular health-related fitness as well as endurance performance.

Subjects

Eleven middle-aged (46 year old [M46; range 35–46 years]) and 11 older (64 year old [M64; range 60–74 years]) men volunteered to participate in this study. Their age, height, body mass, and body fat were 46 ± 3 years, 175 ± 3 cm, 86 ± 11 kg, and $23 \pm 1\%$, respectively, in M46 and 64 ± 2 years, 167 ± 4 cm, 81 ± 10 kg, and $24 \pm 5\%$, respectively, in M64. They were recruited through advertisement and personal letters from a private recreational and physical fitness club. All subjects were informed about the possible risks and benefits of the project that was approved by the Ethical Committee of the Health Department (Government of Navarra). The subjects signed a written consent form before participation in the study. Before inclusion in the study, all subjects were thoroughly screened through 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 by way of one or all of the screening tools, were reasons for exclusion from the study. All subjects were healthy, and none was taking cardiovascular medications. Physical activity questionnaire used to quantify 4-week physical activity energy cost (Minnesota Leisure Time Physical Activity Questionnaire) (39) 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 or endurance training or in competitive sports of any kind. None had been involved in any structured physical fitness program within the last 3 weeks. In the M64 group, all lived at home and were able to perform activities of daily life independently. No medication, which would have been expected to affect physical performance, was being taken by the subjects. This study is a part of a larger research project. Some of the results obtained with these subjects from the 2 age groups have been used earlier to examine the effects of strength training on maximal strength and muscle power performance of the lower- and upper-extremity muscles (26).

Testing Schedule

Before testing and training, each subject was 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 endurance testing was conducted for 2 different sessions separated by 5 days. During the first testing session, each subject was tested for his 1RM from a half-squat position ($1RM_{HS}$). In the second test session, each subject performed a maximal multistage discontinuous incremental cycling test on a mechanically braked cycloergometer. Venous blood samples were drawn between 0800 and 0900 hours to determine serum hormone concentrations. Strength and endurance tests were performed for a given subject at the same time of the day, as was the first test session. Training was integrated into the test week program. A minimum of 48 hours of rest was allowed after the last training sessions of weeks 8 and 16 and the same sequence of testing followed.

Strength Testing

Lower-body maximal strength was assessed using 1RM from $1RM_{HS}$. In the half-squat, the shoulders were in contact with the bar, and the starting knee angle was 90° . 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 determined by the weight plates added to both ends of the bar. The trunk was kept as straight as possible, and security belt was used by all subjects. The test was performed in a squatting apparatus in which the barbell was attached at both ends with linear bearings on 2 vertical bars allowing only vertical movements. Warm-up consisted of a set of 5 repetitions at 40–60% of the perceived maximum. Thereafter, 4–5 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. Maximal strength showed reliability coefficient of 0.95 and coefficient of variation (CV) of 2%.

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

Muscle Cross-Sectional Area and Body Composition

Thigh bone-free muscle cross-sectional area (CSA) of the quadriceps femoris (QF) muscle group (rectus femoris, vastus lateralis, vastus medialis, and vastus intermedialis) was measured at week 0 and after the experimental period (week 16) with a compound ultrasonic scanner (Toshiba SSA-250, Tokyo, Japan) and a 5-MHz convex transducer. The CSA_{QF} was measured at the lower-third portion between the greater trochanter and the lateral joint line of the knee. Two consecutive measurements were taken from the right thigh and then averaged for further analyses. The CSA_{QF} 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 (27). Muscle mass variables showed reliability coefficients greater than 0.74. The CV ranged from 1.4 to 4.3% for the measured circumference and CSA_{QF} .

Cycling Test

Endurance capacity was measured at weeks 0, 8, and 16 by using a maximal multistage discontinuous incremental cycling test on a mechanically braked cycloergometer (Monark Ergonomic 818E, Varberg, Sweden). During the exercise test, the subject was fitted with toe clips and pedaled at a constant rate of 60 rpm while blood pressure and a 12-lead electrocardiogram were monitored. Each subject started with unloaded cycling for 3 minutes, and the load was increased by 30 W every 3 minutes until volitional exhaustion or the required pedaling frequency of 60 rpm could not be maintained. After each workload, the test was interrupted for 60 seconds.

Heart rate was recorded every 15 seconds during cycling (Sport Tester, Polar Electro, Kempele, Finland) and averaged during the last 60 seconds of each work-

load. Subjects were verbally encouraged during the test. Before exercise and immediately after each exercise bout, capillary blood samples for the determination of lactate concentration were obtained from a hyperaemic earlobe. Samples for whole blood lactate determination (100 μ l) were deproteinized, stored at 4°C, and analyzed within 5 days after completing the test. The blood lactate analyzer (YSI 1500, YSI Incorporated, Yellow Springs, OH) was calibrated after every fifth blood sample dosage with 3 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 described 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 threshold and anaerobic threshold, respectively, by some researchers and have been shown to be important determinants of endurance performance capacity (44). This definition has the advantage of being objective and therefore is not subject to bias or variability introduced by different researchers (2).

The W_{max} of each cycling test was calculated using the formula:

$$W_{\text{max}} = W_{\text{com}} + \frac{t}{180} \times \Delta W \quad (1)$$

in which W_{com} is the last workload completed, t the number of seconds the final not completed load was sustained, and ΔW the final load increment (30 W) (32). The criteria used to define a true W_{max} in M46 were as follows: (a) a final heart rate within 10 $\text{b}\cdot\text{min}^{-1}$ of age-predicted maximum (220 $\text{b}\cdot\text{min}^{-1}$ – age) and (b) a peak blood lactate concentration value greater than 8 $\text{mmol}\cdot\text{L}^{-1}$ (41). At week 0, all the subjects in M46 reached a peak blood lactate concentration value greater than 8 $\text{mmol}\cdot\text{L}^{-1}$ (10 of the whole group at weeks 8 and 16, respectively), and 10 of the whole group of middle-aged subjects reached a final heart rate within 10 $\text{b}\cdot\text{min}^{-1}$ of the age-predicted maximum (7 of the whole group at weeks 8 and 16, respectively). The criteria of a peak blood lactate concentration value greater than 8 $\text{mmol}\cdot\text{L}^{-1}$ is not valid in M64 because it is known that peak blood lactate value is lower in this population (6). However, the fact that at week 0, 10 members of the whole older group reached a final heart rate within 10 $\text{b}\cdot\text{min}^{-1}$ of age-predicted maximum (9 of the whole group at weeks 8 and 16, respectively) suggests that true W_{max} was achieved (6). W_{max} was chosen because it has been shown that in healthy sedentary males aged 20–70 years, $\dot{V}O_{2\text{max}}$

can be accurately predicted from maximal work rate attained during a cycloergometer-graded exercise test (42). In addition, Kuipers et al. (32) have found that the day to day variation of $\dot{V}O_{2\text{max}}$ (4–11%) exceeds that of W_{max} (3–7%), suggesting that W_{max} might be a more sensitive parameter than $\dot{V}O_{2\text{max}}$ to detect differences in maximal aerobic power. In a pilot study, the intertest reliability for measuring W_{max} , W_4 , and W_2 was assessed performing 2 cycling tests separated by 4 weeks in 14 middle-aged men and 11 older men. No significant differences were observed between the 4-week measurements. Cycling testing variables showed reliability coefficients ranging from 0.90 to 0.98 in both age groups. The CV for W_{max} was 2.2 and 3.5% in middle-aged and older men, respectively. The CV for W_4 and W_2 ranged between 3.2 and 8.1% in both age groups.

Analytical Methods

Resting blood samples were drawn at week –4 (4 weeks before the start of training) and at weeks 0, 8, and 16 during the training. The subjects reported to the laboratory and rested for 10–15 minutes before giving a blood sample. Venous blood samples were obtained at rest between 0800 and 0900 hours from the antecubital vein to determine concentrations of serum T, FT, and C. Blood samples were taken at the same time of the day to reduce the effects of diurnal variation on hormonal concentrations. Blood was drawn after 12 hours of fasting and after 1 day of minimal physical activity. The samples collected for the analyses of hormones were centrifuged and the serum removed and frozen at –20°C for later analysis. The assays of serum C and T were performed by radioimmunoassays. Serum T and 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, Stillwater, MN). The sensitivity of the total T and FT assays was 0.14 $\text{nmol}\cdot\text{L}^{-1}$ and 0.15 pg/ml , respectively. The sensitivity of the C assay was 0.21 mcg/dl . The coefficient of intraassay variation was 5 and 4% for the total T and FT, respectively. The coefficient of intraassay variation was 6.6 for the C assay. All samples were analyzed using the same assay for each hormone, according to the instructions of the manufacturer.

Periodized Heavy and Explosive Resistance Training Program

The subjects participated in a supervised 16-week strength-training program, with a training frequency of 2 days per week. Each training session included 2 exercises for the leg extensor muscles (bilateral leg press and bilateral knee extension exercises), 1 exercise for the arm extensor muscle (the bench press), and 4–5 exercises for the main muscle groups of the body

Table 1. Physical characteristics of middle-aged (M46) and elderly men (M64) before (week 0) and after 8 weeks (week 8) and 16 weeks (week 16) of strength training.†

	Age (y)	Height (cm)	Body mass (kg)			Body fat (%)			Cross-sectional area quadriceps femoris (cm ²)	
			Week 0	Week 8	Week 16	Week 0	Week 8	Week 16	Week 0	Week 16
M46 (N = 11)	46 ± 3	175 ± 3	86 ± 11	85 ± 11	84 ± 12	23 ± 1	22 ± 4	21 ± 4#	48 ± 8	54 ± 9#
M64 (N = 11)	64 ± 2	167 ± 4	81 ± 10	81 ± 3	80 ± 11	24 ± 5	24 ± 5	22 ± 4#*	46 ± 13	51 ± 16#

† Values are means ± SD.

significantly different ($p < 0.05$) from corresponding value at week 0.

* significantly different ($p < 0.05$) from corresponding value at week 8.

(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 variable machine resistance exercises were used throughout the training period. All the exercises were performed by using concentric muscle actions followed by eccentric actions during the “lowering” phase of the movement. The loads were based on the concentric performance. Resistance used in this study was determined during the training sessions every week for the 16-week training period by using a repetition maximum approach.

During the first 8 weeks of the training period, the subjects trained with loads of 50–70% of the individual 1RM. The subjects performed 10–15 repetitions per set and 3–4 sets of each exercise. During the last 8 weeks of training, the loads were 50–60% and 60–70% of the maximum from weeks 9–12 and 50–60% and 70–80% from weeks 13–16. In the 2 exercises for the leg extensor muscle and in the bench press, 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 5 exercises, the subjects performed 10–12 repetitions per set and performed 3–5 sets. 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 weeks of the training period (from week 8 to week 16) by making the subjects perform a part of the leg extensor and bench press sets with loads ranging from 30 to 50% and 30 to 40% of the maximum, respectively. In this training session, the subjects now performed 6–8 repetitions per set and 3–4 sets of each exercise, but they executed all these repetitions as rapidly as possible. A researcher supervised each workout session to ensure that proper training procedures were followed. The researcher also recorded the compliance and individual workout data during each exercise session.

During the 16-week experimental training period, the subjects continued to take part in physical activi-

ties such as walking or swimming 1–2 times per week as they were used to doing before this experiment.

Statistical Analyses

Standard statistical methods were used for the calculation of the means and SD 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 the differences, if any, in initial strength, endurance, and hormones measures between the 2 groups. A repeated-measures multivariate analysis of variance was used to assess training-related effects within-subject analysis. When appropriate, post hoc comparisons were accomplished using the Scheffe test. ANCOVA was used to adjust post-training values to compare data among groups. For this purpose, pretraining values were used as covariates so that the effects of the covariance could be observed. Multiple regression and first-order partial correlations (controlling for initial W_{max}) were used to determine significant relationships among the delta changes for selected variables. 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 results of muscle CSA and anthropometry variables are presented in Table 1. Significant increases were observed in the CSA of the QF muscle during the 16-week training period in M46 (13%) and M64 (11%). The relative increases in the CSA of the QF muscle group during the training did not differ significantly between the 2 groups. Percentage of body fat decreased significantly only from week 8 to week 16 of training in M46 and M64, whereas no significant changes were observed for body mass after training for either group.

Table 2. Various indices of maximal and submaximal endurance performance during a maximal multistage discontinuous incremental cycling test in middle-aged (A) (M46) and older (B) (M64) men, at weeks 0, 8, and 16 during the 16-week strength training period.*

	M46 (Mean \pm SD)	M64 (Mean \pm SD)
Maximal work load (W)		
Week 0	209 \pm 39	170 \pm 32
Week 8	224 \pm 37*	177.9 \pm 33*
Week 16	229 \pm 35#	181 \pm 35#
Work load at 2 mmol·L ⁻¹ (W)		
Week 0	90.5 \pm 24	76.9 \pm 20
Week 8	106.2 \pm 27*	87 \pm 21*
Week 16	104.5 \pm 23#	84.9 \pm 24
Work load at 4 mmol·L ⁻¹ (W)		
Week 0	137.9 \pm 27	117.1 \pm 20
Week 8	147.9 \pm 30*	126.9 \pm 19*
Week 16	148.2 \pm 26#	126.3 \pm 20#
Maximal blood lactate concentration (mmol·L ⁻¹)		
Week 0	10.3 \pm 1.8	8.5 \pm 1.5
Week 8	11.1 \pm 2	8.3 \pm 1.8
Week 16	11.6 \pm 2.3	8.6 \pm 1.9
Maximal heart rate (b·min ⁻¹)		
Week 0	177 \pm 13	162 \pm 15
Week 8	178 \pm 12	159 \pm 14
Week 16	176 \pm 12	160 \pm 14

* Values are mean \pm SD.

Maximal Concentric 1RM Half-Squat

Maximal 1RM half-squat force increased slightly (3%; $p < 0.03$) during the 4-week control period (from week 4 to week 0) in both age groups. No significant differences were observed between the groups in pretraining strength level for 1RM half-squat. During the 16 weeks of training, significant increases of $45 \pm 6\%$ (from 113 ± 26 kg to 163 ± 27 kg; $p < 0.001$) in M46 and of $41 \pm 16\%$ (from 100 ± 24 kg to 136 ± 28 kg; $p < 0.001$) in M64 were found in maximal concentric 1RM half-squat. The increase in maximal concentric 1RM was already significant during the first 8 weeks of training in M46 ($24 \pm 6\%$ [from 113 ± 26 kg to 140 ± 25 kg; $p < 0.001$]) and in M64 ($27 \pm 6\%$ [from 100 ± 24 kg to 126 ± 28 kg; $p < 0.001$]). ANCOVA showed that the increase in maximal concentric 1RM half-squat observed during the 16-week training period was significantly higher ($p < 0.05$) in M46 than in M64. This difference occurred mainly during the last 8 weeks of training ($p < 0.02$ between weeks 8 and 16) because in the early phase of training (from week 0 to week 8) the increase in 1RM half-squat was similar in both groups.

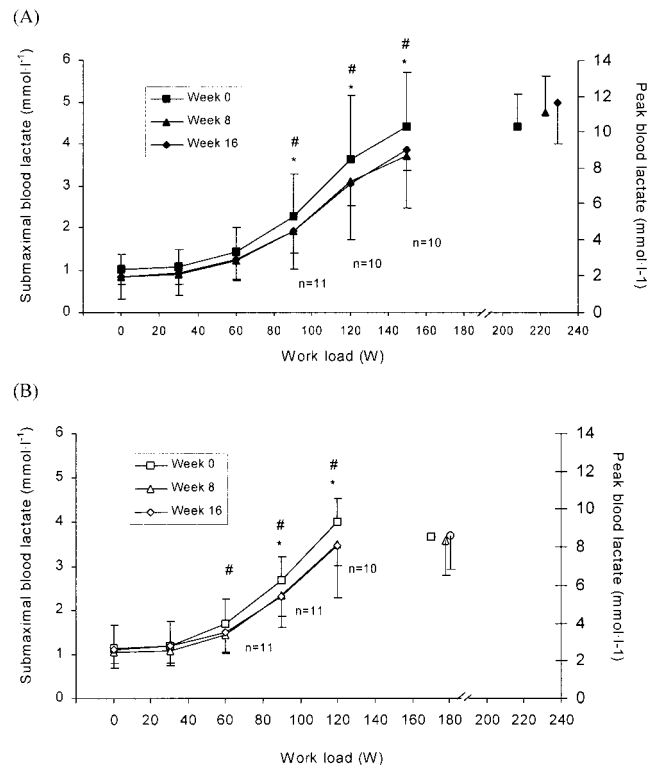


Figure 1. Blood lactate concentrations during a maximal multistage discontinuous incremental cycling test at submaximal and maximal workload in absolute values in middle-aged (a) (M46) and older (b) (M64) men at weeks 0, 8, and 16 during the 16-week strength-training period. # significantly different ($p < 0.05$) between weeks 0 and 16; * significantly different ($p < 0.05$) between weeks 0 and 8. Values are mean \pm SD.

Cycling Exercise Test

M46 showed higher values ($p < 0.05$) than M64 did in pretraining W_{\max} . During the 16 weeks of training, significant increases of $11 \pm 10\%$ ($p < 0.001$) in M46 and of $6 \pm 6\%$ ($p < 0.001$) in M64 were found in W_{\max} . The increase in W_{\max} occurred mainly during the first 8 weeks of training ($8 \pm 7\%$ in M46, $p < 0.001$; $6 \pm 6\%$ in M64, $p < 0.01$). ANCOVA showed that the increase in W_{\max} observed during the 16-week training period was significantly higher ($p < 0.05$) in M46 than in M64 (Table 2).

Figure 1 shows the shapes of the average blood lactate concentration–workload curve observed during the experimental period in both groups. After the first 8 weeks of the training period, the blood lactate concentration during submaximal cycling exercise decreased with increasing workload in both groups. Thus, significant decreases ($p < 0.001$) in blood lactate concentrations were observed after the first 8 weeks of training at 90, 120, and 150 W ($p < 0.01$) in M46 and at 60, 90, and 120 W ($p < 0.05$ – 0.01) in M64. During the subsequent 8 weeks of training, no further changes in blood lactate concentration were observed at any workload in either group. When workload was ex-

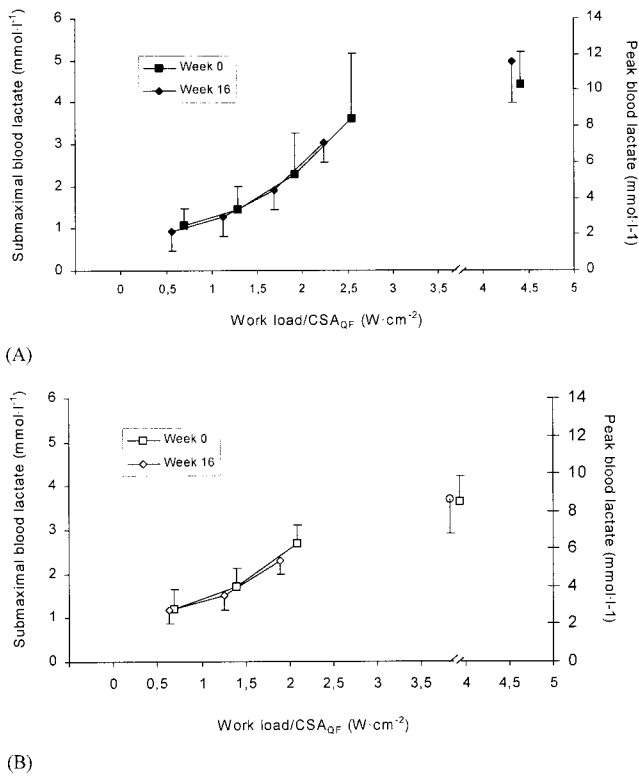


Figure 2. Blood lactate concentrations during a maximal multistage discontinuous incremental cycling test at submaximal and maximal workloads normalized per cross-sectional area of the quadriceps femoris muscle group in middle-aged (A) (M46) and older (B) (M64) men at weeks 0, 8, and 16 during the 16-week strength-training period. Values are mean \pm SD.

pressed relative to muscle CSA of CSA_{QF} (W·cm⁻²), the differences in the response of submaximal blood lactate to cycling exercise during the training period disappeared in both groups (Figure 2).

Data for various maximal and submaximal indices of cycling performance are presented in Table 2. No significant differences were observed between the groups in pretraining workloads, expressed in watts, that brought about a blood lactate concentration of 2 mmol·L⁻¹ (W_2) and 4 mmol·L⁻¹ (W_4). The exercise intensities corresponding to W_2 and W_4 were markedly higher after the 16-week training period. For example, during the 16 weeks of training, the workloads at W_2 and W_4 increased by $19 \pm 17\%$ ($p < 0.001$) and $8 \pm 8\%$ ($p < 0.01$), respectively, in M46 and by $9 \pm 9\%$ (not significant) and $8 \pm 7\%$ ($p < 0.01$), respectively, in M64. Similar to W_{\max} , the increase in W_2 and W_4 occurred mainly during the first 8 weeks of training. ANCOVA showed no differences between the groups in the increase in (W_2) and (W_4) during the 16-week training period. No significant changes were observed in the maximal values of blood lactate concentrations and heart rate during the 16-week training period in both groups (Table 2). During the 16-week training pe-

riod, no significant changes were observed in the percentage of W_4 relative to that of W_{\max} .

Basal Concentrations of Serum Hormones

No significant differences were observed between groups in pretraining serum resting concentrations of T, FT, and C. Serum hormone concentrations of T, FT, and C remained unaltered during the 4-week control period in both groups. During the 16-week training period, no significant changes were observed for T in either group. For C, a significant decrease ($p < 0.05$) was observed in M64 during the last 8 weeks of training, whereas in M46, C remained unchanged throughout the training period. ANCOVA showed that during the 16-week training period, the serum FT concentrations showed greater decrease in M64 than in M46 ($p < 0.05$), mainly during the last 8 weeks of training.

Data showed that statistically significant relationships were observed in M46 and M64 between the training-induced changes observed in W_{\max} during the cycling test and serum hormone concentrations. Thus, in all the subjects, the individual changes observed in W_{\max} during the 16-week training period correlated significantly with the individual changes observed in serum T:C ratio (Figure 3A) and serum FT:C ratio (Figure 3B). In M64 alone, the respective correlations between the changes in W_{\max} and in T, C, and FT, and total T:C ratios were significant ($r = 0.62$, $r = -0.75$, $r = 0.78$, and $r = 0.65$; $p < 0.05$ – 0.01 , respectively), whereas in M46, the respective correlations values did not reach statistically significant levels. In M64, the stepwise multiple regression analyses using the individual changes in W_{\max} during the 16-week training period as the dependent variable and the individual changes in CSA of the QF, maximal bilateral 1RM_{HS}, T:C, and FT:C ratios during the 16-week training period as independent variables showed that the individual changes observed in the T:C ratio ($R^2 = 0.62$; $p < 0.01$) as a single predictor accounted for 62% of the variance in W_{\max} during the strength-training period.

In M46, a statistically significant partial correlation (controlling for the initial W_{\max}) was observed between the initial levels of individual serum T and T:C ratio and the individual changes observed in W_{\max} during the first 8-week ($r = 0.81$ and $r = 0.7$; $p < 0.01$, respectively) and the 16-week training period ($r = 0.81$; $p < 0.01$ with T at month 0) (Figure 4).

Discussion

The primary results of this study demonstrated that the progressive 16-week strength training that led to large gains in maximal strength of the lower extremities (41–45%) in both middle-aged and older men provided a moderate (6–11%) but statistically significant training stimulus for improving W_{\max} during cycling in the first 8 weeks of training. These initial 8 weeks of strength training involved light to moderate resis-

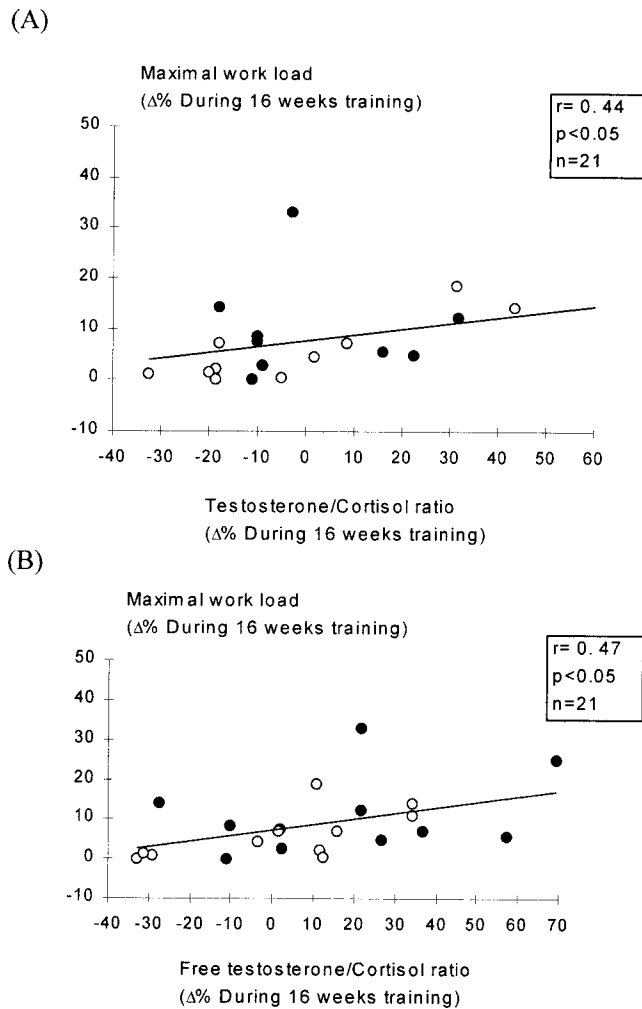


Figure 3. The relationships between the individual changes in maximal workload and the individual changes in serum total testosterone-cortisol (C) ratio (A), free testosterone-C ratio (B) and those during the 16-week training period in the entire group of middle-aged (M46) and older subjects (M64).

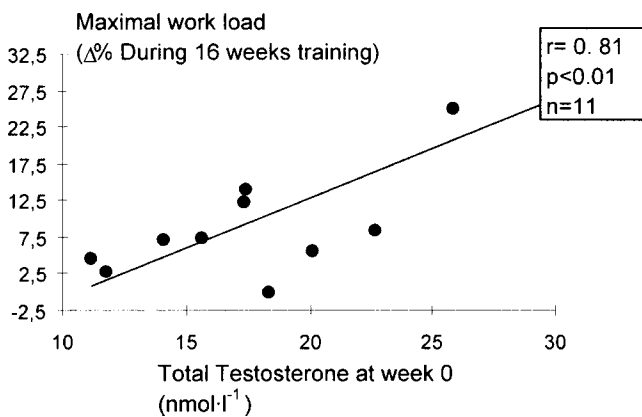


Figure 4. The relationship between the individual initial levels of total testosterone at week 0 and the individual changes in maximal workload during the 16-week training period in middle-aged men (M46).

tances (40–70% 1RM) but were performed using a high number of repetitions (10–15). Previous studies on the effects of strength training in humans have shown no improvements (1, 22–24, 29, 31, 36) or small increases in absolute maximal oxygen consumption ($\dot{V}O_{2\max}$) (11–13, 21, 23, 29, 45) and W_{\max} (21, 28), which can be considered an accurate predictor of $\dot{V}O_{2\max}$ (42).

It is difficult to compare the results of various studies, which differ markedly in a number of factors including the mode, frequency, duration and intensity of training, training history and age of participants, scheduling of training sessions, and dependent variable selection (34). However, in previously untrained subjects, it seems that the type of strength training and the age of subjects have different effects on $\dot{V}O_{2\max}$ and W_{\max} . Thus, in previously untrained young men performing weight training involving light resistance (40–55% 1RM) with a high number of repetitions (10–15) per set, the majority of authors have found small improvements in absolute $\dot{V}O_{2\max}$ and time to exhaustion (12, 13, 29, 45). However, when young and middle-aged untrained men performed traditional heavy resistance training programs involving heavy weights (between 70 and 100% 1RM) and few repetitions (1–10), no increase in $\dot{V}O_{2\max}$ or W_{\max} (1, 20, 22–24, 31, 36) could be observed. Older men respond to heavy resistance training differently than do young men because older men are able to increase the capacity of some components of the oxygen transport system, leading to a small increase in $\dot{V}O_{2\max}$ (11, 21) and W_{\max} (21). The results of this study agree with those of previous studies because a moderate increase in W_{\max} during cycling was observed in previously untrained middle-aged men after 8 weeks of strength training involving light to moderate resistances (40–70% 1RM) performed with a high number of repetitions (10–15). Furthermore, to our knowledge, this is the first study to show that the present moderate resistance but high-repetition strength-training regimen increases W_{\max} during cycling in previously untrained older men.

In addition to the increase observed in W_{\max} , the first 8 weeks of strength training increased the submaximal workload required to bring about a $4 \text{ mmol}\cdot\text{L}^{-1}$ (W_4) blood lactate level and resulted in lower blood lactate levels during submaximal exercise in both middle-aged and older men. Interestingly, the workload that brought about a blood lactate level of $4 \text{ mmol}\cdot\text{L}^{-1}$ occurred at the same percentage of W_{\max} after training. It has been suggested that the exercise intensity required to bring about a given submaximal level of blood lactate and $\dot{V}O_{2\max}$ is determined by different factors. $\dot{V}O_{2\max}$ is mainly dependent on central cardiovascular factors, such as cardiac output and stroke volume, and the submaximal workload to bring about a given level of lactate (i.e., W_4) being mainly dependent on peripheral factors, such as enzyme ac-

tivities of skeletal muscle or the numbers of mitochondria (40, 44). It is not known whether the “aerobiclike” adaptations (increase in W_{\max} and W_4) produced in middle-aged and older men during the first 8 weeks of the present training are peripheral or central in nature because the increase observed in W_4 (8%) in both groups was similar in magnitude to the increase observed in W_{\max} (6–11%). However, several reasons suggest that these adaptations are mainly peripheral in nature: (a) Frontera et al. (11) suggested that the significant improvement in whole body capacity for oxygen use during the leg cycle $\dot{V}O_{2\max}$ test observed after strength training occurs mainly at the muscle level because they found an increased density of capillaries per fiber and an increased citrate synthase activity in the vastus lateralis muscle after strength training. (b) Several authors did not find an increase in maximal oxygen consumption after strength training, but they did find improvements in short-term (22, 23) and long-term (22, 36) endurance performances, which have been shown to be strongly related to W_4 (8, 9, 15). (c) The significant improvement in absolute $\dot{V}O_{2\max}$ observed in previously untrained young and older men after several weeks of weight training (11, 13, 23, 37) may primarily result from changes in muscle mass and not from an improvement in an individual’s ability to deliver oxygen to the working muscles. The improvement in absolute $\dot{V}O_{2\max}$ values was abolished when it was expressed relative to body weight (11, 23), lean body weight (13), or fat-free weight (37). (d) Similar response has been found in this study in both groups during the training period in blood LA during submaximal cycling exercise when the workload was expressed relative to the muscle CSA. This suggests that the demand for aerobic energy per unit of muscle tissue is probably similar after strength training. These observations suggest that heavy resistance training produced aerobiclike variety of adaptations that were mainly peripheral in nature.

Increase in W_4 after training has been interpreted as a measure of the increase in submaximal endurance because several studies have shown that the exercise intensity required to bring about a given level of submaximal blood lactate is strongly related to endurance performance (8, 9, 15). It is not known how strength training could improve cycle endurance performance. Several authors have suggested that the increase in quadriceps strength observed after strength training could improve cycle endurance performance by reducing the percentage of peak tension required for each push of the pedal (22), by reducing the occlusion of blood flow during contraction (36), and by increasing the density of capillaries per fiber and the citrate synthase activity in the quadriceps muscle (11). In addition, increased agonist activation or changes in the degree of agonist-antagonist coactivation, or both, reported with strength training may also account, to

some extent, for a better efficiency-sustained submaximal load (5, 17).

During the last 8 weeks of the 16-week strength-training program, no further increases in W_{\max} or W_4 were observed in middle-aged or older men. The different strength-training protocols used during the last 8 weeks of training, involving higher resistances (60–80% 1RM) and lower number of repetitions (5–12), compared with those used during the first 8 weeks of training (40–70% 1RM, 10–15 reps) could explain the absence of improvement in cycling performance observed during the last 8 weeks of strength training. An alternative explanation could be related to the training status of subjects. Weight training has been shown to be effective in increasing aerobic work capacity in previously untrained subjects but not in trained subjects (29). It may be speculated that middle-aged and older subjects can benefit from an increase in aerobic performance with strength training when they are previously untrained (the first 8 weeks) but not when they are already weight trained (the last 8 weeks).

A unique finding of this study was that the individual increases in the maximal cycling workload (W_{\max}) during the 16-week strength-training period correlated with the individual changes in serum total T:C and FT:C ratios in all the subjects (Figure 3). The same was true for the changes in serum T and C and the changes in maximal cycling workload in the older group alone. In addition, the initial individual levels of serum total T correlated with the changes in maximal cycling workload in the middle-aged group (Figure 4). The findings indicate that men who developed an enhanced anabolic environment during the 16 weeks of strength training showed a greater increase in W_{\max} than did those with minor increases or not to mention those with even some decreases in their anabolic environment, especially in older men. This observation suggests that a low level of the anabolic hormone T may be a limiting factor in endurance development during prolonged strength training, especially in older people. Furthermore, middle-aged men with higher initial concentrations of anabolic hormones showed a greater increase in W_{\max} during the 16-week training period than did those with lower basal levels. Strength training-induced changes in the serum T:C ratio have been demonstrated to have a significant relationship with the changes in strength performance in men (19). The high correlations observed between serum anabolic hormone concentrations and changes in the cycling exercise could be considered as an unexpected finding because cycling is a nonspecific test for measuring the effects of strength training. However, Kraemer et al. (31) have found that the discontinuous progressive exercise test can be appropriate for studying the hormonal adaptations to a strength-training program because this type of exercise produces

high changes in serum T and C levels (14, 28, 31), suggesting increased hormonal secretion, and because after several weeks of strength training, there is a differential hormonal response to this nonspecific type of exercise. We were not able to measure acute hormone responses to the present cycling performance but did determine the basal resting concentrations of the hormones examined. Nevertheless, the relationships found in this study between various indices of cycling testing and serum basal hormone concentrations after strength training suggest that maximal incremental cycling might be used as an additional test to detect anabolic-catabolic responses to prolonged strength training in middle-aged and older men.

The results of this study indicate that a 16-week progressive heavy resistance exercise training program provided a moderate but statistically significant training stimulus for improving W_{\max} and the submaximal workload required to bring about a level of $4 \text{ mmol}\cdot\text{L}^{-1}$ (W_4) during a discontinuous progressive cycling exercise test in both middle-aged and older men. The gains in W_{\max} and W_4 were similar in both age groups and occurred mainly during the first 8 weeks of the strength training. The relationships found in this study between various indices of cycling testing and serum anabolic hormone concentrations after strength training suggest that maximal incremental cycling might be used as an additional test to detect anabolic-catabolic responses to prolonged strength training in middle-aged and older men.

Practical Applications

Training program strategies to improve the quality of life for older individuals has become more important as the aging population continues to grow. The present observations may have important practical relevance for optimal construction of strength-training programs for middle-aged and older men because muscle strength, the ability to develop force rapidly, and endurance performance are important health-related fitness components contributing to several activities of daily life, such as climbing stairs, walking, requiring submaximal efforts and to preserve the independent lifestyle. In general, during the initial phase of short-term strength training (i.e., 8 weeks training, $2 \text{ d}\cdot\text{wk}^{-1}$, 3–5 sets with 50–70% 1RM), large initial increases in maximal strength (25%), muscle mass (11–13%), and endurance performance (6–11%) take place in response to the external demands of the exercise training stimuli in middle-aged and older men. This type of short-term strength training seems to be the solution for preventive purposes to induce impressive strength gains, enhanced muscle CSA, and moderate improvements in endurance performance. However, after an initial 8-week training period, when the overall intensity or the frequency, or both, of the training is in-

creased, a diminished rate of gain or a decreased level of maximal strength and a plateau in endurance performance are observed in older men compared with middle-aged men. This may be associated with a greater decrease in the serum FT levels in older than in middle-aged subjects. Older subjects could be more sensitive to the duration or the intensity of training, or both, than middle-aged subjects. It is possible that during prolonged strength training, maximal strength and endurance development in older subjects become limited in magnitude because of impairment in the plasticity of the endocrine system observed with aging. Therefore, alternate training strategies may be needed after the initial 8 weeks of strength training to improve an individual's performance in dynamic activities that require submaximal efforts.

References

1. ALLEN, T.E., R.J. BYRD, AND D.P. SMITH. Hemodynamic consequences of circuit weight training. *Res. Q.* 47:299–306. 1979.
2. ALLEN, W., D.R. SEALS, B.F. HURLEY, A.A. EHSANI, AND J.M. HAGBERG. Lactate threshold and distance running performance in young and older endurance athletes. *J. Appl. Physiol.* 58:1281–1284. 1985.
3. AMERICAN COLLEGE OF SPORTS MEDICINE. ACSM guidelines on exercise and physical activity for older adults. *Med. Sci. Sports Exerc.* 30:992–1008. 1998.
4. ASTRAND, I., P.O. ASTRAND, I. HALLBACK, AND A. KILBOM. Reduction in maximal oxygen uptake with age. *J. Appl. Physiol.* 35:649–654. 1973.
5. BEHM, D.G., AND D.M. ST-PIERRE. The effects of strength training and disuse on the mechanisms of fatigue. *Sports Med.* 25: 173–189. 1988.
6. BLAIR, S.N., P. PAINTER, R.R. PATE, L.K. SMITH, AND C.B. TAYLOR. (eds.). *Resource Manual for Guidelines for Exercise Testing and Prescription.* American College of Sports Medicine. Philadelphia: Lea & Febiger, 1988. pp. 414–420.
7. COOPER, C., D.R. TAAFFE, D. GUIDO, E. PACKER, L. HOLLOWAY, AND R. MARCUS. Relationship of chronic endurance exercise to the somatotrophic and sex hormone status of older men. *Eur. J. Endocrinol.* 138:517. 1998.
8. COSTILL, D.L., H. THOMASON, AND E. ROBERTS. Fractional utilization of the aerobic capacity during distance running. *Med. Sci. Sports Exerc.* 5:248–252. 1973.
9. COYLE, E.F., A.R. COGGAN, M.K. HOOPER, AND T.J. WALTERS. Determinants of endurance in well-trained cyclists. *J. Appl. Physiol.* 64:2622–2630. 1988.
10. FLEG, J.L., AND E.G. LAKATTA. Role of muscle loss in the age associated reduction in $\dot{V}O_{2\max}$. *J. Appl. Physiol.* 65:1147–1151. 1988.
11. FRONTERA, W.R., C.N. MEREDITH, K.P. O'REILLY, AND W.J. EVANS. Strength training and determinants of $\dot{V}O_{2\max}$ in older men. *J. Appl. Physiol.* 68:329–333. 1990.
12. GETTMAN, L.R., J.J. AYRES, M. POLLOCK, AND A. JACKSON. Effect of circuit weight training on strength, cardiorespiratory function, and body composition of adult men. *Med. Sci. Sports Exerc.* 10:171–176. 1978.
13. GETTMAN, L.R., L.A. CULTER, AND T.A. STRATHMAN. Physiologic changes after 20 weeks of isotonic vs. isokinetic circuit training. *J. Sports Med. Phys. Fitness* 20:265–274. 1980.
14. HACKNEY, A.C., M.C. PREMO, AND R.G. McMURRAY. Influence of aerobic versus anaerobic exercise on the relationship between reproductive hormones in men. *J. Sports Sci.* 13:305–311. 1995.

15. HAGBERG, J.M., AND E.F. COYLE. Physiological determinants of endurance performance as studied in competitive racewalkers. *Med. Sci. Sports Exerc.* 15:287–289. 1983.
16. HÄKKINEN, K., M. ALEN, M. KALLINEN, M. IZQUIERDO, K. JOKELAINEN, H. LASSILA, E. MÄLKIA, W.J. KRAEMER, AND R.U. NEWTON. Muscle cross-sectional area, force production, and neural activation of leg extensor muscles during isometric and dynamic actions in middle-aged and elderly men and women. *J. Aging Phys. Activity* 6:232–247. 1998a.
17. HÄKKINEN, K., M. KALLINEN, M. IZQUIERDO, K. JOKELAINEN, H. LASSILA, E. MÄLKIA, W.J. KRAEMER, R.U. NEWTON, AND M. ALEN. Changes in agonist-Antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J. Appl. Physiol.* 84:1341–1349. 1998b.
18. HÄKKINEN, K., AND A. PAKARINEN. Serum hormones and strength development during strength training in middle-aged and elderly males and females. *Acta Physiol. Scand.* 150:211–219. 1994.
19. HÄKKINEN, K., A. PAKARINEN, M. ALEN, AND P.V. KOMI. Serum hormones during prolonged training of neuromuscular performance. *Eur. J. Appl. Physiol.* 53:287–293. 1985.
20. HENNESSY, L.C., AND A.W. WATSON. The interference effects of training for strength and endurance simultaneously. *J. Strength Cond. Res.* 8(1):12–19. 1994.
21. HEPPEL, R.T., S.L.M. MACKINNON, J.M. GOODMAN, S.G. THOMAS, AND M.J. PLYLEY. Resistance and aerobic training in older men: Effects on VO₂ peak and the capillary supply to skeletal muscle. *J. Appl. Physiol.* 82:1305–1310. 1997.
22. HICKSON, R.C., B.A. DVORAK, E.M. GOROSTIAGA, T.T. KUROWSKI, AND C. FOSTER. Potential for strength and endurance training to amplify endurance performance. *J. Appl. Physiol.* 65:2285–2290. 1988.
23. HICKSON, R.C., M.A. ROSENKOETTER, AND M.M. BROWN. Strength training effects on aerobic power and short-term endurance. *Med. Sci. Sports Exerc.* 12:336–339. 1980.
24. HURLEY, B.F., D.R. SEALS, A.A. EHSANI, L. CARTIER, G.P. DALSKY, J.M. HAGBERG, AND J.O. HOLLOSZY. Effects of high-intensity strength training on cardiovascular function. *Med. Sci. Sports Exerc.* 16:483–488. 1984.
25. IZQUIERDO, M., K. HÄKKINEN, A. ANTÓN, M. GARRUES, J. IBÁÑEZ, 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.* 33:1577–1587. 2001.
26. IZQUIERDO, M., K. HÄKKINEN, J. IBÁÑEZ, M. GARRUES, A. ANTON, A. ZÚÑIGA, J.L. LARRIÓN, AND E.M. GOROSTIAGA. Effects of strength training on maximal strength and muscle power of the upper and lower extremities and serum hormones in middle-aged and older men. *J. Appl. Physiol.* 90:1497–1507. 2001.
27. JACKSON, A.G., AND M.L. POLLOCK. Prediction accuracy of body density, lean body weight and total body volume equations. *Med. Sci. Sports Exerc.* 9:197–201. 1977.
28. JENSEN, J., H. OFTEBRO, B. BREIGAN, A. JOHNSSON, K. OHLIN, H.D. MEE, S.B. STROMME, AND H.A. DAHL. Comparison of changes in testosterone concentrations after strength and endurance exercise in well trained men. *Eur. J. Appl. Physiol.* 63:467–471. 1991.
29. KIMURA, Y., H. ITOW, AND S. YAMAZAKI. Effects of circuit weight training on VO₂ max and body composition of trained and untrained college men. *J. Physiol. Soc. Jpn.* 43:593–596. 1981.
30. KRAEMER, W.J., K. HÄKKINEN, R.U. NEWTON, M. McCORMICK, B.C. NINDL, J.S. VOLEK, L.A. GOTSHALK, S.J. FLECK, W.W. CAMPBELL, S.E. GORDON, P.A. FARRELL, AND W.J. EVANS. Acute hormonal responses to heavy resistance exercise in younger and older men. *Eur. J. Appl. Physiol.* 77:206–211. 1998.
31. KRAEMER, W.J., J.F. PATTON, S.E. GORDON, E.A. HARMAN, M.R. DESCHENES, K. REYNOLDS, R.U. NEWTON, N.T. TRIPLETT, AND J.E. DZIADOS. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J. Appl. Physiol.* 78:976–989. 1995.
32. KUIPERS, H., F.T.J. VERSTAPPEN, H.A. KEIZER, P. GEURTEN, AND G. VAN KRANENBURG. Variability of aerobic performance in the laboratory and its physiological correlates. *Int. J. Sports Med.* 6:197–201. 1985.
33. LARSSON, L. Morphological and functional characteristics of the aging skeletal muscle in man: A cross-sectional study. *Acta Physiol. Scand. Suppl.* 457:1–36. 1978.
34. LEVERITT, M., P.J. ABERNETHY, B.K. BARRY, AND P.A. LOGAN. Concurrent strength and endurance training: A review. *Sports Med.* 28:413–427. 1999.
35. LEXELL, J. Ageing and human muscle: Observations from Sweden. *Can. J. Appl. Physiol.* 18(1):2–18. 1993.
36. MARCINIK, E.J., J. POTTS, W. SCHLABACH, P. DAWSON, AND B.F. HURLEY. Effects of strength training on lactate threshold and endurance performance. *Med. Sci. Sports Exerc.* 23:739–743. 1991.
37. MCCARTHY, J.P., J.C. AGRE, B.K. GRAF, M.A. POZNIAK, AND A.C. VAILAS. Compatibility of adaptive responses with combining strength and endurance training. *Med. Sci. Sports Exerc.* 27:429–436. 1995.
38. POSNER, J.D., K.M. GORMAN, H.S. KLEIN, AND C.J. CLINE. Ventilatory threshold: Measurement and variation with age. *J. Appl. Physiol.* 63:1519–1525. 1987.
39. REIFF, G.G., H.J. MONTOYE, R.D. REMINGTON, J.A. NAPIER, H.L. METZNER, AND H.H. EPSTEIN. Assessment of physical activity by questionnaire and interview. *J. Sports Med. Phys. Fitness* 7:1–32. 1967.
40. RUSKO, H., P. RAHKILA, AND E. KARVINEN. Anaerobic threshold, skeletal muscle enzymes and fiber composition in young female cross-country skiers. *Acta Physiol. Scand.* 108:263–268. 1980.
41. SKELTON, D.A., C.A. GREIG, J.M. DAVIES, AND A. YOUNG. Strength power and related functional ability of healthy people aged 64–89 years. *Age Ageing* 23:371–377. 1994.
42. STORER, T.W., J.A. DAVIS, AND V.J. CAIOZZO. Accurate prediction of VO₂max in cycle ergometry. *Med. Sci. Sports Exerc.* 22:704–712. 1990.
43. THOMAS, S.G., D.A. CUNNINGHAM, J. THOMPSON, AND P.A. RECHNITZER. Exercise training and “ventilation threshold” in elderly. *J. Appl. Physiol.* 59:1472–1476. 1985.
44. WELTMAN, A. *The Blood Lactate Response to Exercise*. Champaign: Human Kinetics, 1995.
45. WILMORE, J.H., R.B. PARR, R.N. GIRANDOLA, P. WARD, AND P.A. VODAK. Physiological alterations consequent to circuit weight training. *Med. Sci. Sports Exerc.* 10:79–84. 1978.

Acknowledgments

This study was supported by grants from the Instituto Navarro de Deporte y Juventud and from Departamento de Salud. Gobierno de Navarra, Spain.

Address correspondence to Dr. Mikel Izquierdo, mizquierdo@jet.es.