

Maximal strength and power, muscle mass, endurance and serum hormones in weightlifters and road cyclists

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Maximal strength, power, muscle cross-sectional area, maximal and submaximal cycling endurance characteristics and serum hormone concentrations of testosterone, free testosterone and cortisol were examined in three groups of men: weightlifters ($n = 11$), amateur road cyclists ($n = 18$) and age-matched controls ($n = 12$). Weightlifters showed 45–55% higher power values than road cyclists and controls, whereas the differences in maximal strength and muscle mass were only 15% and 20%, respectively. These differences were maintained when average power output was expressed relative to body mass or relative to muscle cross-sectional area. Road cyclists recorded 44% higher maximal workloads, whereas submaximal blood lactate concentration was 50–55% lower with increasing workload than in controls and weightlifters. In road cyclists, workloads associated with blood lactate concentrations of 2 and 4 $\text{mmol} \cdot \text{l}^{-1}$ were 50–60% higher and occurred at a higher percentage of maximal workload than in weightlifters or controls. Basal serum total testosterone and free testosterone concentrations were lower in elite amateur cyclists than in age-matched weightlifters or untrained individuals. Significant negative correlations were noted between the individual values of maximal workload, workloads at 2 and 4 $\text{mmol} \cdot \text{l}^{-1}$ and the individual values of muscle power output ($r = -0.37$ to -0.49), as well as the individual basal values of serum total testosterone and free testosterone ($r = -0.39$ to -0.41). These results indicate that the specific status of the participants with respect to training, resistance or endurance is important for the magnitude of the neuromuscular, physiological and performance differences observed between weightlifters and road cyclists. The results suggest that, in cycling, long-term endurance training may interfere more with the development of muscle power than with the development of maximal strength, probably mediated by long-term cycling-related impairment in anabolic hormonal status.

Keywords: cortisol, endurance, muscle strength, power–velocity relationship, testosterone.

Introduction

Heavy-resistance and endurance training specificity in the long term, as well as genetic influences, have been shown to induce distinct changes in maximal strength, muscle power and endurance performance, as a consequence of different neuromuscular, cardiovascular and hormonal adaptations. Several researchers have reported sport-related differences in strength/power and endurance performances (Jürimäe *et al.*, 1997; Kanehisa *et al.*, 1997; Izquierdo *et al.*, 2002). The neuromuscular and endurance characteristics of weightlifters and elite endurance road cyclists, and how they relate to the

specific activity and to performance characteristics, have received limited attention. To the best of our knowledge, this study was the first attempt to characterize long-term training specificity of muscle power/strength and maximal/submaximal endurance adaptations between untrained controls, strength-trained athletes and endurance-trained cyclists.

Several researchers have suggested that basal levels of serum testosterone and cortisol appear to be decreased in professional road cyclists after long-term training or highly demanding competition (Hackney *et al.*, 1988; Lucia *et al.*, 2001a). In contrast, it has been reported that long-term strength training may induce a significant increase in serum basal testosterone after 2 years of weightlifting (Häkkinen *et al.*, 1988) and a decrease in the resting concentration of cortisol (Häkkinen *et al.*,

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1985a). Anabolic and catabolic hormones (e.g. testosterone and cortisol, respectively) may play an important role in the adaptation processes of simultaneous strength and endurance training. However, there are few reports in the literature indicating the extent to which strength/muscle power output characteristics and endurance cycling performance could be related to serum concentrations of circulating anabolic/catabolic hormones in highly trained endurance and strength athletes.

The aims of this study were: (1) to describe differences in maximal strength, muscle power output, muscle cross-sectional area, serum hormone concentrations and various indices of endurance cycling performance, between two groups of elite athletes who had been engaged in strength training (weightlifters) and endurance training (road cyclists) for a prolonged period of time, as well as a group of controls; and (2) to examine possible relationships between strength, muscle power output, endurance performance, muscle cross-sectional area and the anabolic/catabolic hormonal status in groups with clearly different training backgrounds.

Methods

Participants

A group of 41 men volunteered to participate in the study. According to their athletic background, they were divided into three groups: 11 weightlifters aged 22.6 ± 3.8 years (mean \pm s), 18 amateur road cyclists aged 20.6 ± 1.5 years and 12 age-matched controls aged 21.4 ± 1.7 years. The study was performed between February and May before the competitive season, which usually takes place between March and September.

The weightlifters were members of the same team and were trained by the same coach. Some of the weightlifters were placed first or second in their national competition. Their best weightlifting performance in the competition (consisting of the snatch and 'clean and jerk') was 217.5 ± 17.3 kg, with a 262.5 ± 30.1 'Sinclair coefficient' (calculated from the individual weightlifting performance and body mass) (Sinclair, 1985). None of the weightlifters reported using anabolic steroids. During the course of training, the weightlifters trained 5 days a week for 90–150 min, using a variety of typical (free weight) weightlifting exercises (i.e. snatches, cleans, jerks, front squats). These exercises consisted of typical sets with a relative intensity ranging from 70 to 100% of one-repetition maximum, performed for 1–5 repetitions per set. A minimum of 48 h rest was allowed after the last training session before conducting the force and muscle cross-sectional measurements for weightlifters.

The amateur road cyclists belonged to two cycling teams ranked among the top five national amateur teams. The cyclists won more than 25 one-day races and four stages (4–6 days in duration) during the subsequent competitive season. At the end of the subsequent competitive season, 7 of the 18 road cyclists became professionals. They cycled 350–660 km per week (between 11 and 21 h per week) and between 18,000 and 26,000 km in a season, including training and competition distances. In addition to the training described above, at the start of the season the cyclists performed a resistance-training programme lasting 6 weeks, consisting mainly of some callisthenics and exercise-machine exercises for 3 sets of 6–8 repetitions, with a relative intensity of 12–15 repetitions maximum.

The control participants were university students. They were active young men who did not participate in any resistance training or competitive sports, but who did engage in low-intensity recreational physical activities such as walking, cycling, cross-country hiking and, to a lesser extent, swimming less than two times per week.

The participants were fully informed about the experimental procedures and the possible risks and benefits of the study, which was approved by the Institutional Review Committee of the Instituto Navarro de Deporte y Juventud, and carried out according to the Declaration of Helsinki.

Test procedures

The participants were carefully familiarized with the test procedure of voluntary force production during several submaximal and maximal actions a few days before the measurements. They also completed several explosive types of action to familiarize them with the action required to move different loads rapidly. In addition, several warm-up muscle actions were recorded before the maximal and explosive test actions.

Maximal strength and muscle power testing

A detailed description of the maximal strength and muscle power test procedures can be found elsewhere (Izquierdo *et al.*, 2002). In brief, maximal strength of the lower extremity muscles was assessed using one-repetition concentric maximum half-squat. The shoulders were in contact with a bar and the starting knee angle was 90° . On command, the participant performed a concentric leg extension (as fast as possible) starting from the flexed position, to reach 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. Thereafter, four to five separate single attempts were performed until the

participant was unable to extend the legs to the required position. The last acceptable extension with the highest possible load was determined as one-repetition maximum.

The power-load relationship of the leg extensor muscles was also tested in a half-squat position using the relative loads of 15%, 30%, 45%, 60%, 70%, 80% and 100% of one-repetition maximum, respectively. In this test, the participants were instructed to move the load as fast as possible. Two test actions were recorded and the best reading (with the best velocity) was used for further analyses.

During the lower extremity test actions, bar displacement, average velocity and mean power were recorded by linking a rotary encoder to the end of the bar. The rotary encoder recorded the position and direction of the bar to within an accuracy of 0.0002 m. Customized software (JLML I+D, Madrid, Spain) was used to calculate the power output for each repetition of the half-squat performed throughout the whole range of motion. Average power output for each repetition of the half-squat was determined. Power curves were plotted using average power over the whole range of movement as the most representative mechanical parameter associated with a contraction cycle of the leg extensor muscles involved in the half-squat performance (i.e. hip, knee and ankle joints). For comparison purposes, an averaged index of muscle power output with all absolute loads examined was calculated separately for each group. Averaged indices of muscle power were calculated as the average of the power values obtained under all experimental conditions of the half-squat performance. The reproducibility of the measurements has been reported elsewhere (Izquierdo *et al.*, 2002).

In all the neuromuscular performance tests, strong verbal encouragement was given to each participant to motivate them to perform each test action as maximally and as rapidly as possible. The rest period between each trial and set was always 1.5 and 3 min, respectively.

Muscle cross-sectional area

Twenty-four hours before strength testing, the cross-sectional area of the quadriceps femoris muscle group (rectus femoris, vastus lateralis, vastus medialis and vastus intermedialis) was measured with a compound ultrasonic scanner (Toshiba SSA-250) and a 5-MHz convex transducer. Muscle cross-sectional area 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. Muscle cross-sectional area was then calculated from the image using the computerized system of the apparatus. Percentage of adipose tissue in the body was estimated

from skinfold thicknesses (Jackson and Pollock, 1977). Muscle cross-sectional area showed reliability coefficients of 0.85. The coefficient of variation ranged from 1.4 to 4.3% for the measured circumference and cross-sectional area of the quadriceps femoris muscle group, respectively.

Cycling exercise test

In the third test session, each participant performed a maximal multi-stage discontinuous incremental cycling test. The weightlifters and controls performed the cycling test on a mechanically braked cycle ergometer (Monark Ergonomic 818E, Monark-Crescent AB, Vargberg, Sweden), fitted with toe clips, at a constant pedalling cadence of 60 rev·min⁻¹. The road cyclists performed the cycling test on a electromagnetic cycle ergometer (Orion, STE, Toulouse, France) adapted with a racing saddle, drop handlebars and clip-in pedals, at a constant pedalling cadence of 85 rev·min⁻¹. The participants started with unloaded cycling (weightlifters and controls) or with a workload of 1 W·kg⁻¹ body mass (road cyclists) lasting 3 min, with the load being increased by 30 W (weightlifters and controls) or by 1 W·kg⁻¹ body mass (road cyclists) every 3 min, until volitional exhaustion. After each workload, the test was interrupted for 60 s before initiating the next workload. Exhaustion was defined as the participant being unable to maintain the required pedalling cadence. The pedal cadences of 60 rev·min⁻¹ (weightlifters and controls) and 85 rev·min⁻¹ (road cyclists) were chosen based on the preferred cadence at which neuromuscular fatigue is minimized in non-cyclists and cyclists, respectively (Takaishi *et al.*, 1998). Heart rate was monitored continuously using a heart rate monitor (Sportester Polar, Kempele, Finland) and determined during the last 60 s of each stage. The participants were verbally encouraged during the test.

Before exercise, and immediately after each exercise stage, capillary blood samples for the determination of lactate concentration were obtained from a hyperaemic earlobe. Samples for whole blood lactate determination (100 µl) were deproteinized, stored at 4°C and analysed (YSI 1500, Yellow Springs, Ohio, USA) within 5 days of completing the test. The blood lactate analyser was calibrated after every fifth blood sample with three known controls (5, 15 and 30 mmol·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 coefficients using the mathematical function described above was $r = 0.98-0.99$ ($P < 0.001$). From the equation describing the exercise blood lactate curve,

the workloads associated with blood lactate concentrations of 2 and 4 mmol·l⁻¹ were interpolated. A detailed description of the formula for calculation of maximal workload of each cycling test can be found elsewhere (Kuipers *et al.*, 1985; Storer *et al.*, 1990). Workloads associated with blood lactate concentrations of 2 and 4 mmol·l⁻¹ have been shown to be important determinants of endurance performance capacity (Weltman, 1995).

There were two reasons why we used two different ergometers during the cycling test. First, the electromagnetic cycle ergometer is a specific ergometer for well-trained cyclists that allows them to adapt individually to create the same position as in competition. Second, the weightlifters were better adapted to the mechanically braked ergometer with normal saddle and toe clips, whereas the road cyclists were familiar with the electromagnetic cycle ergometer because they had previously been tested on one on several occasions for health or physical fitness purposes.

The concurrent validity of the electromagnetic cycle ergometer was measured 1 month before the beginning of the test procedure by direct calibration, comparing the power (range 30–500 W) of the electromagnetic cycle ergometer with the braking power of a criterion variable. The criterion variable, considered as the 'gold standard', was a dynamic calibration rig that allowed direct continuous and accurate measurement of the applied torque transmitted to the ergometer and the angular velocity of the drive shaft. The driving torque was supplied by a variable-speed motor and reduction gear, and was applied to the axis of the pedal arm. Each of the basic elements used in the criterion variable was initially calibrated against standards by the only national accreditation body recognized by the Spanish government to assess calibration services against internationally agreed standards (ENAC: National Agency of Accreditation, Madrid, Spain). The calibration equation was: $y = 0.9574x + 13.256$ (where x is the conventional power output of the electromagnetic ergometer and y is the power output measured by the dynamic calibration rig). The correlation coefficient, standard error of the estimate and coefficient of variation were 0.99, 2.5 W and 0.7%, respectively.

The mechanically braked cycle ergometer was statically calibrated by checking the zero and then suspending 4 kg from the balance at the point of belt attachment. Power output by the mechanically braked cycle ergometer was estimated to be 9% higher than the power output values visually indicated, due to friction in the transmission system (Åstrand, 1970). Moreover, to test the transferability of workload measurements between the electromagnetic and mechanically braked ergometers, the concurrent validity of the mechanically braked ergometer was indirectly measured by physio-

logical validation, comparing the heart rate when cycling on the mechanically braked ergometer with the heart rate when cycling on the electromagnetic ergometer, throughout a power range of 30–350 W. For a given workload of between 30 and 350 W, heart rates recorded on the electromagnetic cycle ergometer were highly correlated with those obtained on the mechanically braked ergometer, when workloads on the mechanically braked ergometer were estimated to be 9% higher than the visually indicated power output values. The correlation coefficient, standard error of the estimate and coefficient of variation were 0.99, 2.1 beats·min⁻¹ and 1.2%, respectively. These results show that heart rate was not affected by the type of cycle ergometer used. Thus, the reliability of workload measurements on the two cycle ergometers used in the present study was adequate.

Analytical methods

After 12 h of fasting and 1 day of minimal physical activity, venous blood samples were obtained at rest between 08.00 and 09.00 h 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, free testosterone and cortisol concentrations were measured using reagent kits from Diagnostic Product Corporation and INCSTAR Corporation (Coat-A-Count Total testosterone TKTT11CS, Los Angeles, USA and GammaCoat Cortisol Radioimmunoassay Kit, USA). The sensitivity of the total testosterone and free testosterone assays was 0.14 nmol·l⁻¹ and 0.15 pg·ml⁻¹, respectively. The sensitivity of the cortisol assay was 0.21 µg·dl⁻¹. The coefficient of intra-assay variation was 5.1% and 4.2% for the total and free testosterone, respectively. The respective value for the cortisol assay was 6.6%. All samples were analysed in the same assay for each hormone, according to the manufacturer's recommendations.

Statistical analysis

Standard statistical methods were used for the calculation of the mean and standard deviation (s). Pearson product-moment correlation coefficients were used to determine the association between maximal strength, power output, muscle mass, serum hormones and various indices of the cycling exercise test. Differences among the three groups for maximal strength, average muscle power, muscle cross-sectional area, serum hormones, maximal workload and the submaximal

workloads associated with blood lactate concentrations of 2 and 4 mmol·l⁻¹ were determined using one-way analysis of variance (ANOVA), with Scheffé *post-hoc* comparisons. Statistical significance was set at $P < 0.05$.

Results

Physical characteristics

The weightlifters, road cyclists and controls were 1.78 ± 0.05 , 1.81 ± 0.16 and 1.78 ± 0.04 m tall, respectively. The weightlifters were significantly ($P < 0.05$) heavier (80.6 ± 10.1 kg) than the road cyclists and controls (67.1 ± 15.2 kg and 71.9 ± 8.8 kg, respectively). Percent body fat was significantly lower ($P < 0.05$) in the road cyclists ($5.8 \pm 1.0\%$) than in the weightlifters and controls ($11.8 \pm 4.4\%$ and $11.6 \pm 4.1\%$, respectively).

Muscle cross-sectional area and maximal strength

The mean cross-sectional area of the quadriceps femoris muscle group was larger ($P < 0.01$) in the weightlifters (57.8 ± 9.4 cm²) than in the road cyclists and controls (52.1 ± 3.2 and 51.3 ± 5.7 cm², respectively). Maximal bilateral concentric strength expressed in absolute terms, relative to kilograms of body mass (kg·kg⁻¹) and relative to muscle cross-sectional area (kg·cm⁻²), is presented in Table 1. The maximal absolute strength differed between the groups so that the mean value in weightlifters was greater than that recorded in road cyclists ($P < 0.01$) and controls ($P < 0.001$). A similar difference between the groups was also observed when maximal concentric strength was expressed relative to cross-sectional area of the quadriceps femoris muscle group. When maximal concentric strength was expressed relative to body mass, the difference between weightlifters and road cyclists disappeared, but remained significant between weightlifters and controls and between road cyclists and controls. In weightlifters, individual values of muscle

cross-sectional area of the quadriceps femoris muscle group correlated significantly with individual values of maximal concentric strength ($r = 0.94$; $P < 0.001$), whereas no significant correlations were observed in the road cyclists and controls.

Muscle power output

At all absolute workloads examined, average power output of the lower extremities was significantly higher ($P < 0.05$ to 0.001) in weightlifters than that in road cyclists and controls (Fig. 1A). The average absolute power output index at all loads in weightlifters (755 ± 140 W) was 42–48% higher ($P < 0.05$) than in road cyclists (397 ± 99 W) and controls (385 ± 86 W). No differences were observed between road cyclists and controls. These differences in average power output index observed between weightlifters and road cyclists as well as controls were maintained when the averaged power output index was expressed relative to body mass (Fig. 1B) or relative to muscle cross-sectional area (Fig. 1C).

No differences were observed in average power output between road cyclists and controls at any workload. Maximal power output of the lower extremities was reached at a load of 60% maximal concentric strength (453 ± 100 W) for controls and at a load of 45% of maximal concentric strength (937 ± 153 W and 498 ± 110 W) for weightlifters and road cyclists.

Absolute average power output produced with maximal concentric strength in weightlifters was 42–48% higher ($P < 0.01$) than in road cyclists and controls. When power output was expressed relative to body mass (W·kg⁻¹), the difference in power output produced with maximal concentric strength between weightlifters and road cyclists disappeared and between weightlifters and controls it was reduced to 25% ($P < 0.05$) (Fig. 1B). Similar differences were observed between groups when power output was expressed relative to cross-sectional area of the quadriceps femoris muscle group (Fig. 1C).

Table 1. One-repetition maximum half-squat in absolute terms, relative to body mass and relative to muscle cross-sectional area of the quadriceps femoris muscle group in weightlifters, road cyclists and controls (mean \pm s)

	Weightlifters	Road cyclists	Controls
One-repetition maximum (kg)	$157 \pm 18^{a,b}$	134 ± 18^c	105 ± 5
One-repetition maximum · body mass ⁻¹ (kg·kg ⁻¹)	1.96 ± 0.28^b	1.89 ± 0.28^c	1.48 ± 0.14
One-repetition maximum · muscle cross-sectional area ⁻¹ (kg·cm ⁻²)	$2.74 \pm 0.16^{a,b}$	2.57 ± 0.37^c	2.05 ± 0.28

^a Significant difference ($P < 0.05$) between weightlifters and road cyclists.

^b Significant difference ($P < 0.05$) between weightlifters and controls.

^c Significant difference ($P < 0.05$) between road cyclists and controls.

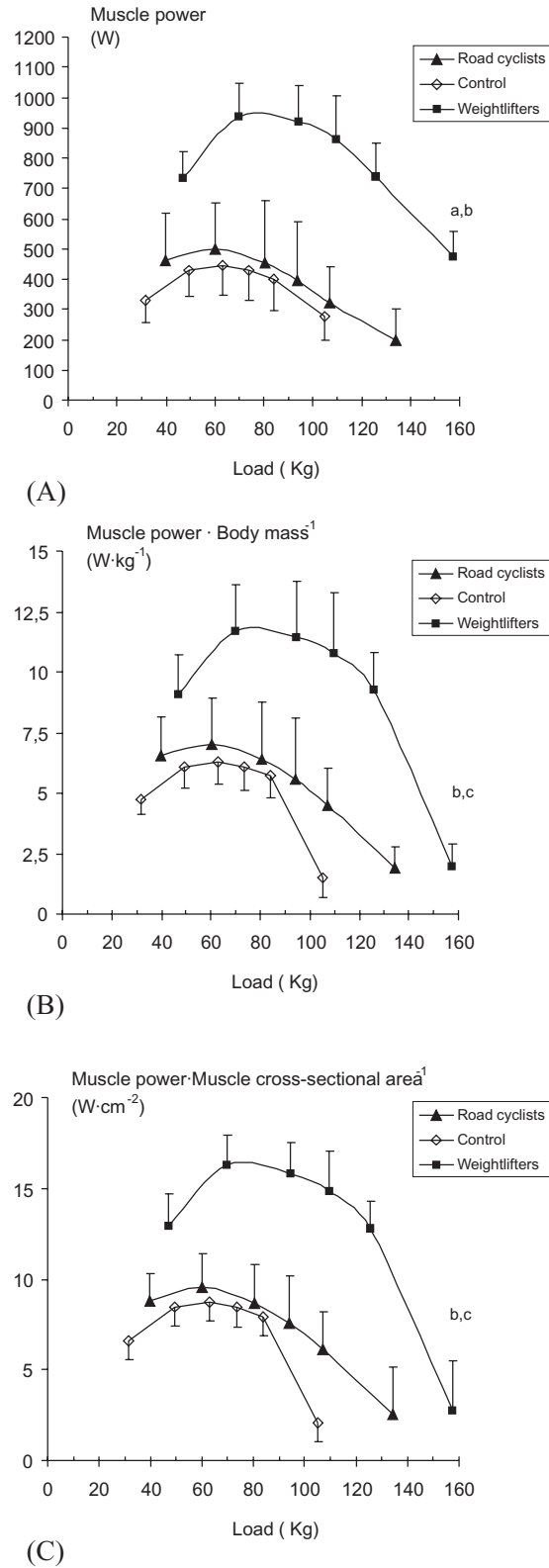


Fig. 1. Muscle power output of the lower extremity muscles during a half-squat at different absolute workloads corresponding to 15, 30, 45, 60, 70 and 100% of one-repetition maximum from a half-squat position in absolute terms (A), normalized for body mass (B) and normalized for cross-sectional area of the quadriceps femoris muscle group (C). ^aSignificant difference ($P < 0.05$) between weightlifters and road cyclists. ^bSignificant difference ($P < 0.05$) between weightlifters and controls. ^cSignificant difference ($P < 0.05$) between road cyclists and controls. Values are mean \pm standard deviation.

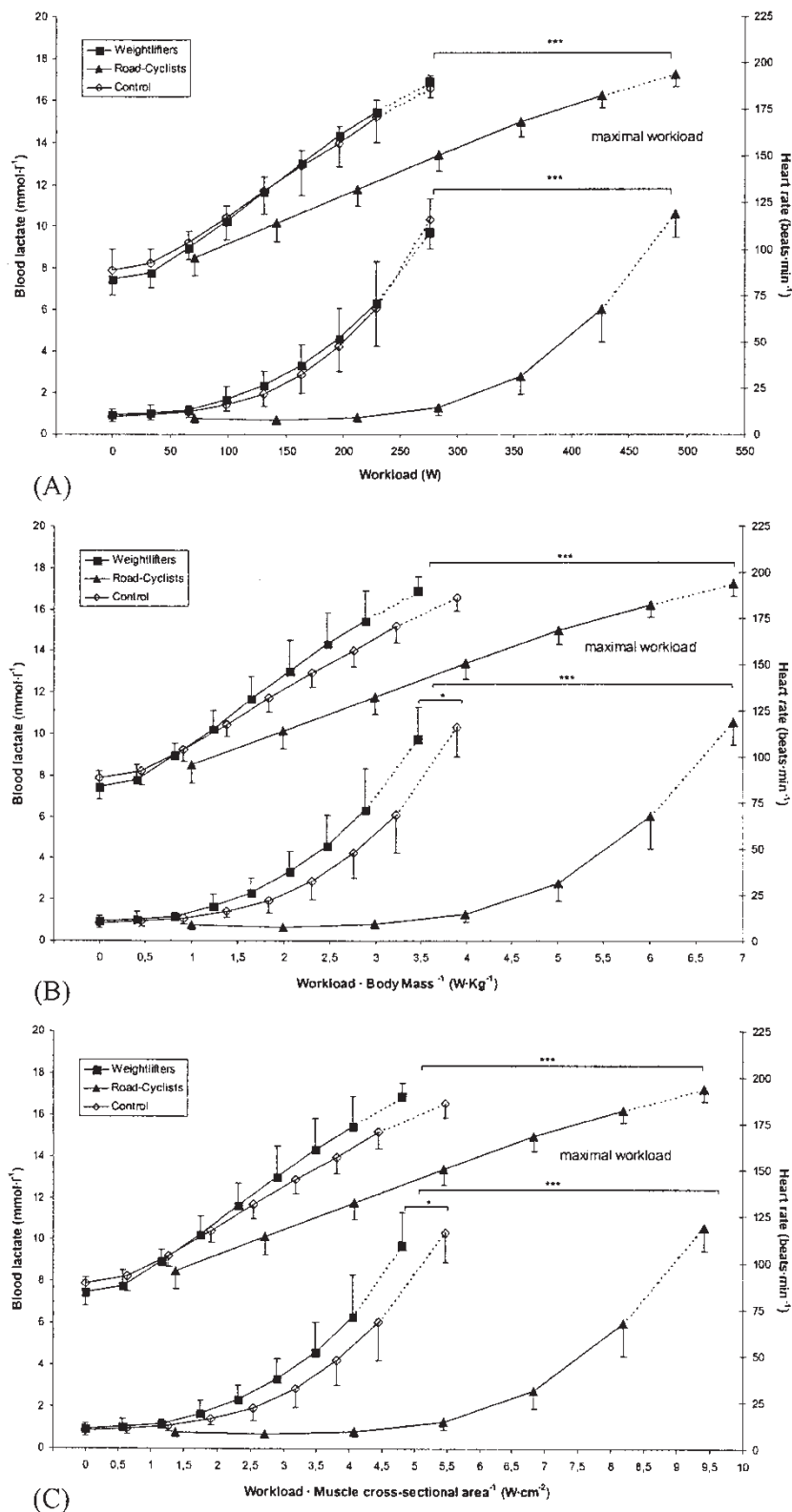


Fig. 2. Heart rate and blood lactate concentrations during a maximal multi-stage discontinuous incremental cycling test at submaximal and maximal workloads in absolute terms (A), normalized to body mass (B) and normalized to the cross-sectional area of the quadriceps femoris muscle group (C). *** Significant difference ($P < 0.001$) compared with weightlifters and controls. * Significant difference ($P < 0.05$) between weightlifters and controls. Values are mean \pm standard deviation.

Cycling exercise test

The maximal workload attained during the cycling exercise test was 44% and 42% higher in road cyclists (490 ± 56 W; $P < 0.001$) than in weightlifters and controls (276 ± 29 and 282 ± 32 W, respectively). When maximal workload was related to body mass, or to the muscle cross-sectional area of the quadriceps femoris muscle group, the difference observed between road cyclists (6.9 ± 0.4 W·kg⁻¹ and 9.4 ± 0.9 W·cm⁻², respectively) and controls (3.5 ± 0.4 W·kg⁻¹ and 5.0 ± 0.7 W·cm⁻², respectively) was maintained ($P < 0.01$), but the controls recorded higher ($P < 0.05$) values than the weightlifters (3.1 ± 0.3 W·kg⁻¹ and 4.4 ± 0.5 W·cm⁻², respectively). No significant differences were observed in maximal blood lactate concentration between road cyclists, weightlifters and controls (10.5 ± 3 , 9.7 ± 1 and 10.3 ± 1 mmol·l⁻¹, respectively). The maximal heart rates of 193 ± 6 and 189 ± 8 beats·min⁻¹ recorded in road cyclists and weightlifters were significantly higher (5 and 3%, respectively; $P < 0.05$) than that recorded in controls (183 ± 7 beats·min⁻¹).

The shapes of the average blood lactate concentration versus workload and heart rate versus workload curves in absolute terms also differed between the groups. During submaximal cycling exercise, blood lactate

concentration and heart rate rose more rapidly with increasing workload in weightlifters and controls than in road cyclists ($P < 0.05$ to 0.01) (Fig. 2A). The workloads (expressed in watts) that elicited blood lactate concentrations of 2 and 4 mmol·l⁻¹ were 50–60% lower ($P < 0.001$) in weightlifters and controls than in road cyclists (130 ± 32 , 143 ± 28 , 326 ± 38 W for workload at 2 mmol·l⁻¹ and 187 ± 29 , 196 ± 27 , 389 ± 42 W for workload at 4 mmol·l⁻¹, respectively), while no significant difference was observed between weightlifters and controls.

When the workload was expressed relative to body mass (W·kg⁻¹), road cyclists maintained higher workloads at concentrations at both 2 and 4 mmol·l⁻¹ than weightlifters and controls (Fig. 2B). However, blood lactate concentration and heart rate rose more rapidly with increasing workload, expressed relative to body mass, in weightlifters than in controls. Thus, workloads (expressed in watts) that elicited blood lactate concentrations of 2 and 4 mmol·l⁻¹ expressed relative to body mass in weightlifters were 18% ($P < 0.05$) and 15% ($P < 0.05$) lower than in controls. When workload was expressed relative to muscle cross-sectional area, similar differences were observed, although the differences between weightlifters and controls only approached statistical significance ($P < 0.07$) (Fig. 2C).

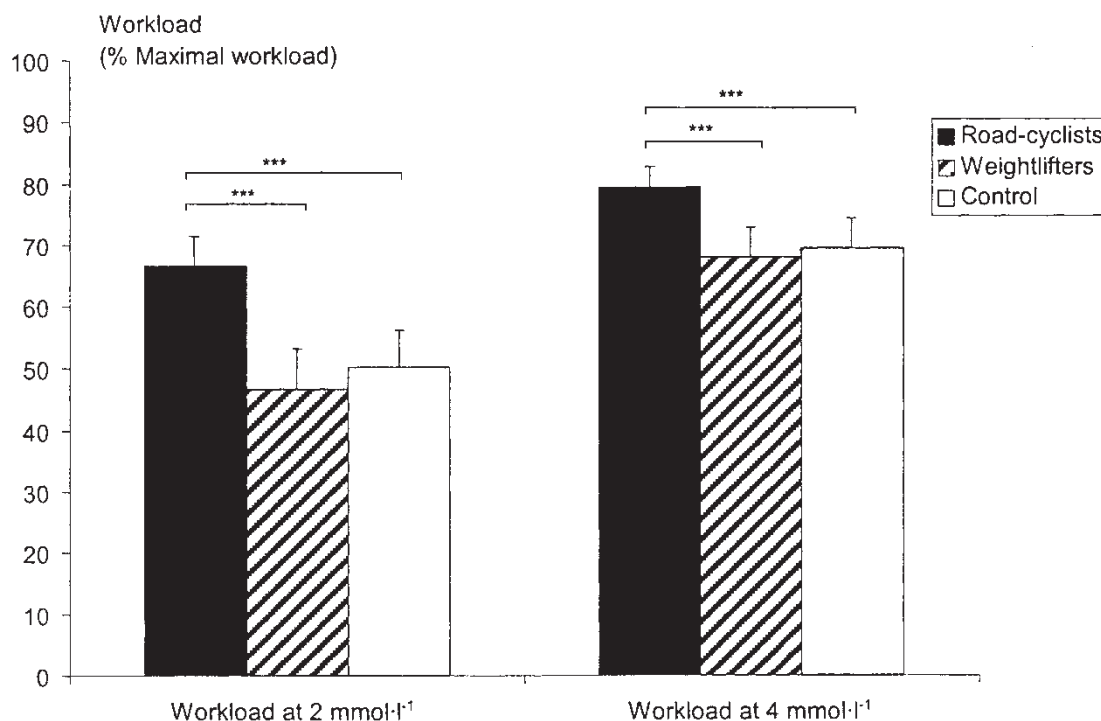


Fig. 3. Workload at blood lactate concentrations of 2 and 4 mmol·l⁻¹ expressed relative to the maximal workload attained during a maximal multi-stage discontinuous incremental cycling test. *** Significant difference ($P < 0.001$) compared with weightlifters and controls. Values are mean \pm standard deviation

When workloads that elicited blood lactate concentrations of 2 and 4 mmol·l⁻¹ were expressed relative to maximal workload, the road cyclists were able to exercise at a higher percentage of maximal workload before reaching a blood lactate concentration of 2 and 4 mmol·l⁻¹ (66±5% and 79±3%, respectively) than the weightlifters (47±7% and 68±5%, respectively; $P < 0.001$) and controls (50±6% and 70±5%, respectively; $P < 0.001$) (Fig. 3).

Serum hormones

The concentration of mean serum total testosterone of 18.1±5.4 nmol·l⁻¹ in road cyclists was 21% lower ($P < 0.05$) than those of 22.9±6.8 nmol·l⁻¹ and 22.9±6.3 nmol·l⁻¹ recorded in weightlifters and controls, respectively. The concentration of mean serum free testosterone of 75.1±26.0 pmol·l⁻¹ in road cyclists was 20–29% lower ($P < 0.05$ to 0.01)

than those of 94.1±20.4 pmol·l⁻¹ and 106±26.9 pmol·l⁻¹ recorded in weightlifters and controls, respectively. No significant differences were observed in the mean serum cortisol concentrations between road cyclists (545±133 nmol·l⁻¹), weightlifters (539±68.9 nmol·l⁻¹) and controls (544±46.6 nmol·l⁻¹). The serum testosterone/cortisol and the free serum testosterone/cortisol ratios did not differ between the groups.

Relationships between serum hormone concentrations, muscle mass and maximal strength/power

The relationships between serum hormone concentrations, some physical characteristics and maximal strength and muscle power indices in the group of participants as a whole are shown in Table 2. Significant correlations ($P < 0.01$) were observed between the

Table 2. Correlation coefficients between one-repetition maximum, averaged index of muscle power and maximal power output during the half-squat performance, and serum hormones, as well as various anthropometric variables for the participants as a whole

Variable	One-repetition maximum (kg)	Averaged index of muscle power (W)	Maximal power output (W)
Total testosterone (nmol·l ⁻¹)	0.09	0.20	0.25
Free testosterone (pmol·l ⁻¹)	-0.37	0.04	0.08
Cortisol (nmol·l ⁻¹)	0.09	0.00	0.00
Testosterone–cortisol ratio	0.00	0.12	0.15
Free testosterone–cortisol ratio	-0.16	0.00	0.04
Body mass (kg)	0.54**	0.58	0.58**
Muscle cross-sectional area (cm ²)	0.61**	0.67**	0.63**

** $P < 0.01$.

Table 3. Correlation coefficients between various indices of cycling testing (maximal workload, and workloads at blood lactate concentrations of 2 and 4 mmol·l⁻¹), and averaged index of muscle power, maximal power output, serum hormones and various anthropometric variables for the group of participants as a whole

Variable	Maximal workload (W)	Workload at 2 mmol·l ⁻¹ (W)	Workload at 4 mmol·l ⁻¹ (W)
Testosterone (nmol·l ⁻¹)	-0.39*	0.39*	-0.41*
Free testosterone (pmol·l ⁻¹)	-0.41**	-0.41**	-0.42**
Cortisol (nmol·l ⁻¹)	0.00	-0.01	0.00
Testosterone–cortisol ratio	-0.22	-0.21	-0.23
Free testosterone–cortisol ratio	0.27	-0.26	-0.28
Body mass (kg)	-0.05	-0.13	-0.10
Muscle cross-sectional area (cm ²)	-0.07	-0.12	-0.10
One-repetition maximum (kg)	0.11	0.07	0.05
Averaged index of muscle power (W)	-0.37*	-0.42**	-0.41**
Maximal power output (W)	-0.47**	-0.49**	-0.48**

* $P < 0.05$, ** $P < 0.01$.

individual values of maximal concentric strength and those of body mass ($r=0.54$; $P<0.001$) and muscle cross-sectional area ($r=0.61$; $P<0.001$).

Relationships between serum hormones, maximal strength/power and the cycling exercise test

Relationships between serum hormones, some physical characteristics, maximal strength and muscle power indices with maximal and submaximal workloads attained during the cycling exercise are shown in Table 3. The individual values of maximal workload attained during the cycling exercise test correlated negatively (from $r=-0.39$ to -0.41 ; $P<0.05$ to 0.01) with the individual concentrations of serum total and free testosterone, as well as with the individual values of average and maximal muscle power output (from $r=-0.37$ to -0.47 ; $P<0.05$ to 0.01) (Table 3).

The individual values of submaximal workload that elicited blood lactate concentrations of 2 and 4 $\text{mmol}\cdot\text{l}^{-1}$ during the cycling exercise test correlated negatively (from $r=-0.39$ to -0.42 ; $P<0.05$ to 0.01) with the individual values of serum total and free testosterone, as well as with the individual values of average and maximal muscle power output (from $r=-0.41$ to -0.49 ; $P<0.05$ to 0.01).

Discussion

The main aim of this study was to examine possible interrelationships between maximal strength, muscle power output, muscle cross-sectional area, serum hormone concentrations and various indices of endurance cycling performance, in two groups of elite athletes who had been engaged in weightlifting and road cycling for several years, and in a group of controls with no systematic training background. As expected, high absolute and relative maximal strength and muscle power output were observed in weightlifters compared with road cyclists and controls. It is well known that, in line with the principles of training specificity, resistance and endurance training induce distinct neuromuscular, physiological and performance improvements (Jürimäe *et al.*, 1997; Kanehisa *et al.*, 1997). Sport-related differences in muscle power output could be attributed to the long-term training-related adaptation of the neuromuscular system with greater maximal strength and muscle mass in the stronger groups (Jürimäe *et al.*, 1997; Kanehisa *et al.*, 1997). In addition, sport-related enhancement of muscle power output production (as observed in weightlifters) may also be related to considerable long-term training-induced changes in the voluntary and/or reflex-induced rapid neural activation of motor units (i.e. improved synchronization and

selective recruitment of fast motor units and/or optimized intramuscular coordination) and/or selective hypertrophy of type II muscle fibres in stronger individuals (Costill *et al.*, 1976; Saltin *et al.*, 1977; Häkkinen *et al.*, 1986; Jürimäe *et al.*, 1997; Kanehisa *et al.*, 1997). Sport-related differences could be also attributable to genetic influences that self-select endurance and/or power athletes.

The differences in the half-squat test between weightlifters, road cyclists and controls were greater during muscle power output with submaximal loads (i.e. 15–80% of one-repetition maximum) than maximal loads. These differences were maintained when power was expressed relative to muscle cross-sectional area or to body mass. Thus, weightlifters showed 45–55% higher power values than road cyclists and controls, whereas the differences in maximal concentric strength and muscle cross-sectional area were only 15% and 20%, respectively. The largest difference observed in the power-generating capacity compared with maximal strength between weightlifters, road cyclists and controls may be related to the specific training status of the weightlifters. Thus, the classic training programme of a weightlifter consists mainly of the actual competitive lifts at near maximal loads, with only a few repetitions per set, as well as assistance exercises performed with additional concentration on speed and explosiveness (power) in most of the training movements. This long-term heavy-resistance/low-repetition training programme, performed with explosive muscle actions, induces only minor hypertrophic changes (Häkkinen *et al.*, 1985b), but it can greatly improve the rapid neural activation of the trained muscle recorded during maximum voluntary contractions. This may explain in part the greater difference observed in the muscle power-generating capacity with submaximal loads than with maximal loads between the weightlifters, road cyclists and controls.

Maximal strength was 28% higher in road cyclists than in controls, but average absolute power at all loads was similar in the two groups. The high values of maximal strength observed in elite road cyclists compared with sedentary controls are due to the significant recruitment of fast-twitch fibres that takes place during cycling training and competition. Thus, at the average submaximal intensities used by elite cyclists during training and competition (60–70% of maximal oxygen uptake; Lucia *et al.*, 2001b), a secondary recruitment of fast-twitch fibres occurs as the slow-twitch fibres become depleted of their glycogen stores (Gollnick *et al.*, 1973b). In addition, during competitive road cycling, short bursts of extremely high, instantaneous power outputs of 800–1000 W, demanding the recruitment of predominantly fast-twitch fibres (Gollnick *et al.*, 1973b), are interspersed with longer periods

of cycling at submaximal intensities. However, the similar average absolute power at all loads during half-squat actions observed in road cyclists and controls is a surprising finding, considering the observed differences in maximal strength between the two groups and its important influence on power production, especially with increasing external loads (Cronin *et al.*, 2000). In addition, the individual values of muscle power output correlated negatively with the individual values of maximal workload and submaximal cycling variables (workloads at 2 and 4 mmol·l⁻¹) attained during the cycling exercise test. This indicates that those participants with lower muscle power outputs may be able to achieve the highest maximal workloads during a progressive cycling test. It is possible that the high volume of aerobic training and competition (12–21 h per week) performed by road cyclists, involving the recruitment of predominantly low force-generating capacity slow-twitch fibres (Coyle *et al.*, 1991), might interfere with the development of muscle power or this inherent attribute is not a limiting factor to be successful in cycling. The results suggest that, in cycling, long-term endurance training may interfere more with the development of muscle power than with the development of maximal strength. It is also likely that differences in muscle fibre distribution between road cyclists and controls (predominance of slow-twitch fibres in endurance athletes compared with untrained individuals) (Costill *et al.*, 1976; Saltin *et al.*, 1977) could contribute, in part, to the differences observed in maximal strength and muscle power output. However, it should be pointed out that, because the study was not longitudinal in nature, any differences between the groups could have developed over time or have developed at an early age.

Several researchers have suggested that body size variables may affect maximal strength and the ability to generate power (Jones and Lindstedt, 1993; Jaric, 2002). In accordance with the results of previous studies (Häkkinen *et al.*, 1986; Patton *et al.*, 1990; Jaric, 2002), body size indicators such as muscle cross-sectional area and body mass correlated positively with the individual values of maximal strength when all participants were pooled. Despite this association, body mass and muscle cross-sectional area accounted for less than 45% of the shared variance in maximal strength and muscle power across individuals. Possible explanations for this poor correlation may be associated with the force–length and force–velocity relationships during movement, including: (1) variations in the specific tension of the involved muscles related to different muscle architecture (i.e. length and muscle pennation angle, myofibrillar packing density) (Gülch, 1994); (2) the influence of antagonist muscles during maximal and/or rapid actions with the agonist muscles; (3) the

contributions of other muscles to the performance of the movement; and (4) the assumption that maximal neural activation of the entire muscle mass can be activated (for a review, see Enoka, 2002).

Maximal oxygen uptake was not measured in this study. However, maximal workload, an accurate predictor of maximal oxygen uptake (Storer *et al.*, 1990), was measured. Maximal workload was 44% higher and submaximal blood lactate accumulation was 50–55% lower with increasing workload in road cyclists than in controls and weightlifters. These differences were maintained when the workload was expressed relative to body mass or to muscle cross-sectional area of the quadriceps femoris muscle group. The specific training status of the participants with respect to cycling exercise is important for the magnitude of the differences observed between road cyclists and the other two groups of participants. It is known that cycling endurance training induces increases in maximal aerobic power and in oxidative capacity (Gollnick *et al.*, 1973a). Thus, endurance-trained cyclists possess a higher maximal oxygen uptake (Tanaka *et al.*, 1993), higher percentage of type I muscle fibres (Coyle *et al.*, 1991), greater muscle capillary density (Coyle *et al.*, 1991), muscle citrate synthase activity (Coyle *et al.*, 1991) and muscle succinate dehydrogenase activity (Gollnick *et al.*, 1973a; Burke *et al.*, 1977) in the leg musculature than sedentary individuals and weightlifters. In addition, elite cyclists are better able to exert force than non-cycling-trained individuals during the knee flexion phase of cycling (Coyle *et al.*, 1991). All these specific adaptations result in slower utilization of muscle glycogen and less lactate production during cycling exercise in cyclists than in weightlifters and controls (Holloszy, 1984). These adaptations played an important role in the performance of road cyclists during the incremental cycling test.

The workloads that elicited blood lactate concentrations of 2 and 4 mmol·l⁻¹ were 50–60% higher and occurred at a higher percentage of maximal workload in road cyclists than in weightlifters or controls. This indicates that road cyclists, in addition to recording higher absolute workloads (expressed in watts) that elicited blood lactate concentrations of 2 and 4 mmol·l⁻¹ than weightlifters and controls, do not accumulate lactate in their blood until they are at a higher percentage of maximal workload. This capacity to exercise at a higher percentage of their maximal aerobic power before blood lactate begins to accumulate is a characteristic of endurance-trained compared with sedentary or strength-trained individuals (Sjodin and Svedenhag, 1985). In addition, this capacity seems to be a more sensitive parameter than maximal workload or maximal oxygen uptake in detecting physiological differences between professional and elite amateur

cyclists (Coyle *et al.*, 1991; Hoogeveen and Zonderland, 1996). Furthermore, the elite amateur cyclists in the present study showed similar average maximal power outputs ($6.9 \text{ W} \cdot \text{kg}^{-1}$ versus $6.0\text{--}7.3 \text{ W} \cdot \text{kg}^{-1}$, respectively) (Hoogeveen and Zonderland, 1996; Padilla *et al.*, 1999) to those reported in the literature for professional cyclists during an incremental test, but recorded lower workloads (expressed in watts) that elicited a blood lactate concentration of $4 \text{ mmol} \cdot \text{l}^{-1}$ (79% versus 84–90% of W_{max} , respectively) (Hoogeveen and Zonderland 1996; Padilla *et al.*, 1999; Lucia *et al.*, 2001b). The factors associated with a lower lactate accumulation for a given percentage of maximal aerobic power in cyclists appear to be years of cycling experience and percent type I muscle fibres (Coyle *et al.*, 1991). The differences between the cycling procedures (i.e. continuous versus discontinuous exercise, duration of the increments, type of cycle ergometer used) used in this and previous studies make it difficult to make comparisons.

No differences were observed in maximal workload or submaximal blood lactate concentration between controls and weightlifters when workload was expressed in absolute terms. However, when workload was expressed relative to body mass or to muscle cross-sectional area of the quadriceps femoris, maximal workload was 11% lower and submaximal blood lactate accumulation was 15–18% higher with a higher workload in weightlifters than in controls. It has been shown that a high submaximal blood lactate response to exercise is mainly determined by peripheral factors such as low capillary density or low oxidative enzyme activities of skeletal muscle (Rusko *et al.*, 1980). The higher submaximal blood lactate concentration found among weightlifters in this study when the workload was expressed relative to muscle cross-sectional area is in line with previous studies that have shown that the activity of oxidative enzymes (Tesch *et al.*, 1989), capillary density (Tesch *et al.*, 1984) and mitochondrial volume density (MacDougall *et al.*, 1979) are lower in weightlifters who perform low-volume, heavy-resistance exercise, than in sedentary individuals. This contrasts with the small but significant improvements in endurance and oxidative capacity that have been observed in young people performing light-resistance, high-volume training (Wilmore *et al.*, 1978; Gettman *et al.*, 1980). The increase in endurance of the strength-trained muscles may be partially mediated by significant fast fibre type conversion (from IIB to IIA) as a result of resistance training (Staron *et al.*, 1991). Unfortunately, oxidative enzyme activity and oxygen consumption were not measured in the present study, and the related underlying mechanisms were not established.

To our knowledge, this is the first study to demonstrate that basal serum total and free testosterone concentrations are lower in elite amateur cyclists than in

age-matched weightlifters or untrained individuals. Subclinically reduced resting serum total testosterone and free testosterone have been observed in elite endurance runners compared with age-matched untrained individuals (Hackney *et al.*, 1988; Wheeler *et al.*, 1991). Although the mechanisms for these alterations in basal hormone concentrations in the endurance-trained male athletes are unknown, they might involve:

- (1) Hypervolaemia. It is known that endurance training in humans is accompanied by a 9–25% increase in plasma volume (Fellmann, 1992). Thus, the 20–29% lower total and free testosterone concentrations found in road cyclists could be explained by the higher plasma volume observed in endurance-trained individuals.
- (2) Loss of body mass and/or low dietary fat. It has been shown that a loss of mass in lean men (Wheeler *et al.*, 1991) and the consumption of a diet low in fat (Volek *et al.*, 1997) can result in a decrease in testosterone. The low body fat (5.8% in the present study) and the consumption of a diet low in fat usually observed in cyclists could explain their low testosterone concentrations.
- (3) There is a possibility that decreased levels of testosterone may be the result of repeated acute changes that occur during previous cycling training sessions without a sufficient period of recovery (Hoogeveen and Zonderland, 1996).
- (4) Dysfunction of the hypothalamic–pituitary–testicular axis of endurance-trained males due to altered central stimulation of the gonads, gonadal impairment (Hackney *et al.*, 1988), greater use of testosterone by muscle tissue or greater hepatic clearance of the hormone (De Souza *et al.*, 1994). This dysfunction may be caused by prolonged and repetitive elevations of gonadal steroids and other hormones (i.e. plasma prolactin, cortisol and testosterone) that occur during daily training and competition in high-standard cyclists (MacConnie *et al.*, 1986).

Finally, we observed that, in the combined group of road cyclists, weightlifters and controls, the individual basal values of anabolic hormones (free testosterone or total testosterone) correlated negatively with the individual values of maximal workload and submaximal cycling variables attained during the cycling exercise test. This indicates that individuals with lower serum anabolic hormones may be able to reach the highest maximal and submaximal workloads during a progressive cycling test. Taken together, these observations suggest that anabolic hormones may affect elite road cycling performance. Further research may determine the reasons and consequences of these alterations in basal serum hormones in endurance-trained males.

In summary, our results show greater maximal strength and muscle power output in the lower extremities of weightlifters compared with cyclists and controls. The differences in half-squat performance between weightlifters, road cyclists and controls were greater with submaximal (i.e. 15–80% of one-repetition maximum) than with maximal loads. When muscle power was expressed relative to muscle cross-sectional area or to body mass, this difference was maintained. Maximal workload was 44% higher and submaximal blood lactate concentration was 50–55% lower with increasing workload in road cyclists than in controls and weightlifters. In road cyclists, the workloads that elicit blood lactate concentrations of 2 and 4 mmol·l⁻¹ were 50–60% higher and occurred at a higher percentage of maximal workload than in weightlifters and controls. Within the limits of the design of the study, the results also show that basal serum total and free testosterone concentrations are lower in elite amateur cyclists than in age-matched weightlifters and untrained individuals. Finally, in the combined group of road cyclists, weightlifters and controls, significant negative correlations were shown to exist between various indices of cycling and the individual values of muscle power output and basal androgenic hormones. The results suggest that, in cycling, long-term endurance training may interfere more with the development of explosive performance than with the development of maximal strength, probably mediated by long-term cycling-related impairment in anabolic hormonal status. These results indicate that the specific training status of individuals with respect to training, resistance and endurance affect the magnitude of the neuromuscular, physiological and performance differences observed between weightlifters and road cyclists.

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