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The effects of strength training on endurance performance and muscle characteristics

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ABSTRACT TOP

The effects of strength training on endurance performance and muscle characteristics. *Med. Sci. Sports Exerc.,* Vol. 31, No. 6, pp. 886-891, 1999.

Purpose: The purpose of this study was to determine the effects of resistance training on endurance performance and selected muscle characteristics of female cyclists.

Methods: Twenty-one endurance-trained, female cyclists, aged 18-42 yr, were randomly assigned to either a resistance training (RT; *N* = 14) or a control group (CON; *N* = 7). Resistance training ($2\times\cdot wk^{-1}$) consisted of five sets to failure (2-8 RM) of parallel squats for 12 wk. Before and immediately after the resistance-training period, all subjects completed an incremental cycle test to allow determination of both their lactate threshold (LT) and peak oxygen consumption V□O_2). In addition, endurance performance was assessed by average power output during a 1-h cycle test (OHT), and leg strength was measured by recording the subject's one repetition maximum (1 RM) concentric squat. Before and after the 12-wk training program, resting muscle was sampled by needle biopsy from m. vastus lateralis and analyzed for fiber type diameter, fiber type percentage, and the activities of 2-oxoglutarate dehydrogenase and phosphofructokinase.

Results: After the resistance training program, there was a significant increase in 1 RM concentric squat strength for RT (35.9%) but not for CON (3.7%) ($P < 0.05$). However, there were no significant changes in OHT performance, LT, V□O_2, muscle fiber characteristics, or enzyme activities in either group ($P > 0.05$).

Conclusion: The present data suggest that increased leg strength does not improve cycle endurance performance in endurance-trained, female cyclists.

Many competitive endurance athletes incorporate resistance training into their training in the hope that it will improve endurance performance. However, adaptations to exercise are generally considered to be specific to the type of training stimulus. For example, light resistance, high repetition endurance exercises, such as running, swimming, and cycling generally increase V□O_2 without increasing strength (23). In contrast, heavy resistance, low repetition resistance exercises normally increase strength (16,47) with little or no change in V□O_2 (4,26).

Although many adaptations are specific to the type of training, some changes that occur with resistance training could potentially influence endurance performance. For example, muscle fiber hypertrophy generally associated with heavy resistance training may decrease the oxidative potential per total muscle mass (47) and impair endurance performance. In contrast, fiber transformations after resistance training (IIB → IIA; 4,46) are similar to those reported for endurance training (IIB → IIA → I; 1,25) and may assist endurance performance. Furthermore, it has been hypothesized that resistance training may improve endurance cycling performance by decreasing the proportion of the maximal pedal force required for each pedal thrust and altering the pattern of fiber recruitment during cycling (22).

To date, only three studies have investigated the influence of resistance training on endurance performance. Recently, Bishop and Jenkins (4) reported that, in untrained male subjects, 6 wk of resistance training did not significantly improve endurance performance, despite significantly increasing one repetition maximum (1 RM) leg press. Hakkinen et al. (18) have reported that, in response to resistance training, fast-twitch (FT) fiber hypertrophy precedes that in slow-twitch (ST) fibers and that significant ST fiber hypertrophy is not evident during the first 8 wk of resistance training. Therefore, 6 wk of resistance training may not have been of sufficient duration to induce adaptations in the ST fibers, the predominant fiber type recruited during endurance exercise.

Two longer duration studies have reported significantly improved cycle endurance performance after 10-12 wk of resistance training (22,33). However, both these studies employed high volumes (> 30 sets·wk^{-1}) of lower body resistance training. As many of the adaptations to resistance training are dependent on the volume of training, it remains to be determined whether increases in strength or other adaptations were responsible for the reported improvements in endurance performance.

It should also be noted that both previous studies reporting improved endurance performance after resistance training have used time-to-fatigue tasks to assess changes in endurance performance (22,33). Time-to-fatigue tests have been criticized for not accurately representing endurance performance and for being unreliable (28). The coefficient of variation (CV) reported for time-to-fatigue tasks has been reported to be 18.0-26.6% (28,35). In contrast, the CV for time-trial protocols, lasting approximately 1 h, has been reported to be less than 3.0% (3,28). The influence of resistance training on endurance performance could therefore be more reliably assessed by using a time trial protocol.

Thus, the purpose of the present study was to examine the influence of 12 wk of low-volume resistance training, designed to increase maximum strength, on time-trial performance, V□O_2, LT, muscle fiber-type composition, and the activities of phosphofructokinase (PFK) and 2-oxoglutarate dehydrogenase (OGDH) in endurance-trained female cyclists. It was hypothesized that increases in leg strength would be confined to the training exercise and would not produce improvements in endurance cycling performance.

METHODS TOP

Experimental overview. Twenty-one trained female cyclists (18-42 yr) were randomly assigned to a resistance training group (RT; *N* = 14) or to a control group (CON; *N* = 7). Subjects had been cycling for 2.5 ± 1.2 yr (range = 1.0-5.0 yr). Before initial testing, each subject was familiarized with the testing protocol and completed a full practice testing session. Testing was conducted at week 0 and week 12 (i.e., immediately pre- and post-training). The test data included V□O_2 and LT, endurance performance, 1 RM concentric-squat strength, fiber type, and the activities of PFK and OGDH in the m. vastus lateralis; 1 RM squat strength and endurance performance were also measured at week 6 to assess the time course of potential changes in strength and endurance. Body mass was measured pre- and post-training using a calibrated, balance beam scale (Mercury 211FP, Thebarton, Australia).

Supervised resistance training was performed twice a week and undertaken at least 24 h after normal off-season, endurance-training sessions. None of the subjects had been resistance training in the 6 months before inclusion in this study. All subjects were asked to maintain their normal endurance-training program; in addition, control subjects were asked to avoid any resistance training. Daily activity for all participants was recorded in a logbook. After being fully informed of the risks associated with participation, each subject gave her written consent. Testing procedures were approved by the Medical Research Ethics Committee of The University of Queensland.

Peak V□O $_2$. Peak V□O_2 was determined on an electronically braked cycle ergometer (Lode Excalibur Sport, Quinton, Seattle, WA) using a continuous test modified from that described by Bruce et al. (8). The saddle and handle bar positions of the cycle ergometer were adjusted to resemble each cyclist's bicycle. Subjects first completed a 5-min warm-up cycling at 50 W and then the V□O_2 test commenced at an initial workload of 50 W with increments of 25 W applied at 3-min intervals until exhaustion. Expired air was collected each minute in Douglas bags and later analyzed for F_EO_2 and F_ECO_2 using Ametek gas analyzers (SOV S-3A11 and COV CD3A, Pittsburgh, PA); ventilation (V□E) was also recorded every min using a turbine ventilometer (Morgan, model 096, Kent, England).

The gas analyzers were calibrated immediately before and after each test using a certified gravimetric beta gas mixture (Commonwealth Industrial Gas Ltd., Brisbane, Australia); the ventilometer was calibrated pre- and post-exercise using a 1-L syringe in accordance with the manufacturer's instructions. In addition to calculating each subject's V□O_2, the peak power output achieved at the end of the V□O_2 test (W_{peak}) was also recorded (21).

Lactate analysis. Finger-tip capillary blood (20 µL) was sampled during the last 30 s of each 3-min work bout during the V□O_2 test. Plasma lactate was determined from these samples using reflectance spectrophotometry (Kodak Ektachem DT60, Doncaster, Australia). The lactate threshold (LT_D) was calculated using the D_{max} method (9). This method has been shown to be reliable (55) and related to endurance performance (5).

Endurance performance. Endurance performance was assessed by averaging the second-by-second power output (W) produced during the OHT. This test has been shown to be both a valid (12) and reliable (3) measure of endurance performance. Exercise was completed on a calibrated, wind-braked cycle ergometer (South Australian Sports Institute, Adelaide, Australia), in controlled environmental conditions (temperature = 19-21°C, relative humidity = 55-65%, and barometric pressure = 760-770 mm Hg). This ergometer was equipped with racing handlebars and seat as well as "aero bars" and the cyclist's own pedals for cleated shoes. The subjects were instructed to generate the highest power output possible throughout the 60 min of cycling. During the initial 8 min of exercise the power output was preset, based on performance prediction from the results of the incremental exercise test, after which subjects could vary both pedal cadence and force (12). Subjects were continually provided with visual feedback of pedalling cadence, power output, HR, and elapsed time.

1 RM Concentric squat strength. Each subject's 1 RM strength was determined for the concentric squat (Plyopower, Lismore, Australia). After three warm-up lifts, the subject's near maximal resistance was estimated. The resistance was then gradually increased until the subject could only lift the resistance once (1RM) and not twice. This was recorded as the subject's 1 RM. Feet position and bar height for the concentric squat were positioned so that the subject began the squat with her knees at an angle of 90°. There was at least 5 min rest between each attempt.

Muscle sampling and analyses. Three days after the strength test, muscle (80-120 mg) was sampled from the vastus lateralis muscle (mid-way between the anterior superior iliac spine and the patella) using the needle biopsy technique (6) with suction (15). Due to reported variations in fiber type distribution from superficial to deep and proximal to distal (6), we attempted to standardize the biopsy location by using depth markings on the needle and taking the posttest sample □0.5 cm lateral to the biopsy scar. The muscle sample was divided in two; the largest sample was mounted in OCT embedding medium (TissueTek, Thuringowa, Australia), quickly immersed in isopentane cooled in liquid nitrogen for 1 min and stored at -70°C until later histochemical analysis. The muscle samples were sectioned (10 µm) in a cryostat at -20°C, and placed on glass coverslips for histochemical analysis. The fibers were stained histochemically for identification of Type I, Type IIa, and Type IIb fibers by the myofibrillar adenosinetriphosphatase reaction using acid and alkaline preincubation (7). Fiber areas and least fiber diameter were calculated on a Macintosh 8100 av computer using the public domain NIH Image program (version 1.57, Springfield, VA).

A second portion of the sample was quickly frozen in liquid nitrogen and also stored at -70°C until analyzed for 2-oxogluterate dehydrogenase (OGDH) activity (44) and phosphofructokinase (PFK) activity (17). The activities of enzymes were measured fluorometrically (AmincoBowman Series 2 Luminescence Spectrometer, Urbana, IL), with the spectrometer compartment maintained at 5°C with a circulator bath. Enzyme activities,

determined from the linear portion of the reaction time course were calculated in μmol·g^{-1}·wet weight·min^{-1} and in μmol·g^{-1}·protein·min^{-1}. Protein concentration in the homogenate was measured as described by Lowry and Passonneau (31).

Resistance training. The twice-weekly resistance training sessions were conducted and supervised at the Department of Human Movement Studies. Squat training was performed on a "Plyopower" resistance machine (Lismore, Australia) and each session commenced with a 5-min general warm-up on a cycle ergometer followed by 5 min of stretching. A specific warm-up also preceded each session and involved:

SET 1: 15 repetitions with 50% of 1 RM

SET 2: 8 repetitions with 70% of 1 RM

SET 3: 5 repetitions with 80% of 1 RM

To maximize strength gains, the training program was periodized with respect to resistance, number of sets, and repetitions (Table 1). A 3-min rest period was enforced between all sets.

	Week					
	1–2	3–4	5–6	7–8	9–10	11–12
Sets	5	4	3	5	4	3
Repetitions	6–8 RM	4–6 RM	2–4 RM	6–8 RM	4–6 RM	2–4 RM

TABLE 1. Resistance training program for the training group.

Statistics. After the 12-wk training period, the results of each dependent variable were analyzed by a two-way ANOVA (2 groups by 2 or 3 times) with repeated measures on time. Alpha was preset at 0.05, and a Newman Keuls *post hoc* test was applied when significance was found.

RESULTS TOP

Effectiveness of the training program. The 12-wk training program resulted in a significantly greater increase in 1 RM squat strength for RT (35.9%) than for CON (3.7%; Fig. 1). The strength improvement in RT was significantly greater than the strength improvement in CON after 6 wk ($F[1,19] = 14.32$, $P < 0.01$) and also after 12 wk ($F[1,19] = 19.68$, $P < 0.001$). There was a significant effect of time on body mass ($F[2,38] = 4.24$, $P < 0.05$). *Post hoc* analysis revealed that posttraining and mid-training body mass were significantly different from pretraining body mass in RT only ($P < 0.05$). There was no significant difference between the average volume of endurance training conducted by CON (123.6 ± 35.8 km·wk^{-1}) and RT (110.2 ± 29.4 km·wk^{-1}) ($F[1,19] = 0.11$, $P = 0.64$).

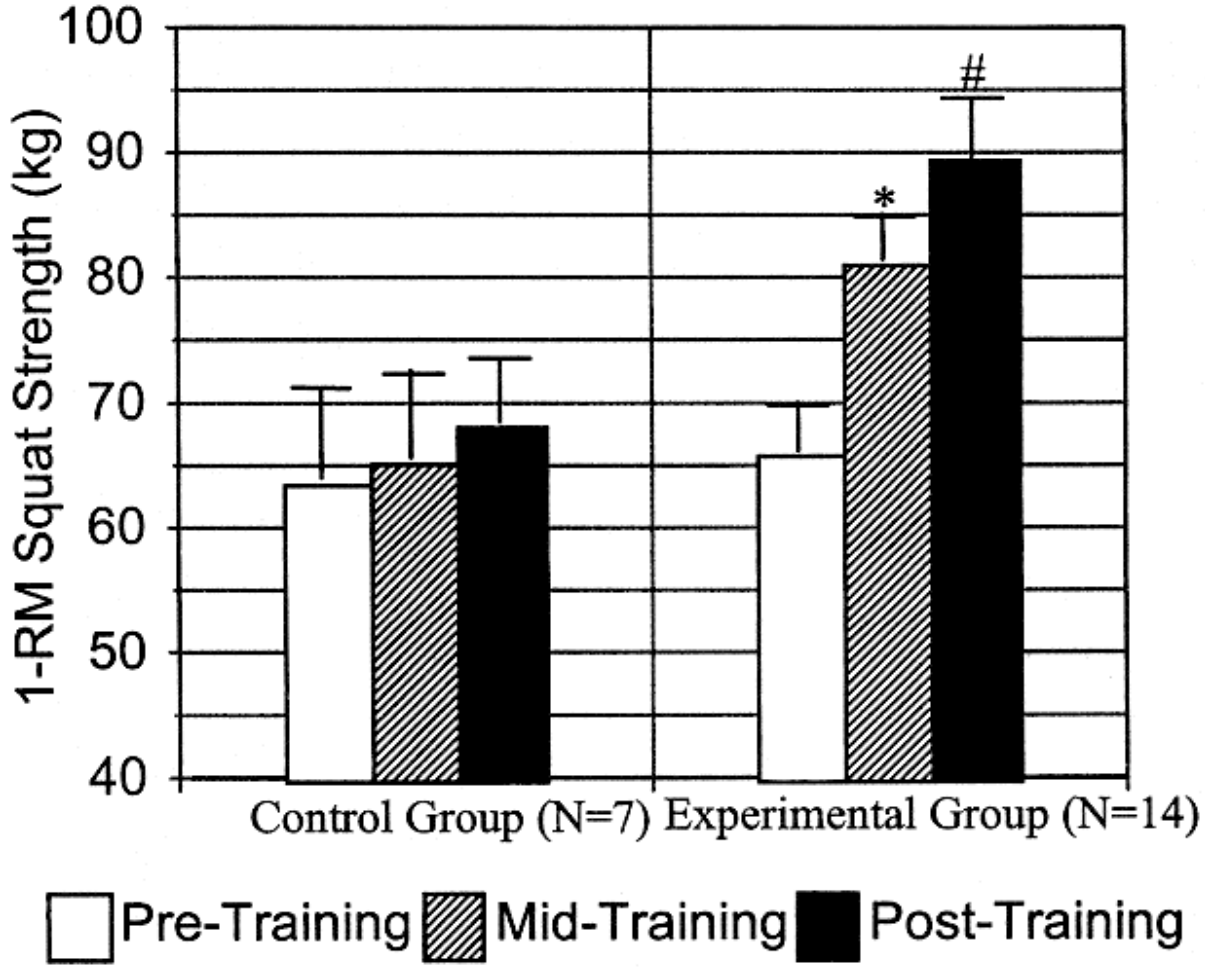

Figure 1-1 RM squat values (mean ± SD) at weeks 0, 6, and 12 in both the control and training groups. (*P < 0.01; significantly different from week 0; #P < 0.001; significantly different from week 0 and week 6).

Peak V□O $_2$, LT $_D$, and OHT performance. There was no significant change in V□O_2 expressed either in mL·kg^{-1}·min^{-1} (F[1,19] = 0.001, P = 0.98; Table 2) or L·min^{-1} (F[1,19] = 0.140, P = 0.71; Table 2) after the 12 wk of resistance training. There was also no significant change in the LT ($F_{[1,19]}$ = 0.119, P = 0.73) or OHT performance (F[1,19] = 0.379, P = 0.69; Table 2).

	Body Mass (kg)	Peak $\dot{V}O_2$ (mL·kg^{-1}·min^{-1})	Peak $\dot{V}O_2$ (L·min^{-1})	LT (W)	OHT (W)
Training group					
Pretraining	59.3 ± 1.7	48.2 ± 5.8	2.97 ± 0.32	177.7 ± 35.0	186.1 ± 20.3
Mid-training (week 6)	60.0 ± 1.6				185.3 ± 18.8
Posttraining	60.2 ± 1.7	48.4 ± 5.5	2.90 ± 0.30	183.3 ± 24.1	187.9 ± 20.4
Control group					
Pretraining	60.3 ± 2.4	48.3 ± 6.7	2.86 ± 0.16	179.1 ± 11.7	186.8 ± 14.5
Mid-training (week 6)	60.3 ± 2.3				184.8 ± 14.8
Posttraining	60.7 ± 2.5	48.4 ± 9.7	2.86 ± 0.33	179.9 ± 15.5	192.1 ± 14.7

TABLE 2. Peak V□O_2, lactate threshold (LT), and 1-h test (OHT) performance results in control and training subjects before and after the 12-wk resistance-training program (values are mean ± SD).

Enzyme activities. There were no significant changes in PFK (F[1,13] = 0.391, P = 0.54) or OGDH activities (F[1,13] = 0.339, P = 0.57) in either RT or CON after the 12-wk period (Table 3).

	Enzyme Activity ($mmol \cdot mg^{-1} \cdot min^{-1}$)		Fiber Percentage			Fiber Area (μm^2)		Fiber Least Diameter (μm)	
	PFK	OGDH	Type I	Type IIa	Type IIb	Type I	Type II	Type I	Type II
Control group									
Pretraining	25.6 ± 7.6	0.95 ± 0.24	58.0 ± 17.1	38.3 ± 13.8	3.0 ± 2.9	4195 ± 1045	3769 ± 932	53.6 ± 5.2	51.0 ± 2.2
Posttraining	23.8 ± 7.9	0.94 ± 0.29	52.4 ± 24.6	42.8 ± 19.9	4.1 ± 3.4	3799 ± 803	3962 ± 1486	49.7 ± 3.3	51.7 ± 6.5
Training group									
Pretraining	24.0 ± 11.2	1.02 ± 0.49	54.3 ± 14.6	45.6 ± 13.6	1.4 ± 2.3	4255 ± 1588	3761 ± 1093	52.6 ± 6.1	50.0 ± 7.0
Posttraining	20.4 ± 9.7	1.05 ± 0.42	59.8 ± 13.5	39.2 ± 14.2	1.3 ± 2.2	4179 ± 1584	3797 ± 1104	52.9 ± 7.4	51.1 ± 8.4

TABLE 3. Changes in OGDH and PFK activities and muscle fiber characteristics of the vastus lateralis after 12 wks of resistance training (values are mean ± SD).

Muscle fiber characteristics. A mean of 320 muscle fibers per sample were used to determine all muscle fiber characteristics. Vastus lateralis fiber composition did not change significantly in either group after the training period ($F[1,15] = 0.051$, $P = 0.82$; Table 3). There were also no significant changes in Type I fiber area ($F[1,15] = 0.134$, $P = 0.72$), Type II fiber area ($F[1,15] = 0.051$, $P = 0.82$), Type I least diameter ($F[1,15] = 0.164$, $P = 0.69$), or Type II least diameter ($F[1,15] = 0.065$, $P = 0.80$; Table 3).

DISCUSSION TOP

The female cyclists in the present study achieved significant gains in 1 RM squat strength after resistance training was added to their endurance training for 6 wk (22.5%; $P < 0.01$) and for 12 wk (35.9%; $P < 0.001$). However, despite comparable gains in leg strength to those reported in male subjects after 12 wk of circuit-weight training (□40%; 32) and greater gains in leg strength than those reported after 10 wk of resistance training (27%; 22), the present resistance-training program did not improve endurance performance. This contrasts with the findings of previous studies reporting that 10-12 wk of resistance training can enhance cycle endurance performance (22,33) and that this improvement is related to increases in leg strength. It is, however, consistent with the present study's unchanged measures of $V□O_2$, LT_D, muscle fiber composition, and oxidative enzyme activity.

Consistent with the present findings, previous studies have typically reported no change in $V□O_2$ (4,22,26,33) or oxidative enzyme activity (24,48) in response to resistance training. However, the unchanged fiber composition, observed in the present study, contrasts with the findings of other resistance training studies which have reported an increased Type IIa percentage at the expense of a decreased Type IIb percentage (20,45,46). The absence of changes in fiber composition in the present study can most likely be attributed to the subjects' small initial percentage of Type IIb fibers (1.4%). In previous studies demonstrating fiber conversions in women, the initial percentage of Type IIb fibers was greater than 15% (45,46). Thus, because of their training status, subjects in the present study may have possessed limited potential for Type IIb to Type IIa fiber transition.

Despite also finding no change in $V□O_2$, oxidative enzyme (citrate synthase) activity, or fiber composition, Hickson et al. (22) reported that resistance training improved endurance-cycling performance in endurance-trained male subjects. They argued that this indicated that increases in leg strength, rather than metabolic adaptations, were responsible for the improvements in endurance performance after resistance training. Similarly, Marcinik et al. (33) suggested that increased leg strength was also responsible for the improvements in the LT and endurance performance reported in their study. Increased leg strength, however, did not result in improved endurance performance in the present study.

Hickson et al. (22) suggested that an increase in leg strength may improve time to exhaustion by decreasing the proportion of the maximal force required for each pedal thrust, thus altering the fiber-type recruitment during exercise. This would theoretically increase participation by Type I fibers and delay recruitment of the more glycolytic Type II fibers. Postponement of Type II fiber involvement may reduce glycogenolysis and lactate production and improve time to exhaustion. However, a proportional increase in maximal pedal force may not necessarily occur after lower-body resistance training. After 12 wk of leg-extension training, Rutherford et al. (39) reported a large increase (200%) in the weight lifted but no improvement in the peak power measured on a cycle ergometer. This is consistent with the results of other studies which demonstrate that improvements in training exercises exceed improvements in unfamiliar actions using the same muscles

(38,50,53). Movement specificity may therefore explain why increased leg strength did not result in improved endurance performance in the present study. That is, the increased leg strength in the present study may have been confined to the training exercise (i.e., 1 RM squat) and not transferred to endurance-cycling performance.

In addition to being movement specific, gains in strength also appear to be velocity specific. Velocity specificity is characterized by the greatest gains in strength occurring at or near the velocity of the resistance-training exercise. Although a velocity-specific training response has not been observed in all studies (14,37), it has been observed when isokinetic training is performed at different velocities (11,29,36) and when conventional heavy-resistance training was compared with "explosive" jump training (19). Although muscle contraction velocity was not measured during either mode of exercise in the present study, previous research has reported the average preferred cadence for cyclists to be 85 rpm (34). This is likely to be considerably higher than the "cadence" used in the high-resistance, low-repetition resistance training employed in this study. Thus, a velocity-specific adaptation to the "slow" maximal strength training employed in the present study may also have contributed to the inability of the present resistance-training program to improve cycle endurance performance.

Despite the possible influence of movement and/or velocity specificity upon strength gains, two previous studies have reported improvements in endurance performance after resistance training (22,33). However, the nonsignificant change in endurance performance in the present study and a previous study (4), despite comparable gains in leg strength, suggests that factors other than increased leg strength may have been responsible for the improvements in endurance performance reported by Hickson et al. (22) and Marcinik et al. (33) after resistance training.

Many of the adaptations to resistance training appear to be dependent on the volume of training. Therefore, adaptations resulting from the higher volumes of lower-body resistance training performed in the studies by Hickson et al. (22)(5 RM, 33 sets·wk^{-1}) and Marcinik et al. (33)(15-20 RM, 45 sets·wk^{-1}), when compared with the present study (2-8 RM,6-10 sets·wk^{-1}), rather than increases in leg strength, may have been responsible for the previously reported improvements in endurance performance (22,33). For example, it appears that left-ventricular volume is increased by bodybuilding-type resistance training but not Olympic or power lifting-type training (13). Similarly, it has been reported that bodybuilders (2,42) but not weight/power lifters (49) have more capillaries per fiber than untrained controls. It has also been shown that high-volume resistance training can increase muscle glycogen stores (32) and oxidative enzyme activity (41). These and other volume-dependent adaptations to resistance training may explain the increased endurance performance reported by Hickson et al. (22) and Marcinik et al. (33) but not the present study, despite similar increases in leg strength.

As both previous studies reporting improvements in endurance performance have involved male subjects (22,33), there also remains the possibility that resistance training improves endurance performance in male but not female subjects. Male subjects normally have 10 times the blood testosterone levels of female subjects (54) and female subjects typically do not demonstrate an exercise-induced increase in testosterone consequent to resistance training (30,51). However, studies have failed to find gender differences in the relative proportion of slow and fast-twitch muscle fibers and selected enzyme activities (10,40,43) or muscular strength relative to cross-sectional area (27,52). Therefore, the lower levels of testosterone and the lack of exercise-induced increase in testosterone consequent to resistance training appear to be the most striking difference between male and female subjects. Whether or not such differences influence changes in endurance performance as a result of resistance training remain to be demonstrated.

In summary, the major finding of the present study is that 12 wk of high resistance, low repetition, resistance training significantly improved 1 RM squat strength but did not improve endurance performance in endurance-trained female cyclists. This contrasts with two previous studies but is consistent with the unchanged V□O_2, LT_D, muscle fiber composition and oxidative enzyme activity observed in the present study. The gains in 1 RM squat strength observed in the present study were similar to the leg-strength gains reported in previous studies that have reported improvements in endurance performance. This suggests that factors other than an increase in leg strength *per se* (e.g., volume of resistance training) may be responsible for previously reported improvements in endurance performance after resistance training.

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