Maximal Leg-Strength Training Improves Cycling Economy in Previously Untrained Men

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ABSTRACT

LOVELESS, D. J., C. L. WEBER, L. J. HASELER, and D. A. SCHNEIDER. Maximal Leg-Strength Training Improves Cycling Economy in Previously Untrained Men. *Med. Sci. Sports Exerc.*, Vol. 37, No. 7, pp. 1231–1236, 2005. **Purpose:** This study examined cycling economy before and after 8 wk of maximal leg-strength training. **Methods:** Seven previously untrained males (25 ± 2 yr) performed leg-strength training 3 $\text{d}\cdot\text{wk}^{-1}$ for 8 wk using four sets of five repetitions at 85% of one repetition maximum (1RM). Body mass, lean-leg muscle mass (LLM), percentage of body fat, and leg strength (1RM) were measured at 0, 4, and 8 wk of training. Cycling economy was calculated as the $\Delta\dot{V}O_2/\Delta WR$ (change in the O_2 cost of exercise divided by the change in the power between two different power outputs). **Results:** There were significant increases in LLM and 1RM from 0 to 4 wk of training (LLM: 25.8 ± 0.7 to 27.2 ± 0.8 kg; 1RM: 138 ± 9 to 215 ± 9 kg). From 4 to 8 wk of training, 1RM continued to increase significantly (215 ± 9 to 266 ± 8 kg) with no further change observed in LLM. Peak power during incremental cycling increased significantly (305 ± 14 to 315 ± 16 W), whereas the power output achieved at the gas-exchange threshold (GET) remained unchanged. Peak O_2 uptake and the O_2 uptake achieved at the GET also remained unchanged following training. Cycling economy improved significantly when the power output was increased from below the GET to above the GET but not for power outputs below the GET. **Conclusion:** Maximal leg-strength training improves cycling economy in previously untrained subjects. Increases in leg strength during the final 4 wk of training with unchanged LLM suggest that neural adaptations were present. **Key Words:** DYNAMIC EXERCISE, OXYGEN CONSUMPTION, RESISTANCE TRAINING, HEAVY EXERCISE, EFFICIENCY

It is common for endurance athletes to perform both strength and endurance training in order to improve race performance. It was initially thought that the strength-training regimen should consist of low resistance with a higher number of repetitions (traditional resistance training). However, several recent studies have demonstrated that a period of strength training using high resistance and a low number of repetitions with maximum velocity of the concentric phase (maximal strength training), increased time to exhaustion and/or reduced race times (16,18,25). Endurance performance and aerobic fitness are improved by increasing the body's ability to take up, distribute, and use O_2 and are commonly assessed as an increase in peak O_2 uptake ($\dot{V}O_{2peak}$) and the gas-exchange threshold (GET) and/or improved exercise economy (6). It is well established that strength training does not alter $\dot{V}O_{2peak}$ or the GET (17). This suggests that enhanced endurance performance after maximal strength training is associated with improved exercise economy.

A series of studies by Hoff et al. (16,18) and Østerås et al. (25) has shown that an 8- to 12-wk period of maximal strength training improves running (16) and cross-country skiing (18,25) race times or time to exhaustion. The increase in endurance performance after strength training found in these studies (16,18,25) occurred with no changes in $\dot{V}O_{2peak}$ or the GET but with improvements in running and cross-country skiing economy. The specific strength-training adaptations responsible for improving exercise economy are unclear. These studies used athletes who were performing concurrent strength and endurance training and a control group that performed endurance training only. Therefore, it is unclear whether improvements in running and cross-country skiing economy are due to a combination of strength and endurance training or whether strength training alone also improves economy.

Only one previous study has examined the impact of a period of strength training on cycling efficiency (3). Bastiaans et al. (3) investigated cycling time trial performance and efficiency in two groups of trained cyclists following either 9 wk of concurrent strength and endurance training (experimental group) or 9 wk of endurance training only (control group). Cycling time trial performance improved significantly in both the experimental and control groups, with the level of improvement being the same in both

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groups. Although cycling efficiency appeared to improve in the combined strength- and endurance-trained group, the increases were not statistically significant. The investigators concluded that it is unclear whether strength training improves cycling efficiency. Previous strength-training studies observing improvements in running and skiing economy used maximal strength training, which is different from the traditional resistance training used by Bastiaans et al. (3) (four sets of 30 repetitions at a low weight and high speed of movement). The traditional resistance-training program may not have resulted in the training adaptations needed to improve cycling efficiency (9) in the study by Bastiaans et al. (3). The specific training adaptations that could improve cycling efficiency have not been investigated and are not well understood.

In contrast to traditional resistance training, maximal strength training consists of low repetitions (fewer than six) of a high intensity with an explosive velocity of the concentric movement. This form of strength training usually results in large improvements in strength with minimal muscle hypertrophy (4,22). The high-intensity and fast-velocity characteristics of maximal strength training are thought to result in neuromuscular adaptations that may be less likely to occur with traditional resistance training. Neural adaptations following maximal strength training in athletes may be responsible for the improved running and cross-country skiing economy found in previous studies. If this is the case, exercise economy may not only be improved by combined strength and endurance training but also by maximal strength training alone.

To our knowledge, no previous study has examined the influence of maximal leg-strength training on cycling economy in previously untrained subjects. Previous research suggests that neuromuscular adaptations associated with strength training improve the neuromuscular function and contractile properties within the trained muscle that increases the muscle force production and performance (13). Changes in neuromuscular function and muscle fiber recruitment patterns associated with maximal strength training may improve cycling economy. The purpose of the present study was to determine whether an 8-wk period of maximal leg-strength training, in the absence of concurrent endurance training, improves economy during moderate- or high-intensity cycling in previously untrained male subjects.

METHODS

Subjects. Seven healthy, untrained male subjects (age 25 ± 2 yr; height 179 ± 2 cm) volunteered to participate in the present study. Volunteers were considered untrained if they were not currently training or participating in exercise for more than 2 $d \cdot wk^{-1}$. The Griffith University human research ethics committee approved the study, and informed consent was obtained from each subject. Power calculations were performed in order to determine that the sample size of seven was adequate. A large effect size of 1.0 was chosen to ensure that any observed changes in the measured variables were physiologically significant. Significance was set at 0.05, and for a paired sample, two-tailed *t*-test, the power value obtained was 0.89.

Experimental procedures. All pre- and posttraining test procedures and the strength-training program were completed within a 10-wk period. Pre- and posttraining tests consisted of identical procedures that included five separate cycle ergometry tests, anthropometric measurements, and leg-strength assessment performed over five consecutive days. Additionally, anthropometric measurements were obtained at week 4, and leg strength was assessed at 2-wk intervals during the training program. Posttraining tests commenced at least 2 d after completing the 8-wk strength-training program, but no more than 4 d after training. Pretest familiarization and the monitoring of physical activity and dietary patterns allowed the subjects to sufficiently act as their own controls.

All five exercise tests were performed on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, the Netherlands). Pedal cadence was maintained at 70 rpm for all tests to ensure that any changes in $\dot{V}O_2$ or power output were due to strength training and not due to a change in cadence. The pedal cadence during all cycling tests was continuously monitored visually by the subject and supervised by one of the investigators. The first test performed by each subject was an incremental cycling test (25 $W \cdot min^{-1}$) to volitional fatigue in order to determine $\dot{V}O_{2peak}$ and to estimate the GET using standard, noninvasive, gas-exchange criteria (27). Subsequently, four constant-load cycling tests were performed to determine cycling economy. The constant-load cycling tests were performed for 7 min at three power outputs below the subject's GET (30, 60, and 90% of GET) and at one power output above the subject's GET (120% of GET). All constant-load tests were preceded by 3 min of cycling at a power output corresponding to 20% of the power output achieved at the GET. The four constant-load tests were conducted in random order over 3 d with the two tests of lowest intensity performed 30 min apart on the same day. This was to ensure that the subjects were fully recovered between tests.

Experimental equipment. During each of the five cycling tests, pulmonary gas exchange was measured breath by breath using a metabolic measurement system (MedGraphics CardiO_2, Cardiopulmonary Diagnostic Systems, St. Paul, MN). Subjects wore a nose clip and breathed through a low-resistance mouthpiece and volume sensor assembly (pneumotachograph). Gases were drawn continuously from the mouthpiece assembly through a capillary line and analyzed for O_2 and CO_2 concentrations by fast-response analyzers. The O_2 and CO_2 analyzers and the pneumotachograph were calibrated before and after each test using gases of known concentration and a 3-L syringe, respectively. Heart rate and rhythm were monitored continuously during exercise using a CM5 electrode configuration and a Lohmeier electrocardiograph (M607, Munchen, Germany), with the ECG signal transferred into the metabolic measurement system for storage.

Determination of cycling economy. Breath-by-breath $\dot{V}O_2$ data were averaged over 60-s intervals with the last minute of each test used as a measure of the O_2 cost for each predetermined power output. Cycling economy was calculated as the $\Delta\dot{V}O_2/\Delta WR$ ($mL \cdot min^{-1} \cdot W^{-1}$), where $\dot{V}O_2$ ($mL \cdot min^{-1}$) measured during the last 60 s of each exercise bout was averaged and the difference between two exercise intensities ($\Delta\dot{V}O_2$) was then divided by the difference between the two power outputs (ΔWR) (e.g., between 30% GET and 60% GET or between 90% GET and 120% GET) (14).

Maximal strength-training program. Fully supervised maximal leg-strength training was undertaken for 8 wk using a hack-squat apparatus. The protocol used for the maximal leg-strength training was consistent with the methods previously described by Hoff et al. (17) consisting of four sets of five repetitions performed 3 $d \cdot wk^{-1}$. The weight (kg) lifted was equal to 85% of the weight lifted for one repetition maximum (1RM) with subjects instructed to perform at maximal speed during the concentric phase of the squat. Training weight was readjusted after each 2-wk 1RM measurement to allow for continued strength improvements.

Leg-strength assessment. Leg strength was assessed as 1RM (at 0, 2, 4, 6, and 8 wk of the maximal leg-strength training program) using the same hack-squat apparatus that was used for training. Subjects were familiarized with the hack-squat apparatus, and a pretest 1RM measurement was made in the week leading up to the first 1RM measurement and the commencement of training. After two five-repetition warm-up sets at 20 kg, an eight-repetition maximum (8RM), and a three-repetition maximum (3RM) were performed. The subject's near-maximal resistance was then estimated, and the subject performed one lift of this weight. Following a 4-min recovery period, the weight was slightly increased, and subjects performed another one repetition until failure. The last weight fully lifted, with correct form, was recorded as the subject's 1RM (kg).

Determination of lean-leg mass and percentage of body fat. Anthropometric techniques previously described by Shephard et al. (28) were used to determine lean-leg muscle mass (LLM, kg). Measurements were obtained at 0, 4, and 8 wk of training to determine changes in LLM that occurred as a result of maximal strength training. The percentage of body fat (%BF) was determined using skinfold measurements (mm) that were converted to body density and subsequently to %BF according to formulas previously described (11).

Data analysis. All group data are reported as means and SEM (±SEM). A paired sample *t*-test was used to compare differences in pre- and posttesting measurements of cycling economy, $\dot{V}O_{2peak}$, peak power, and the GET. A repeated-measures ANOVA with Bonferroni *post hoc* adjustments was used to determine significant changes in physical characteristics (body mass, %BF, and LLM) at 0, 4, and 8 wk of training and significant changes in 1RM (kg) at 0, 2, 4, 6, and 8 wk of training. Pearson correlation coefficients were calculated to examine relationships between changes in physical characteristics, leg strength, incremental cycling data, and cycling economy. Statistical significance was accepted at $P < 0.05$.

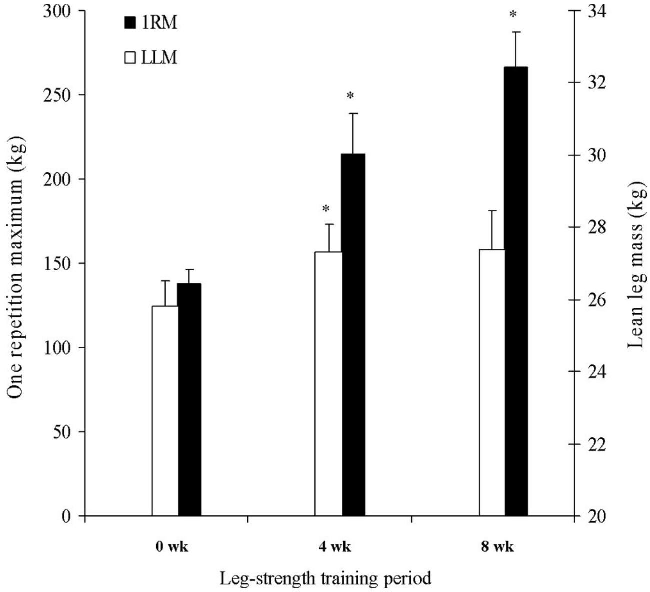

FIGURE 1—Increase in lean-leg muscle mass (LLM) and one repetition maximum (1RM) from 0 to 8 wk of maximal leg-strength training. Values presented are means ± SEM. *Significantly different from previous measurement; $P < 0.05$.

RESULTS

Physical characteristics and leg strength. There were no significant changes in body mass (73.1 ± 1.2; 74.6 ± 2.0 kg) and %BF (16.1 ± 1.0; 14.8 ± 1.1%) from 0 to 8 wk of training. Figure 1 shows that the first 4 wk of training resulted in significant increases in LLM, with no further significant change at 8 wk of training. Leg strength increased significantly over the training period (Fig. 1), with a 97 ± 11% increase in 1RM weight from 0 to 8 wk of training. The greatest increase in leg strength occurred following the first 4 wk of training (58 ± 6%). Despite the continued increase in leg strength from 4 to 8 wk of training (39 ± 6%), LLM did not change significantly during the final 4 wk of training.

Peak exercise and GET values. Table 1 presents the peak exercise values and GET values achieved during incremental cycling pre- and posttraining. The peak power achieved during the incremental cycling test increased significantly after 8 wk of training. $\dot{V}O_2$ expressed in absolute terms ($L \cdot min^{-1}$) and relative to body mass ($mL \cdot kg^{-1} \cdot min^{-1}$), and peak exercise

TABLE 1. Peak exercise and values obtained at the GET during incremental cycling.

	Pretraining	Posttraining
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	3.29 ± 0.25	3.45 ± 0.22
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	46.7 ± 2.4	46.7 ± 2.9
Peak HR ($beats \cdot min^{-1}$)	197 ± 2	191 ± 4
Peak power output (W)	305 ± 14	315 ± 16*
$\dot{V}O_2$ at GET ($L \cdot min^{-1}$)	1.75 ± 0.12	1.74 ± 0.39
Power output at GET (W)	137 ± 11	134 ± 10

Values presented are means ± SEM. $\dot{V}O_{2peak}$, peak oxygen uptake; $\dot{V}O_2$, oxygen uptake; GET, gas-exchange threshold.
*Significantly different from pretraining; $P < 0.05$.

TABLE 2. $\Delta\dot{V}O_2/\Delta WR$ (mL·min^{-1}·W^{-1}) values calculated between power outputs below the GET and when the power output was increased from below the GET to above the GET.

	Pretraining	Posttraining
Power outputs below GET		
30% GET to 60% GET	9.7 ± 0.6	10.3 ± 0.4
30% GET to 90% GET	10.4 ± 0.4	10.9 ± 1.2
60% GET to 90% GET	11.1 ± 0.5	11.4 ± 0.3
Power outputs below to above GET		
30% GET to 120% GET	11.3 ± 0.2	11.1 ± 0.2
60% GET to 120% GET	13.3 ± 0.2	11.6 ± 0.3*
90% GET to 120% GET	13.1 ± 0.6	11.7 ± 0.6*

Values presented are means ± SEM. $\Delta\dot{V}O_2/\Delta WR$, change in O_2 uptake divided by the change in power output (economy); GET, gas-exchange threshold; % GET, power output at the indicated percentage of the power output achieved at GET.
*Significantly different from pretraining; $P < 0.05$.

heart rate values were not significantly different from pre- to posttraining. The $\dot{V}O_2$ and power output values achieved at the GET were not changed with training.

Cycling economy. The $\Delta\dot{V}O_2/\Delta WR$ (cycling economy) values obtained from the four constant-load cycling tests are presented in Table 2. Economy was reduced as the work intensity increased both pre- and posttraining. Economy improved significantly after training when calculated for a change in power output from below the GET to above the GET (60% GET to 120% GET and 90% GET to 120% GET). However, economy did not change after training for power outputs performed below the GET. No significant correlations were observed between changes in LLM, leg strength, peak power, or cycling economy.

DISCUSSION

This is the first study to investigate cycling economy in previously untrained subjects before and after a short-term strength-training program. The major finding was that 8 wk of maximal leg-strength training improved cycling economy when the power output was increased from below the GET to above the GET (60% GET to 120% GET and from 90% GET to 120% GET). There was no change in cycling economy when power was increased between two power outputs that were below the GET. These findings suggest that the O_2 cost of high-intensity cycling was decreased, whereas the O_2 cost of low- to moderate-intensity cycling was unchanged with training. The observed improvement in cycling economy occurred with no corresponding increase in $\dot{V}O_{2peak}$ or in the GET. Leg strength improved constantly during the full 8 wk of training. Increases in LLM were also observed but only in the first 4 wk of training (Fig. 1). The increase in leg strength with no corresponding increase in muscle hypertrophy during the last 4 wk of training suggests that neural adaptations were involved in strength development.

Previous strength-training studies have observed improvements in running economy (16,21) and cross-country skiing economy (18,25) with no change in $\dot{V}O_{2peak}$ or in the GET. The specific causes of improved cycling economy following strength training are unclear; however, a number of mechanisms have been proposed (16,18,21,25). Unlike the present study, these studies used highly trained runners, soccer players, or cross-country skiers who were performing concurrent strength and endurance training. It is unclear whether the improvements in economy found in these studies were due to the strength training alone or the combined strength and endurance training. In the present study, subjects were previously untrained and only performing maximal leg-strength training. Therefore, the mechanisms responsible for the improvements in cycling economy must be related to the leg-strength training program performed on the hack-squat apparatus.

Johnston et al. (21) proposed that increased whole-body strength would alter running biomechanics, resulting in improved running economy. An increase in leg strength is less likely to alter cycling biomechanics because the length and velocity of movements of the muscle-tendon complex are more constrained during cycling than during running (24). Therefore, it is unlikely that an increase in leg strength improved cycling economy by changing the biomechanics of cycling. Furthermore, studies using traditional resistance-training protocols (high repetitions of more than eight with slow movements) caused increases in leg strength and muscle size with no effect on cycling performance (5), suggesting that increased leg strength and muscle mass alone do not improve cycling economy.

Relationships between muscle hypertrophy and muscle metabolism during submaximal exercise have previously been investigated in a 12-wk strength training study (12). Goreham et al. (12) found that 4 wk of leg-strength training resulted in a higher phosphocreatine and glycogen content at the end of a 30-min period of cycling at 72% of $\dot{V}O_{2peak}$. These metabolic changes occurred before any fiber hypertrophy occurred at 7 wk of training (12). Goreham et al. (12) concluded that a strength-training adaptation other than muscle hypertrophy caused the metabolic changes observed at 4 wk of training. Therefore, it is reasonable to assume that muscle hypertrophy alone was not the primary factor responsible for the improved cycling economy found in the present study.

A series of maximal strength-training studies by Hoff et al. (16,18) and Østerås et al. (25) investigated potential mechanisms for improved running and skiing economy following maximal strength-training. Østerås et al. (25) observed improvements in the rate of force development, increased peak force and shorter time to peak force following 9 wk of upper body strength training. It was suggested that these mechanisms could be responsible for the improvements observed in cross-country skiing economy. Furthermore, Marcinik et al. (23) suggested that increased peak muscle tension during cycling may be responsible for improvements in cycling time to exhaustion following strength training. Both Marcinik et al. (23) and Østerås et al. (25) suggested that an increased peak force and shorter time to peak force may allow a shorter time for the restriction of blood flow and this would improve the delivery of O_2 and substrates to the active muscle. It is unclear how improved blood flow would alter exercise economy. An improved delivery of O_2 and substrates to the muscle could delay muscle fiber fatigue resulting in the reduced recruitment of less efficient type II fibers during high-intensity exercise. It is generally believed that type II muscle fibers are metabolically less efficient than type I muscle fibers (10). The recruitment of less type II muscle fibers during exercise could result in a reduced O_2 cost of exercise and this would improve economy.

Increases in strength demonstrated with maximal leg-strength training are primarily due to neuromuscular adaptations (17). It is unclear why an increase in LLM was observed in the first 4 wk of training in the present study. However, the increase in LLM was relatively small compared to the large increase observed in 1RM (Fig. 1). Furthermore, the increase in leg strength with no corresponding increase in LLM obtained between 4 and 8 wk of training suggests that neural adaptations contributed to the gain in leg strength observed in the present study. Johnston et al. (21) proposed that adaptations in the nervous system following strength training would result in more efficient muscle fiber recruitment patterns. It was suggested that this would allow an individual to more fully coordinate the activation of all relevant muscles, thus producing a greater net force in the intended direction of movement. The increased peak power output obtained during incremental cycling in the present study is consistent with an increase in net force, which is most likely associated with either neural adaptations or muscle hypertrophy.

An increase in peak power may result in fewer muscle fibers being recruited or muscle fibers working at a smaller percentage of their maximum force to perform a pretraining submaximal power output. This in turn might delay the fatigue of individual motor units and allow the recruited fibers to maintain force production during high-intensity cycling. Delayed muscle fiber fatigue could explain the improved exercise economy at high-intensities, since the efficiency of a muscle fiber is reduced following a moderate level of fatigue (2).

A delay in muscle fiber fatigue following strength training is also suggested to result in reduced recruitment of type II muscle fibers during exercise (15). Bastiaans et al. (3) further hypothesized that a reduced recruitment of type II fibers during cycling would result in a higher economy because cycling economy is related to the percentage of type I fibers in the active muscle (8). The maximal strength-training program used in the present study may have caused a delay in type I fiber fatigue, reducing the recruitment of type II fibers and in turn improving cycling economy. Reduced type II fiber recruitment following strength training is also consistent with the unchanged economy observed during low-intensity cycling where the recruitment of type II fibers would be less (20).

Previous strength training studies have shown that neuromuscular adaptations associated with strength training may result in improved muscle coactivation, augmented contractile properties and more efficient muscle fiber recruitment patterns within the muscle (13). Such neural adaptations would increase the muscle force development and production (1,13) and stability of movement coordination (7), and potentially increase fatigue resistance (29). Such changes in neuromuscular function and control could possibly change metabolism within the exercising muscles causing a reduced O_2 cost of cycling and this would improve cycling economy. Only a small number of studies have investigated the relationship between neuromuscular activity and $\dot{V}O_2$ during dynamic exercise (19,26). Further research is needed to identify the exact association between neural control and exercise economy.

This study is the first to find improvements in cycling economy following a period of leg-strength training performed without concurrent endurance training in previously untrained subjects. The observed increase in leg strength and muscle hypertrophy may be responsible for the improved cycling economy during high-intensity submaximal cycling. The increase in leg strength with no muscle hypertrophy observed in the last 4 wk of training suggests that neural adaptations may be involved in strength development. Neuromuscular mechanisms may also be associated with the improved cycling economy found in response to maximal leg-strength training in the present study.

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