MAXIMAL STRENGTH TRAINING IMPROVES CYCLING ECONOMY IN COMPETITIVE CYCLISTS

ARNSTEIN SUNDE,[1] **ØYVIND STØREN,**[1,2] **MARIUS BJERKAAS,**[1] **MORTEN H. LARSEN,**[1] **JAN HOFF,**[2,3] **AND JAN HELGERUD**[2,4]

[1]*Department of Sport and Outdoor Life Studies, Telemark University College, Bø, Norway;* [2]*Department of Circulation and Medical Imaging, Faculty of Medicine, Norwegian University of Science and Technology, Trondheim, Norway;* [3]*Department of Physical Medicine and Rehabilitation, St. Olavs University Hospital, Trondheim, Norway; and* [4]*Hokksund Medical Rehabilitation Centre, Hokksund, Norway*

ABSTRACT

Sunde, A, Støren, Ø, Bjerkaas, M, Larsen, MH, Hoff, J, and Helgerud, J. Maximal strength training improves cycling economy in competitive cyclists. *J Strength Cond Res* 24(8): 2157–2165, 2010—The purpose of the present study was to investigate the effect of maximal strength training on cycling economy (CE) at 70% of maximal oxygen consumption ($\dot{V}O_2$max), work efficiency in cycling at 70% $\dot{V}O_2$max, and time to exhaustion at maximal aerobic power. Responses in 1 repetition maximum (1RM) and rate of force development (RFD) in half-squats, $\dot{V}O_2$max, CE, work efficiency, and time to exhaustion at maximal aerobic power were examined. Sixteen competitive road cyclists (12 men and 4 women) were randomly assigned into either an intervention or a control group. Thirteen (10 men and 3 women) cyclists completed the study. The intervention group (7 men and 1 woman) performed half-squats, 4 sets of 4 repetitions maximum, 3 times per week for 8 weeks, as a supplement to their normal endurance training. The control group continued their normal endurance training during the same period. The intervention manifested significant ($p < 0.05$) improvements in 1RM (14.2%), RFD (16.7%), CE (4.8%), work efficiency (4.7%), and time to exhaustion at pre-intervention maximal aerobic power (17.2%). No changes were found in $\dot{V}O_2$max or body weight. The control group exhibited an improvement in work efficiency (1.4%), but this improvement was significantly ($p < 0.05$) smaller than that in the intervention group. No changes from pre- to postvalues in any of the other parameters were apparent in the control group. In conclusion, maximal strength training for 8 weeks improved CE and efficiency and increased time to exhaustion at maximal aerobic power among competitive road cyclists, without change in maximal oxygen uptake, cadence, or body weight. Based on the results from the present study, we advise cyclists to include maximal strength training in their training programs.

KEY WORDS road cycling, rate of force development, half-squat, oxygen cost of cycling

INTRODUCTION

Road cycling competitions last approximately 10–500 minutes. Endurance performance in road cycling is thus approximately 80–99% dependent on aerobic metabolism (1). In road cycling as in other endurance sports, the 3 major factors accounting for interindividual variance in aerobic endurance performance are considered to be maximal oxygen consumption ($\dot{V}O_2$max), lactate threshold (LT), and cycling economy (CE) (25). Cycling economy is commonly referred to as the steady-rate oxygen cost of a standard power output measured as $L{\cdot}min^{-1}$ (2,3,9). In previous studies on cycling, it has been more common to measure efficiency than economy (4,7,22). Work efficiency is typically defined as the relationship between mechanical work done and the chemical energy spent in doing it, that is, the ratio between work output and the net oxygen cost (23).

The term "maximal strength training" has been used to describe strength training using high loads, few repetitions, and emphasis on neural adaptations to strength enhancement rather than muscular hypertrophy (16). Strength training has been associated with reduced endurance development (6,30). But when combining endurance training with maximal strength training, several studies have reported improved work economy of approximately 5% in various different activities such as cross-country skiing (13,24), soccer (13,14), and running (29). Based on these previous findings, it would seem natural to assume the same improvements in CE after maximal strength training as a supplement to endurance training.

Hansen et al. (9) have reported a 3% improvement in CE, accompanied with 20% increase in 1 repetition maximum (1RM) squats and a decrease in cadence of 8 rounds per

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Address correspondence to Arnstein Sunde, arnstein.sunde@hit.no.

24(8)/2157–2165

Journal of Strength and Conditioning Research

minute (RPM) at a cycling intensity of 37% of maximal aerobic power. The study was carried out on 14 noncyclists who performed several different strength exercises (3–4 to 2–12 RM) 4 days per week for 12 weeks. Also, Loveless et al. (20) have shown a significant improvement in CE of approximately 12% measured as $\Delta\dot{V}O_2/\Delta WR$ (work rate) among previously untrained subjects after 8 weeks of maximal strength training. While the studies by Hansen et al. (9) and Loveless et al. (20) were performed on noncyclists, Jackson et al. (17) applied maximal strength training in addition to the regular cycling among competitive cyclists. Jackson et al. (17) found no improvements in CE after 10 weeks of maximal strength training. But Jackson et al. (17) used 4 different strength exercises, and the cyclists participating in this study had well-developed bases of strength and conditioning from previous training prior to the intervention period. The 3 studies regarding cycling differ from the studies on cross-country skiing, soccer, and running (13–15,24,29) in that they are performed on untrained subjects (9,20) and on previously strength trained subjects (17) or that CE is measured at a very low intensity (9).

In the present study, we therefore wanted to investigate if maximal strength training as a supplement to regular cycle training would improve CE among competitive but not previously strength trained cyclists to the same amount that has been shown by Støren et al. (29) on running. Støren et al. (29) found significant improvements in running economy (RE) after 8 weeks of maximal strength training among well-trained long-distance runners. The maximal strength training intervention exhibited improvements in 1RM half-squat (33.2%), rate of force development (RFD) half-squat (26.0%), RE at 70% $\dot{V}O_2max$ (5.0%), and time to exhaustion at maximal aerobic speed (21.3%). No changes were observed in body weight or $\dot{V}O_2max$. Part of the explanation of improved work economy in this study was reduced relative load and a possible more optimal activation of motoneurons and muscle fibers. The effects of maximal strength training on economy when running do not necessarily transfer to CE in cycling. The training effects of maximal strength training could be different from what is shown among long-distance runners. In cycling unlike running, vertical movement of the center of mass is minimal, unless riding uphill. The braking forces are first and foremost represented by the resistance to the cyclist and bicycle moving forward, or by the artificial braking of the flywheel if riding an ergometer cycle, and transferred to the pedals. Consequently, elastic storage of energy that is reported to play an important role in RE (18,28) should logically not be as important in cycling. However, there are some suggestible adaptations to maximal strength training in running that may be of equal importance in cycling. With increased 1RM, a lower percent of 1RM in the lower limb extensors would be taxed in each movement cycle, as shown in Hoff et al. (15), lowering the actual demands of motor units recruited. Støren et al. (29) found a significant correlation between pre-intervention RFD and pre-intervention RE values, suggesting that there may be a relationship between RFD in the muscles active in running movements and RE. The same study also exhibited a significantly longer time to exhaustion at maximal aerobic speed after the maximal strength training intervention. The question was therefore if the same improvements as shown in running (29) would be accomplished in cycling using a similar intervention design.

The aim of this study was thus to assess to what extent maximal strength training with emphasis on neural adaptations, supposedly not increasing body mass, as a supplement to endurance training would affect CE and efficiency among competitive road cyclists. The hypothesis was that maximal strength training performed as half-squats and as a supplement to endurance training would improve 1RM half-squat, RFD half-squat, CE, work efficiency, and time to exhaustion at maximal aerobic power.

METHODS

Experimental Approach to the Problem

The main objectives of the present study were to investigate the effect of maximal strength training on CE among competitive road cyclists and further to evaluate if the possible effect on the strength training would affect time to voluntary exhaustion at maximal aerobic power. We wanted to investigate if the improvements previously reported in Støren et al. for running would also apply for cycling using approximately the same study design. To do this, well-trained competitive road cyclists performed maximal strength training in addition to their regular cycle training. The cyclists were tested for 1RM and RFD in half-squats to evaluate if the strength training would improve force characteristics. $\dot{V}O_2max$ was tested to evaluate if the strength training would affect maximal aerobic capacity. Cycling economy and work efficiency were tested to evaluate if the strength training would affect CE or efficiency. Time to exhaustion at pretest maximal aerobic power was tested to evaluate a possible effect on cycling performance because of the strength training. All variables were tested before and after an 8-week intervention. A control group performed the same tests before and after the intervention period, without any maximal strength training intervention, to investigate if the results in the intervention group were because of coincidence.

Subjects

Thirteen well-trained and competitive (10 men and 3 women) cyclists participated in this study. All cyclists were informed of the experimental risks and signed an informed consent document prior to the investigation. The investigation was approved by the regional medical human research committee for the south of Norway. Eight of the cyclists (7 men and 1 woman) were randomly assigned to the intervention group, whereas the remaining 5 cyclists (3 men and 2 women) acted as time controls. Although the groups were only matched for $\dot{V}O_2max$ ($L\cdot min^{-1}$), there were no significant differences in

Table 1. Physical characteristics of cyclists.*

Variables	Intervention group ($n = 8$) (7 men and 1 woman)	Control group ($n = 5$) (3 men and 2 women)
Age (y)	29.9 ± 7.2	35.8 ± 11.8
Weight (kg)	72.5 ± 7.3	75.4 ± 11.2
Height (cm)	178 ± 8	178 ± 13

*Values are mean ± *SD*; weight is measured preintervention.

any other physiological variables measured at the onset of the study (Table 2). None of the subjects had participated in any form of resistance training program for the last 6 months prior to the study. All the cyclists had participated in competitions during the season, but their performance levels ranged from regional to national. The study was carried out postseason from October to January. Subject characteristics are presented in Tables 1 and 2.

Procedures

All cyclists participated in an 8-week study. For the intervention group, a pretest proceeded 8 weeks of maximal strength training in addition to the subjects' normal endurance training. After the intervention period, a posttest, the same as the pretest, was performed. The control group only performed their regular endurance training in between the tests. The subjects were tested on 2 different days, with a minimum of 1 day and a maximum of 6 days of rest or easy training between each. The cyclists were made acquainted to performing half-squats in the Smith machine and to ride the modified ergometer cycle on 1 or more separate days prior to the pretest. By subjective evaluations from the test leader, all participants were reckoned able to perform half-squats in the Smith machine and to ride the ergometer cycle without technical limitations. The first day of testing consisted of measurements of heart rate (HR), blood lactate concentration $[La^-]_b$, oxygen consumption ($\dot{V}O_2$), and cadence (RPM) during 5-minute work periods at several different set workloads, always at freely chosen cadence. Mean cadence was measured electronically from the ergometer apparatus over the same time as $\dot{V}O_2$ and HR, that is, during the fourth minute of every work period. A Lode Corival 906900 (Lode, Groningen, the Netherlands), modified with racing pedals, racing seat, a horizontal and vertical adjustable seat pin, and racing handlebars and calibrated for power output and cadence, was used for all cycling tests. The cycle ergometer was electrically braked. $\dot{V}O_2$ was measured using the metabolic test system, SensorMedics Vmax Spectra (SensorMedics 229; Yorba Linda, CA). Lactate measurements were performed using an Arkray Lactate Pro LT-1710 analyser (whole blood) (Arkray Inc., Kyoto, Japan), and HR was measured using Polar s610 heart rate monitors (Polar Elektro Oy, Kempele, Finland). The subjects started at a power assumed to represent 40–50% of their $\dot{V}O_2$max corresponding between 100 and 200 W, which was held for 10 minutes. Each of 2 subsequent 4-minute steps from there on, the brake power was increased by either 25 or 50 W after subjective evaluation. Every 5 minutes after the first 2 steps, the brake power was increased by either 10 or 25 W until the protocol terminated at more than 10 W above the subjects' LT. Lactate threshold was defined as the warm-up $[La^-]_b$ value (i.e., measured after the lowest velocity) + 2.3 $mmol \cdot L^{-1}$. This is in accordance with the protocol demonstrated by Helgerud et al. (11). After 60 minutes of rest, a $\dot{V}O_2$max test was performed using an incremental protocol. The subjects started at an intensity representing 0–25 W below their individual LT intensity level. Every 30 or 60 seconds, the power was increased by 10–25 W, based on the subjective evaluation of the test leader. The test terminated at voluntary fatigue by the subjects. Heart rate (≥98% HRmax), R (≥1.05), and $[La^-]_b$ (≥8.0 $mmol \cdot L^{-1}$) values, as well as a possible plateau of the $\dot{V}O_2$ curve, were used to evaluate if $\dot{V}O_2$max was obtained. Maximal aerobic power was calculated on the basis of these measurements and was defined as the velocity point where the horizontal line representing $\dot{V}O_2$max meets the extrapolated linear regression representing the submaximal $\dot{V}O_2$ measured in the LT assessment. The linearity from this regression averaged an $R^2 = 0.992 \pm 0.005$. By plotting $\dot{V}O_2$ data against cycling brake power, individual regression equations for each subject were obtained. Cycling economy and work efficiency were calculated at the brake power output representing 70% $\dot{V}O_2$max. Work efficiency was calculated using the equation

$$\left(\frac{\text{Workrate}}{\text{Energyexpenditure} - \text{basalenergymetabolism}}\right) \cdot 100.$$

Both measures of work and energy expenditure were converted into kilocalories. The basal energy metabolism was calculated as a $\dot{V}O_2$ of 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$. This amount of oxygen consumption was then subtracted from the total $\dot{V}O_2$ before a correction for R values and converting into kilocalories.

The second day of testing consisted of measurements of time, HR, $[La^-]_b$, and $\dot{V}O_2$ during cycling to voluntary exhaustion at maximal aerobic power. Voluntary exhaustion was defined as the point where the cyclists could no longer manage to pedal the wattage representing maximal aerobic power, and they were encouraged to perform their best. Although they were made acquainted to ride the test ergometer, the cyclists had not practiced this test prior to the experimental day. The wattage representing pretest maximal aerobic power was also used during the test to exhaustion postintervention. To avoid the psychological benefit of

TABLE 2. Physiological results in intervention and control groups.*†

	Intervention group (I) ($n = 8$)			Control group (C) ($n = 5$)		
Variables	Pre-training	Post-training	Difference	Pre-training	Post-training	Difference
Weight (kg)	72.5 ± 7.3	72.6 ± 7.1	0.1 ± 1.1	75.4 ± 11.1	75.2 ± 11.1	−0.2 ± 2.2
$\dot{V}O_2$max						
ml·kg^{-1}·min^{-1}	63.4 ± 6.0	63.9 ± 5.6	0.5 ± 2.3	58.7 ± 8.8	58.0 ± 10.8	−0.7 ± 3.3
ml·kg$^{-0.67}$·min^{-1}	260.0 ± 24.0	262.6 ± 24.6	2.6 ± 10.9	244.3 ± 41.6	241.7 ± 51.9	−2.6 ± 16.1
L·min^{-1}	4.6 ± 0.6	4.6 ± 0.6	−0.1 ± 0.2	4.5 ± 1.1	4.4 ± 1.3	−0.3 ± 0.4
LT						
% $\dot{V}O_2$max	77.3 ± 4.9	74.7 ± 4.5	−2.6 ± 2.2	83.8 ± 5.3	84.4 ± 5.9	0.6 ± 1.8
W	243 ± 44	248 ± 42	5.0 ± 9.3	258 ± 74	262 ± 78	4.6 ± 11.7
MAP						
time (s)	360 ± 101	422 ± 115	62 ± 59‡	567 ± 214	597 ± 244	30 ± 39
CE 70						
W	217 ± 26	232 ± 36	15 ± 17‡	215 ± 57	216 ± 65	1 ± 13
ml·kg^{-1}·W^{-1}	0.205 ± 0.022	0.199 ± 0.023	−0.007 ± 0.003‡§	0.196 ± 0.033	0.195 ± 0.033	−0.001 ± 0.002
ml·kg$^{-0.67}$·W^{-1}	0.840 ± 0.065	0.800 ± 0.078	−0.04 ± 0.03‡§	0.815 ± 0.102	0.804 ± 0.091	−0.01 ± 0.01
ml·W^{-1}	14.75 ± 0.43	14.04 ± 0.79	−0.7 ± 0.0.6‡§	14.71 ± 0.6	14.46 ± 0.63	−0.2 ± 0.2‡
$<_C$(b·min^{-1})	147 ± 12	143 ± 9	−4 ± 6	142 ± 15	141 ± 11	−1 ± 7
WE (%)	21.1 ± 0.7	22.1 ± 1.2	1.0 ± 1.0‡§	21.5 ± 0.9	21.8 ± 07	0.3 ± 0.3‡
RPM	95 ± 10	94 ± 10	−1 ± 5	95 ± 5	94 ± 5	−1 ± 5
Strength						
1RM Squat 90° (kg)	155.0 ± 40.6	177.5 ± 50.7	22.5 ± 19.7‡§	151.0 ± 36.0	154.0 ± 39.3	3.0 ± 6.7
RFD Squat 90° (W)	802.6 ± 141.0	936.6 ± 170.0	134.0 ± 171.6‡§	872.4 ± 201.4	849.8 ± 202.6	−22.6 ± 48.8
Training						
Tot. cycling (min)	311 ± 318	273 ± 288	−39 ± 45‡§	361 ± 321	401 ± 326	40 ± 46‡
Tot. training (min)	600 ± 212	588 ± 208	−12 ± 4	589 ± 316	599 ± 318	10 ± 6

*$\dot{V}O_2$max = maximal oxygen consumption; LT = lactate threshold; MAP = maximal aerobic power; $<_C$ = heart rate; CE 70 = cycling economy measured on cycle ergometer at 70% of $\dot{V}O_2$max; WE = work efficiency; W = watts; RPM = cadence in rounds per minute; 1RM = 1 repetition maximum; RFD = rate of force development; Tot. cycling = total cycling time in minutes per week; Tot. training = total training time in minutes per week.

†Values are mean ± *SD*.

‡$p < 0.05$, significant difference from before to after intervention.

§$p < 0.05$, significantly different from Δ control value.

knowing the pretests' time to exhaustion at the posttest, time to exhaustion during the pretest was not communicated to the subjects. After a rest period of minimum 30 minutes, the subjects were then tested for 1RM in half-squat using a Smith machine. From pilot testing in Støren et al. (29) regarding maximal aerobic speed tests in running and using the same protocol, there was observed no deterioration in 1RM 30 minutes after the maximal aerobic speed test compared with 1RM without this test. Each lift was performed with a controlled slow eccentric phase, a complete stop of movement for approximately 1 second in the lowest position, followed by a maximal mobilization of force in the concentric phase ensuring a follow-up by use of plantar flexors. The measurements of lifting time, distance of work, and thus RFD were performed using the Muscle Lab system (Ergo test Technology, Langesund, Norway). The Muscle Lab system measures lifting time electronically. This test started using 5 reps at a weight load assumed to be approximately 50% of 1RM. After 3 minutes of rest, 3 reps at approximately 60% 1RM. After another 3 minutes of rest, 2 reps at approximately 70% 1RM and then 3 minutes of rest before 1 rep at approximately 80% 1RM. From there on, 1 rep at a weight load increased by 2.5–5 kg from the subsequent lift, followed by 3 minutes of resting until reaching 1RM. The time spent in each lift, as well as the work distance, was measured. As the external force of each lift is represented by the weight of the lifted bars, the RFD can be calculated and expressed as $\text{N}\cdot\text{m s}^{-1}$ or watts (W).

Training Interventions

The intervention group completed an 8-week training intervention period, whereas the controls completed an 8-week normal training period. During these weeks, both the intervention group and the control group were thus given instructions to perform their cycling as normal. To control the training, each subject had to report weekly the exact amount of time spent in the different training intensity zones 60–85, 85–90, and 90–95% of heart rate maximum (HRmax). In addition to their normal endurance training, the intervention group completed a maximal strength training session in a Smith machine, consisting of 4 sets of 4RM half-squats, divided by 3 minutes of rest between each, 3 days a week. Every time a subject managed to do 5 repetitions during a set, 2.5 kg were added for the next set. Guidance and instructions were given all participants during the training period. All participants in the intervention group had to report the amount of maximal strength training sessions completed. A threshold was set at 70% participation. The 70% threshold was selected on the basis of minimum training response expected. Seventy percent of 3 times per week average 2 times per week, which is considered sufficient by Kraemer and Ratamess (19) for not strength trained subjects to significantly increase strength. Furthermore, this training only takes about 20 minutes to perform and has previously been shown to ensure maximal activation of the neural-muscular system with no or minimal weight gain or effect on maximal oxygen consumption (13–15,24,29). Because of the small amount of extra training in this intervention, we did not expect any overreach reaction among the subjects. If any subjects completed less than 70% of the planned 24 strength training sessions, or if they suffered from illness or injuries lasting more than 1 week during the intervention period, they were to be taken out from the statistical material. None of the subjects met the exclusion criteria.

Allometric Scaling

$\dot{V}O_2$max considerations in the present study are related to the expression not only in $\text{ml}\cdot\text{kg}^{-0.67}\cdot\text{min}^{-1}$ and in $\text{L}\cdot\text{min}^{-1}$ as proposed by Åstrand and Rodahl (1) but also in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$. Cycling economy considerations are related to the expression in $\text{ml}\cdot\text{kg}^{-0.67}\cdot\text{W}^{-1}$ as proposed by Åstrand and Rodahl (1), in $\text{ml}\cdot\text{W}^{-1}$, which is proportionally the same as $\text{L}\cdot\text{min}^{-1}$ at a specific power output, used by Hansen et al. (8) and by Foss and Hallèn (3), and also in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{W}^{-1}$. In running, allometric scaling to the power of 0.75 and meter has been reported to decrease the *SD* in RE between subjects (10–12,14).

Statistical Analyses

Statistical analyses were performed using the software program SPSS, version 14.0 (Statistical Package for Social Science, Chicago, IL). In all cases, $p \le 0.05$ was taken as the level of significance in 2-tailed tests. Because of the small number of subjects, nonparametric tests were used to evaluate pre- to postintervention differences (the Wilcoxon signed rank test and the Mann-Whitney *U*-test). Although the use of nonparametric tests, descriptive statistics were displayed as mean and *SD*s to be comparable to previously published results. Previous studies at this laboratory have

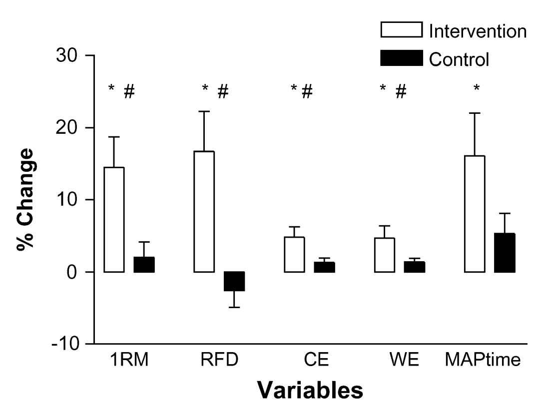

Figure 1. Percent changes from before to after intervention in the intervention group ($n = 8$) and the control group ($n = 5$). 1RM = 1 repetition maximum half-squat; RFD = rate of force development half-squat; CE = cycling economy ($\text{ml}\cdot\text{kg}^{-0.67}\cdot\text{W}^{-1}$); WE = work efficiency; tMAP = time to exhaustion at pre-intervention maximal aerobic power. $^{*}p < 0.05$, changes from before to after in the intervention group. $^{\#}p < 0.05$, between group differences.

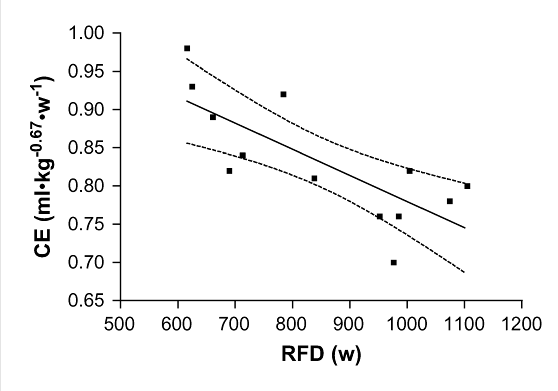

Figure 2. Relationship between pre-intervention RFD (W) and CE ($ml{\cdot}kg^{-0.67}{\cdot}W^{-1}$) ($n = 13$). RFD = rate of force development; CE = cycling economy. $R^2 = 0.58$, $p < 0.01$.

revealed test-to-test variations of ≤2.7% (1RM), ≤3.0% (RFD), and ≤1.0% ($\dot{V}O_2$).

Results

Physiological Results in Intervention and Control Groups

After the 8-week maximal strength training intervention, significant improvements in 1RM half-squat (14.2%), RFD half-squat (16.7%), CE at 70% of $\dot{V}O_2$max expressed as $ml{\cdot}kg^{-1}{\cdot}W^{-1}$, $ml{\cdot}kg^{-0.67}{\cdot}W^{-1}$, and $ml{\cdot}W^{-1}$ (3.0, 4.8, and 4.8%, respectively), work efficiency at 70% of $\dot{V}O_2$max (4.7%), power at 70% $\dot{V}O_2$max (6.9%), and time to exhaustion at maximal aerobic power (17.2%) in the intervention group were shown (Figure 1). The control group exhibited an improvement in work efficiency (1.4%), but this improvement was significantly smaller than that in the intervention group. No changes from pre- to postvalues in any of the other parameters were apparent in the control group (Table 2). No changes in body weight, $\dot{V}O_2$max, LT power, or cadence (RPM) in neither the intervention group nor the control group were apparent (Table 2).

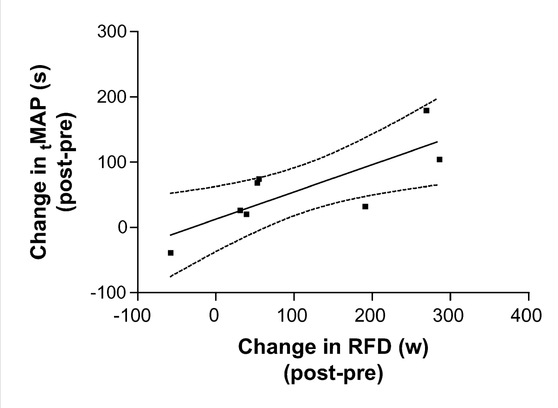

Figure 3. Relationship between pre- to postintervention differences in RFD (W) and tMAP ($n = 8$). RFD = rate of force development; tMAP = time to exhaustion at pre-intervention maximal aerobic power. $R^2 = 0.64$, $p < 0.05$.

The intervention group completed 21 ± 2 (87%) maximal strength training sessions, ranging from 17 (71%) to 24 (100%) of the scheduled maximal strength training sessions. The cycling endurance training time completed by the cyclists during this period decreased significantly by 12.2%, compared with the training before the intervention in the intervention group (total mean of 311 minutes before intervention vs. 273 minutes during intervention). Mean differences in cycle training between the intervention and the control groups was found to be significantly different ($p < 0.05$). Other endurance training such as running and cross-country skiing remained unchanged in both groups during the intervention period and constituted approximately 50 and 40% of total training in the intervention group and in the control group, respectively. Also, the distribution of the training in different intensity zones remained unchanged from before to during the intervention period in both groups. The distribution in the different zones (60–85, 85–90, and 90–95% of HRmax) was in the intervention group 84, 12, and 4% (before) vs. 85, 10, and 5% (after). In the control group, the corresponding distribution was 86, 10, and 4% (before) vs. 84, 10, and 6% (after).

Correlations

A strong significant ($p < 0.01$) correlation was found between pre-intervention RFD and CE expressed in $ml{\cdot}kg^{-0.67}{\cdot}W^{-1}$ ($R^2 = 0.58$) (Figure 2). Improvements in RFD during the intervention period correlated significantly ($p < 0.05$) with the improvements in time to exhaustion at maximal aerobic power ($R^2 = 0.64$) (Figure 3).

Discussion

The major finding in this study is that maximal strength training significantly improved CE, work efficiency in cycling, and time to exhaustion at maximal aerobic power. These results are in close agreement with the intervention study by Støren et al. (29) using the same study design but for running.

The maximal strength training intervention improved CE when expressed independent of body mass, relative to body mass raised to the power of 0.67, and relative to full body mass. The average 5% improvement in CE in the present study is in agreement with results shown in cross-country skiing of 9–23% (13,24), soccer of 5% (15), and running of 5% (29). The results from the present study are also in agreement with results on cycling from Loveless et al. (20), who showed a significant improvement in CE of approximately 12% measured as $\Delta\dot{V}O_2/\Delta WR$ among previously untrained subjects but only at intensities above the gas exchange threshold (which was about 50% $\dot{V}O_2$max). The present results are partly in agreement with the 3% improvement in CE in cycling shown by Hansen et al. (9). But the study design in Hansen et al. (9) differs from that of the present study in 3 major ways. First, in the study by Hansen et al. (9), the subjects were previously untrained. Second, Hansen et al. (9) used a variety of strength exercises, where only 2 of the 4 strength training days per week consisted of leg exercises (squat, knee extension, sitting leg curl, and standing calf raise). Lastly, the improvement in CE in Hansen et al. (9) was measured at a work intensity of only 37% of maximal aerobic power. However, the CE results from the present study are in opposition to those from Jackson et al. (17), who found no improvements in CE after 10 weeks of maximal strength training among competitive cyclists. But Jackson et al. (17) used 4 different strength exercises, and the cyclists participating in this study had well-developed bases of strength and conditioning from previous training prior to the intervention period.

Although work economy is a usual measure in activities such as running, it is more common to measure work efficiency in cycling. However, in the few previously published studies on maximal strength training and endurance performance in cycling (9,17,20), measures of economy rather than efficiency have been used.

In the present study, no changes in the freely chosen mean cadence were apparent in neither the intervention nor the control group after the 8-week intervention period (approximately 95 RPM in both groups). This is in opposition to the results from Hansen et al. (9) who showed a reduced freely chosen cadence after 12 weeks of maximal strength training among noncyclists. This lower cadence corresponded to the 3% improvement in CE, measured at 37% maximal aerobic power. The results from Hansen et al. (9) are in agreement with those from Foss and Hallèn (2) who found the gross efficiency among elite cyclists to be significantly higher at a lower cadence (80 RPM) than the cyclists freely chosen cadence (90 RPM). However, Lucia et al. (22) found both CE and gross cycling efficiency to improve with an increasing cadence, measured at 60, 80, and 100 RPM among professional road cyclists. Professional cyclists are thus reported to choose a cadence around 90 RPM in group starts and time trials (21).

In the present study, 1RM half-squat increased by 22.5 kg in the intervention group, representing 14.2%, with no change from before to after intervention in 1RM in the control group. In kilogram, this is in close agreement with the results from Støren et al. (29) on runners but in percent somewhat lower in the present study. We suggest that this may be because of the higher pre-intervention 1RM among the cyclists (155 kg) in Smith machine compared with the pre-intervention 1RM among the runners (73.4 kg) with free weights. The improvement in 1RM in the present study is above the 9.9% reported for cross-country skiers in a cable pulley apparatus by Hoff et al. (13) but somewhat below the 33.7% improvement in half-squat among soccer players reported by Hoff and Helgerud (14). The present improvement in 1RM is also somewhat lower than the 20% improvement reported in Hansen et al. (9). The cyclist's body weight did not change from before to after intervention in the present study. As they were all lean well-trained competitive cyclists with low body weight, we do not expect a change in body composition because of loss of adipose tissue. However, this was not measured in the present study. Increases in muscle strength are resulted by either neural or hypertrophic adaptations or a combination of the both (19). Although some hypertrophic response is to be expected after maximal strength training, we suggest that the main responses to the maximal training are neural adaptations.

Rate of force development in half-squat improved significantly in the intervention group in the present study by 108.3 W or by 16.7%, which is also significantly different from the results of the control group. Although there is only half the improvement in percent, the improvement in watts in the present study is almost identical to that reported in Støren et al. (29) (108 vs. 121 W). We suggest that the difference in percent improvement may be because of the higher pre-intervention level among the cyclists (832.6 W) compared with the pre-intervention level among the runners (466.7 W) in Støren et al. (29). The RFD results in the present study are however well below the 52.3% improvement reported by Hoff and Helgerud (14). The present study shows highly significant correlation between pretest RFD in half-squat and pretest CE. Only pre-intervention data were used in this correlation to include data from both the intervention group and the control group. This correlation indicates a possible relationship between RFD in half-squat and CE before any training intervention. However, no correlation was found between improvements in RFD and improvements in CE in the intervention group. The present study also showed a significant correlation between improvements in RFD in half-squat and improvements in time to exhaustion at maximal aerobic power, indicating a possible relationship between improvements in RFD and time to exhaustion at a given intensity. If RFD in half-squat is related to contraction time in working muscles during cycling, a shorter contraction time may be expected. This could prolong transit time at a given cyclus frequency. Arterial inflow to exercising muscle occurs almost exclusively between muscle contractions (27). Because mean transit time is found to correlate positively with A-$\dot{V}O_2$ difference (26), the prolonged transit time should thus better the access to O_2 and substrates. However, transit time was not measured in the present study. The increase in RFD may also represent a more optimal activation of motoneurons and muscle fibers. However, RFD was not measured during cycling. Central changes affecting muscle activation can occur at both a supraspinal and a spinal level (5). Human muscle fatigue is according to Gandevia (5) not only dependent on peripheral factors at the muscle level but also dependent on the central nervous systems' ability to adequately drive the motor neurons. So, if fewer motor units need to be recruited at the same time at a given intensity, a longer time to onset of muscle fatigue and thus a longer time to exhaustion at that specific intensity may be expected (13,16).

Time to exhaustion at pretest maximal aerobic power increased by 62 seconds or 17.2%. This is in accordance with the results from Støren et al. (29) on runners (72 seconds and 21.3%). As in Støren et al. (29), no changes were found in the present study regarding body weight, $\dot{V}O_2$max, or wattage at lactate threshold (LTw). There was no change in cycling cadence from before to after intervention. Pretest time to exhaustion at maximal aerobic power was found to correlate significantly with LT expressed as % $\dot{V}O_2$max. However, LT expressed as % $\dot{V}O_2$max did not change from before to after intervention. The improved time to exhaustion may thus be because of both improvements in CE or to other factors postponing muscular fatigue. Muscular fatigue was not directly measured in the present study. We suggest that the improvement in cycling time to exhaustion at pretest maximal aerobic power is mainly because of the 4.8% improvement in CE. This is well in line with previous studies (13–15,24,29) where an approximately 5% improvement in economy is accompanied with a threefold to fourfold improvement in time to exhaustion at intensities representing 85–100% $\dot{V}O_2$max.

Eight weeks of maximal strength training improved CE, work efficiency, and time to exhaustion at maximal aerobic power among competitive road cyclists in spite of a decrease in total weekly cycle training. There was no concurrent increase in body weight or maximal oxygen uptake.

PRACTICAL APPLICATIONS

The results from this study show an improvement in CE without any decline in maximal oxygen consumptions. This means that maximal strength training improves cycling performance, which is also shown by an improvement in time to exhaustion at maximal aerobic power. A 5% improvement in CE should actually account for a 5% improvement in time performance over a given distance. Therefore, we advise cyclists at both recreational and higher levels to include maximal strength training as a supplement to their endurance training program. We suggest a protocol of 4·4 RM 2–3 times per week using half-squats. This training session only takes about 20 minutes to perform, it ensures maximal activation of the neural-muscular system, and it has been shown to give no or minimal weight gain and does not affect maximal oxygen consumption.

ACKNOWLEDGMENT

This work was supported by Telemark University College.

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