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Strength training improves 5-min all-out performance following 185 min of cycling

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To investigate the effects of heavy strength training on the mean power output in a 5-min all-out trial following 185 min of submaximal cycling at 44% of maximal aerobic power output in well-trained cyclists. Twenty well-trained cyclists were assigned to either usual endurance training combined with heavy strength training [*E+S*; *n* = 11 (♂ = 11)] or to usual endurance training only [*E*; *n* = 9 (♂ = 7, ♀ = 2)]. The strength training performed by *E+S* consisted of four lower body exercises [3 × 4–10 repetition maximum (RM)], which were performed twice a week for 12 weeks. *E+S* increased 1 RM in half-squat ($P \leq 0.001$), while no change occurred in *E*. *E+S* led to greater reductions than *E* in oxygen consumption, heart rate, blood lactate concentration, and rate of perceived exertion ($P < 0.05$) during the last hour of the prolonged cycling. Further, *E+S* increased the mean power output during the 5-min all-out trial (from 371 ± 9 to 400 ± 13 W, $P < 0.05$), while no change occurred in *E*. In conclusion, adding strength training to usual endurance training improves leg strength and 5-min all-out performance following 185 min of cycling in well-trained cyclists.

Training is the first and most obvious way to improve cycling performance (Jeukendrup & Martin, 2001). Substantial effort and resources are therefore invested in studying various training methods that have the potential to enhance cycling performance. Incorporation of strength training into cyclists' preparation has received some attention during the last two decades (Hickson et al., 1988; Bishop et al., 1999; Bastiaans et al., 2001). An early hypothesis suggested that strength training may improve endurance cycling performance by decreasing the fraction of the maximal pedal force necessary for each pedal thrust, thereby shifting the pattern of muscle fiber recruitment toward more active type I fibers, ultimately resulting in reduced energy expenditure (Hickson et al., 1988). This hypothesis was presented in a paper that reported that duathletes increased their time to exhaustion during cycling at 80% of VO_{2max} after augmenting their regular endurance training with strength training for 10 weeks (Hickson et al., 1988). It should be noted that this study had no control group, and so the results should be interpreted with caution. Another study in which cyclists completed 9 weeks of light loaded explosive-type strength training with many repetitions (maximal mobilization in the concentric phase) found no difference between the control group and the intervention group in time trial performance and cycling economy (Bastiaans et al., 2001). Thus, the effect of strength training on cycling performance is unclear.

Many cycling road races include large portions of exercise at low intensity. In both the Tour de France and Vuelta a Espana, around 70% of the race duration is spent at exercise intensities characterized as "light intensity" (below the ventilatory threshold) (Luciá et al., 1999, 2003). The effect of strength training on cycling economy is therefore particularly relevant. If strength training can improve cycling economy and thereby reduce metabolic load, slower emptying of glycogen stores and a potentially increased capacity for high-intensity performance following prolonged cycling may be expected. Whether strength training can improve performance during intensive cycling following prolonged cycling has, however, not been investigated previously.

A common scenario in road races is a long initial ($\geq$ 180 min) period of cycling at a low to moderate intensity, followed by very intensive cycling at the end of the race. The long duration of the road cycling competitions presents a unique challenge to researchers. Practical considerations often result in scientific evaluations of training methods not properly simulating a long exercise duration. Rather, indirect performance measurements such as maximal oxygen consumption (VO_{2max}), lactate threshold, and work economy or efficiency are evaluated (Bassett & Howley, 2000). Such parameters are also relevant for endurance performance, but they appear secondary to direct measures of performance like power output in all-out trials.

The primary aim of the present study was to investigate how adding heavy strength training to usual endurance training for 12 weeks affects the mean power output during a 5-min all-out trial performed following 185 min of submaximal cycling. A secondary objective was to investigate the effect of strength training on both physiological responses and perceived exertion during prolonged submaximal cycling. The subjects were well-trained cyclists. It was hypothesized that adding heavy strength training to endurance training would improve repetition maximum (1 RM) in half-squat, cycling economy during prolonged cycling, and the mean power output in a 5-min all-out trial performed following prolonged cycling.

Methods

Subjects

Twenty-three well-trained cyclists volunteered for the study, which was approved by the Southern Norway regional division of the National Committees for Research Ethics in Norway. All cyclists signed an informed consent form before participation. None of the cyclists had performed any strength training during the preceding 6 months. Three of the cyclists did not complete the study due to illness during the intervention period and their data are excluded. The characteristics of the cyclists at baseline and after the intervention period are presented in Table 1.

Experimental design

The tests were conducted at the start (pre-intervention) and the conclusion (post-intervention) of the 12-week intervention. The cyclists could themselves choose which group to attend. The test group [$E+S$; $n = 11$ (♂ = 11), age 27 ± 2 years] performed heavy strength training in addition to usual endurance training. The cyclists in the control group [E; $n = 9$ (♂ = 7, ♀ = 2), age 30 ± 2 years] simply continued their usual endurance training. The intervention was completed during the preparation phase leading up to the competition season.

Table 1. Results from the maximal oxygen consumption test before (pre) and after (post) 12 weeks of combined endurance training and heavy strength training ($E+S$) and endurance training only (E)

	$E+S$ ($n = 11$)		E ($n = 9$)	
	Pre	Post	Pre	Post
BM (kg)	76.1 ± 2.8	76.7 ± 2.5*	74.9 ± 3.1	74.1 ± 3.1
VO_{2max}				
L/min	5.10 ± 0.17	5.28 ± 0.22*	5.10 ± 0.33	5.20 ± 0.33*
ml/kg/min	66.8 ± 1.6	69.0 ± 1.6*	65.9 ± 2.0	69.8 ± 2.5*
RER	1.10 ± 0.01	1.10 ± 0.01	1.08 ± 0.01	1.07 ± 0.01
HR_{max}	188 ± 3	188 ± 3	185 ± 3	184 ± 3
$[La^-]$	13.0 ± 0.6	14.0 ± 0.5	12.2 ± 0.9	12.6 ± 0.6
RPE	18.9 ± 0.2	19.1 ± 0.2	19.0 ± 0.2	18.9 ± 0.2

Values are mean ± SE.

*Different from pre ($p < 0.05$).

BM, body mass; VO_{2max}, maximal oxygen consumption; RER, respiratory exchange ratio; HR_{max}, maximal heart rate; $[La^-]$, blood lactate concentration; RPE, rate of perceived exertion.

Training

Endurance training consisted primarily of cycling, but some cross country skiing was also performed (up to 10% of the total training volume). Training volume and intensity were calculated on the basis of recordings from heart rate (HR) monitors (Polar, Kempele, Finland). The endurance training was divided into five HR zones: (1) 60–72%, (2) 73–82%, (3) 83–87%, (4) 88–92%, and (5) 93–100% of the maximal HR. An overview of the distribution of the endurance training into the five intensity zones for both groups is presented in Fig. 1. The total time spent on endurance training and the distribution of this training within the training zones were similar between groups.

The heavy strength training performed by the cyclists in $E+S$ targeted leg strength and was performed twice a week. On days where both strength and endurance training were scheduled, the cyclists were encouraged to perform strength training in the first training session of the day and endurance training in the second session. A review of the cyclists' training diaries confirmed that the cyclists largely complied with this guideline (0–5 strength training sessions were performed after an endurance training session). At the start of each strength training session, cyclists performed a ~ 10-min warm-up at a self-selected intensity on a stationary cycle ergometer, followed by two to three warm-up sets of half-squat with a gradually increasing load. The strength exercises performed were: half-squat in a Smith-machine (Gym 80 International, Gelsenkirchen, Germany), leg press with one foot at a time, one-legged hip flexion, and toe raise. All cyclists were supervised by an investigator at all workouts during the first 2 weeks and thereafter at least once every second week throughout the intervention period. During the first 3 weeks, cyclists trained with 10 RM sets at the first weekly session and 6 RM sets at the second weekly session. During the next 3 weeks, sets were adjusted to 8 RM and 5 RM for the first and second weekly sessions, respectively. During the final 6 weeks, sets were adjusted to 6 RM and 4 RM, respectively. Cyclists were encouraged to continuously increase their RM loads throughout the intervention period and they were allowed assistance on the last repetition. The number of sets in each exercise was always three. Based on the assumption that it is the intended rather than the actual velocity that determines the velocity-specific training response (Behm & Sale, 1993), the heavy strength training was conducted with the intention of maximal acceleration of the load during the concentric phase (lasting around 1 s), while the eccentric phase was performed more slowly (lasting around 2–3 s).

Testing

The pre- and post-intervention tests were each divided into three separate test sessions: maximal strength, maximal oxygen consumption, and cycling performance. The cyclists were instructed to refrain from intense exercise the day preceding a test and to consume the same type of meal before testing. They were not allowed to eat during the hour preceding a test or to consume coffee or other products containing caffeine during the last 3 h before a test. The cyclists were cooled with a fan throughout the exercise bouts. All tests were performed under similar environmental conditions (20–22 °C). The pre- and post-intervention tests were performed at approximately the same time of the day to avoid circadian variance. All cycling

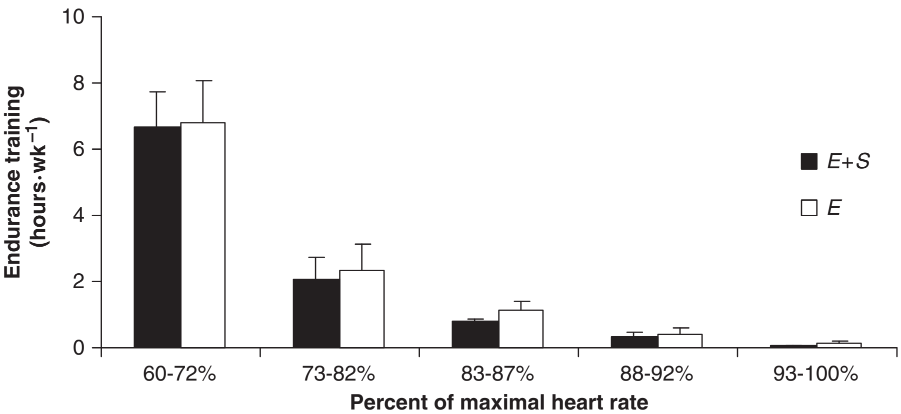

Fig. 1. Endurance training throughout 12 weeks of combined endurance and heavy strength training (*E+S*) and endurance training only (*E*).

tests were performed on the same electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode B. V., Groningen, the Netherlands), which was adjusted according to each cyclist's preferences for seat height, distance between the seat and the handle bars, and horizontal distance between the tip of the seat and the bottom bracket. Cyclists were allowed to choose their preferred cadence during all cycling tests and they used their own shoes and pedals.

Maximal strength

Strength was measured in the first test session. Maximal strength in leg extensors was measured as 1 RM half-squat in a Smith-machine. Before the baseline test, two familiarization sessions were conducted with the purpose of instructing the cyclists in the proper lifting technique and testing procedure. Strength tests were always preceded by a 10-min warm-up on a cycle ergometer. Following warm-up, the cyclists performed a standardized protocol consisting of three sets with a gradually increasing load (40%, 75%, and 85% of predicted 1 RM) and decreasing number of repetitions (10, 7, and 3). The depth of half-squat in the 1 RM test was set to a knee angle of 90°. To ensure similar knee angles during all tests, the cyclist's squat depth was carefully monitored and marked on a scale on the Smith-machine. Thus, each cyclist had to reach his or her individual depth marked on the scale for the lift to be accepted. Similarly, the placement of the feet was monitored for each cyclist to ensure identical test positions during all tests. The first 1 RM attempt was performed with a load approximately 5% below the predicted 1 RM load. After each successful attempt, the load was increased by 2–5% until the cyclist failed to lift the same load after two to three consecutive attempts. The rest period between each attempt was 3 min. The pre- and post-intervention tests were conducted using the same equipment with identical positioning of the cyclist relative to the equipment and monitored by the same experienced investigator. The post-intervention test for strength was conducted 3–5 days after the last strength training session. The coefficient of variation for test–retest reliability for this test has been found to be 2.9% (Rønnestad, 2009).

Maximal oxygen consumption

In the second test session, the cyclists performed an incremental cycle ergometer test for determination of VO_{2max}. The second test session was performed 2–5 days after the first test session. The cyclists began with a 10-min warm-up on the cycle ergometer, followed by a short rest. The VO_{2max} test was then initiated with 1-min cycling at a power output corresponding to 3 W/kg (rounded down to the nearest 50 W). Power output was then increased by 25 W every 1 min until exhaustion. When the cyclists predicted that they were not able to manage another 25 W increase in power output, they were encouraged to simply continue cycling at the current power output as long as possible (usually 30–90 s). The cyclists were verbally encouraged to continue as long as possible. Oxygen consumption (VO_2) and respiratory exchange ratio (RER) were measured (30 s sampling time) using a computerized metabolic system with a mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). This metabolic system has been validated against the Douglas bag method and found to be an accurate system for measuring VO_2 (Foss & Hallén, 2005). The gas analyzers were calibrated against certified calibration gases of known concentrations before every test. The flow turbine (Triple V, Erich Jaeger) was calibrated before every test with a 3 L, 5530 series, calibration syringe (Hans Rudolph, Kansas City, Missouri, USA). VO_{2max} along with the complementary data were calculated as the average of the two highest VO_2 measurements. HR was measured using a HR monitor (Polar, Kempele, Finland). W_{max} was calculated at baseline as the mean power output during the last 2 min of the incremental test. This W_{max} was used to calculate the relative power output to be used for the prolonged cycling in the final test session. After the incremental test, the cyclists performed 15 min of low-intensity cycling before the test session was concluded with a familiarization trial for the 5-min all-out trial.

Prolonged cycling followed by 5-min all-out cycling

In the third test session (2–5 days after the second test session), the cyclists performed 185 min of cycling at 44% of W_{max} (determined at the second test session). W_{max} was found to be 407 ± 10 W in *E+S* and 403 ± 26 W in *E*. The mean power output during the prolonged cycling was consequently 179 ± 4 W and 177 ± 11 W in *E+S* and *E*, respectively. The same absolute power output was used in the post-intervention test. The apparently modest power output was chosen based on previous research that has shown that competitive road cyclists spend nearly half of the racing time riding at a power output of <150 W (Brooker, 2003). During the prolonged cycling, the ergometer was in a cadence-independent mode (constant-Watt production), so that the preset power output was not affected by the cyclist's chosen cadence. Cyclists were allowed to occasionally stand in the pedals during the prolonged cycling, but not during the final 5-min all-out trial. VO_2, RER, HR, cadence, rate of perceived exertion (RPE), and blood lactate concentration ($[La^-]$) were determined during 5-min periods every half an hour throughout the prolonged cycling. [La^-] was measured in whole blood from the finger tips using a Lactate Pro LT-1710 analyzer (Arcray Inc., Kyoto, Japan). The Borg RPE scale for perceived exertion was used to determine RPE as a subjective indirect measurement of performance (Borg, 1982). During the prolonged cycling, the cyclists were allowed to consume a sport drink containing 75 g/L carbohydrates, *ad libitum*, in order to maintain fluid balance and mimic race conditions. Two minutes after conclusion of the 185 min of prolonged cycling, a 5-min all-out trial was performed for objective direct determination of cycling performance. In line with an earlier study (Hansen et al., 2006), the 5-min all-out trial was chosen as a functional measure of the capacity for very intensive cycling, such as occurs during a breakaway attempt, crosswind cycling, or steep uphill cycling, all of which may be decisive situations in a road race. For the 5-min all-out trial, the ergometer mode was changed to the cadence-dependent mode, in which the power output increases with increasing cadence according to the following formula: $W = L \times (\text{r.p.m.})^2$ where W is the power output, r.p.m. is the cadence, and the constant (L) in the formula was set to 0.044. L determines the electronic gearing of the system. Based on findings from a previous study (Hansen et al., 2006), we predicted that the mean power output during the 5-min all-out trial would be between 360 and 400 W. Because the preferred cadence for many cyclists at this intensity is around 90–95 r.p.m., the constant in the formula was set to 0.044. As an example, a constant cadence of 93 r.p.m. would result in a mean power output of 381 W during the 5-min all-out trial. All cyclists were encouraged to produce as high a mean power output as possible during the 5-min all-out trial. They received feedback regarding power output production and time elapsed, but not HR and cadence. The mean power output was calculated and used in statistical analyses.

Statistics

All the values presented in the text, figures, and tables are mean ± SE. To test for differences between groups at baseline, unpaired Student's *t*-tests were used. Pre- and post-intervention measurements for each group were compared using a paired-Student's *t*-test (1 RM in half-squat, VO_{2max}, and mean power output during the 5-min all-out trial). To test for any differences in the relative changes between the groups in half-squat 1 RM, VO_{2max}, and mean power output in the 5-min all-out trial, unpaired Student's *t*-tests were performed. *T*-tests were performed in Excel 2003 (Microsoft Corporation, Redmond, Washington, USA). Two-way repeated measures analysis of variance (ANOVA) (time of intervention period and time during prolonged cycling as factors) with Bonferroni's *post hoc* tests were performed to evaluate differences (post- vs pre-values) in responses during the prolonged cycling within groups. In addition, for prolonged cycling, the average values for each hour were analyzed by a two-way repeated measures ANOVA (group and time point during prolonged cycling as factors) with Bonferroni's *post hoc* tests for evaluation of differences in relative changes (post- vs pre-values) between groups. ANOVA analyses were performed in GraphPad Prism 5 (GraphPad Software Inc., California, USA). All analyses resulting in $P \leq 0.05$ were considered statistically significant.

Results

Baseline

There were no significant differences between $E+S$ and E before the intervention period with respect to body mass, 1 RM in half-squat, or VO_{2max} and its complementary measurements (Table 1 and Fig. 2).

Strength

During the intervention period, $E+S$ increased half-squat 1 RM (26 ± 2%, $P < 0.01$, Fig. 2), while this measure remained unchanged in E. Thus, the change in half-squat 1 RM from before to after the intervention period was larger in $E+S$ than in E ($P < 0.01$).

VO_{2max} and body mass

Both $E+S$ and E increased VO_{2max} during the intervention period ($P \leq 0.05$). The increase in VO_{2max} averaged 3 ± 1% for $E+S$ and 6 ± 2% for E, with no statistical difference between groups (Table 1). There was a small, but statistically significant increase in body mass in $E+S$ (1.2 ± 0.4%; $P < 0.05$), while no change occurred in E. There was no significant difference between groups in relative changes in body mass from before to after the intervention.

Responses during prolonged cycling

ANOVA analysis showed that absolute oxygen consumption remained unchanged from before to after the intervention period for both groups during the prolonged cycling (Fig. 3). However, the mean relative oxygen consumption (mL O_2/min/kg) during the 185-min cycling decreased from 52.7 ± 0.8% to 50.7 ± 0.8% of VO_{2max} ($P < 0.05$) in $E+S$, while no significant change occurred in E (the baseline value was 52.4 ± 1.1% of VO_{2max}). HR and [La^-] during the last hour of prolonged cycling were lower at the post-intervention test than at the pre-intervention test for $E+S$ ($P < 0.05$, Fig. 3). In addition, RPE for $E+S$ was lower at all time points at the post-intervention test compared with the pre-test ($P < 0.05$). The only change for E after the intervention period

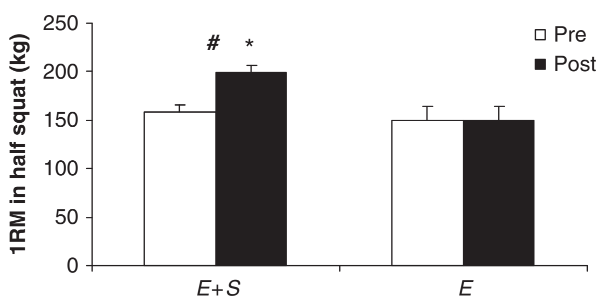

Fig. 2. 1 RM in half-squat before (Pre) and after (Post) the 12-week intervention period in which one group added heavy strength training to the usual endurance training ($E+S$) and another group simply performed the usual endurance training (E). *Different from Pre ($P < 0.01$). #Difference between groups in relative change from pre-test to post-test ($P < 0.01$). RM, repetition maximum.

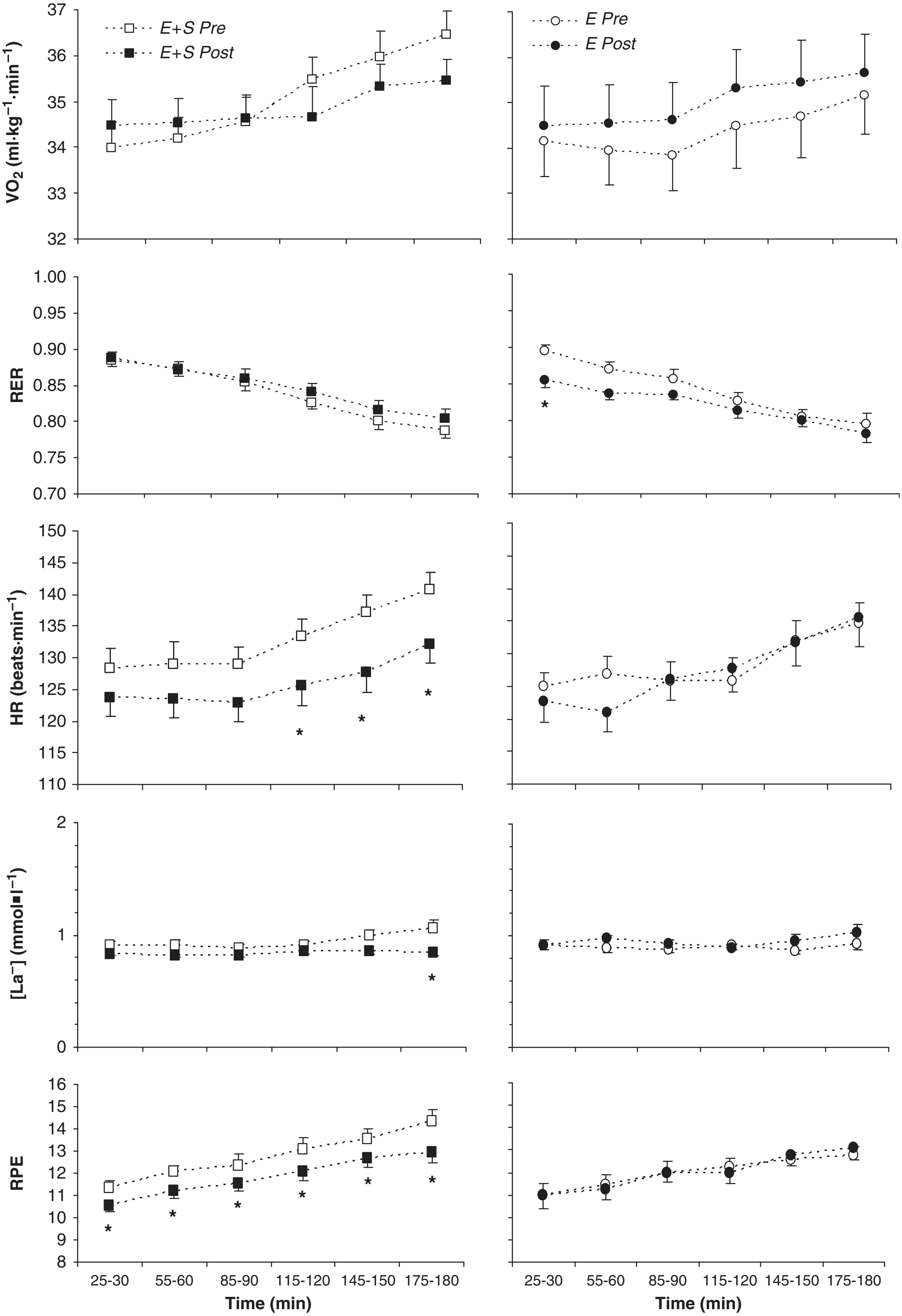

Fig. 3. Responses during 180 min of cycling at 44% of baseline W_{max} before (pre) and after (post) 12 weeks of endurance and heavy strength training (*E+S*; left panels) and usual endurance training only (*E*; right panels). *Different from Pre ($P<0.05$).

was a lower RER 30 min into the prolonged cycling ($P<0.05$, Fig. 3). Cadence during prolonged cycling (80 ± 2 r.p.m. as a mean across study groups, time points, and times of intervention period) remained unchanged from baseline to post-intervention for both groups.

A comparison between *E+S* and *E* of the relative changes over the intervention period showed that during the last hour of the prolonged cycling, there were statistically significant differences in VO_2 ($-2.2 \pm 0.6\%$ for *E+S* vs $1.9 \pm 1.5\%$ for *E*), HR ($-6.5 \pm 1.6\%$ for *E+S* vs $0.3 \pm 2.3\%$ for *E*), [La^-] ($-14.0 \pm 4.7\%$ for *E+S* vs $11.3 \pm 5.5\%$ for *E*), and RPE ($-8.2 \pm 1.6\%$ for *E+S* vs $2.0 \pm 2.3\%$ for *E*) ($P<0.05$, Fig. 4). There was no difference between groups in relative changes in RER.

Mean power output in the 5-min all-out trial

The mean power output during the 5-min all-out trial following the 185-min prolonged cycling increased $7.2 \pm 2.0\%$ from pre- to post-intervention in *E+S* ($P<0.01$, Fig. 5), while no change occurred in *E*. The relative change in the mean power output during the 5-min all-out trial was also different between the groups ($P<0.01$, Fig. 5).

Discussion

A novel finding of the present study was that adding heavy strength training to the usual endurance training of well-trained cyclists resulted in increased mean power output production in a 5-min all-out trial performed following 185 min of submaximal cycling. This power output in the 5-min all-out trial constituted the objective direct measurement of performance in the present study. In addition, the relative changes over the intervention period in VO_2, HR, [La^-], and RPE during prolonged cycling were all in favor of the cyclists who had performed heavy strength training, suggesting that strength training improves performance in prolonged cycling. Notably, the reduced physiological and psychophysiological responses among the strength-trained cyclists generally occurred during the last hour of the prolonged cycling, a finding that underscores the relevance of completing prolonged tests to better simulate road cycling in studies that evaluate the effectiveness of different training methods.

The observed 26% increase in half-squat 1 RM is in line with previously reported 27% and 25% increases in squat 1 RM in duathletes and triathletes following 10 and 14 weeks of training, respectively (Hickson et al., 1988; Millet et al., 2002). The athletes in these previous studies also performed endurance and strength training concurrently. The increase in

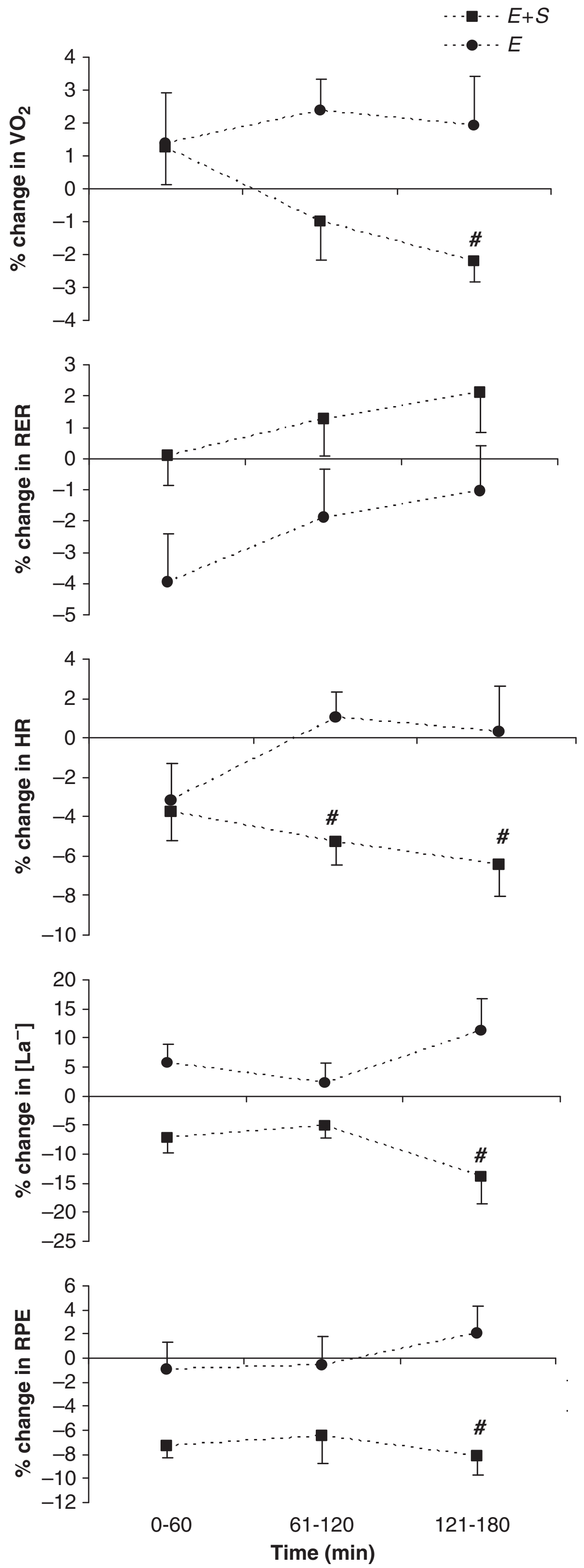

Fig. 4. Relative changes (post- vs pre-intervention) in responses during 180 min of cycling at 44% of baseline W_{max}. #Different from *E* ($P<0.05$).

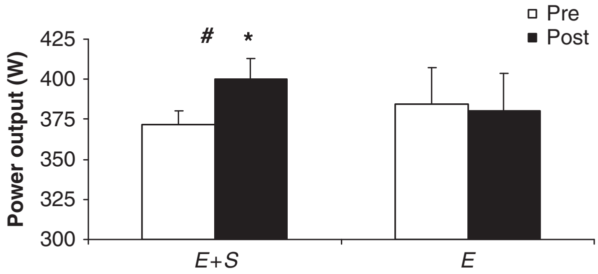

Fig. 5. Mean power output during the 5-min all-out trial performed following 185 min of cycling at 44% of baseline W_{max} before (pre) and after (post) 12 weeks of combined endurance and heavy strength training ($E+S$) or endurance training only (E). *Different from Pre ($P<0.01$). #Difference between groups in relative change from pre-test to post-test ($P<0.01$).

strength also concurs with studies that added heavy strength training to distance running for 8–10 weeks (Johnston et al., 1997; Støren et al., 2008). Thus, the strength training protocol in the present study was successful in increasing leg strength to an extent that would be expected when strength training is added to endurance training. Further, the results of the present study indicate that a substantial increase in 1 RM can be achieved with little or no increase in body weight, a concern among athletes for whom a low body mass is important for performance in e.g., uphill cycling or running. It is possible that the increase in 1 RM was partly due to alterations in neural factors caused by the high intensity of training (Häkkinen et al., 1988; Aagaard et al., 2002; Del Balso & Cafarelli, 2007). It is also possible that hypertrophy in leg muscles may have contributed to the increase in 1 RM. Leg muscle mass could have increased without a concomitant increase in body mass because a change in body composition (decreased fat, increased muscle) is likely to occur in the pre-season preparation phase of the training, during which the present study was conducted. It has also been suggested that a response to strength training may be consolidation of tissue as the muscle fibers increase in girth at the expense of extracellular spaces (Goldspink & Harridge, 2003).

The mean power output in the 5-min all-out trial following 185 min of submaximal cycling increased by $\sim 7\%$ for the cyclists who added heavy strength training to their usual endurance training, while no change occurred for the cyclists who performed usual endurance training only. This mean power output was identified as the objective direct performance measurement. The present study thus supports the hypothesis stated two decades ago that strength training can potentially increase cycling performance (Hickson et al., 1988). However, in a previous study in which moderately trained female cyclists added heavy strength training to their usual cycling training, no difference was found between the intervention group and the control group in the average power output during a 1-h cycling test (Bishop et al., 1999). Although the increase in half-squat 1 RM found in the present study was comparable to that found in the study by Bishop et al. (1999), the strength training regimens were quite different. The present study included four lower body exercises, including half-squat, while squats were the only exercise in the study by Bishop et al. (1999). The difference in strength training volume and exercises, gender, and performance test may account for the divergent findings, as a substantially (threefold) greater volume of strength training was performed in the present study as compared with that of Bishop et al. (1999).

RPE was determined during prolonged cycling as a subjective indirect measure of performance. It has been suggested that the linear increase in perceived exertion over exercise time can be used as a sensitive predictor of time to exhaustion during exercise (Horstman et al., 1979; Crewe et al., 2008). Interestingly, at the post-intervention test, cyclists in $E+S$ reported lower RPE at all time points during the prolonged cycling, while there was no change in E. During the last hour of the prolonged cycling, the relative change in RPE in $E+S$ was superior to that in E. One interpretation is that the strength-trained cyclists were further from exhaustion at the end of the 185-min prolonged cycling and therefore capable of producing higher mean power output during the final 5-min all-out trial.

Several models attempt to explain fatigue and consequently performance during prolonged cycling. One model suggests that fatigue is governed by economy and that an improvement in economy will lead to a reduction in VO_2, reduced depletion of energy stores, delayed accumulation of metabolites, and an attenuated increase in core body temperature (Abbiss & Laursen, 2005). In the present study, adding strength training to the usual endurance training resulted in a group-by-training effect on percentage change in cycling economy in the strength-trained cyclists, as indicated by superior VO_2 improvement in $E+S$ during the last hour of the prolonged cycling. This is underlined by the findings of superior reductions in [La^-] and HR in $E+S$, during the last hour of the prolonged cycling. It is likely that the improved performance in the 5-min all-out trial by the strength-trained cyclists at the post-intervention test is a result of the superior improvement in $E+S$ compared with E in economy during the prolonged cycling gained from strength training. Studies with distance runners and cross country skiers have also found improved economy after a period of strength training (Johnston et al., 1997; Hoff et al., 1999, 2002; Millet et al., 2002). However, another study using cyclists found no improvement in cycling economy (Bastiaans et al., 2001). Bastiaans et al. (2001) added light-loaded explosive strength training to the cyclists' endurance training rather than heavy-loaded strength training as in the present study. This may partly explain the different findings. Explosive-type strength training with low loads and many repetitions is known to induce inferior strength gain compared with heavy-loaded strength training (Weiss et al., 1999). Another methodological difference between the present study and that of Bastiaans et al. (2001) is in how economy was measured. While Bastiaans et al. (2001) measured economy during an incremental test with 2.5 min of cycling at every power output, we measured economy during 5-min periods every half an hour throughout the 185 min of submaximal cycling. During the first 2 h of cycling in the present study, there was no difference between groups in economy, but during the last hour the changes from pre- to post-intervention became significantly different between groups.

The difference between groups in relative change in economy during the last hour of prolonged cycling seems to be partly due to a non-significant impairment in economy in *E* and partly due to a non-significant improvement in economy in *E+S*. This is similar to results from an earlier study conducted on well-trained triathletes (Millet et al., 2002). After the intervention period in that study, the athletes who performed strength training in addition to endurance training had a superior running economy compared with the athletes who merely continued their regular endurance training. Still, as with the present study, the changes were not significant. The authors speculated that the lack of significant improvement in running economy in the strength-trained athletes could be due to the fact that these well-trained athletes have a narrow margin of improvement after several years of training. This could also be the case in the present study and further emphasizes the notable finding of an increased mean power output in the 5-min all-out trial following the prolonged cycling for *E+S*. The oxygen pulse (VO_2/HR), a measurement considered as a cardiovascular "efficiency" parameter, showed larger values for *E+S* during the last hour of the 185 min cycling whereas no changes occurred in *E*. No differences occurred between groups (data not shown). While the specific causes for the favorable adaptation in economy when adding heavy strength training to endurance training remain unclear, a number of mechanisms, including some briefly mentioned below, may be involved.

Muscle fiber type recruitment pattern may also play a role in economy. It has been shown that type I muscle fibers are more efficient than type II fibers when performing exercise at a given power output during submaximal exercise (Coyle et al., 1992; Hansen et al., 2002; Majerczak et al., 2006; Krustrup et al., 2008). Therefore, because strength training increases maximal force, the peak force or muscle fiber tension developed in each pedal thrust would decrease to a lower percentage of the maximal values. Further, according to the size principle of muscle fiber type recruitment (Henneman et al., 1965), this would allow reduced reliance on type II muscle fibers, improving economy, reducing overall muscle fatigue, and increasing the cyclist's ability to ride longer until exhaustion (Hickson et al., 1988; Coyle et al., 1992; Horowitz et al., 1994).

Increased VO_{2max} could not explain the improved performance in *E+S*, because VO_{2max} increased for both groups after the intervention period and there was no difference between groups. The increase in VO_{2max} in *E+S* contradicts other studies, which have found no change in VO_{2max} after a period of added strength training (Johnston et al., 1997; Hoff et al., 1999, 2002; Millet et al., 2002). However, the increase in VO_{2max} in the present study was expected, because the pre-testing was conducted ~ 1 month after the end of the competition season, a time of the year when a decline in endurance training is observed. During the preparatory phase, the start of which coincided with the pre-tests, both groups substantially increased endurance training, which is a likely explanation for the increased VO_{2max}. Interestingly, the addition of heavy strength training twice a week during the 12-week intervention period did not negatively affect the development of VO_{2max}. Other studies have also found no impairment of VO_{2max} development in a similar period of concurrent endurance and strength training (McCarthy et al., 1995; Bell et al., 2000; Balabinis et al., 2003).

In conclusion, the addition of heavy strength training twice a week to high-volume endurance training increased leg strength in well-trained cyclists, as expected. Of even larger practical importance to the cyclists, the strength training also resulted in a higher mean power output in a 5-min all-out trial following 185 min of submaximal cycling. This objective performance improvement in the 5-min all-out trial was accompanied by larger reductions in RPE scores as well as measures of VO_2, HR, and $[La^-]$ during the prolonged cycling for the strength-trained cyclists compared with the cyclists who had performed usual endurance training.

Perspectives

Incorporation of strength training into cyclists' preparation has received some attention during the last two decades, with divergent findings. Heavy strength training should, based on the results from the present study, be included in training for improvement of performance in well-trained cyclists. These results are in agreement with previous findings in well-trained cross country skiers (Hoff et al., 2002), runners (Støren et al., 2008), and well-trained triathletes (Millet et al., 2002). The results from the present study indicate that heavy strength training can improve the ability to cycle intensively at the end of a long race and thus improve cycling performance. The present study is limited by the fact that the well-trained cyclists were not randomized into an intervention and a control group. Furthermore, data on muscle activation and intramuscular glycogen content after 185 min of submaximal cycling would be interesting to investigate to further explore the possible mechanism behind the improved performance at the end of prolonged exercise.

Key words: half-squat, work economy, aerobic power, maximal oxygen consumption, concurrent training.

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