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

Running head: "*Strength training and cycling performance*"

Bent R. Rønnestad¹, Ernst A. Hansen², and Truls Raastad²

¹Lillehammer University College, Lillehammer, Norway

²Norwegian School of Sport Sciences, Oslo, Norway

Corresponding author:

Bent R. Rønnestad

Lillehammer University College

PB. 952, 2604 Lillehammer

Norway

E-mail: bent.ronnestad@hil.no

Phone: +47 61288193

Fax: +47 61288200

ABSTRACT

To investigate the effects of heavy strength training on 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 x 4-10 repetition maximum (RM)], which were performed twice a week for 12 weeks. *E+S* increased 1RM in half squat ($p \leq 0.001$), while no change occurred in *E*. *E+S* obtained 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 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.

Key words: HALF SQUAT, WORK ECONOMY, AEROBIC POWER, MAXIMAL OXYGEN CONSUMPTION, CONCURRENT TRAINING

INTRODUCTION

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 in 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 towards more active type 1 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, so 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 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 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

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3 improve performance during intensive cycling following prolonged cycling has, however, not
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5 previously been investigated.
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10 A common scenario in road races is a long initial (≥ 180 min) period of cycling at low to
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12 moderate intensity followed by very intensive cycling at the end of the race. The long
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14 duration of the road cycling competitions presents a unique challenge to researchers. Practical
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16 considerations often result in scientific evaluations of training methods not properly
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18 simulating long exercise duration. Rather, indirect performance measurements such as
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20 maximal oxygen consumption (VO_{2max}), lactate threshold, and work economy or efficiency
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22 are evaluated (Bassett & Howley 2000). Such parameters are also relevant for endurance
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24 performance, but they appear secondary to direct measures of performance like power output
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26 in all-out trials.
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34 The primary aim of the present study was to investigate how adding heavy strength training to
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36 usual endurance training for 12 weeks affects mean power output during a 5-min all-out trial
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38 performed following 185 min of submaximal cycling. A secondary objective was to
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40 investigate the effect of strength training on both physiological responses and perceived
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42 exertion during prolonged submaximal cycling. The subjects were well-trained cyclists. It was
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44 hypothesized that adding heavy strength training to endurance training would improve 1RM
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46 in half squat, cycling economy during prolonged cycling, and mean power output in a 5-min
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48 all-out trial performed following prolonged cycling.
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55 **METHODS**

56 *Subjects*

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58 Twenty-three well-trained cyclists volunteered for the study, which was approved by the
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60 Southern Norway regional division of the National Committees for Research Ethics in

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3 Norway. All cyclists signed an informed consent form prior to participation. None of the
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5 cyclists had performed any strength training during the preceding 6 months. Three of the
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7 cyclists did not complete the study due to illness during the intervention period and their data
8
9 are excluded. Characteristics of the cyclists at baseline and after the intervention period are
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11 presented in Table 1.
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17 *Experimental design*

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

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38 Endurance training consisted primarily of cycling, but some cross-country skiing was also
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40 performed (up to 10% of total training volume). Training volume and intensity were
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42 calculated on basis of recordings from heart rate monitors (Polar, Kempele, Finland). The
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44 endurance training was divided into five heart rate zones: 1) 60%-72%, 2) 73%-82%, 3) 83%-
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46 87%, 4) 88%-92%, and 5) 93%-100% of maximal heart rate. An overview of the distribution
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48 of the endurance training into the 5 intensity zones for both groups is presented in Figure 1.
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51 The total time spent on endurance training and the distribution of this training within the
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53 training zones were similar between groups.
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(Insert Figure 1 about here)

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3 The heavy strength training performed by the cyclists in *E+S* targeted leg strength and was
4 performed twice a week. On days where both strength and endurance training were scheduled,
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6 the cyclists were encouraged to perform strength training in the first training session of the
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8 day and endurance training in the second session. A review of the cyclists' training diaries
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10 confirmed that the cyclists largely complied with this guideline (0-5 strength training sessions
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12 were performed after an endurance training session). At the start of each strength training
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14 session, cyclists performed a ~10-min warm-up at self-selected intensity on a stationary cycle
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16 ergometer, followed by two to three warm-up sets of half squat with gradually increasing
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18 load. Strength exercises performed were: half squat in a Smith-machine (Gym 80
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20 International, Germany), leg press with one foot at a time, one-legged hip flexion, and toe
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22 raise. All cyclists were supervised by an investigator at all workouts during the first two
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24 weeks and thereafter at least once every second week throughout the intervention period.
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26 During the first three weeks, cyclists trained with 10RM sets at the first weekly session and
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28 6RM sets at the second weekly session. During the next three weeks, sets were adjusted to
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30 8RM and 5RM for the first and second weekly sessions, respectively. During the final 6
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32 weeks, sets were adjusted to 6RM and 4RM, respectively. Cyclists were encouraged to
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34 continuously increase their RM loads throughout the intervention period and they were
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36 allowed assistance on the last repetition. The number of sets in each exercise was always
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38 three. Based on the assumption that it is the intended rather than actual velocity that
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40 determines the velocity-specific training response (Behm & Sale 1993), the heavy strength
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42 training was conducted with intention of maximal acceleration of the load during the
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44 concentric phase (lasting around 1 s), while the eccentric phase was performed more slowly
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46 (lasting around 2-3 s).
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Testing

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3 The pre- and post-intervention tests were each divided into three separate test sessions:
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5 maximal strength, maximal oxygen consumption, and cycling performance. The cyclists were
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7 instructed to refrain from intense exercise the day preceding a test and to consume the same
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9 type of meal before testing. They were not allowed to eat during the hour preceding a test or
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11 consume coffee or other products containing caffeine during the last three hours before a test.
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13 The cyclists were cooled with a fan throughout the exercise bouts. All tests were performed
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15 under similar environmental conditions (20-22°C). The pre- and post-intervention tests were
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17 performed at approximately the same time of the day to avoid circadian variance. All cycling
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19 tests were performed on the same electromagnetically braked cycle ergometer (Lode
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21 Excalibur Sport, Lode B. V., Groningen, The Netherlands), which was adjusted according to
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23 each cyclist's preferences for seat height, distance between seat and handle bars, and
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25 horizontal distance between tip of seat and bottom bracket. Cyclists were allowed to choose
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27 their preferred cadence during all cycling tests and they used their own shoes and pedals.
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36 *Maximal strength*

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38 Strength was measured in the first test session. Maximal strength in leg extensors was
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40 measured as 1RM half squat in a Smith-machine. Prior to the baseline test, two familiarization
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42 sessions were conducted with the purpose of instructing the cyclists in proper lifting technique
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44 and testing procedure. Strength tests were always preceded by a 10-min warm-up on a cycle
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46 ergometer. Following warm-up, the cyclists performed a standardized protocol consisting of 3
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48 sets with gradually increasing load (40%, 75%, 85% of predicted 1RM) and decreasing
49
50 number of repetitions (10, 7, 3). The depth of half squat in the 1RM test was set to a knee
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52 angle of 90°. To ensure similar knee angles during all tests, the cyclist's squat depth was
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54 carefully monitored and marked on a scale on the Smith-machine. Thus, each cyclist had to
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56 reach his or her individual depth marked on the scale for the lift to be accepted. Similarly, the
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58 placement of the feet was monitored for each cyclist to ensure identical test positions during
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3 all tests. The first 1RM attempt was performed with a load approximately 5% below the
4 predicted 1RM load. After each successful attempt, the load was increased by 2-5% until the
5 cyclist failed to lift the same load after 2-3 consecutive attempts. The rest period between
6 each attempt was 3 min. The pre- and post-intervention tests were conducted using the same
7 equipment with identical positioning of the cyclist relative to the equipment and monitored by
8 the same experienced investigator. The post-intervention test for strength was conducted 3-5
9 days after the last strength training session. The coefficient of variation for test-retest
10 reliability for this test has been found to be 2.9% (Rønnestad in press).
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25 *Maximal oxygen consumption*

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

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24 In the third test session (2-5 days after the second test session), the cyclists performed 185
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26 min of cycling at 44% of W_{max} (determined at the second test session). W_{max} was found to be
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28 407 ± 10 W in $E+S$ and 403 ± 26 W in E . Mean power output during the prolonged cycling
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30 was consequently 179 ± 4 W and 177 ± 11 W in $E+S$ and E , respectively. The same absolute
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32 power output was used in the post-intervention test. The apparently modest power output was
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34 chosen based on previous research that has shown that competitive road cyclists spend nearly
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36 half of the racing time riding at a power output of less than 150 W (Brooker 2003). During the
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38 prolonged cycling, the ergometer was in a cadence-independent mode (constant-Watt
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40 production), so that the preset power output was not affected by the cyclist's chosen cadence.
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42 Cyclists were allowed to occasionally stand in the pedals during the prolonged cycling, but
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44 not during the final 5-min all-out trial. VO_2 , RER, HR, cadence, rate of perceived exertion
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46 (RPE), and blood lactate concentration ($[\text{La}^-]$) were determined during five-min periods every
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48 half hour throughout the prolonged cycling. $[\text{La}^-]$ was measured in whole blood from the
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50 finger tips using a Lactate Pro LT-1710 analyzer (Arcray Inc. Kyoto, Japan). The Borg RPE
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52 scale for perceived exertion was used to determine RPE as a subjective indirect measurement
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54 of performance (Borg 1982). During the prolonged cycling, the cyclists were permitted to
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56 consume a sport drink containing 75 g/l carbohydrates, *ad libitum*, in order to maintain fluid
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3 balance and mimic race conditions. Two min after conclusion of the 185 min of prolonged
4 cycling, a 5-min all-out trial was performed for objective direct determination of cycling
5 performance. In line with an earlier study (Hansen et al. 2006), the 5-min all-out trial was
6 chosen as a functional measure of the capacity for very intensive cycling, such as occurs
7 during a break away attempt, crosswind cycling, or steep uphill cycling, all of which may be
8 decisive situations in a road race. For the 5-min all out trial, the ergometer mode was changed
9 to cadence-dependent mode, in which power output increases with increasing cadence
10 according to the following formula: $W = L \times (\text{rpm})^2$ where W is power output, rpm is
11 cadence, and the constant (L) in the formula was set to 0.044. L determines the electronic
12 gearing of the system. Based on findings from a previous study (Hansen et al. 2006), we
13 predicted that the mean power output during the 5-min all-out trial would be between 360 W
14 and 400 W. Since the preferred cadence for many cyclists at this intensity is around 90-95
15 rpm, the constant in the formula was set to 0.044. As an example, a constant cadence of 93
16 rpm would result in a mean power output of 381 W during the 5-min all-out trial. All cyclists
17 were encouraged to produce as high mean power output as possible during the 5-min all-out
18 trial. They received feedback regarding power output production and time elapsed, but not HR
19 and cadence. Mean power output was calculated and used in statistical analyses.
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45 46 *Statistics*

47 All values presented in the text, figures, and tables are mean \pm SE. To test for differences
48 between groups at baseline, unpaired Students t -tests were used. Pre- and post-intervention
49 measurements for each group were compared using paired Students t -test (1RM in half squat,
50 $\text{VO}_{2\text{max}}$, and mean power output during the 5-min all-out trial). To test for any differences in
51 relative changes between the groups in half squat 1RM, $\text{VO}_{2\text{max}}$, and mean power output in
52 the 5-min all-out trial, unpaired Students t -tests were performed. T-tests were performed in
53 Excel 2003 (Microsoft Corporation, Redmond, WA, USA). Two-way repeated measures
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3 ANOVA (time of intervention period and time during prolonged cycling as factors) with
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5 Bonferroni post hoc tests were performed to evaluate differences (post- vs. pre-values) in
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7 responses during the prolonged cycling within groups. In addition, for prolonged cycling,
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9 average values for each hour were analyzed by a two-way repeated measures ANOVA (group
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11 and time point during prolonged cycling as factors) with Bonferroni post hoc tests for
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13 evaluation of differences in relative changes (post- vs. pre-values) between groups. ANOVA
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15 analyses were performed in GraphPad Prism 5 (GraphPad Software, Inc. CA, USA). All
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17 analyses resulting in $p \leq 0.05$ were considered statistically significant.
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24 RESULTS

25 *Baseline.*

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

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41 During the intervention period, $E+S$ increased half squat 1RM ($26 \pm 2\%$, $p < 0.01$, Figure 2),
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43 while this measure remained unchanged in E . Thus, the change in half squat 1RM from before
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45 to after the intervention period was larger in $E+S$ than in E ($p < 0.01$).
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51 *VO_{2max} and body mass.*

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53 Both $E+S$ and E increased VO_{2max} during the intervention period ($p \leq 0.05$). The increase in
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55 VO_{2max} averaged $3 \pm 1\%$ for $E+S$ and $6 \pm 2\%$ for E , with no statistical difference between
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57 groups (Table 1). There was a small, but statistically significant increase in body mass in $E+S$
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59 ($1.2 \pm 0.4\%$; $p < 0.05$), while no change occurred in E . There was no significant difference
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between groups in relative changes in body mass from before to after the intervention.

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12 *Responses during prolonged cycling.*

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14 ANOVA analysis showed that absolute oxygen consumption remained unchanged from
15 before to after the intervention period for both groups during the prolonged cycling (Figure 3).
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17 However, the mean relative oxygen consumption ($\text{ml O}_2 \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$) during the 185 min
18 cycling decreased from $52.7 \pm 0.8\%$ to $50.7 \pm 0.8\%$ of $\text{VO}_{2\text{max}}$ ($p < 0.05$) in *E+S*, while no
19 significant change occurred in *E* (baseline value was $52.4 \pm 1.1\%$ of $\text{VO}_{2\text{max}}$). Heart rate and
20 $[\text{La}^-]$ during the last hour of prolonged cycling were lower at the post-intervention test than at
21 pre-intervention test for *E+S* ($p < 0.05$, Figure 3). In addition, RPE for *E+S* was lower at all
22 time points at the post-intervention test compared to the pre-test ($p < 0.05$). The only change
23 for *E* after the intervention period was a lower RER 30 min into the prolonged cycling
24 ($p < 0.05$, Figure 3). Cadence during prolonged cycling (80 ± 2 rpm as a mean across study
25 groups, time points, and times of intervention period) remained unchanged from baseline to
26 post-intervention for both groups.
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51 A comparison between *E+S* and *E* of the relative changes over the intervention period showed
52 that during the last hour of the prolonged cycling there were statistically significant
53 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.
54 $0.3 \pm 2.3\%$ for *E*), $[\text{La}^-]$ ($-14.0 \pm 4.7\%$ for *E+S* vs. $11.3 \pm 5.5\%$ for *E*), and RPE ($-8.2 \pm 1.6\%$ for
55 *E+S* vs. $2.0 \pm 2.3\%$ for *E*) ($p < 0.05$, Figure 4). There was no difference between groups in
56 relative changes in RER.
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12 *Mean power output in 5-min all-out trial.*

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15 Mean power output during the 5-min all-out trial following the 185-min prolonged cycling
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17 increased $7.2 \pm 2.0\%$ from pre- to post-intervention in *E+S* ($p < 0.01$, Figure 5), while no change
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19 occurred in *E*. The relative change in mean power output during the 5-min all-out trial was
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21 also different between the groups ($p < 0.01$, Figure 5).
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26 27 **DISCUSSION**

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30 A novel finding of the present study was that adding heavy strength training to the usual
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32 endurance training of well-trained cyclists resulted in increased mean power output
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34 production in a 5-min all-out trial performed following 185 min of submaximal cycling. This
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36 power output in the 5-min all-out trial constituted the objective direct measurement of
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38 performance in the present study. In addition, the relative changes over the intervention period
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40 in VO_2 , HR, $[\text{La}^-]$, and RPE during prolonged cycling were all in favor of the cyclists who
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42 had performed heavy strength training, suggesting that strength training improves
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44 performance in prolonged cycling. Notably, the reduced physiological and
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46 psychophysiological responses among the strength-trained cyclists generally occurred during
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48 the last hour of the prolonged cycling, a finding that underscores the relevance of completing
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50 prolonged tests to better simulate road cycling in studies that evaluate the effectiveness of
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52 different training methods.
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60 The observed 26% increase in half squat 1RM is in line with previously reported 27% and
25% increases in squat 1RM in duathletes and triathletes following 10 and 14 weeks of

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

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46 Mean power output in the 5-min all-out trial following 185 min of submaximal cycling
47 increased by ~ 7% for the cyclists who added heavy strength training to their usual endurance
48 training, while no change occurred for the cyclists who performed usual endurance training
49 only. This mean power output was identified as the objective direct performance
50 measurement. The present study thus supports the hypothesis stated two decades ago that
51 strength training can potentially increase cycling performance (Hickson et al. 1988).
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60 However, in a previous study in which moderately trained female cyclists added heavy
strength training to their usual cycling training, no difference between intervention group and

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3 control group was found in average power output during a 1-h cycling test (Bishop et al.
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5 1999). Although the increase in half squat 1RM found in the present study was comparable to
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7 that found in the study by Bishop et al. (1999), the strength training regimens were quite
8
9 different. The present study included four lower body exercises, including half squat, while
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11 squats were the only exercise in the study by Bishop et al. (1999). The difference in strength
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13 training volume and exercises, gender, and performance test may account for the divergent
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15 findings, as a substantially (3-fold) greater volume of strength training was performed in the
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17 present study as compared to that of Bishop et al. (1999).
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24 RPE was determined during prolonged cycling as a subjective indirect measure of
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26 performance. It has been suggested that the linear increase in perceived exertion over exercise
27
28 time can be used as a sensitive predictor of time to exhaustion during exercise (Horstman et
29
30 al. 1979; Crewe et al. 2008). Interestingly, at the post-intervention test, cyclists in *E+S*
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32 reported lower RPE at all time points during the prolonged cycling, while there was no
33
34 change in *E*. During the last hour of the prolonged cycling, the relative change in RPE in *E+S*
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36 was superior to that in *E*. One interpretation is that the strength-trained cyclists were further
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38 from exhaustion at the end of the 185-min prolonged cycling and therefore capable of
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40 producing higher mean power output during the final 5-min all-out trial.
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48 Several models attempt to explain fatigue and consequently performance during prolonged
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50 cycling. One model suggests that fatigue is governed by economy and that an improvement in
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52 economy will lead to reduction in VO_2 , reduced depletion of energy stores, delayed
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54 accumulation of metabolites, and attenuated rise in core body temperature (Abbiss & Laursen
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56 2005). In the present study, adding strength training to the usual endurance training resulted in
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58 a group-by-training effect on percentage change in cycling economy in the strength-trained
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60 cyclists, as indicated by superior VO_2 improvement in *E+S* during the last hour the prolonged

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3 cycling. This is underlined by the findings of superior reductions in $[La^-]$ and HR in $E+S$,
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5 during the last hour of the prolonged cycling. It is likely that the improved performance in the
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7 5-min all-out trial by the strength-trained cyclists at the post-intervention test is a result of the
8
9 superior improvement in $E+S$ compared to E in economy during the prolonged cycling gained
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11 from strength training. Studies with distance runners and cross-country skiers have also found
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13 improved economy after a period of strength training (Johnston et al. 1997; Hoff et al. 1999;
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15 2002; Millet et al. 2002). However, another study using cyclists found no improvement in
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17 cycling economy (Bastiaans et al. 2001). Bastiaans et al. (2001) added light-loaded explosive
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19 strength training to the cyclists' endurance training rather than heavy-loaded strength training
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21 as in the present study. This may partly explain the different findings. Explosive-type strength
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23 training with low loads and many repetitions is known to induce inferior strength gain
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25 compared to heavy-loaded strength training (Weiss et al. 1999). Another methodological
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27 difference between the present study and Bastiaans et al. (2001) is in how economy was
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29 measured. While Bastiaans et al. (2001) measured economy during an incremental test with
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31 2.5 min of cycling at every power output; we measured economy during 5-min periods every
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33 half hour throughout the 185 min of submaximal cycling. During the first two hours of
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35 cycling in the present study there was no difference between groups in economy, but during
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37 the last hour the changes from pre- to post-intervention became significantly different
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39 between groups.
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50 The difference between groups in relative change in economy during the last hour of
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52 prolonged cycling seems to be partly due to a non-significant impairment in economy in E
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54 and partly due to a non-significant improvement in economy in $E+S$. This is similar to results
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56 from an earlier study conducted on well-trained triathletes (Millet et al. 2002). After the
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58 intervention period in that study, the athletes who performed strength training in addition to
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60 endurance training had a superior running economy compared to the athletes who merely

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3 continued their regularly endurance training. Still, as with the present study, the changes were
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5 not significant. The authors speculated that the lack of significant improvement in running
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7 economy in the strength-trained athletes could be due to the fact that these well-trained
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9 athletes have a narrow margin of improvement after several years of training. This could also
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11 be the case in the present study and further emphasizes the notable finding of increased mean
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13 power output in the 5-min all-out trial following the prolonged cycling for *E+S*. The oxygen
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15 pulse ($\text{VO}_2 \cdot \text{HR}^{-1}$), a measurement considered as a cardiovascular 'efficiency' parameter,
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17 showed larger values for *E+S* during the last hour of the 185 min cycling whereas no changes
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19 occurred in *E*. No differences between groups occurred (data not shown). While the specific
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21 causes for the favorable adaptation in economy when adding heavy strength training to
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23 endurance training remain unclear, a number of mechanisms, including some briefly
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25 mentioned below, may be involved.
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34 Muscle fiber type recruitment pattern may also play a role in economy. It has been shown that
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36 type I muscle fibers are more efficient than type II fibers when performing exercise at a given
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38 power output during submaximal exercise (Coyle et al. 1992; Hansen et al. 2002; Majerczak
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40 et al. 2006; Krustup et al. 2008). Therefore, because strength training increases maximal
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42 force, the peak force or muscle fiber tension developed in each pedal thrust would decrease to
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44 a lower percentage of the maximal values. Further, according to the size principle of muscle
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46 fiber type recruitment (Henneman et al. 1965), this would allow reduced reliance on type II
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48 muscle fibers, improving economy, reducing overall muscle fatigue, and increasing the
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50 cyclist's ability to ride longer until exhaustion (Hickson et al. 1988; Coyle et al. 1992;
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52 Horowitz et al. 1994).
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60 Increased $\text{VO}_{2\text{max}}$ should not explain the improved performance in *E+S*, because $\text{VO}_{2\text{max}}$
increased for both groups after the intervention period and there was no difference between

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3 groups. The increase in VO_{2max} in *E+S* contradicts other studies, which have found no change
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5 in VO_{2max} after a period of added strength training (Johnston et al. 1997; Hoff et al. 1999;
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7 2002; Millet et al. 2002). However, the increase in VO_{2max} in the present study was expected,
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9 because the pre-testing was conducted ~1 month after the end of the competition season, a
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11 time of the year when a drop in endurance training is observed. During the preparatory phase,
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13 the start of which coincided with the pre-tests, both groups substantially increased endurance
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15 training, which is a likely explanation for the increased VO_{2max} . Interestingly, the addition of
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17 heavy strength training twice a week during the 12-week intervention period did not
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19 negatively affect the development of VO_{2max} . Other studies have also found no impairment of
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21 VO_{2max} development in a similar period of concurrent endurance and strength training
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23 (McCarthy et al. 1995; Bell et al. 2000; Balabinis et al. 2003).
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32 In conclusion, the addition of heavy strength training twice a week to high-volume endurance
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34 training increased leg strength in well-trained cyclists, as expected. Of even larger practical
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36 importance to the cyclists, the strength training also resulted in higher mean power output in a
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38 5-min all-out trial following 185 min of submaximal cycling. This objective performance
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40 improvement in the 5-min all-out trial was accompanied by larger reductions in RPE scores as
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42 well as measures of VO_2 , HR, and $[La^-]$ during the prolonged cycling for the strength-trained
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44 cyclists compared to the cyclists who had performed usual endurance training.
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50 PERSPECTIVES

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52 Incorporation of strength training in cyclists' preparation has received some attention during
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54 the last two decades with divergent findings. Heavy strength training should, based on the
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56 results from the present study, be included in training for improvement of performance in
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58 well-trained cyclists. These results are in agreement with previous findings in well-trained
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60 cross-country skiers (Hoff et al. 2002), runners (Støren et al. 2008), and well-trained

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3 triathletes (Millet et al. 2002). The results from the present study indicate that heavy strength
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5 training can improve the ability to cycle intensively at the end of a long race and thus improve
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7 cycling performance. The present study is limited by the fact that the well-trained cyclists
8
9 were not randomized into intervention and control group. Furthermore, data on muscle
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11 activation and intramuscular glycogen content after 185 min submaximal cycling would be
12
13 interesting to investigate to further explore possible mechanism behind the improved
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15 performance at the end of prolonged exercise.
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23
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28 There is no conflict of interest.
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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*).

	<i>E+S</i> (n=11)		<i>E</i> (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 ⁻¹	5.10 ± 0.17	5.28 ± 0.22*	5.10 ± 0.33	5.20 ± 0.33*
ml·kg ⁻¹ ·min ⁻¹	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. 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.

*Different from Pre (*p*<0.05)

FIGURE CAPTIONS

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

Figure 2 1RM 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 usual endurance training (E). *Different from Pre ($p<0.01$). #Difference between groups in relative change from pre-test to post-test ($p<0.01$).

Figure 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 ($p<0.05$).

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

Figure 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 ($p<0.01$).

FIGURE 1

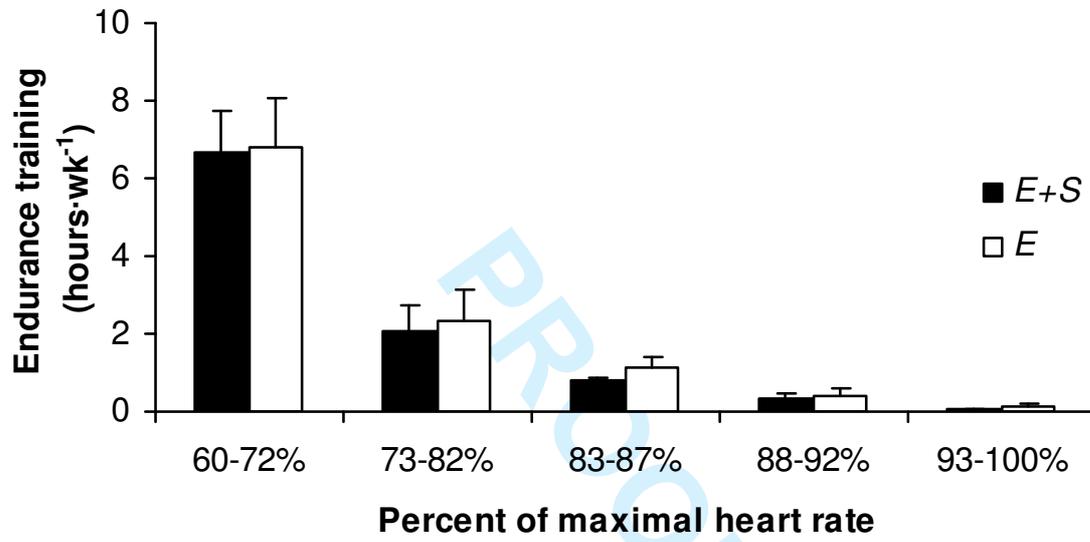


FIGURE 2

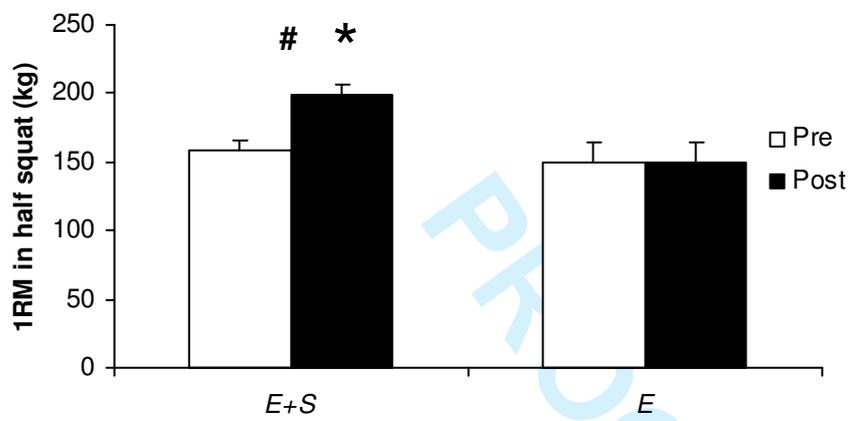


FIGURE 3

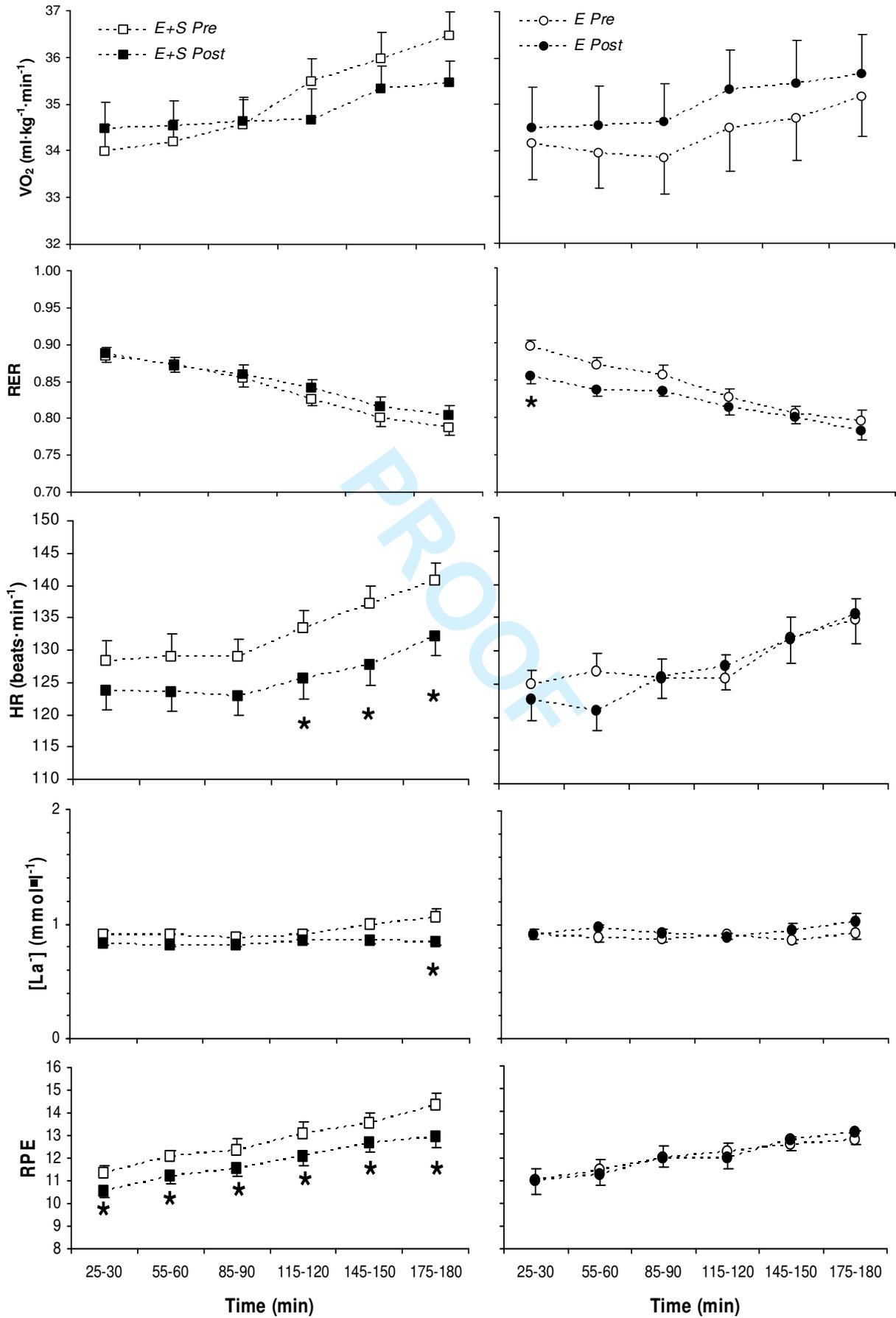


FIGURE 4

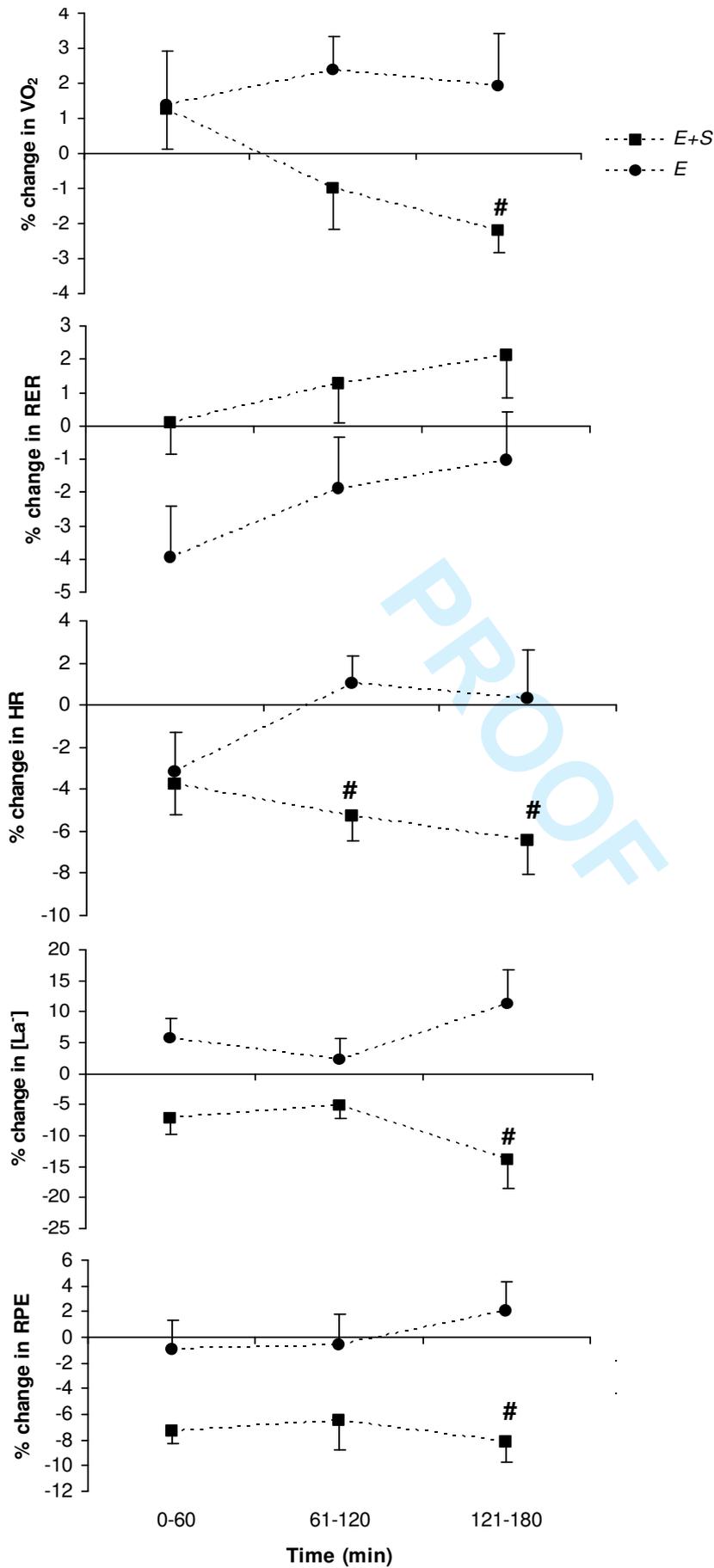


FIGURE 5

