Rønnestad, B. R., Hansen, E. A., Raastad, T. (2010). In-season strength maintenance training increases well-trained cyclists' performance. *European Journal of Applied Physiology, 110*, 1269-1282.

In-season strength maintenance training increases well-trained cyclists' performance

Running head: *"Strength maintenance training in cyclists"*

Bent R. Rønnestad[1], Ernst Albin Hansen[2], and Truls Raastad[2]

[1]Lillehammer University College, Lillehammer, Norway

[2]Norwegian 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

We investigated the effects of strength maintenance training on thigh muscle cross-sectional area (CSA), leg strength, determinants of cycling performance, and cycling performance. Well-trained cyclists completed either 1) usual endurance training supplemented with heavy strength training twice a week during a 12-week preparatory period followed by strength maintenance training once a week during the first 13 weeks of a competition period (*E+S*; n=6 [♂=6]), or 2) usual endurance training during the whole intervention period (*E*; n=6 [♂=5, ♀=1]). Following the preparatory period, *E+S* increased thigh muscle CSA and 1RM ($p<0.05$), while no changes were observed in *E*. Both groups increased maximal oxygen consumption and mean power output in the 40-min all-out trial ($p<0.05$). At thirteen weeks into the competition period, *E+S* had preserved the increase in CSA and strength from the preparatory period. From the beginning of the preparatory period to 13 weeks into the competition period, *E+S* increased peak power output in the Wingate test, power output at 2 $\text{mmol}\cdot\text{l}^{-1}$ [la^-], maximal aerobic power output (W_{max}), and mean power output in the 40-min all-out trial ($p<0.05$). The relative improvements in the last two measurements were larger than in *E* ($p<0.05$). For *E*, W_{max} and power output at 2 $\text{mmol}\cdot\text{l}^{-1}$ [la^-] remained unchanged. In conclusion, in well-trained cyclists, strength maintenance training in a competition period preserved increases in thigh muscle CSA and leg strength attained in a preceding preparatory period, and further improved cycling performance determinants and performance.

Key words: AEROBIC POWER OUTPUT, PEAK POWER OUTPUT, CONCURRENT TRAINING, WEIGHT TRAINING, ENDURANCE PERFORMANCE

INTRODUCTION

Incorporation of strength training into cyclists' preparatory period has received some attention during the last two decades (Bastiaans et al. 2001; Bishop et al. 1999; Hausswirth et al. 2010; Hickson et al. 1988; Rønnestad et al. 2009; 2010). However, the effect of strength training on endurance cycling performance and traditional indicators of cycling performance like lactate threshold, maximum aerobic power output (W_{max}), and cycling economy, is still somewhat unclear. Importantly, adding strength training to usual endurance training does not appear to negatively affect maximal oxygen consumption (VO_{2max}) in cyclists (Bishop et al. 1999; Hausswirth et al. 2010; Rønnestad et al. 2010). Strength training has been shown to improve lactate threshold in untrained individuals (Marcinik et al. 1991). However, studies of trained cyclists have reported both no change in lactate threshold (Bishop et al. 1999; Hausswirth et al. 2010) and increased power output at a blood lactate concentration ($[la^-]$) of 2 $mmol \cdot l^{-1}$ after a period of concurrent strength and endurance training (Rønnestad et al. 2010). Improvement in cycling economy after a period of strength training has been observed for untrained individuals (Loveless et al. 2005) and trained cyclists (Sunde et al. 2009), but not well-trained cyclists (Aagaard et al. 2007; Rønnestad et al. 2010). We have recently reported that strength training can improve performance during all-out cycling performed immediately following prolonged submaximal cycling, which simulates, for example, the final kilometers of a road race (Rønnestad et al. 2009). The intervention in the majority of the above cited studies lasted for ~10-12 weeks and was conducted during the preparatory period. To preserve strength gained during the preparatory period, we know that cyclists must perform some sort of strength maintenance training during the competition period, but how this maintenance training should be performed and how it will affect performance is not clear. Interestingly, maintenance of strength gained in the preparatory period may give some additional performance enhancing effects in the competition period because all other determinants of cycling performance are optimal in this period, and because the cyclists have had the time to adjust to their new level of strength. However, whether strength maintained in the competition period really results in enhanced performance remains to be demonstrated. Thus, the effect of strength maintenance training during the competition period on cycling performance and performance determinants in well-trained cyclists should be investigated.

Performance in road cycling races depends on a number of factors in addition to those mentioned above. One of these additional factors is the ability to generate high power output over a short period of cycling. This ability is essential for a cyclist who needs to close a gap, break away from the pack, or perform well in a sprint. The W_{max} as well as the mean and peak power output in a Wingate test reflect the ability to generate high power output over a short period of time. Peak power output in the Wingate test has been reported to be increased after a period of strength training in both non-cyclists (Beck et al. 2007) and cyclists (Bastiaans et al. 2001; Rønnestad et al. 2010). These findings are supposedly explained by the facts that peak power output in cycling is affected by leg muscle cross-sectional area (CSA) and that strength training increases this CSA (Izquierdo et al. 2004). However, it has been reported that only a small part (0%-45%) of the strength gained during a previous strength training period is preserved after 8-12 weeks without strength training (Andersen et al. 2005; Graves et al. 1988; Narici et al. 1989). Such a period without strength training is accompanied by reduction in muscle fiber and muscle CSA (Andersen et al. 2005; Narici et al. 1989) as well as reduced peak power output during a Wingate test (Kraemer et al. 2002). To mitigate such detraining effects, inclusion of strength maintenance programs that require high intensity muscle actions but low training volume and frequency has been recommended (Graves et al. 1988; Mujika and Padilla 2000). It has been reported that it is possible to maintain previously gained strength with one high-intensity strength training session per week in recreationally strength-trained subjects (Graves et al. 1988). However, it has also been observed that adding large volumes of endurance training to strength training may inhibit adaptations to strength training (Kraemer et al. 1995). Therefore, whether it is possible to maintain an initial gain in strength and related variables during a subsequent period of high volume of concurrent endurance training in cyclists is unclear and should be investigated.

The primary aim of the present study was to investigate the hypothesis that a strength maintenance training program consisting of one weekly session conducted during the first 13 weeks of the competition period would positively affect long-term endurance performance (mean power output in a 40-min all-out trial) at the end of that period. As a part of this, determinants of long-term endurance cycling performance, including cycling economy and power output at 2 $\text{mmol}\cdot\text{l}^{-1}$ [la^{-}] were measured. In addition, vigorous aspects of a road cycling race, including power output in a Wingate test and W_{max} should also be positively affected by the strength maintenance training. As a prerequisite for the hypothesized effects on in-season performance, strength maintenance training must be capable of preserving the previous increases in thigh muscle CSA and strength (1RM in half squat). Consequently, this was controlled for in the present study.

METHODS

Participants

Twelve well-trained cyclists competing at a national level volunteered for the study, which was approved by the Southern Norway regional division of the National Committees for Research Ethics. The cyclists were classified as well-trained based on the criteria suggested by Jeukendrup et al. (2000). All cyclists signed an informed consent form prior to participation. None of the cyclists had performed any strength training during the preceding six months. The intervention started at the same time as the start of the preparatory period. The pre-tests were thus preceded by a transition period of ~ 3-4 weeks with low endurance training volume.

Experimental design

Tests were conducted at three time points: 1) the beginning of a 12-week preparatory period (pre-intervention) that preceded the competition period, 2) the end of the preparatory period/beginning of the competition period (12 weeks), and 3) 13 weeks into the competition period (25 weeks). The cyclists were divided into two groups. The cyclists in the experimental group (*E+S*; n=6 [♂=6], age 29±3 years, height 185±3 cm) performed heavy strength training in addition to usual endurance training. The cyclists in the control group (*E*; n=6 [♂=5, ♀=1], age 31±3 years, height 181±4 cm) simply continued their usual endurance training.

Training

Endurance training consisted primarily of cycling, but some cross-country skiing was also performed during the preparatory period (up to 10% of total training duration). Training duration and intensity were calculated based on recordings from heart rate (HR) monitors (Polar, Kempele, Finland). Endurance training was divided into three HR zones: 1) 60%-72%, 2) 73%-87%, and 3) 88%-100% of maximal HR. The weekly duration of the endurance training and the distribution of this training within the three intensity zones were similar between groups in the preparatory period (*E+S*: 7.4±1.5 hrs, 3.3±1.1 hrs, and 0.4±0.1 hrs, respectively and *E*: 7.2±1.6 hrs, 3.8±1.0 hrs, and 0.7±0.3 hrs, respectively) and in the competition period (*E+S*: 6.3±1.7 hrs, 4.7±1.7 hrs, and 0.6±0.2 hrs, respectively and *E*: 7.3±1.7 hrs, 4.3±0.8 hrs, and 0.8±0.4 hrs, respectively). No significant difference between *E+S* and *E* was found when comparing total training duration (which included competitions, strength training, core stability training and stretching) in the preparatory period (165 ± 17 hrs and 149 ± 12 hrs, respectively, *p*=0.44) or in the competition period (175 ± 9 hrs and 179 ± 29 hrs, respectively, *p*=0.88). The cyclists in *E+S* and *E* participated in the same number of competitions during the competition period (11 ± 2 and 10 ± 1, respectively).

The heavy strength training that was performed by the cyclists in *E+S* targeted leg muscles and was planned to be performed twice per week during the preparatory period and once per week during the competition period. Adherence to the strength training was high, with *E+S* cyclists completing 97±1% of the planned strength training sessions during the preparatory period and 86±4% of the planned strength training sessions during the competition period. The strength training regimen was designed to improve cycling performance by using as cycling-specific exercises as possible. Since peak force during pedalling occurs at approximately a 100° knee angle (Coyle et al. 1991), strength training exercises were performed with a knee angle between 90° and almost full extension. Thus, the strength training exercises focused on the muscles involved in the primarily power generating phase (the downstroke: e.g. m. gluteus maximus, the quadriceps, and the triceps surae), but also muscles involved in the transition phase at the bottom dead center (e.g. m. gastrocnemius) and in the upstroke (e.g. m. rectus femoris and m. iliopsoas) were trained during the strength exercises (Hug & Dorel 2009). In addition, since cyclists work each leg alternately when cycling, and it has been observed a force deficit during bilateral leg exercises (Cresswell and Ovendal 2002; Schantz et al. 1989), one-legged exercises were chosen where practical. Based on the assumption that it is the intended rather than actual velocity that determines the velocity-specific training response (Behm and Sale 1993), the heavy strength training was conducted with focus on maximal mobilization in the concentric phase (lasting around 1 s), while the eccentric and non-cycling specific phase was performed more slowly (lasting around 2-3 s).

At the start of each strength training session, cyclists performed a ~10-min warm-up at self-selected intensity on a cycle ergometer, followed by 2-3 warm-up sets of half squat with gradually increasing load. The performed exercises were: half squat, recumbent leg press with one leg at a time, standing one-legged hip flexion, and ankle plantar flexion (Figure 1). All cyclists were supervised by an investigator at all workouts during the first two weeks and thereafter at least once every second week throughout the intervention period. During the first three weeks, cyclists trained with 10RM sets at the first weekly session and 6RM sets at the second weekly session. During the following three weeks, sets were adjusted to 8RM and 5RM, respectively. During the final six weeks of the preparatory period, sets were adjusted to 6RM and 4RM, respectively (Table 1). The cyclists were encouraged to increase their RM loads continually throughout the intervention period and they were allowed assistance on the last repetition. The number of sets in each exercise was always three during the preparatory period. During the competition period, the order of the strength training exercises was the same, but the number of sets was reduced to two in half squat and leg press. These two exercises were performed with five repetitions at a load corresponding to 80-85% of 1RM. Hip flexion and ankle plantar flexion were performed with only one set and a load corresponding to 6RM (Table 1). During the competition period, strength training exercises were performed with maximal effort in the concentric phase and 2 min rest period between each set and exercise.

(Insert Figure 1 about here)

(Insert Table 1 about here)

Testing

Testing was completed as follows: day 1) measurement of thigh muscle CSA, day 2) maximal strength tests, day 3) incremental cycle tests for determination of blood lactate profile and VO_{2max}, and day 4) 30-s Wingate test and 40-min all-out trial. This test order was repeated at all test occasions. The cyclists were instructed to refrain from intense exercise the day preceding testing, to prepare for the trial as they would have done for a competition, and to consume the same type of meal before each test. They were not allowed to eat during the hour preceding a test or trial or to consume coffee or other products containing caffeine during the preceding three hours. The cyclists were cooled with a fan during cycling. All cycling was performed under similar environmental conditions (20-22˚C). Testing at pre-intervention, 12 weeks, and 25 weeks was conducted at the same time of day to avoid influence of circadian rhythm. All cycling was 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 preference for seat height, horizontal distance between tip of seat and bottom bracket, and handlebar position. Cyclists were allowed to choose their preferred cadence during all cycling and they used their own shoes and pedals.

Thigh muscle cross-sectional area measurement

Magnetic resonance tomography (MR) (Magnetom Avanto 1.5 Tesla, Siemens AG, Munich, Germany) was used to measure thigh muscle CSA. Participants were scanned in supine position. The feet were fixed and elevated by a pad placed at the back of the knees to prevent the muscles on the back of the thighs from compressing against the bench. The machine was centred 2/3 distally on the femur and nine cross-sectional images were sampled starting at the proximal edge of the patella and moving towards the iliac crest, with 35 mm interslice gaps. Each image represented a 5 mm thick slice. The images were subsequently uploaded to a computer for further analysis. The images of the thigh muscles were divided into knee extensor and knee flexor/adductor compartments using a tracer function in the software. The CSA of the thigh muscles was measured from the three most proximal images and the average CSA of these three images was used for statistical analysis. Thirty images were reanalysed for CSA by the same investigator. Mean CSA was found not to be different in the two analyses and the CV of the differences between first and second measurement was 1.6%.

Strength test

Maximal strength of the leg extensors was measured as 1RM in half squat performed in a Smith-machine. Prior to the pre-intervention test, two familiarization sessions were conducted with the purpose of instructing the cyclists in proper half squat 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 3 sets with gradually increasing load (40%, 75%, and 85% of predicted 1RM) and decreasing number of repetitions (10, 7, and 3). The depth of the half squat 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 1RM attempt was performed with a load approximately 5% below the predicted 1RM load. After each successful attempt, the load was increased by 2%-5% until the cyclist failed to lift the same load after 2-3 consecutive attempts. Subjects rested for 3 min between each attempt. All strength tests throughout the study were conducted using the same equipment with identical positioning of the cyclist relative to the equipment and monitored by the same experienced investigator. The strength test at 25 weeks 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).

Blood lactate profile test

A blood lactate profile was determined for each cyclist by plotting [la$^-$] vs. power output performed during the submaximal continuous incremental cycling. The test started without warm-up, with 5 min cycling at 125 W. Cycling continued and power output was increased by 50 W every 5 min. Blood samples were taken from a finger tip while the cyclists were seated on the cycle ergometer at the end of each 5-min bout and were analyzed for whole blood [la$^-$] using a portable lactate analyzer (Lactate Pro LT-1710, Arcray Inc. Kyoto, Japan). The test was terminated when a [la$^-$] of 4 mmol·l^{-1} or higher was measured. The female cyclist in *E* achieved 4 mmol·l^{-1} [la$^-$] before the 225 W bout and her data is therefore not included in the figure presenting the results from the continuous incremental test. However, including her data in the bouts she did complete did not change the statistical outcome. VO_2, respiratory exchange ratio (RER), and HR were measured during the last 3 min of each bout, and mean values were used for statistical analysis. HR was measured using a Polar S610i heart rate monitor (Polar, Kempele, Finland). VO_2 was measured (30 s sampling time) using a computerized metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). The gas analyzers were calibrated with certified calibration gases of known concentrations before every test. The flow turbine (Triple V, Erich Jaeger, Hoechberg, Germany) was calibrated before every test with a 3 l, 5530 series, calibration syringe (Hans Rudolph, Kansas City, USA). Rate of energy expenditure was calculated from gross VO_2

values and their matching RER values using the same method as Coyle et al. (1992). Rate of perceived exertion (RPE) was recorded 4 min and 50 s into each bout, using Borg's 6-20 scale (Borg 1982). From this continuous incremental cycling test, the power output at 2 $mmol \cdot l^{-1}$ $[la^{-}]$ was calculated for each cyclist. The power output was calculated from the relationship between $[la^{-}]$ and power output using linear regression between data points.

VO_{2max} test

After termination of the blood lactate profile test, the cyclists rested for 3 h before completing another incremental cycling test for determination of VO_{2max}. This test has been described elsewhere (Rønnestad et al. 2009). Briefly, the cyclists completed a 10-min warm-up followed by a 1-min rest. The test was then initiated with 1 min of cycling at a power output corresponding to 3 $W \cdot kg^{-1}$ (rounded down to the nearest 50 W). Power output was subsequently increased by 25 W every minute until exhaustion. When the cyclists predicted that they would not be able to complete another 25 W increase in power output, they were encouraged to simply continue cycling at the current power output for as long as possible (usually 30 to 60 s). VO_{2max} (along with the complementary data) was calculated as the average of the two highest VO_2 measurements. W_{max} was calculated as the mean power output during the last 2 min of the incremental test.

Wingate test

The 30-s Wingate test was also performed on the Lode cycle ergometer. Braking resistance was set to 0.8 $Nm \cdot kg^{-1}$ body mass. The Wingate protocol was managed from a personal computer (running the Lode Wingate software, version 1.0.14) that was connected to the cycle ergometer. After a 10-min warm-up and a 1-min rest, cyclists started cycling at ~ 60 rpm without braking resistance. Then, following a 3-s countdown, the braking resistance was applied to the flywheel and remained constant throughout the 30-s all-out test. The cadence was sampled at 5 Hz by a computer and matching power output values were calculated by the software. The Lode Wingate software presented peak power output as the highest power output achieved at any time during the 30-s all-out test. Mean power output was presented as the average power output sustained throughout the 30 s, while minimal power was presented as the lowest power output achieved during the 30 s. Peak and minimal power output were used to calculate the fatigue index, defined here as the decline in power output per second from peak power output to minimal power output. Cyclists remained seated throughout the test and strong verbal encouragement was provided from the test personnel during the test. To attain the highest possible peak power, subjects were instructed to pedal as fast as possible from the start and not to preserve energy for the last part of the test. Cyclists then recovered by cycling at ~100 W for 10 min before starting the 40-min all-out trial.

40 min all-out trial

In this 40-min trial the cyclists were instructed to cycle at as high an average power output as possible. This type of test with a closed end has been shown to have a low coefficient of variation (CV<3.5 %; Jeukendrup et al. 1996). Performance was measured as the average power output during the trial. The cyclists were allowed to adjust the power output throughout the trial using an external control unit mounted on the handlebar. The cyclists received no feedback about HR and cadence, but they were aware of remaining time and instantaneous power output. The cyclists were allowed to occasionally stand in the pedals during the trial and to drink water *ad libitum*.

Statistics

All data in the text, figures, and tables are presented as mean±SE. To test for differences between groups at pre-intervention, unpaired Student's *t*-tests were used. In the 40-min all-out trial there was a statistical power of 80% to detect a difference between the groups of 25 W with a significance level (alpha) of 0.05 (two-tailed). This difference between groups is recognised as a significant performance enhancement. For each group, measurements at pre-intervention, at 12 weeks, and 25 weeks were compared using one-way repeated measures ANOVA. If the ANOVA reached significance, a Tukey's HSD test was performed for *post hoc* analysis. To test for differences between groups in relative changes, two-way repeated measures ANOVA (time of intervention and group as factors) with Bonferroni *post hoc* tests were performed to evaluate differences. In addition, two-way repeated measures ANOVA (time of intervention and group as factors) with Bonferroni *post hoc* tests were performed for evaluation of differences between groups in absolute values. ANOVA analyses were performed in GraphPad Prism 5 (GraphPad Software Inc., CA, USA). Student's *t*-tests were performed in Excel 2003 (Microsoft Corporation, Redmond, WA, USA). All analyses resulting in $p \leq 0.05$ were considered statistically significant.

RESULTS

Comparison of groups at pre-intervention

There were no significant differences between *E+S* and *E* at pre-intervention with respect to body mass, thigh muscle CSA (Figure 2), 1RM in half squat (Figure 3), VO_{2max} (Table 2), or measurements in any of the cycling performance tests except body mass-adjusted peak power output during the Wingate test (Table 3).

Body mass, thigh muscle cross-sectional area, and strength

Body mass was unchanged from pre-intervention to 25 weeks in both *E+S* and *E* (pre-intervention values were 79.7±4.4 kg and 73.7±4.2 kg, respectively). Thigh muscle CSA (sum of flexors and extensors) increased by 4.4±0.6% in *E+S* during the preparatory period ($p<0.01$), while no changes occurred in *E* from pre-intervention to 25 weeks. The relative change in thigh muscle CSA during the preparatory period was greater in *E+S* than in *E* ($p<0.01$). Furthermore, this larger thigh muscle CSA was preserved at 25 weeks ($p<0.05$, Figure 2). Strength measured as 1RM in half squat increased by 23±3% in *E+S* during the preparatory period ($p<0.01$) and this strength was preserved at 25 weeks. Strength remained unchanged in *E* from pre-intervention to 25 weeks (Figure 3). Thus, the change in 1RM half squat during the preparatory period and from pre-intervention to 25 weeks was larger in *E+S* than in *E* ($p<0.01$).

(Insert Figure 2 about here)

(Insert Figure 3 about here)

VO_{2max} and W_{max}

Body mass-adjusted VO_{2max} increased by 6±2% in *E+S* and 8±2% in *E* during the preparatory period ($p<0.05$, Table 2). *E+S* achieved a further significant improvement from 12 weeks to 25 weeks (7±2%, $p<0.05$, Table 2), although there was no difference between groups. W_{max} in *E+S* increased by 8±1% from pre-intervention to 25 weeks ($p<0.05$), while no change occurred in *E* (Table 2). The relative change in W_{max} was larger in *E+S* than in *E* ($p<0.05$). There were no differences between the groups in blood lactate concentrations obtained after the VO_{2max} test at any test occasion (Table 2).

(Insert Table 2 about here)

Blood lactate profile

Power output at 2 mmol·l^{-1} [la^{-}] did not change for either group during the preparatory period. However, *E+S* increased power output at 2 mmol·l^{-1} [la^{-}] from 253±16 W at pre-intervention to 284±13 W at 25 weeks (p<0.05), while no change was observed in *E* (pre-intervention value of 248±26 W). There was, however, no statistically significant difference between groups in relative change in power output at 2 mmol·l^{-1} [la^{-}]. Lactate concentration at 275 W was lower for both *E+S* and *E* at 12 weeks than at pre-intervention (p<0.05, Figure 4). The relative decrease in [la^{-}] at 25 weeks was larger in *E+S* than in *E* (p<0.05). ANOVA analysis showed that during the blood lactate profile test, cycling economy, determined as body mass-adjusted oxygen consumption at a given power output, remained unchanged during the intervention period (pre-intervention to 25 weeks) for *E+S*. In contrast, cycling economy was impaired (i.e., VO_2 increased) for cyclists in *E* at the three highest power outputs (175 W, 225 W, and 275 W) (p<0.05, Figure 4). Only *E+S* reduced RPE at 225 W and 275 W at 25 weeks (p<0.05, Figure 4). Both groups had decreased HR at all four power outputs from pre-intervention to 25 weeks (p<0.05, Figure 4). RER at 275 W was reduced during the preparatory period in both groups (p<0.05). *E+S* also had a reduced RER from pre-intervention to 25 weeks at all power outputs (p<0.05, Figure 4). A comparison between *E+S* and *E* of the relative changes from pre-intervention to 25 weeks showed no significant difference between groups in VO_2, RER, HR or RPE during the blood lactate profile test. Furthermore, there was no change in gross efficiency during the intervention period in any of the groups. The gross efficiency at a power output of 125 W, 175 W, 225 W, and 275 W was 18.6±0.4%, 20.0±0.2%, 20.8±0.1%, and 21.0±0.1%, respectively, as mean values across groups, time points in the tests, and time points of intervention.

(Insert Figure 4 about here)

Power output in the 40-min all-out trial

Mean power output during the 40-min all-out trial increased during the preparatory period in both *E+S* and *E* (8±2% and 4±1%, respectively; p<0.05, Figure 5), with no difference between groups in relative increase. The increase in mean power output in the 40-min all-out trial from pre-intervention to 25 weeks was larger in *E+S* than in *E* (14±3% vs. 4±1%, respectively; *p*<0.05, Figure 5).

(Insert Figure 5 about here)

Power output in the Wingate test

Peak power output in the 30-s Wingate test increased in *E+S* from pre-intervention to 25 weeks, in both absolute values and when these were calculated relative to body mass (6±2% and 8±2%, respectively, *p*<0.05, Table 3). No changes occurred in *E*. Neither of the groups had significant changes in mean power output in the 30-s Wingate test (Table 3). The relative change in fatigue index was larger in *E+S* than in *E* at the end of the preparatory period (*p*<0.05, Table 3), resulting in a significant difference between groups at this point (*p*<0.05, Table 3). However, fatigue index did not change for either group from pre-intervention to 25 weeks and there was no difference between groups at 25 weeks.

(Insert Table 3 about here)

Freely chosen cadence

Freely chosen cadence was unchanged from pre-intervention to 25 weeks in both groups. The freely chosen cadence during the lactate profile test, VO_{2max} test, and 40-min all-out trial was 87±2 rpm, 95±2 rpm, and 92±2 rpm, respectively, as mean values across groups, points of time in the tests, and points of time in the intervention.

DISCUSSION

A novel finding of the present study was that strength maintenance training performed once a week during a 13-week competition period preserved leg strength and thigh muscle CSA increases achieved by well-trained cyclists during a preceding 12-week preparatory period. Of practical importance, these in-season adaptations to strength maintenance training were accompanied by superior adaptations in performance, measured as changes in 1) average power output in a 40-min all-out trial, 2) $[la^-]$ at a power output of 275 W, and 3) W_{max}.

Strength, thigh muscle CSA, and power output in Wingate test

As expected, two sessions per week of strength training increased leg strength and thigh muscle CSA in *E+S* during the preparatory period. No changes in these measurements occurred in *E*. It has been reported previously that if strength training is not maintained after a strength training period, only a part (0%-45%) of the strength gained is retained after 8-12 weeks (Andersen et al. 2005; Graves et al. 1988; Narici et al. 1989). The loss of strength after cessation of strength training is related to a reduction in muscle fiber CSA and muscle CSA. These changes have also been shown to reduce peak power output in the Wingate test (Andersen et al. 2005; Kraemer et al. 2002; Narici et al. 1989). Thus, to face the challenge of counteracting in-season detraining effects, it has been suggested that during the competition period athletes should complete strength maintenance programs that include high intensity muscle actions and low weekly training volume and frequency (Graves et al. 1988; Mujika and Padilla 2000). One challenge is that large volumes of endurance exercise may inhibit adaptations to strength training (Kraemer et al. 1995). This may be interpreted as a need to further increment volume and/or intensity in the in-season strength maintenance training program since this is performed simultaneously with a large volume of endurance training. To our knowledge the present study is the first to demonstrate that competitive cyclists can maintain the initial strength and muscle CSA increases attained in a preceding preparatory period with just a single heavy strength training session per week during a 13-week competition period.

Peak power output often occurs during the first 5 s of an all-out Wingate test. Thus, peak power output is mainly dependent on the size of the involved muscle mass and maximal leg strength (Izquierdo et al. 2004). Therefore, the finding that *E+S* increased peak power output during the intervention period may be explained by the increase in thigh muscle CSA and leg strength. Correspondingly, the finding of no change in peak power output in *E* is probably explained by no changes in thigh muscle CSA or leg strength. This finding has practical implications, since the ability to generate high power output during a short period of time is an important aspect of overall cycling performance (Atkinson et al. 2003).

VO_{2max}, W_{max}, and blood lactate profile

The finding of increased VO_{2max} in both groups of cyclists from pre-intervention to 25 weeks agrees with previous findings in cyclists (Sassi et al. 2008; White et al. 1982). This finding was expected since the pre-intervention tests were conducted ~1 month after the end of the competition season, a period of the year when endurance training volume is typically low.

Importantly, the added strength training did not impair the development of VO_{2max} during either the preparatory period or the first 13 weeks of the competition period. In fact, only *E+S* achieved a statistically significant increase in VO_{2max} from 12 to 25 weeks, though there was no difference between groups. The observed increase in VO_{2max} during the competition period in *E+S* may be related to a smaller (but not significantly different from *E*) increase in VO_{2max} during the preparatory period. A closer examination of the endurance training reveals that *E+S* had a larger, though not statistically significant, increase in the weekly amount of endurance training in intensity zones 2 and 3 (73-100% of maximum HR) from the preparatory period to the competition period (from 3.7±1.1 to 5.3±1.8 hrs for *E+S*, from 4.6±1.2 to 5.1±1.2 hrs for *E*). This change in the endurance training intensity may also affect the adaptations in VO_{2max}. The finding of no degradation of VO_{2max} adaptations agrees with other studies that have found no impairment of VO_{2max} development for either trained or untrained individuals performing concurrent endurance and strength training (McCarthy et al. 1995; Østerås et al. 2002).

There is no major difference between well-trained cyclists and elite cyclists in VO_{2max} (Lucia et al. 1998). Even though VO_{2max} and W_{max} are related, it seems that W_{max} is the key indicator separating elite cyclists from well-trained cyclists (Lucia et al. 1998). It is therefore interesting to note that although both groups increased VO_{2max}, only *E+S* increased W_{max} from pre-intervention to 25 weeks, with the relative increase being larger for *E+S* than *E*. W_{max} is influenced not only by VO_{2max} and cycling economy, but also by anaerobic capacity (Jones and Carter 2000). Therefore, the findings of larger increase in peak power output during the Wingate test, 1RM, and thigh muscle CSA in *E+S* compared with *E*, in addition to a slightly impaired cycling economy in *E* and no change in cycling economy in *E+S,* are all likely contributors to the larger gain in W_{max} in *E+S*. Power output determines velocity during cycling and thus greatly affects performance. While our results concur with results from a strength training study on untrained persons (Loveless et al. 2005), they contradict a study in which trained cyclists replaced a portion of their endurance training with explosive strength training (Bastiaans et al. 2001). The reason for such divergent findings remains unclear, but can be due to differences in strength training programs, compliance, or circumstances related to testing protocols.

Both groups reduced their HR at all power outputs from 125 W to 275 W after 25 weeks. The finding of reduced HR at submaximal power outputs from the preparatory period into the competition period is in line with other findings in trained cyclists (Hopker et al. 2009). Power output at 2 $\mathrm{mmol{\cdot}l^{-1}}$ $[\mathrm{la^-}]$ was unchanged in both groups after the preparatory period, but *E+S* improved power output at 2 $\mathrm{mmol{\cdot}l^{-1}}$ $[\mathrm{la^-}]$ at 25 weeks. This improvement for *E+S* was accompanied by reduced RPE at the power outputs when 2 $\mathrm{mmol{\cdot}l^{-1}}$ $[\mathrm{la^-}]$ was approached. The finding of improved power output at 2 $\mathrm{mmol{\cdot}l^{-1}}$ $[\mathrm{la^-}]$ after adding strength training agrees with a previous study on untrained persons (McCarthy et al. 1995), but contradicts findings in trained female (Bishop et al. 1999) and male cyclists (Sunde et al. 2009). Interestingly, the latter two studies were performed during the preparatory period only and, as in the present study, no change was observed. Since *E+S* increased power output at 2 $\mathrm{mmol{\cdot}l^{-1}}$ $[\mathrm{la^-}]$ while *E* did not, and the groups did not differ in $\mathrm{VO_{2max}}$, an improved cycling economy in *E+S* might be expected. An improvement in cycling economy, measured as $\mathrm{VO_2}$ at submaximal power outputs, could then have explained the observed increase in power output at 2 $\mathrm{mmol{\cdot}l^{-1}}$ $[\mathrm{la^-}]$. However, this was not the case, as cycling economy and gross efficiency did not improve significantly in *E+S*. The finding of no change in cycling economy is in accordance with a study in which well-trained cyclists combined heavy strength training with endurance training (Aagaard et al. 2007). The differences between groups in power output at 2 mmol·l^{-1} [la^{-}] are therefore likely to be affected by the slightly impaired cycling economy in *E*. Indeed, an inverse relationship between VO_{2max} and efficiency has previously been observed in professional cyclists (Lucia et al. 2002). Similar observations have been conducted on distance runners (Pate et al. 1992). The added strength training may therefore contribute to maintenance of the cycling economy, despite increased VO_{2max}. The power output corresponding to a set [la^{-}] or inflection point obtained during a continuous incremental exercise test has been suggested to be a more important determinant of endurance cycling performance than VO_{2max} (Bishop et al. 1998; Coyle et al. 1991). Thus, the improved power output at 2 mmol·l^{-1} [la^{-}] potentially reflects superior endurance cycling performance.

40-min all-out trial

Mean power output in the 40-min all-out trial is mainly determined by performance oxygen consumption and cycling economy (Joyner and Coyle 2008). The performance oxygen consumption is again largely affected by VO_{2max} and lactate threshold. The findings of improved VO_{2max} and reduced [la^{-}] at a submaximal power output of 275 W in both groups after the preparatory period may thus contribute to the improved mean power output in the 40-min all-out trial at 12 weeks. However, at 13 weeks into the competition period, the further relative increase in mean power output during the 40-min all-out trial was significantly greater in *E+S* than in *E*. This larger improvement in *E+S* may be explained by a combination of this group's larger relative reduction in [la^{-}] at a power output of 275 W, larger relative increase in W_{max}, further improvement in VO_{2max} into the competition period, as well as a slight impairment of the cycling economy in *E*.

The present results agree with previous findings of ~8% increased mean power output during 45-min all-out cycling in national level cyclists after 16 weeks of added heavy strength training (Aagaard et al. 2007). Bastiaans et al. (2001) found similar improvements in a 1-h time trial for trained cyclists who had a portion of their endurance training replaced with low loaded explosive strength training. This improvement was, however, not different from another group of trained cyclists who simply continued their endurance training. It may thus be suggested that low loaded explosive strength training do not enhance cycling performance during a 9 week training period. The two latter studies were performed during the preparatory period. Bishop et al. (1999) reported no improvement in performance for trained female cyclists in a 1-h time trial after performing concurrent strength and endurance training during the preparatory period. Notably, the female participants only performed squat exercise, while four lower body exercises were performed in the present study. Thus, it is possible that the difference in strength training exercises, gender, and performance test may account for the divergent findings.

The larger improvements in mean power output during the 40-min all-out trial and in [la$^-$] at 275 W in *E+S* at 25 weeks, may be related to postponed activation of type II muscle fibers due to increased strength in type I fibers. A positive correlation between percentage type I muscle fibers in m. vastus lateralis and efficiency during exercise at a given submaximal power output has been reported (Coyle et al. 1992; Hansen et al. 2002). An increase in the strength of type I fibers may delay recruitment of the less economical type II fibers, resulting in a higher power output at 2 $\text{mmol}\cdot\text{l}^{-1}$ [la$^-$]. Delayed recruitment of type II fibers may also explain the larger reduction in [la$^-$] at a power output of 275 W during the blood lactate profile test after 25 weeks in *E+S*. Theoretically, if the hypothesis regarding postponed recruitment of type II fibers is true, an improved cycling economy should possibly be detected. But this was not the case. On the other hand, a reduction in RER at all power outputs during the blood lactate profile test in *E+S* at 25 weeks may indicate a larger energy supply from fatty acids, leading to a slightly larger demand of VO_2. The reduction in RER is also in line with increased work performed by type I fibers, which, even in endurance trained individuals, are thought to be superior to type II fibers in their ability to use fat as energy source (Chi et al. 1983). Although reduced RER was observed, no statistically significant changes were observed in gross efficiency.

We recently published a study on well-trained cyclists, where it was found that the group completing 12 weeks of strength training improved cycling economy during the last hour of 185-min submaximal cycling more than the control group (Rønnestad et al. 2009). The improved economy was accompanied by reduced HR, $[la^-]$, and improved performance in a 5-min all-out trial performed immediately following the 185 min of submaximal cycling. We hypothesized that postponed activation of type II fibers could contribute to the findings. Furthermore, increases in specific force and unloaded shortening velocity of single muscle fibers, which did not change the myosin heavy chain expression, have been observed in response to strength training (Pansarasa et al. 2009). This may also contribute to improved endurance performance after adding the heavy strength training. Increased rate of force development (RFD) and/or maximum strength has been hypothesized to positively affect endurance performance through improved blood flow to the exercising muscles during exercise (Østerås et al. 2002). This is explained by the assumption that 1) increased RFD may allow a longer relaxation time and thereby increased blood flow and/or 2) increased maximum strength may reduce the relative force and thus reduce constriction of the blood flow. In the present study maximum strength did increase, and increased RFD is usually observed after strength training periods similar to the present intervention; containing heavy loaded exercises performed with maximal mobilization in the concentric phase (e.g. Aagaard et al 2002). The improved performance in *E+S* may therefore be partly due to improved blood flow to the exercising muscles.

There were no significant differences between groups in the 40-min performance test after the preparatory period. This may be explained by the fact that, for well-trained endurance athletes with several years of training, improvements in aerobic performance come in smaller increments (Paavolainen et al. 1999). Furthermore, it may be hypothesized that the cyclists in *E+S* needed more than 12 weeks to fully translate the increased strength into improved cycling performance. Thus, the performance enhancing effect of the strength training was not detectable before the gained strength had been maintained for 13 weeks into the competition period.

In conclusion, performing just one weekly strength maintenance training session for 13 weeks into a competition period allowed well-trained cyclists to maintain the increases in leg strength and thigh muscle CSA that were attained during a preceding 12-week preparatory period. The development of VO_{2max} was not compromised by the strength training. Of even greater practical importance, the in-season maintenance of the strength training adaptations resulted in larger improvements in cycling performance and factors relevant for performance, for both sprint and prolonged cycling as compared to cyclists performing only usual endurance training.

Acknowledgements

The authors express their thanks to the participants for their time and effort.

No founding was received for this work.

Conflict of interest

The authors declare that they have no conflict of interest.

References

Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P (2002) Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol 93:1318-1326

Aagaard P, Bennekou M, Larsson B, Andersen JL, Olesen J, Crameri R, Magnusson PS, Kjaer M (2007) Resistance training leads to altered fiber type composition and enhanced long-term cycling performance in elite competitive cyclists [abstract]. Med Sci Sports Exerc 39:S448-S449

Andersen LL, Andersen JL, Magnusson SP, Suetta C, Madsen JL, Christensen LR, Aagaard P (2005) Changes in the human muscle force-velocity relationship in response to resistance training and subsequent detraining. J Appl Physiol 99:87-94

Atkinson G, Davison R, Jeukendrup A, Passfield L (2003) Science and cycling: current knowledge and future directions for research. J Sports Sci 21:767-787

Bastiaans JJ, van Diemen AB, Veneberg T, Jeukendrup AE (2001) The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists. Eur J Appl Physiol 86:79-84

Beck TW, Housh TJ, Johnson GO, Coburn JW, Malek MH, Cramer JT (2007) Effects of a drink containing creatine, amino acids, and protein combined with ten weeks of resistance training on body composition, strength, and anaerobic performance. J Strength Cond Res 21:100-104

Behm DG, Sale DG (1993) Velocity specificity of resistance training. Sports Med 15:374-388

Bishop D, Jenkins DG, Mackinnon LT (1998) The relationship between plasma lactate parameters, Wpeak and 1-h cycling performance in women. Med Sci Sports Exerc 30:1270-1275

Bishop D, Jenkins DG, Mackinnon LT, McEniery M, Carey MF (1999) The effects of strength training on endurance performance and muscle characteristics. Med Sci Sports Exerc 31:886-891

Borg GA (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14:377-381

Chi MM, Hintz CS, Coyle EF, Martin WH 3rd, Ivy JL, Nemeth PM, Holloszy JO, Lowry OH (1983) Effects of detraining on enzymes of energy metabolism in individual human muscle fibers. Am J Physiol 244:C276-287

Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, Abraham LD, Petrek GW (1991) Physiological and biomechanical factors associated with elite endurance cycling performance. Med Sci Sports Exerc 23:93-107

Coyle EF, Sidossis LS, Horowitz JF, Beltz JD (1992) Cycling efficiency is related to the percentage of type I muscle fibers. Med Sci Sports Exerc 24:782-788

Cresswell AG, Ovendal AH (2002) Muscle activation and torque development during maximal unilateral and bilateral isokinetic knee extensions. J Sports Med Phys Fitness 42:19-25

Graves JE, Pollock ML, Leggett SH, Braith RW, Carpenter DM, Bishop LE (1988) Effect of reduced training frequency on muscular strength. Int J Sports Med 9:316-319

Hansen EA, Andersen JL, Nielsen JS, Sjøgaard G (2002) Muscle fibre type, efficiency, and mechanical optima affect freely chosen pedal rate during cycling. Acta Physiol Scand 176:185-194

Hausswirth C, Argentin S, Bieuzen F, Le Meur Y, Couturier A, Brisswalter J (2010) Endurance and strength training effects on physiological and muscular parameters during prolonged cycling. J Electromyogr Kinesiol 20:330-339

Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C (1988) Potential for strength and endurance training to amplify endurance performance. J Appl Physiol 65:2285-2290

Hopker J, Coleman D, Passfield L (2009) Changes in cycling efficiency during a competitive season. Med Sci Sports Exerc 41:912-919

Hug F, Dorel S (2009) Electromyographic analysis of pedaling: a review. J Electromyogr Kinesiol 19:182-198

Izquierdo M, Ibáñez J, Häkkinen K, Kraemer WJ, Ruesta M, Gorostiaga EM (2004) Maximal strength and power, muscle mass, endurance and serum hormones in weightlifters and road cyclists. J Sports Sci 22:465-478

Jeukendrup A, Saris WH, Brouns F, Kester AD (1996) A new validated endurance performance test. Med Sci Sports Exerc 28:266-270

Jeukendrup AE, Craig NP, Hawley JA (2000) The bioenergetics of World Class Cycling. J Sci Med Sport 3:414-433

Jones AM, Carter H (2000) The effect of endurance training on parameters of aerobic fitness. Sports Med 29:373-386

Joyner MJ, Coyle EF (2008) Endurance exercise performance: the physiology of champions. J Physiol 586:35-44

Kraemer WJ, Koziris LP, Ratamess NA, Hakkinen K, Triplett-McBride NT, Fry AC, Gordon SE, Volek JS, French DN, Rubin MR, Gomez AL, Sharman MJ, Michael Lynch J, Izquierdo M, Newton RU, Fleck SJ (2002) Detraining produces minimal changes in physical performance and hormonal variables in recreationally strength-trained men. J Strength Cond Res 16:373-382

Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, Dziados JE (1995) Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. J Appl Physiol 78:976-989

Loveless DJ, Weber CL, Haseler LJ, Schneider DA (2005) Maximal leg-strength training improves cycling economy in previously untrained men. Med Sci Sports Exerc. 37:1231-1236

Lucía A, Hoyos J, Pérez M, Santalla A, Chicharro JL (2002) Inverse relationship between VO2max and economy/efficiency in world-class cyclists. Med Sci Sports Exerc 34:2079-2084

Lucía A, Pardo J, Durántez A, Hoyos J, Chicharro JL (1998) Physiological differences between professional and elite road cyclists. Int J Sports Med 19:342-348

Marcinik EJ, Potts J, Schlabach G, Will S, Dawson P, Hurley BF (1991) Effects of strength training on lactate threshold and endurance performance. Med Sci Sports Exerc 23:739-743

McCarthy JP, Agre JC, Graf BK, Pozniak MA, Vailas AC (1995) Compatibility of adaptive responses with combining strength and endurance training. Med Sci Sports Exerc 27:429-436

Mujika I, Padilla S (2000) Detraining: loss of training-induced physiological and performance adaptations. Part II: Long term insufficient training stimulus. Sports Med 30:145-154

Narici MV, Roi GS, Landoni L, Minetti AE, Cerretelli P (1989) Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. Eur J Appl Physiol Occup Physiol 59:310-319

Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H (1999) Explosive-strength training improves 5-km running time by improving running economy and muscle power. J Appl Physiol 86:1527-1533

Pansarasa O, Rinaldi C, Parente V, Miotti D, Capodaglio P, Bottinelli R (2009) Resistance training of long duration modulates force and unloaded shortening velocity of single muscle fibres of young women. *J Electromyogr Kinesiol.* 19:e290-E300

Pate RR, Macera CA, Bailey SP, Bartoli WP, Powell KE (1992) Physiological, anthropometric, and training correlates of running economy. Med Sci Sports Exerc 24:1128-1133

Rønnestad BR, Hansen EA, Raastad T (2010) Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. Eur J Appl Physiol 108:965-975

Rønnestad BR, Hansen EA, Raastad T (2009) Strength training improves 5-min all-out performance following 185 min of cycling. Scand J Med Sci Sports [Epub ahead of print, cited Nov 9]. doi: 10.1111/j.1600-0838.2009.01035.x

Rønnestad BR (2009) Acute effects of various whole body vibration frequencies on 1RM in trained and untrained subjects. J Strength Cond Res 23:2068-2072

Sassi A, Impellizzeri FM, Morelli A, Menaspà P, Rampinini E (2008) Seasonal changes in aerobic fitness indices in elite cyclists. Appl Physiol Nutr Metab 33:735-742

Schantz PG, Moritani T, Karlson E, Johansson E, Lundh A (1989) Maximal voluntary force of bilateral and unilateral leg extension. Acta Physiol Scand 136:185-192

Sunde A, Støren O, Bjerkaas M, Larsen MH, Hoff J, Helgerud J (2009) Maximal Strength Training Improves Cycling Economy in Competitive Cyclists. J Strength Cond Res [Epub ahead of print, cited Oct 22]. doi:10.1519/JSC.0b013e3181aeb16a

White JA, Quinn G, Al-Dawalibi M, Mulhall J (1982) Seasonal changes in cyclists' performance. Part I. The British Olympic road race squad. Br J Sports Med 16:4-12

Østerås H, Helgerud J, Hoff J (2002) Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. Eur J Appl Physiol 88:255-263

Figure Captions

Fig. 1 Strength exercises (A) half squat in Smith-machine, (B) recumbent leg press with one leg at a time, (C) standing one-legged hip flexion, and (D) ankle plantar flexion.

Fig. 2 Thigh muscle cross-sectional area (CSA) separated into area of knee extensors (upper panels) and knee flexors (lower panels) before the preparatory period (Pre), after the preparatory period (12 weeks), and 13 weeks into the competition period (25 weeks). One group of cyclists added heavy strength training to their endurance training (*E+S*; n=6, panel a and c) while cyclists in the other group simply performed their usual endurance training (*E*; n=6, panel b and d). Mean and each individual data points are presented. *Larger than at Pre ($p<0.05$). $^{\#}$The relative change from Pre is larger than in *E* ($p<0.01$). $^{\#\#}$Larger than in *E* ($p<0.05$)

Fig. 3 1RM in half squat before (Pre), after the 12 week preparatory period (12 weeks), and 13 weeks into the competition period (25 weeks). For explanation of *E+S* (panel a) and *E* (panel b), the reader is referred to Figure 2. Mean and each individual data points are presented. *Larger than at Pre ($p<0.01$). $^{\#}$The relative change from Pre is larger than in *E* ($p<0.01$). $^{\#\#}$Larger than in *E* ($p<0.01$)

Fig. 4 Responses during the continuous incremental cycle test before (Pre), at the end of the preparatory period (12 weeks), and 13 weeks into the competition period (25 weeks). For explanation of *E+S* (left panels) and *E* (right panels), the reader is referred to Figure 2. *Different from Pre ($p<0.05$). §Different from 12 weeks ($p<0.05$). $^{\#}$The relative change from Pre is larger than in *E* ($p<0.05$)

Fig. 5 Mean power output (W) during the 40-min all-out trial before (Pre), at the end of the preparatory period (12 weeks), and 13 weeks into the competition period (25 weeks). For explanation of *E+S* (panel a) and *E* (panel b), the reader is referred to Figure 2. Mean and each individual data points are presented. *Larger than at Pre ($p<0.05$). $^{\#}$The relative change from Pre is larger than in *E* ($p<0.01$)

Figure 2

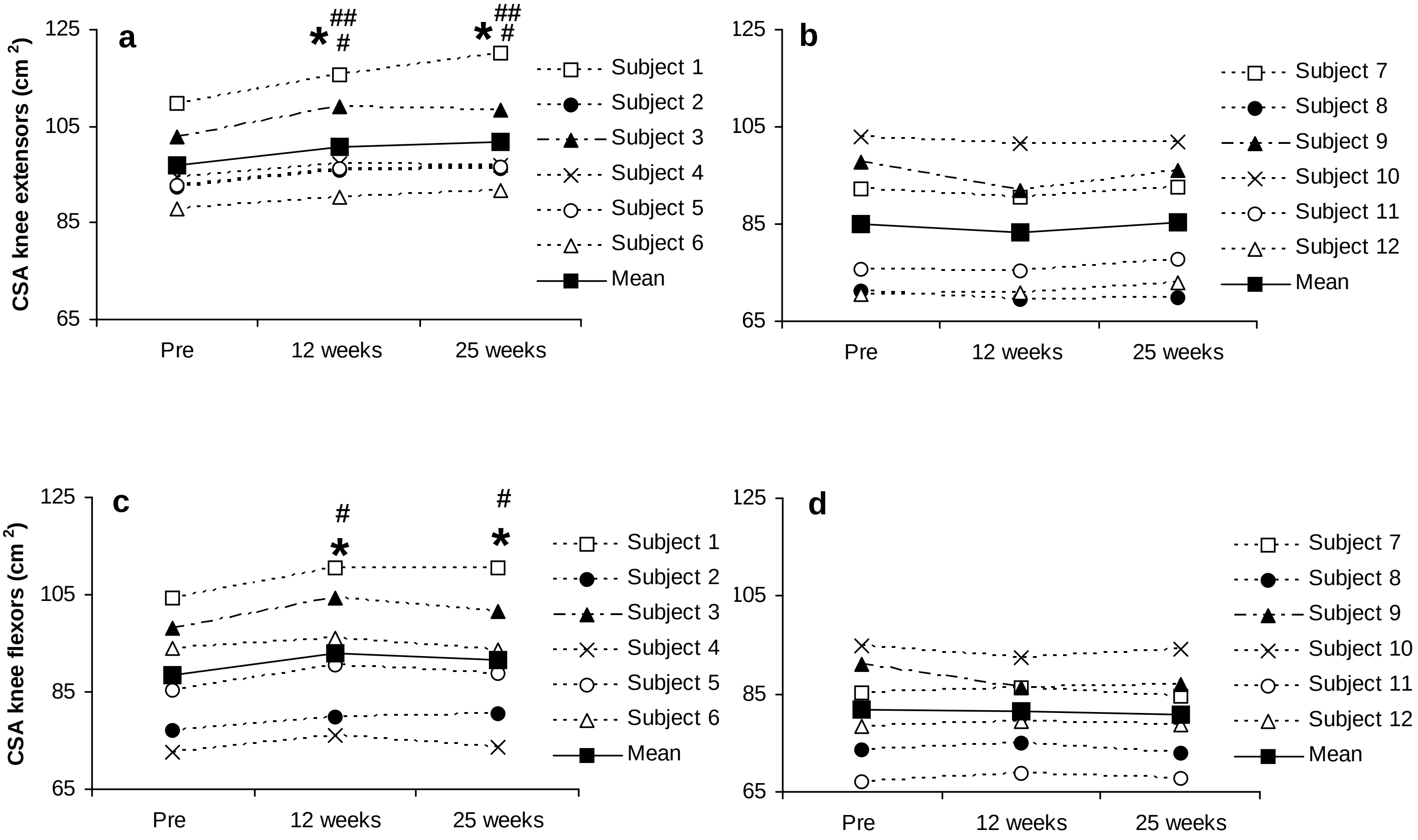
a
b
c
d
CSA knee extensors (cm 2)
CSA knee flexors (cm 2)
125
105
85
65
Pre
12 weeks
25 weeks
*
#
##
Subject 1
Subject 2
Subject 3
Subject 4
Subject 5
Subject 6
Subject 7
Subject 8
Subject 9
Subject 10
Subject 11
Subject 12
Mean

Figure 3

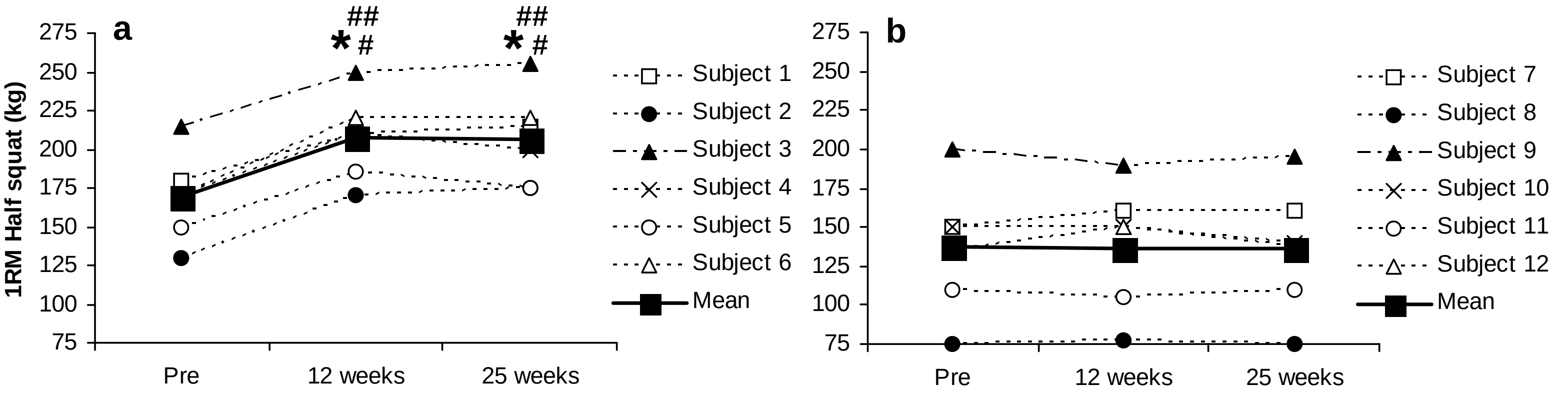
a
b
1RM Half squat (kg)
275
250
225
200
175
150
125
100
75
Pre
12 weeks
25 weeks
*
##
#
Subject 1
Subject 2
Subject 3
Subject 4
Subject 5
Subject 6
Mean
Subject 7
Subject 8
Subject 9
Subject 10
Subject 11
Subject 12
Mean

Figure 4

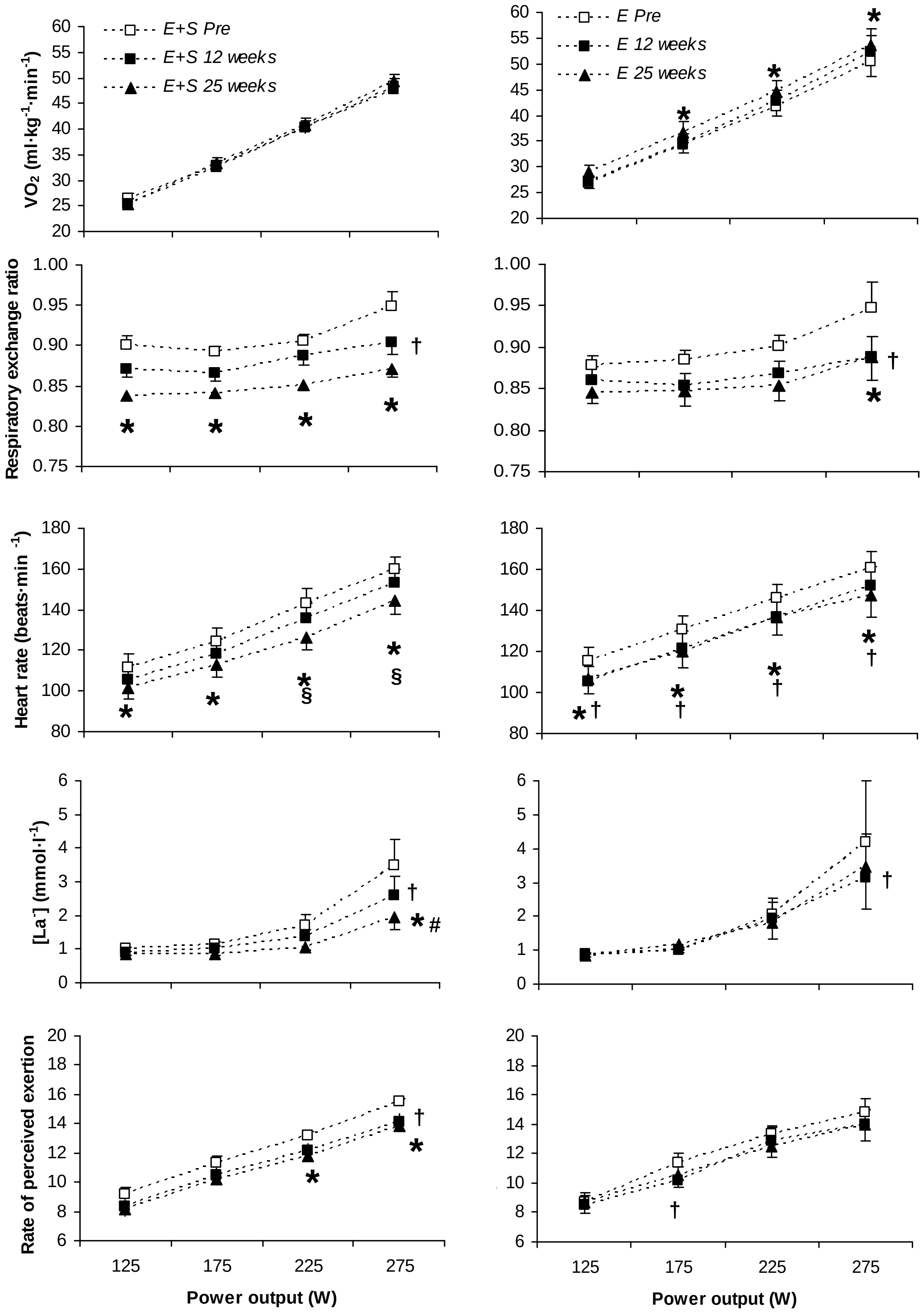
E+S Pre
E+S 12 weeks
E+S 25 weeks
E Pre
E 12 weeks
E 25 weeks
VO$_2$ (ml·kg^{-1}·min^{-1})
Respiratory exchange ratio
Heart rate (beats·min $^{-1}$)
[La$^-$] (mmol·l^{-1})
Rate of perceived exertion
125
175
225
275
Power output (W)
*
†
§
#

Figure 5

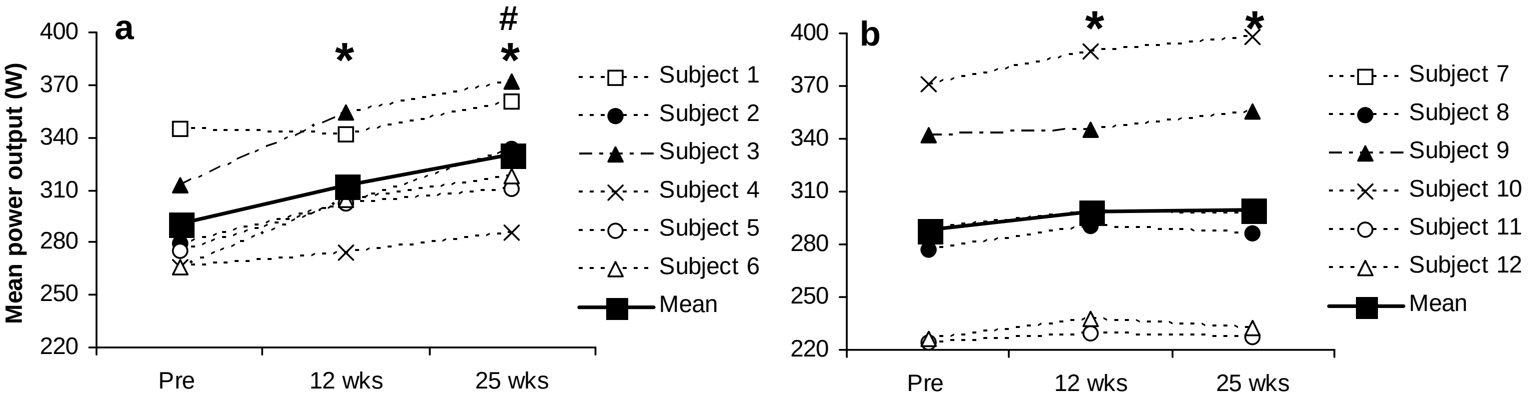

Table 1 Strength training program for the cyclists who performed heavy strength training.

	Preparatory period						Competition period
	Week 1-3		Week 4-6		Week 7-12		Week 13-25
	1. Bout	2. Bout	1. Bout	2. Bout	1. Bout	2. Bout	1. Bout
Half squat	3x10RM	3x6RM	3x8RM	3x5RM	3x6RM	3x4RM	2x5 reps @80-85% of 1RM
One-legged leg press	3x10RM	3x6RM	3x8RM	3x5RM	3x6RM	3x4RM	2x5 reps @80-85% of 1RM
One-legged hip flexion	3x10RM	3x6RM	3x8RM	3x5RM	3x6RM	3x4RM	1x6RM
Ankle plantar flexion	3x10RM	3x6RM	3x8RM	3x5RM	3x6RM	3x4RM	1x6RM

Table 2 Results from the incremental cycle test for measurement of maximal oxygen consumption before (Pre), after the preparatory period (12 weeks), and 13 weeks into the competition period (25 weeks) in the group that had heavy strength training added to their endurance training (*E+S*) and the group which performed usual endurance training only (*E*).

	E+S (n=6)			*E* (n=6)		
	Pre	12 weeks	25 weeks	Pre	12 weeks	25 weeks
VO_{2max} ($L \cdot min^{-1}$)	5.20 ± 0.28	5.53 ± 0.36*	5.65 ± 0.36*§	5.00 ± 0.45	5.28 ± 0.42*	5.27 ± 0.45*
($ml \cdot kg^{-1} \cdot min^{-1}$)	65.2 ± 2.2	69.0 ± 2.4*	73.9 ± 3.2*§	67.3 ± 2.7	72.5 ± 2.7*	73.4 ± 3.1*
W_{max} (W)	420 ± 15	442 ± 22	454 ± 19*$^{\#}$	401 ± 37	412 ± 34	399 ± 33
RER	1.10 ± 0.01	1.07 ± 0.02	1.06 ± 0.01	1.08 ± 0.01	1.06 ± 0.01	1.05 ± 0.01
HR_{max} ($beats \cdot min^{-1}$)	186 ± 4	187 ± 4	186 ± 4	183 ± 3	183 ± 3	182 ± 4
[La^{-}] ($mmol \cdot l^{-1}$)	12.9 ± 0.7	14.1 ± 0.6	13.6 ± 0.8	12.0 ± 1.3	12.4 ± 0.8	12.0 ± 0.8
RPE	19.2 ± 0.2	19.0 ± 0.3	19.0 ± 0.0	19.0 ± 0.3	18.7 ± 0.2	18.7 ± 0.4

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. *Larger than at Pre (p<0.05). §Larger than at 12 weeks (p<0.05). $^{\#}$The relative change from Pre is larger than in *E* (p<0.05).

Table 3 Results from the Wingate test before (Pre), after the preparatory period (12 weeks), and 13 weeks into the competition period (25 weeks). For explanation of *E+S* and *E*, the reader is referred to Table 1.

	E+S (n=6)			*E* (n=6)		
	Pre	12 weeks	25 weeks	Pre	12 weeks	25 weeks
Peak power output (W)	1470 ± 51	1557 ± 63[§]	1557 ± 55[§]*	1178 ± 123	1162 ± 140	1157 ± 157
Peak power output, body mass-adjusted ($W\cdot kg^{-1}$)	18.5 ± 0.4	19.5 ± 0.8	19.9 ± 0.8[§]*	15.7 ± 1.1	15.8 ± 1.3	16.0 ± 1.6
Mean power output (W)	828 ± 33	814 ± 29	805 ± 39	696 ± 69	683 ± 64	667 ± 68
Mean power output, body mass-adjusted ($W\cdot kg^{-1}$)	10.2 ± 0.3	10.2 ± 0.3	10.2 ± 0.4	9.3 ± 0.6	9.4 ± 0.6	9.3 ± 0.7
Fatigue index ($W\cdot s^{-1}$)	34.0 ± 1.2	38.0 ± 2.0[#][§]	36.3 ± 3.1	25.6 ± 3.4	24.4 ± 3.8	24.6 ± 4.4

Values are mean±SE. *Larger than at Pre ($p<0.01$), [#]The relative change from Pre is larger than in *E* ($p<0.05$). [§]Larger than in *E* ($p<0.05$)