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ORIGINAL ARTICLE

Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists

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Abstract The purpose of this study was to investigate the effect of heavy strength training on thigh muscle cross-sectional area (CSA), determinants of cycling performance, and cycling performance in well-trained cyclists. Twenty well-trained cyclists were assigned to either usual endurance training combined with heavy strength training [$E + S$; $n = 11$ (♂ = 11)] or to usual endurance training only [E; $n = 9$ (♂ = 7, ♀ = 2)]. The strength training performed by $E + S$ consisted of four lower body exercises [3 × 4–10 repetition maximum (RM)], which were performed twice a week for 12 weeks. Thigh muscle CSA, maximal force in isometric half squat, power output in 30 s Wingate test, maximal oxygen consumption (VO_{2max}), power output at 2 mmol l^{-1} blood lactate concentration ([la$^-$]), and performance, as mean power production, in a 40-min all-out trial were measured before and after the intervention. $E + S$ increased thigh muscle CSA, maximal isometric force, and peak power in the Wingate test more than E. Power output at 2 mmol l^{-1} [la$^-$] and mean power output in the 40-min all-out trial were improved in $E + S$ ($P < 0.05$). For E, only performance in the 40-min all-out trial tended to improve ($P = 0.057$). The two groups showed similar increases in VO_{2max} ($P < 0.05$). In conclusion, adding strength training to usual endurance training improved determinants of cycling performance as well as performance in well-trained cyclists. Of particular note is that the added strength training increased thigh muscle CSA without causing an increase in body mass.

Keywords Aerobic power output · Peak power output · Concurrent training · Weight training · Endurance performance

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Introduction

Performance in cycling time trials lasting more than 10–15 min is determined mainly by performance oxygen consumption (the oxygen consumption that can be sustained for a given period of time) and cycling economy (Joyner and Coyle 2008). The performance oxygen consumption is again determined by maximal oxygen consumption (VO_{2max}) and the ability to work at a high percentage of VO_{2max} during the competition (Jones and Carter 2000). The performance oxygen consumption and cycling economy are important determinants of critical power. The latter is in theory the highest constant-load power-output that can be sustained for a prolonged duration and is related to endurance ability (Poole et al. 1988). The critical power has been shown to be a useful fitness measure in trained cyclists (Smith et al. 1999) and is related to the maximal lactate steady state (Jones and Carter 2000). Furthermore, it has been shown that any rightward shift of the power output–blood lactate relation reflects improved lactate threshold regardless how the lactate threshold have been determined (Tokmakidis et al. 1998). This agrees with the finding that six different methods of determine the lactate threshold all showed significant correlations with 1-h time trial cycling performance (Bishop et al. 1998). Aerobic endurance training has the potential to enhance these performance determinants (Jones and Carter 2000) and has therefore been the preferred training type for improving cycling performance. However, incorporation of strength training in trained cyclists' preparation has also received some attention during the last two decades (Bastiaans et al. 2001; Bishop et al. 1999; Hickson et al. 1988).

The effect of strength training on endurance cycling performance and traditional indicators of cycling performance, like lactate threshold and cycling economy, is unclear. Adding strength training to usual endurance training does not appear to affect VO_{2max} in endurance trained individuals (Bishop et al. 1999; Hausswirth et al. 2009; Hoff et al. 1999; Millet et al. 2002; Paavolainen et al. 1999; Støren et al. 2008). Strength training has been shown to improve lactate threshold in untrained individuals (Izquierdo et al. 2003; Marcinik et al. 1991) but not in endurance trained individuals (Bishop et al. 1999; Hausswirth et al. 2009; Millet et al. 2002; Støren et al. 2008). Untrained individuals have also been shown to improve cycling economy after a period of strength training (Loveless et al. 2005), a finding that agrees with findings with endurance trained runners (Millet et al. 2002; Støren et al. 2008), but contradicts findings with well-trained cyclists (Aagaard et al. 2007).

Performance in cycling road races depends on a number of factors in addition to those mentioned above. One of these factors is the ability to generate high power output over a short period of time. This ability is essential when the cyclist needs to close a gap, break away from the pack, or win a final sprint. The W_{max} and the mean and peak power output in a Wingate test are factors that reflect the ability to generate high power output over a short period of time. It has been reported that peak power output in strength trained individuals is higher than in untrained individuals (Häkkinen et al. 1987) and that strength training in non-cyclists increases peak power output (Beck et al. 2007; Chromiak et al. 2004). The latter findings are supposedly explained by the fact 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, concurrent strength and endurance training has been shown to impair the development of power production compared with strength training alone (Häkkinen et al. 2003; Kraemer et al. 1995). It has also been shown that training strength and endurance concurrently interferes with the development of muscle hypertrophy (Kraemer et al. 1995; Putman et al. 2004). Bastiaans et al. (2001) found that replacing a portion of the endurance training with lightly loaded explosive strength training improved short-term peak power output more than endurance training alone. However, the effects of adding heavy strength training to usual cycle endurance training on muscle CSA, Wingate peak power output, and W_{max} in well-trained cyclists has not been investigated.

The primary aim of the present study was to investigate how adding heavy strength training to usual endurance training for 12 weeks would affect thigh muscle CSA, muscle strength and performance determinants that reflect the more vigorous aspects of a cycling race, like power output in a Wingate test and W_{max} in well-trained cyclists. In addition, we also investigated the effects of strength training on determinants of long-term endurance cycling performance, including cycling economy and power output at 2 mmol l^{-1} [la^-], as well as actual long-term endurance performance (mean power output in a 40-min all-out trial). It was hypothesized that adding heavy strength training to usual endurance training would increase thigh muscle CSA, maximal force in isometric half squat, Wingate peak power output, W_{max}, cycling economy, power output at 2 mmol l^{-1} [la^-], and mean power output in a 40-min all-out trial.

Methods

Participants

Twenty-three 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. All cyclists signed an informed consent form prior to participation. None of the cyclists had performed any strength training during the preceding 6 months. Three of the cyclists did not complete the study due to illness during the intervention period and their data are excluded.

Experimental design

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

Training

Endurance training consisted primarily of cycling, but some cross-country skiing was also performed (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 five HR zones: (1) 60–72%, (2) 73–82%, (3) 83–87%,

Table 1 Duration (in hours) of the endurance training and total training performed during the 12-week intervention period in the group which added heavy strength training to their endurance training ($E + S$) and the group which performed usual endurance training only (E)

Intensity zone (relative to HR_{max}) (%)	$E + S$ ($n = 11$)	E ($n = 9$)
60–72	80.2 ± 12.3	81.4 ± 15.5
73–82	24.7 ± 8.2	28.1 ± 9.4
83–87	9.4 ± 1.4	13.4 ± 3.6
88–92	4.2 ± 1.0	5.2 ± 2.3
93–100	0.8 ± 0.2	1.7 ± 1.0
Total training time	151 ± 13	138 ± 13

Values are mean ± SE

HR_{max} maximal heart rate

(4) 88–92%, and (5) 93–100% of maximal HR. An overview of the distribution of the endurance training into the five intensity zones for both groups is presented in Table 1. The duration of the endurance training and the distribution of this training within the five training zones were similar between groups. No significant difference between $E + S$ and E was found when comparing total training duration, including the strength training as well as core stability training and stretching (151 ± 13 and 138 ± 13 h, respectively ($P = 0.47$). This is mainly due to a non-significant larger endurance training volume in E.

The heavy strength training performed by the cyclists in $E + S$ targeted leg muscles and was performed twice a week. On days where both strength and endurance training were scheduled, the cyclists were encouraged to perform strength training in the first training session of the day and endurance training in the second. A review of the cyclists' training diaries confirmed that the cyclists largely complied with this guideline. Adherence to the strength program was high, with $E + S$ cyclists completing 97 ± 1% of the prescribed strength training sessions. The goal of the strength training program was to improve cycling performance using cycling-specific exercises whenever possible. Since peak force during pedalling occurs at approximately a 90° knee angle (Coyle et al. 1991), strength training exercises were performed with a knee angle between 90° and almost full extension. In addition, since cyclists work each leg alternately when cycling, one-legged exercises were chosen where practical. Even though it has been reported no significant force deficit during bilateral as compared to unilateral knee extension in cyclists (Howard and Enoka 1991), other studies have found a force deficit during bilateral leg exercises (Cresswell and Ovendal 2002; Schantz et al. 1989). 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 two to three warm-up sets of half squat with gradually increasing load. The strength exercises performed were: half squat, leg press with one leg at a time, one-legged hip flexion, and ankle plantar flexion. All cyclists were supervised by an investigator at all workouts during the first 2 weeks and thereafter at least once every second week throughout the intervention period. During the first 3 weeks, cyclists trained with 10 repetition maximum (RM) sets at the first weekly session and 6RM sets at the second weekly session. During the following 3 weeks, sets were adjusted to 8RM and 5RM for the first and second weekly sessions, respectively. During the final 6 weeks, sets were adjusted to 6RM and 4RM, respectively. 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.

Testing

Each of the pre- and post-intervention tests were divided into four separate test sessions on separate days as follows: (day 1) measurement of thigh muscle CSA; (day 2) maximal strength tests; (day 3) incremental cycling test for determination of blood lactate profile and maximal oxygen consumption; and (day 4) 30-s Wingate test and 40-min all-out trial. The cyclists were instructed to refrain from intense exercise the day preceding a test, to prepare for the trial as they would 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 consume coffee or other products containing caffeine during the last 3 h before a test. The cyclists were cooled with a fan throughout the cycling tests. All tests were performed under similar environmental conditions (20–22°C). The pre and post-intervention tests were performed at the same time of day to avoid influence of circadian rhythm. All cycling tests were performed on the same electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode B. V., Groningen, The Netherlands), which was adjusted according to each cyclist's preferences for seat height, distance between seat and handlebars, and horizontal distance between tip of seat and bottom bracket. Cyclists were allowed to choose their preferred cadence during all cycling tests and they used their own shoes and pedals.

Thigh muscle cross-sectional area measurement

Magnetic resonance tomography (Magnetom Avanto 1.5 Tesla, Siemens AG, Munich, Germany) was used to measure thigh muscle CSA. Participants were scanned in the supine position with the feet fixed and elevated on a pad to keep the muscle on 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 gap. Each image represented a 5-mm thick slice. The images were subsequently uploaded to a computer for further analysis. The thigh muscles were divided into extensor and flexor/adductor compartments using a tracer function in the software. The CSA of the thigh muscles was measured at the three most proximal images and the average CSA of all three images was used for statistical analysis. Using a similar method, the coefficient of variation has been reported to be 2% in repeated examinations in eight individuals (Moss et al. 1997).

Strength test

Maximal strength in leg extensors was measured as maximal force against a force plate (SG-9, Advanced Mechanical Technologies, Newton, MA, USA, sampling frequency of 1 kHz) during an isometric half squat. This test was performed using a custom built rack located over the force plate and bolted to the floor. Verbal encouragement was given throughout the test. Four maximal voluntary isometric half squats with 2 min recovery between each attempt were performed. The highest value achieved from the four attempts was used in the statistical analysis. Prior to the pre-intervention test, two familiarization sessions were conducted with the purpose of familiarizing the cyclists with proper squat technique and testing procedure. Strength tests were always preceded by a 10-min warm-up on a cycle ergometer. The depth of half squat was set so that the knee angle was 90°. To ensure similar knee angles during all tests, each cyclist's squat depth was carefully monitored and marked on a scale on the rack. Similarly, placement of the feet was monitored for each cyclist to ensure identical test positions during all tests. The pre- and post-intervention tests were conducted using the same equipment with identical positioning of the cyclist relative to the equipment and monitored by the same investigator. The post-intervention strength test was conducted three to 5 days after the last strength training session.

Blood lactate profile test

Blood lactate profile was determined for each participant by plotting [la$^-$] as a function of power output. The continuous incremental cycling test for measurement of blood lactate profile 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 at the end of each 5-min period and were analysed for whole blood [la$^-$] using a portable lactate analyser (Lactate Pro LT-1710, Arcray Inc., Kyoto, Japan). The test was terminated when a [la$^-$] of 4 mmol l^{-1} or higher was measured. Oxygen consumption (VO_2) and HR were measured during the last 3 min of each period, and mean values were used for statistical analysis. HR was measured using a Polar S610i heart rate monitor (Electro Oy, 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 metabolic system has been validated against the Douglas bag method and found to be an accurate system for measuring VO_2 (Foss and Hallén 2005). The gas analysers 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 perceived exertion was recorded 4 min and 50 s into each period, using Borg's 6–20 scale (Borg 1982). From this continuous incremental cycling test, the power output at a [la$^-$] of 2 mmol l^{-1} was calculated. 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 lactate profile test, the cyclists rested for 3 h before they completed another incremental cycle test for determination of maximal oxygen consumption (VO_{2max}). This incremental test and its results have been described elsewhere (Rønnestad et al. 2009). Briefly, the cyclists completed a 10-min warm-up followed by a short rest. The test was then initiated with 1 min cycling at a power output corresponding to 3 W kg^{-1} (rounded down to the nearest 50 W). Power output was then increased by 25 W every min until exhaustion. When the cyclists predicted that they would not be able to manage another 25 W increase in power output, they were encouraged to simply continue cycling at the current power output as long as possible (usually 30–90 s). VO_{2max} along with the complementary data were calculated as the average of the two highest VO_2 measurements. Maximal aerobic power output (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 N m kg^{-1} body mass (BM). 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 1-min rest, cyclists started pedalling at ~ 60 rpm without braking resistance. Following a 3-s countdown, the braking resistance was applied to the flywheel and remained constant throughout the 30-s all-out cycling bout. Mechanical power output was calculated by the software as force × velocity. The pedalling speed was detected online by a computer, and mechanical power values were obtained instantaneously. The Lode Wingate software presented peak power output as the highest power output achieved at any time during the 30-s all-out cycling bout. Mean power output was presented as the average power output sustained throughout the 30 s, and minimal power was presented as the lowest power output achieved during the 30-s Wingate test. The peak power output 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. Strong verbal encouragement was provided during the test. To get the highest possible peak power, subjects were instructed to pedal as fast as possible from the start and to not preserve energy for the last part of the test. After the Wingate test, cyclists recovered by cycling at ~ 100 W for 10 min before starting the 40-min all-out trial.

40-min all-out trial

In this trial the cyclists were instructed to perform as high an average power output as possible. Performance was measured as the average power output over 40-min cycling. The cyclists were allowed to adjust the power output throughout the trial using an electronically controlled 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. Pre- and post-intervention measurements for each group were compared using paired Student's *t* test. To test for differences in relative changes (from pre- to post-intervention) between the groups, unpaired Student's *t* tests were performed. Two-way repeated measures ANOVA (time of intervention period and power output as factors) with Bonferroni post hoc tests were performed to evaluate differences within groups (post- vs. pre-values) in responses during the lactate profile test. In addition, two-way repeated measures ANOVA (group and power output as factors) with Bonferroni post hoc tests were performed for evaluation of differences in relative changes (post- vs. pre-values) between groups. ANOVA analyses were performed in GraphPad Prism 5 (GraphPad Software, Inc. CA, USA). Correlation analyses (Pearson product–moment correlation coefficient) and *t* test were calculated in Excel 2003 (Microsoft Corporation, Redmond, WA, USA). All analyses resulting in $P \leq 0.05$ were considered statistically significant.

Results

Pre-intervention

There were no significant differences between $E + S$ and E before the intervention period with respect to BM, thigh muscle CSA, maximal force in isometric half squat, VO_{2max}, or measurements in any of the cycling performance tests.

Body mass, thigh muscle cross-sectional area, and maximal force

There was a tendency for increased BM in $E + S$ from 76.0 ± 2.8 kg before the intervention to 76.7 ± 2.5 kg after the intervention period (1.0 ± 0.5%; $P = 0.066$), while no significant change occurred in E (pre-intervention value was 75.2 ± 3.2 kg). There was no significant difference between groups in relative changes in BM from pre- to post-intervention. The relative changes in thigh muscle CSA from pre-to post intervention were greater in $E + S$ than E ($P < 0.01$, Fig. 1), as $E + S$ increased the thigh muscle CSA by 4.6 ± 0.5% ($P < 0.01$), while no changes occurred in E. Maximal force in isometric half squat increased for $E + S$ by 21.2 ± 4.9% ($P < 0.01$, Fig. 2), while this measure remained unchanged in E. Consequently, the increase in strength from pre- to post-intervention period was larger in $E + S$ than in E ($P < 0.01$).

Power output in the Wingate test

The increase in peak power output during the 30-s Wingate test was larger in $E + S$ than E ($P < 0.05$, Fig. 3), as peak power output increased in $E + S$ (9.4 ± 2.9%, $P < 0.01$), while no significant changes occurred in E. At pre-intervention, pooled data of both groups in maximal force in isometric half squat and CSA of knee extensors correlated with Wingate peak power output ($r = 0.70$ and 0.69 respectively, $P < 0.001$). Furthermore, the increase in CSA of

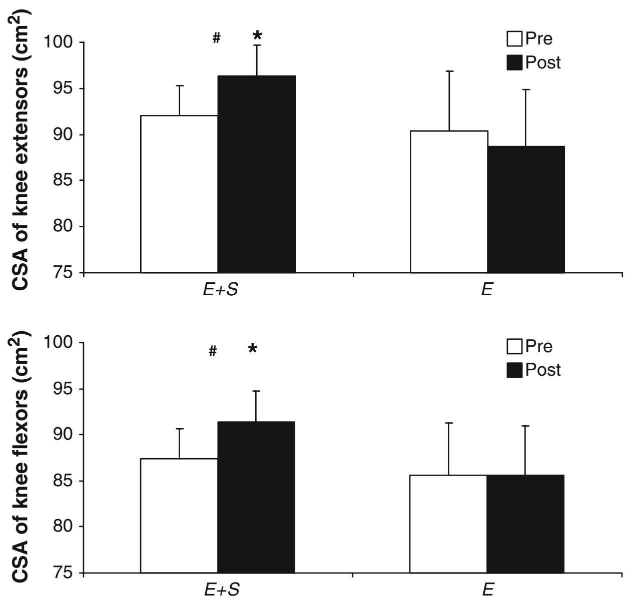

Fig. 1 Cross-sectional area (*CSA*) of knee extensors (*upper panel*) and knee flexors (*lower panel*) before (Pre) and after (Post) the 12-week intervention period in which one group of cyclists added heavy strength training to their endurance training ($E + S$; $n = 11$), while the other group of cyclists performed endurance training only (E; $n = 9$). Different from Pre (*$P < 0.05$). The relative change from Pre to Post is larger in $E + S$ than in E ($^{\#}P < 0.01$)

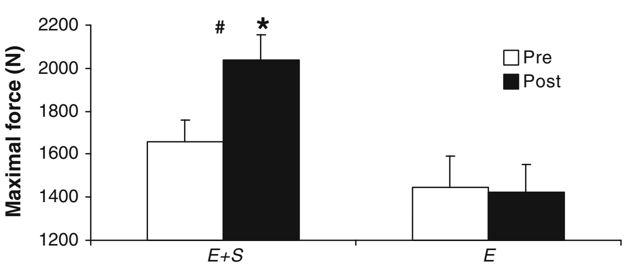

Fig. 2 Maximal force in isometric half squat before (Pre) and after (Post) the 12-week intervention period in which one group of cyclists added heavy strength training to their endurance training ($E + S$; $n = 11$), while the other group of cyclists performed their usual endurance training (E; $n = 9$). Different from Pre (*$P < 0.01$). The relative change from Pre to Post is larger in $E + S$ that in E ($^{\#}P < 0.01$)

knee extensors was correlated with the increase in Wingate peak power output ($r = 0.47$, $P < 0.05$). Due to a non-significant increase in mean power output during 30-s Wingate test in $E + S$ ($1.2 \pm 1.1\%$) and a non-significant decrease in E ($-1.8 \pm 1.1\%$), relative change in mean power output from pre- to post-intervention tended to be different between the groups ($P = 0.065$, Table 2). The fatigue index increased in $E + S$ ($20 \pm 7\%$, $P < 0.05$), while no significant changes occurred in E, resulting in a significant difference between groups ($P < 0.05$, Table 2). There was no significant change for either group in minimum power output during the 30-s Wingate test.

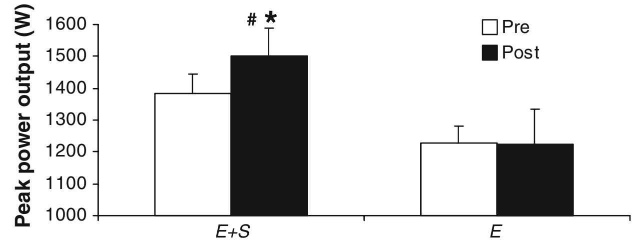

Fig. 3 Peak power output in the Wingate test before (Pre) and after (Post) the 12-week intervention period in which one group of cyclists added heavy strength training to their endurance training ($E + S$; $n = 11$), while the other group of cyclists performed their usual endurance training (E; $n = 9$). Different from Pre (*$P < 0.01$). The relative change from Pre to Post is larger in $E + S$ that in E ($^{\#}P < 0.01$)

VO_{2max} and W_{max}

Both $E + S$ and E increased VO_{2max} during the intervention period ($P \leq 0.05$). The increase in BM adjusted VO_{2max} averaged $3.3 \pm 1.4\%$ for $E + S$ and $6.0 \pm 2.0\%$ for E, with no statistical difference between groups (Table 3). W_{max} increased by $4.3 \pm 1.1\%$ in $E + S$ ($P < 0.05$), while no significant change occurred in E (Table 3).

Blood lactate profile

$E + S$ increased power output at 2 mmol l^{-1} [la^-] from 242 ± 10 to 251 ± 10 W ($P < 0.05$), while no significant change was observed in E (baseline value was 246 ± 20 W). Accordingly, the [la^-] profile of $E + S$ shifted to the right due to reduced [la^-] at the highest power output (275 W; $P < 0.05$), whereas no such change was observed in E. ANOVA analysis showed that during the continuous incremental test, cycling economy, determined as BM adjusted oxygen consumption, remained unchanged during the intervention period for $E + S$ and E at the different power outputs (125, 175, 225, and 275 W). HR was on average 6 ± 1 beats min^{-1} lower at the four power outputs in the post-intervention test compared with the pre-intervention test for $E + S$, while E had a HR that on average was 7 ± 2 beats min^{-1} lower across the three lowest power outputs ($P < 0.05$). A comparison between $E + S$ and E of the relative changes from pre- to post-intervention showed no significant difference between groups in parameters measured during the lactate profile test.

Mean power output in the 40-min all-out trial

Mean power output during the 40-min all-out trial increased $6.0 \pm 1.7\%$ ($P < 0.01$) from pre- to post-intervention in $E + S$ (from 281 ± 8 to 297 ± 9 W, respectively) and tended to increase by $4.6 \pm 2.0\%$ ($P = 0.054$) in E (baseline value was 281 ± 16 W). There was no significant

Table 2 Data from the Wingate test before (Pre) and after (Post) the 12-week intervention period in which one group of cyclists added heavy strength training to their endurance training ($E + S$), while the other group of cyclists performed usual endurance training only (E)

	$E + S$ ($n = 11$)		E ($n = 9$)	
	Pre	Post	Pre	Post
Peak power (W)	1,382 ± 63	1,502 ± 55*,#	1,230 ± 98	1,223 ± 110
Peak power, body mass-adjusted (W kg^{-1})	18.1 ± 0.6	19.6 ± 0.6*,#	16.2 ± 0.9	16.2 ± 1.0
Mean power (W)	794 ± 21	803 ± 20	724 ± 53	710 ± 52
Mean power, body mass-adjusted (W kg^{-1})	10.4 ± 0.2	10.5 ± 0.2	9.6 ± 0.5	9.5 ± 0.4
Minimal power (W)	572 ± 18	558 ± 13	524 ± 30	531 ± 34
Fatigue index (W s^{-1})	31.0 ± 2.0	36.3 ± 1.8*,#	27.1 ± 2.8	26.7 ± 3.1

Values are mean ± SE

* Different from Pre ($P < 0.01$)

The relative change from Pre to Post is larger in $E + S$ that in E ($P < 0.05$)

Table 3 Results from the incremental test for measurement of maximal oxygen consumption before (Pre) and after (Post) 12 weeks of combined heavy strength training and endurance training ($E + S$) and endurance training only (E)

	$E + S$ ($n = 11$)		E ($n = 9$)	
	Pre	Post	Pre	Post
W_{max} (W)	407 ± 10	425 ± 14*	403 ± 25	411 ± 24
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} (beats min^{-1})	188 ± 3	188 ± 3	185 ± 3	184 ± 3
[La$^-$] (mmol l^{-1})	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 ($P < 0.05$)

difference between groups in relative change from pre- to post-intervention.

Freely chosen cadence

Freely chosen cadence remained unchanged from baseline to post-intervention for both groups. The freely chosen cadence during the lactate profile test, VO_{2max} test, and 40-min all-out trial was 87 ± 2, 94 ± 2, and 94 ± 1 rpm, respectively (as a mean across study groups, time points, and times of intervention period).

Discussion

A novel finding of the present study was that Wingate peak power output, W_{max}, power output at 2 mmol l^{-1} [la$^-$], and mean power output during a 40-min all-out trial increased in well-trained cyclists who added heavy strength training to usual endurance training. Both groups increased their VO_{2max}. For the cyclists in the control group, who performed usual endurance training only, a tendency towards increased average power output in the 40-min all-out trial was the only change observed among the measured variables.

The observed 21% increase in maximal force during isometric half squat is slightly less than the 27–38% increase observed in previous investigations of 1RM in endurance athletes performing strength and endurance training concurrently over 12 weeks (Bishop et al. 1999; Guglielmo et al. 2009; Hickson et al. 1988). In those studies, the 1RM tests were performed using one of the training exercises, while the exercises used in our strength tests were different from those used during the intervention strength training, so lack of exercise specificity is probably responsible for the lesser increase. In fact, inferior strength improvement after a strength training period is commonly observed when strength is tested in a manner different than the training exercises (Murphy and Wilson 1996; Wilson et al. 1996). Thus, the strength training protocol in the present study was successful in increasing leg strength to an extent that would be expected when strength training is added to endurance training.

The results of the present study suggest that a substantial increase in leg muscle strength can be achieved with little or no increase in body weight, which is highly relevant for athletes competing in sports in which low BM is important for performance (e.g. uphill cycling or running). Similar observations have been reported in studies performed with triathletes and cross-country skiers (Hoff et al. 1999; Millet et al. 2002). Interestingly, without measuring muscle CSA, the authors often conclude that in the absence of increased BM, increased strength is most likely due primarily to neural adaptations. Indeed, during a short strength training period, the relative contribution of neural adaptations to strength enhancement may be larger than in a longer strength training period. Most interventions with concurrent strength and endurance training in endurance athletes are conducted at the start of the preparation phase to the following season after a recovery phase from the previous competition season. Therefore, it is possible that, even though the athletes have a low body fat percentage, some fat mass may be replaced by muscle mass during a period of concurrent strength and endurance training, resulting in an increase in muscle mass and decrease in fat mass, with no net change in BM. In the present study, thigh muscle CSA increased by ~ 4.5%. This change is about half of the ~ 9–11% increase in CSA observed in studies employing similar strength training, but without endurance training (McCarthy et al. 2002; Rønnestad et al. 2007). Therefore, the present finding seems to support the hypothesis that concurrent strength and endurance training compromises adaptations to strength training (Hickson 1980). However, our findings contradict the hypothesis that neural adaptations alone explain all strength improvements in endurance athletes performing strength and endurance training concurrently with no increase in BM.

The finding of improved Wingate peak power output after a period of combined strength and cycle endurance training is similar to results obtained after a period of strength training only (Beck et al. 2007; Chromiak et al. 2004). The fact that the ability to generate high power output for a short period of time is an important factor in cycling performance highlights the practical importance of the present finding (Atkinson et al. 2003). Peak power output often occurs during the first 5 s of an all-out sprint. Thus, peak power output is mainly dependent on the size of the involved muscle mass and maximal leg strength (Izquierdo et al. 2004; Van Praagh 2007). Therefore, the improved peak power output observed in $E + S$ is probably due to the increased thigh muscle CSA and leg strength. The correlation between increase in CSA of knee extensors and improvement in Wingate peak power output supports this theory, and is further corroborated by the results for E: no changes in thigh muscle CSA or leg strength, and no improvement in peak power output. There were no significant changes in mean power output during the 30-s Wingate test in either group. Since the glycolytic anaerobic energy system is a major energy contributor during a 30-s all-out sprint (Spriet et al. 1989), and since strength training has been found to only minimally affect this system (Minahan and Wood 2008; Tesch et al. 1987), this finding was not surprising.

Most importantly, the addition of heavy strength training twice a week during the 12-week intervention period did not negatively affect the development of VO_{2max}. Other studies have also found no impairment of VO_{2max} development for either trained or untrained individuals during a similar period of concurrent endurance and strength training (Balabinis et al. 2003; McCarthy et al. 1995). In fact, VO_{2max} increased in both E and $E + S$, a finding that contradicts other studies in which well-trained cross-country skiers and triathletes did not improve VO_{2max} after a period of supplemental strength training (Hoff et al. 1999, 2002; Millet et al. 2002). However, the increase in VO_{2max} in the present study was not that surprising since the pre-intervention tests were conducted ~ 1 month after the end of the competition season, a time of the year when endurance training volume typically drops. During the preparatory phase, the start of which coincided with the pre-intervention testing, both groups substantially increased endurance training volume, which likely explains the increased VO_{2max}.

While W_{max} is a good predictor of cycling performance (Hawley and Noakes 1992), in terms of VO_{2max}, there is no major difference between well-trained cyclists and elite cyclists (Lucía et al. 1998). In other words, even though there is a known relationship between VO_{2max} and W_{max}, it seems that W_{max} is the key indicator separating well-trained cyclists from elite cyclists (Lucía et al. 1998). Therefore, it is interesting to note that although both groups increased VO_{2max}, only $E + S$ increased W_{max}. Power output determines velocity during cycling and thus greatly affects performance. Findings are equivocal, however. While our results are corroborated by one strength training study on untrained persons (Loveless et al. 2005), they are disputed by another 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.

In the present study, adding strength training to usual endurance training improved power output at 2 mmol l^{-1} [la^{-}] in the strength-trained cyclists, while no changes occurred in the cyclists who performed usual endurance training only. This finding agrees with a previous study on untrained persons (Marcinik et al. 1991), but contradicts a study on trained female cyclists (Bishop et al. 1999). Gender differences, lack of specificity in the strength training, or a low strength training volume are possible explanations for the lack of improvement in lactate threshold in the study by Bishop et al. (1999). 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. 2000; Coyle et al. 1991). Thus, the improved power output at 2 mmol l^{-1} [la^{-}] potentially reflects superior cycle endurance performance. The mechanisms explaining this finding are unknown, though some have been suggested. For example, it has been shown that type I muscle fibres are more efficient than type II fibres when performing exercise at a given power output during submaximal exercise (Coyle et al. 1992; Hansen et al. 2002; Krustrup et al. 2008; Mogensen et al. 2006). An increase in the strength of type I fibres may delay activation of the less economical type II fibres, resulting in a higher power output at 2 mmol l^{-1} [la^{-}].

Performance in the 40-min all-out trial is mainly determined by performance oxygen consumption and cycling economy (Joyner and Coyle 2008). Based on the findings of improved VO_{2max}, W_{max}, and power output at 2 mmol l^{-1} [la^{-}], it was not surprising that $E + S$ also improved performance in the 40-min all-out trial. However, E also showed a tendency towards improvement in 40-min all-out trial, without significant changes in W_{max} or power output at 2 mmol l^{-1} [la^{-}]. The increased VO_{2max} probably resulted in increased performance oxygen consumption during the 40-min all-out trial in both groups and thus likely explains the tendency for improvement in E. The addition of improved power output at 2 mmol l^{-1} [la^{-}] in $E + S$ may have resulted in further enhancement of the performance oxygen consumption and could thus explain the significant improvement in the 40-min all-out trial performance in this group. Since cycling economy did not improve for either group, it should not explain the change in 40-min all-out performance. When mean power output during the 40-min all-out trial is expressed as a percentage of W_{max}, no change in either group is seen. However, the increased W_{max} in $E + S$ may contribute to the significant improvement in mean power output during the 40-min all-out trial.

Bastiaans et al. (2001) found similar improvements in 1-h time trial for trained cyclists who replaced a portion of their endurance training with explosive strength training and for trained cyclists who simply continued their endurance training. However, the time trial improvements in that study may be explained by improved W_{max} in both groups. The observed increase in 40-min all-out performance contradicts a study that found that trained female cyclists did not improve performance in a 1-h time trial after a period of concurrent strength and endurance training (Bishop et al. 1999). In the present study though, four lower body exercises were included, while only squat exercise was performed in the study by Bishop et al. (1999). The difference in strength training regimen, gender, and performance test may account for the divergent findings. In the present study there were significant larger improvements in $E + S$ in strength, CSA and Wingate peak power output, which potentially improves the cyclists' ability to generate high power output over a short period of time. The findings of no significant difference between groups regarding changes in W_{max}, power output at 2 mmol l^{-1} [la^{-}], and mean power output in the 40-min all-out trial may be interpreted as adding strength training does not improve long-term endurance performance. However, only $E + S$ achieved significant improvements in these measurements and taking the high training- and performance status of the cyclists into consideration, it can be suggested that the observed improvements in $E + S$ are of physiological relevant significance. It has been suggested that well-trained endurance athletes have a narrow margin of improvement in aerobic capacity after several years of training (Paavolainen et al. 1999).

In conclusion, adding heavy strength training to usual endurance training twice a week increased thigh muscle CSA and leg strength in well-trained cyclists without compromising the development of VO_{2max}. Of even larger practical importance to the cyclists, the strength training also resulted in improvement in parameters relevant for performance in the more vigorous parts of a cycle race, including Wingate peak power output and W_{max}. Furthermore, the cyclists who added strength training improved power output at 2 mmol l^{-1} [la^{-}], a parameter traditionally related to long-term endurance cycling performance, as well as performance (mean power output) in 40-min all-out trial. The only apparent improvement for cyclists performing usual endurance training only was increased VO_{2max} and a tendency for improved performance in the 40-min all-out trial.

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