

## Strength training improves performance and pedaling characteristics in elite cyclists

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The purpose was to investigate the effect of 25 weeks heavy strength training in young elite cyclists. Nine cyclists performed endurance training and heavy strength training (ES) while seven cyclists performed endurance training only (E). ES, but not E, resulted in increases in isometric half squat performance, lean lower body mass, peak power output during Wingate test, peak aerobic power output ( $W_{\max}$ ), power output at 4 mmol L<sup>-1</sup> [Ia<sup>-</sup>], mean power output during 40-min all-out trial, and earlier occurrence of peak torque during the pedal stroke ( $P < 0.05$ ). ES achieved superior improvements in  $W_{\max}$  and mean power output during 40-min all-out trial com-

pared with E ( $P < 0.05$ ). The improvement in 40-min all-out performance was associated with the change toward achieving peak torque earlier in the pedal stroke ( $r = 0.66$ ,  $P < 0.01$ ). Neither of the groups displayed alterations in  $VO_{2\max}$  or cycling economy. In conclusion, heavy strength training leads to improved cycling performance in elite cyclists as evidenced by a superior effect size of ES training vs E training on relative improvements in power output at 4 mmol L<sup>-1</sup> [Ia<sup>-</sup>], peak power output during 30-s Wingate test,  $W_{\max}$ , and mean power output during 40-min all-out trial.

Incorporation of strength training into cyclists' preparatory period has received increasing attention during the last years. The general finding is that concurrent strength and endurance training improves various factors related to cycling performance (Hauswirth et al., 2010; Koninckx et al., 2010; Rønnestad et al., 2010a,c, 2011a; Sunde et al., 2010; Aagaard et al., 2011; Barrett-O'Keefe et al., 2012). However, only one of these studies was performed on elite cyclists, and the strength training intervention lasted for 16 weeks (Aagaard et al., 2011), while the others studies typically lasted 8–12 weeks. Thus, there is need for further investigation of the effect of adding heavy strength training to endurance training in elite cyclists. It seems likely that better trained athletes require longer periods with increased strength before they experience a positive impact on endurance performance (Millet et al., 2002; Aagaard & Raastad, 2012).

We have previously reported an additive effect of incorporating heavy strength training on time-trial performance in well-trained cyclists (Rønnestad et al., 2010c, 2011a). However, the mechanisms behind this improvement in time-trial performance are somewhat unclear. It might be related to an improved cycling economy, as observed after adding strength training to the ongoing endurance training in moderate trained cyclists (Sunde

et al., 2010). However, this has not been reported in any of the abovementioned studies on well-trained and elite, measured during short-time submaximal power outputs (Rønnestad et al., 2010a,c; Aagaard et al., 2011). Furthermore, increase in type IIA proportion at the expense of type IIX fibers have been observed in elite cyclists and can also contribute to improved time trial performance (Aagaard et al., 2011). It is well known that adding strength training to endurance training can increase maximal strength and rate of force development in cyclists (Hauswirth et al., 2010; Koninckx et al., 2010; Rønnestad et al., 2010a; Sunde et al., 2010; Aagaard et al., 2011). In theory, this may improve pedaling characteristics by increasing peak torque in the pedal stroke, reducing time to peak torque and reducing the pedaling torque relative to maximal strength, which in turn may allow for higher power output and/or increased blood flow. Indeed, in a cross-sectional study of cyclists with similar maximal oxygen consumption ( $VO_{2\max}$ ) and peak aerobic power output ( $W_{\max}$ ) demonstrated lowered electromyography (EMG) activity during the pedal stroke in the cyclists with higher maximal strength (Bieuzen et al., 2007). To our best knowledge, no prior studies have investigated the effects of adding strength training to ongoing endurance training on the temporal torque profile during the pedal stroke.

The purpose of the present study was to investigate the hypothesis that a 10-week strength development period would increase lower body muscle strength, and that this adaptation would be maintained by a subsequent 15-week strength maintenance period consisting of one strength training session every 7–10 days. It was further hypothesized that this relative long time with maintained strength training adaptations would have positive effects on pedal stroke characteristics and sustained power output performance (mean power output in a 40-min all-out trial). Also, determinants of long-term endurance cycling performance, such as cycling economy and power output at a blood lactate concentration ( $[La^-]$ ) of  $4 \text{ mmol L}^{-1}$ , were measured. In addition, we also hypothesized that the improvements in muscle strength would lead to improvement in vigorous aspects of road cycling races, measured as maximal power output in a Wingate test and  $W_{\max}$ .

## Methods

### Participants

Sixteen elite cyclists competing at the national ( $n = 8$ ) or international level ( $n = 8$ ) and fulfilled at least two of Jeukendrup et al.'s (Jeukendrup et al., 2000) descriptions of an elite cyclist completed the study. The study was approved by the local Ethical Committee of Lillehammer University College and was carried out in accordance with the Declaration of Helsinki. All cyclists gave written informed consent. Prior to study start, we reasoned that the risk for withdrawals was larger among cyclists performing combined endurance and strength training and therefore chose to allocate more cyclists to strength training than the control group. However, there were no differences between groups, and three cyclists from each group dropped out from the study. The cyclists were randomly distributed to either adding heavy strength training to the ongoing endurance training (ES,  $n = 9$ , age:  $19.1 \pm 1.7$  years, body mass:  $66.0 \pm 8.0$  kg, height:  $178 \pm 7$  cm,  $VO_{2\max}$ :  $78 \pm 6 \text{ mL kg}^{-1} \text{ min}^{-1}$ ) or endurance training only (E,  $n = 7$ , age:  $20.1 \pm 1.6$  years, body mass:  $74.3 \pm 7.5$  kg, height:  $183 \pm 9$  cm,  $VO_{2\max}$ :  $73 \pm 5 \text{ mL kg}^{-1} \text{ min}^{-1}$ ). The study was initiated 2 weeks after finalization of the racing season and lasted for 25 weeks. Pretests were performed 2 weeks after the last race of the season was finished.

### Experimental design

A 10-week strength development period with two strength training sessions per week was performed, and followed by a 15-week

strength maintenance period with one strength training session per 7–10 days (25 weeks). Isometric half-squat performance was measured at three time points: (1) pre-intervention, (2) after the strength development period (10 weeks) and (3) after the strength maintenance period (15 weeks). Lean lower body mass, mean power output during 40-min all-out,  $VO_{2\max}$ ,  $W_{\max}$ , 30-s Wingate test, cycling economy, pedal stroke characteristics, and power output at  $4 \text{ mmol L}^{-1} [La^-]$  was measured before the intervention and after 25 training weeks.

### Training

Endurance training duration and intensity were calculated based on heart rate (HR) recordings. 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 10-week strength development period and the subsequent 15-week strength maintenance period (Table 1). No significant difference between ES and E was found when comparing total training duration (included the strength training). The reason to no differences in total training volume is a non-significant larger endurance training volume in E (Table 1).

The heavy strength training that was performed in ES group 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 ES cyclists completing  $19.4 \pm 0.7$  of the planned 20 strength training sessions during the 10-week strength development period. Furthermore, during the 15 weeks strength maintenance period they performed  $12.5 \pm 1.5$  strength training sessions. This corresponds to one session every ~8 days that agreed well with the planned protocol. The strength training regimen was designed to improve cycling performance by emphasizing cycling-specific exercises as described elsewhere (Rønnestad et al., 2010c). Thus, strength-training exercises were performed with a knee angle between  $90^\circ$  and close to full extension. In addition, since cyclists work each leg alternately during cycling, they were instructed to perform two of the four exercises unilaterally.

The heavy strength training was conducted with focus on maximal effort in the concentric phase (duration around 1 s), while the eccentric phase was performed more slowly (duration 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, unilateral leg press, standing unilateral hip flexion, and ankle plantar flexion. All cyclists were supervised by an investigator at all workouts during the first two weeks and thereafter at least once every second week

Table 1. Duration (in hours per week) of the endurance training performed during the 10-week strength development phase (week 1–10) and the 15-week strength maintenance period (week 11–15) in the group that performed endurance and strength training (ES) and the group that performed only endurance training (E)

Intensity zone	ES		E	
	Week 1–10	Week 11–25	Week 1–10	Week 11–25
Intensity zone I (60–82% of $HR_{\max}$ )	$7.9 \pm 2.0$	$12.3 \pm 3.1$	$10.1 \pm 2.6$	$13.4 \pm 3.7$
Intensity zone II (83–87% of $HR_{\max}$ )	$1.2 \pm 0.6$	$1.4 \pm 0.9$	$1.1 \pm 0.5$	$1.2 \pm 0.6$
Intensity zone III (88–100% of $HR_{\max}$ )	$0.7 \pm 0.4$	$0.8 \pm 0.4$	$0.6 \pm 0.4$	$0.7 \pm 0.4$
Heavy strength training	$1.4 \pm 0.1$	$0.6 \pm 0.1$	0	0
Total training time	$11.3 \pm 1.5$	$15.2 \pm 3.1$	$11.7 \pm 3.1$	$15.3 \pm 3.9$

Values are mean  $\pm$  SD.

$HR_{\max}$ , maximal heart rate.

throughout the strength development period. During the first 3 weeks, cyclists trained with 10 repetition maximum (RM) sets at the first session and 6RM sets at the second session. During the following three weeks, sets were adjusted to 8RM and 5RM, respectively. During the final four weeks of the preparatory period, sets were adjusted to 6RM and 4RM, respectively. The cyclists were encouraged to increase their RM loads continually throughout the intervention period and were allowed assistance on the last repetition. The number of sets in each exercise was always three, separated by 2-min rest periods. During the strength maintenance period, one strength training session was performed every 7–10 days, with the order of exercises and number of sets being the same as during the first 10-week period. In this maintenance period, strength training was not performed until failure. The cyclists performed five repetitions with maximal effort in the concentric phase with a load corresponding to 8–10RM and 2-min rest period between each set and exercise. We have previously shown that this strength training regime is sufficient to maintain developed strength in well-trained cyclists (Rønnestad et al., 2010c).

### Testing

Testing before and after the 25-week intervention period was completed as follows: day (1) measurement of lean lower-body mass, day (2) maximal strength test and 30-s Wingate test, day (3) incremental cycle tests for determination of blood lactate profile followed by a  $\text{VO}_{2\text{max}}$  test, and day (4) 40-min all-out trial. The cyclists were instructed to refrain from intense exercise the day preceding testing. They were also instructed to prepare for the trial as if it was 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. All cycling tests were performed under similar environmental conditions (19–21 °C) and included a fan for cooling. For each individual cyclist, testing was performed at the same time of day to avoid influence of circadian rhythm. All cycling tests, except the 40-min all-out trial, which was performed on the cyclists' own bike, was performed on the same electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode B. V., Groningen, The Netherlands). In accordance with the manufacturer's guidelines, the cycle ergometer is calibrated by the manufacturer once a year. The ergometer was adjusted according to each cyclist's preference for seat height, horizontal distance between tip of seat and bottom bracket, and handlebar position. The crank arm length on the Lode cycle ergometer was individually adjusted in order to be identical with the crank arm length on their own bike and equipped with the cyclists own clip pedals.

### Lean lower body mass

Lean lower body mass was determined by dual-energy x-ray absorptiometry using a Lunar Prodigy densiometer (Prodigy Advance PA+302047, Lunar, San Francisco, CA, USA), performed in a highly standardized manner. Cyclists were instructed to refrain from training for the 24 h preceding the measurement. They were also instructed to avoid ingestion of food or liquid for the 3 h preceding the measurement.

### Strength test

Maximal strength in leg extensors was measured as maximal vertical ground reaction 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. Three maximal voluntary isometric squats were performed with 1 min recovery between each attempt. Each lift was performed for 3 s, during which all athletes were given strong verbal encouragement. To ensure similar knee and hip angles during all tests, each athlete's squat depth was carefully monitored and marked on a scale on the rack. Similarly, placement of the feet was monitored for each athlete to ensure identical test positions during all tests. All test sessions were conducted using the same equipment with identical positioning of the athletes relative to the equipment and were monitored by the same investigator. The best attempt out of three was reported as the isometric strength and used for statistical calculations.

### Wingate test

After maximal strength testing before and after the entire 25-week intervention, a 15-min warm-up (including 2–3 submaximal sprints and a 1-min rest) on the Lode cycle ergometer was performed. The 30-s all-out Wingate test started while pedaling at 60 rpm without braking resistance. Then, following a 3-s count-down, braking resistance was applied to the flywheel and remained constant throughout the 30-s all-out test. Braking resistance was set to 0.8 Nm kg<sup>-1</sup> body mass. The cadence was sampled at 5 Hz and matching power output values were calculated (Lode Ergometry Manager 9.3.1.0 Lode B.V., Groningen, The Netherlands). Peak power output was presented as the highest power output achieved at any time during the Wingate test. Mean power output was presented as the average power output sustained throughout the 30 s. Cyclists remained seated throughout the test, and strong verbal encouragement was provided throughout. Cyclists were instructed to pedal as fast as possible from the start and not to conserve energy for the last part of the test.

### Blood lactate profile test

A blood lactate profile was determined for each cyclist by plotting [ $\text{la}^-$ ] vs power output during submaximal continuous incremental cycling by a test described elsewhere (Rønnestad et al., 2010a). Briefly, the test started without warm-up, with 5 min cycling at 125 W. Power output was increased by 50 W every 5 min. At the end of each 5-min bout, blood was sampled from a fingertip and were analyzed for whole blood [ $\text{la}^-$ ] using a Biosen C-Line lactate analyzer (EKF Diagnostic GmbH, Barleben, Germany). This continuous protocol was terminated when [ $\text{la}^-$ ] of 4 mmol L<sup>-1</sup> or higher was measured.  $\text{VO}_2$ , 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).  $\text{VO}_2$  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, MO, USA). Gross efficiency was calculated by the measured  $\text{VO}_2$  values and their matching RER values to establish the energy expended and divide this by the power output and multiply by 100. Rating of perceived exertion (RPE) was recorded 4 min and 50 s into each bout, using Borg's 6–20 scale (Borg, 1982). For each cyclist, the power output at 4 mmol L<sup>-1</sup> [ $\text{la}^-$ ] was calculated from the relationship between [ $\text{la}^-$ ] and power output using linear regression. Cyclists initially selected their preferred pedal cadence, which they were then required to hold constant throughout all testing sessions.

### Pedal force measurements

The torque generated at the crank axle was measured by strain gauges developed and bonded on to the crank arm by the Lode

cycle ergometer manufacturer. The torque acting perpendicular to the crank was recorded at every 2°. The peak torque (mean of the highest propulsive torque during the downstroke phase), angle of peak torque (in degrees), and minimum torque (mean of the highest resistive torque during the upstroke phase, mainly caused by the weight of the limb moving upwards) were averaged from both legs. Crank angle was referenced to 0° at the top dead center and 180° at the bottom dead center, and zero adjustment calibration in Lode software was performed prior to every test (Lode Ergometry Manager 9.3.1.0). The crank torque data was recorded as the average from 1.5 to 4.5 min during the 5-min exercise period from the blood lactate profile that had the closest power output to the power output at 4 mmol L<sup>-1</sup> [la<sup>-</sup>] (4.3 ± 0.4 W kg<sup>-1</sup> for the ES group and 4.3 ± 0.4 W kg<sup>-1</sup> for the E group). This power output was chosen due to the experience that power output at 4 mmol L<sup>-1</sup> [la<sup>-</sup>] is quite close to the mean power output during an 40-min all-out trial and we wanted to relate the crank torque data to performance in the 40-min all-out trial. At posttest, individual crank torque measurements were performed at the same power output and using the same cadence as during the pretest.

#### VO<sub>2max</sub> test

After termination of the submaximal blood lactate profile test, the cyclists rested for 10 min before completing another incremental cycling test for determination of VO<sub>2max</sub> as described elsewhere (Rønnestad et al., 2011a). 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 kg<sup>-1</sup> (rounded down to the nearest 50 W). Power output was subsequently increased by 25 W every minute until exhaustion. VO<sub>2max</sub> was calculated as the average of the two highest 30-s VO<sub>2</sub> measurements. W<sub>max</sub> was calculated as the mean power output during the last 2 min of the incremental test.

#### 40-min all-out trial

The 40-min all-out trial was performed on the last test day and was initiated following a 20-min individual warm-up, concluded by 2–3 submaximal sprints. The cyclists used their own road racing bicycle connected to the same electromagnetically braked roller (Computrainer LabTM, Racer Mate Inc, Seattle, WA, USA) at pre- and post-test. Similar and proper tire pressure was ensured. After 15-min of the warm-up was the roller calibrated to quantify and adjust wheel-ergometer rolling resistance to 2.5–3.5 lbs, as prescribed by the manufacturer. This procedure was repeated just prior to start of the trial, whereupon the cyclists were asked to rate their perceived feeling of wellbeing in the legs using a 9 point scale, going from *very very good* to *very very heavy* (Rønnestad et al., 2014). The cyclists were allowed to freely adjust power output throughout the trial, and were allowed to freely change gearing and pedal frequency, as if riding on the road. They were continuously provided feedback regarding remaining time and instantaneous power output. The cyclists were instructed to cycle at as high average power output as possible. Performance was measured as the average power output during the trial. The cyclists were allowed to occasionally stand in the pedals during the trial and to drink water *ad libitum*.

#### Statistical analysis

All data in the text, figures, and tables are presented as mean ± standard deviation. To test for differences between groups at pre-intervention, unpaired Student's *t*-tests were used. For each group, measurements of maximal strength at pre-intervention, after 10 weeks, and after 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 in maximal strength, two-way repeated measures ANOVA (time of intervention and group as factors) with Bonferroni post-hoc tests were performed to evaluate differences. Due to the small sample size and expectations of small changes in these elite cyclists, within and between group analyses on changes in cycling specific tests were performed with paired and unpaired *t*-tests, respectively, and by calculation of effect size. Effect sizes for the key performance/physiological adaptation measures were calculated as Cohen's *d* to compare the practical significance of the performance improvements among the two groups. The criteria to interpret the magnitude of the effect size were the following: 0.0–0.2 trivial, 0.2–0.6 small, 0.6–1.2 moderate, 1.2–2.0 large, and >2.0 very large (Hopkins et al., 2009). Correlation analyses were performed using the Pearson product-moment method, and correlation coefficients were interpreted according to Hopkins et al. (2009); *r* < 0.1 = trivial, 0.1–0.3 = small, 0.3–0.5 = moderate, 0.5–0.7 = large, 0.7–0.9 = very large, 0.9 = nearly perfect, and 1.0 = perfect. Multifactor regression analysis was performed on selected variables. ANOVA analyses were performed in GraphPad Prism 5 (GraphPad Software Inc., La Jolla, CA, USA). Student's two-tailed *t*-tests were performed in Excel 2003 (Microsoft Corporation, Redmond, WA, USA). All analyses resulting in *P* ≤ 0.05 were considered statistically significant. *P* values between 0.06 and 0.10 are described as tendencies.

## Results

### Comparison of groups at pre-intervention

There were no significant differences between ES and E at pre-intervention except for body mass. Therefore, maximal strength, VO<sub>2</sub>, and power output measurements are presented relative to body mass.

### Maximal strength, body mass, lean lower body mass, and Wingate test

ES increased maximal strength in isometric half squat by 20 ± 12% during the 10 weeks of strength development (*P* < 0.01). The increased strength was preserved during the following 15-week strength maintenance period (Fig. 1). Maximal strength remained unchanged in E from pre- to post-intervention (Fig. 1). The change in maximal strength during the strength development period and ultimately during the entire 25 weeks was larger in ES than in E (*P* < 0.01). Accordingly, an effect size analysis revealed a very large practical effect of ES compared with E training (effect size = 2.12). Overall body mass was slightly increased from pre-intervention to 25 weeks in both ES (from 65.8 ± 8.1 kg to 66.9 ± 8.0 kg, *P* < 0.05) and E (from 74.6 ± 7.1 kg to 75.9 ± 7.2 kg, *P* < 0.05). Lean lower body mass increased from pre- to post-intervention by 2 ± 1% in ES (from 19782 ± 2944 to 20131 ± 3066 g, *P* < 0.05), while there was no change in E (21599 ± 3008 g vs 21728 ± 2822 g, respectively, *P* > 0.05). No statistical significant difference were apparent in change of lean lower body mass between groups. However, an effect size analysis revealed a small practical effect of ES compared with E (effect size = 0.43). Peak power output in

the 30-s Wingate test tended to increase by  $2 \pm 3\%$  in ES from pre- to post-intervention ( $P = 0.07$ , Table 2), while no change occurred in E. An effect size analysis revealed a moderate effect of ES on peak power output compared with E (effect size = 0.76). Neither of the groups showed significant changes in mean power output in the 30-s Wingate test (Table 2).

$VO_{2max}$  and  $W_{max}$

There was no significant change in  $VO_{2max}$  from pre- to post-intervention in either of the groups (Table 2). ES increased  $W_{max}$  by  $3 \pm 3\%$  from pre-intervention to 25 weeks ( $P < 0.05$ ), while there was a non-significant reduction of  $3 \pm 6\%$  in E ( $P > 0.05$ ; Fig. 2a). The relative change in  $W_{max}$  was larger in ES than in E ( $P < 0.05$ ) and the effect size of the relative improvement in  $W_{max}$  revealed a moderate effect of ES training vs E training (effect size = 0.89).

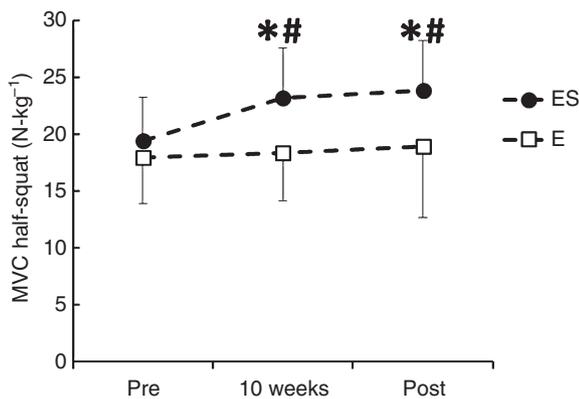


Fig. 1. Maximal strength in isometric half squat at before the intervention period (Pre), after the 10-week strength development period (10 weeks), and after the 15-week strength maintenance period (Post) for the cyclists performing endurance training and strength training (ES) and the cyclists performing endurance training only (E). \*Larger than at Pre ( $P < 0.01$ ), #the relative change from Pre is larger than in E ( $P < 0.01$ ).

Table 2. Data from the maximal oxygen consumption ( $VO_{2max}$ ) and Wingate tests before (Pre) and after the intervention period (Post) in the endurance and strength training group (ES) and the endurance training group (E)

	ES (n = 9)		E (n = 7)	
	Pre	Post	Pre	Post
<b><math>VO_{2max}</math> test</b>				
$VO_{2max}$ ( $mL \cdot kg^{-1} \cdot min^{-1}$ )	78 ± 6	80 ± 6	73 ± 5	75 ± 7
$HR_{peak}$ ( $beats \cdot min^{-1}$ )	197 ± 6	197 ± 7	194 ± 6	194 ± 5
[La <sup>-</sup> ] ( $mmol \cdot L^{-1}$ )	13.3 ± 2.0	13.7 ± 1.8	11.7 ± 2.1	11.1 ± 2.2
RPE	19 ± 1	19 ± 1	19 ± 1	19 ± 1
<b>Wingate test</b>				
Peak Wingate power ( $W \cdot kg^{-1}$ )	23.6 ± 2.9	24.2 ± 3.4*	22.9 ± 2.4	22.6 ± 1.7
Mean Wingate power ( $W \cdot kg^{-1}$ )	10.9 ± 0.9	10.9 ± 1.1	10.7 ± 0.7	10.5 ± 0.9

\*Tendency toward being larger than Pre ( $P = 0.07$ ).

$HR_{peak}$ , peak heart rate; [La<sup>-</sup>], blood lactate concentration; RPE, rate of perceived exertion.

Power output at 4  $mmol \cdot L^{-1}$  [La<sup>-</sup>], pedaling characteristics, and cycling economy

Power output at 4  $mmol \cdot L^{-1}$  [La<sup>-</sup>] increased by  $3.2 \pm 3.5\%$  in ES from pre- to post-intervention ( $P < 0.05$ ), while there was a non-significant reduction of  $4.1 \pm 12.2\%$  in E ( $P > 0.05$ ; Fig. 2b). There was, however, no statistically significant difference between groups in relative change in power output at 4  $mmol \cdot L^{-1}$  [La<sup>-</sup>] ( $P = 0.11$ ), but the effect size analysis showed a moderate effect of ES training vs E training (effect size = 0.81). Peak torque occurred earlier in the pedal stroke after the intervention period in ES ( $P < 0.05$ ; Fig. 2c), while no change was seen for E (Table 3). There were no significant changes in any other pedaling characteristics in any of the groups (Table 3). There was a significant difference between the groups in alteration of the timing of peak torque occurrence during the pedal stroke ( $P < 0.05$ ). An effect size analysis confirmed a moderate practical effect of ES compared with E (effect size = 1.19). From pre- to post-intervention, there was no change in fractional utilization of  $VO_{2max}$  at the power output at 4  $mmol \cdot L^{-1}$  [La<sup>-</sup>] in either ES ( $78 \pm 3\%$  vs  $80 \pm 3\%$ , respectively) or E ( $80 \pm 3\%$  and  $81 \pm 6\%$ , respectively). Furthermore, there was no significant 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, was  $16.7 \pm 1.2\%$ ,  $18.4 \pm 1.2\%$ , and  $19.2 \pm 0.8\%$ , respectively, as mean values across groups and time points of intervention.

Power output in the 40-min all-out trial

Mean power output during the 40-min all-out trial increased from pre- to post-intervention in ES ( $6.5 \pm 5.7\%$ ,  $P < 0.01$ , Fig. 2d), while no change occurred in E (Fig. 2d). The relative increase in mean power output was larger in ES than in E ( $P = 0.05$ ), which was confirmed through an effect size analysis as a moderate effect of ES compared with E (effect size = 1.04). Across groups, improvement in 40-min all-out trial correlated largely with both changes toward

Table 3. Data from the measurements of pedalling characteristics before (Pre) and after the intervention period (Post) in endurance and strength training group (ES) and the endurance training group (E)

	ES (n = 9)		E (n = 7)	
	Pre	Post	Pre	Post
Power output (W kg <sup>-1</sup> )	4.3 ± 0.4	4.3 ± 0.4	4.3 ± 0.4	4.3 ± 0.5
Peak torque (Nm)	59 ± 12	60 ± 13	62 ± 8	61 ± 7
Angle of peak torque (°)	86 ± 4	83 ± 3*†	87 ± 6	88 ± 5
Minimum torque (Nm)	-10 ± 3	-10 ± 2	-9 ± 2	-10 ± 2
rpm (rev min <sup>-1</sup> )	97 ± 9	97 ± 6	94 ± 8	94 ± 7

Values are mean ± SD.

\*Different from Pre (P < 0.05).

†The change from Pre is larger than in E (P < 0.05).

rpm, revolutions per minute.

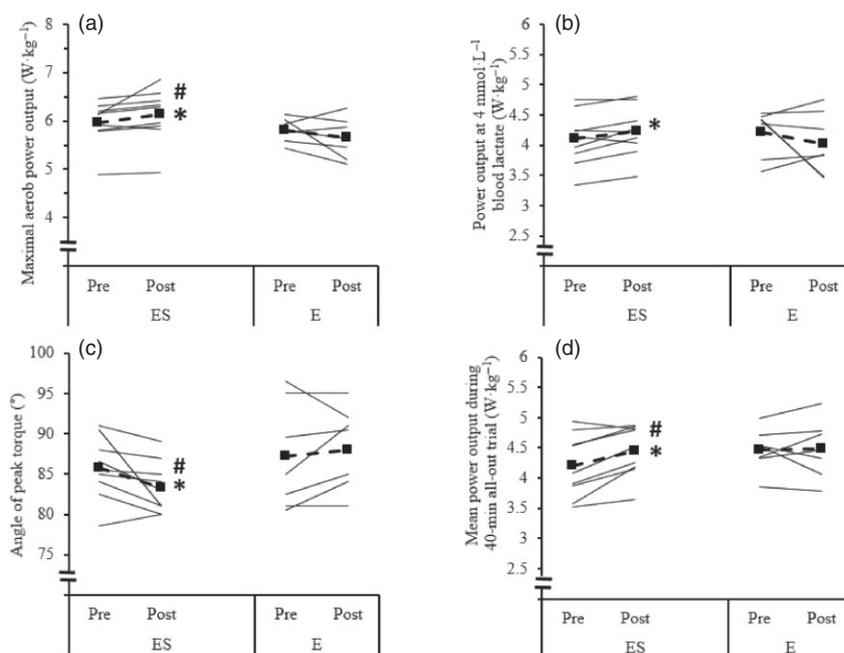


Fig. 2. Individual data points and mean values (solid line) before (Pre) and after the 25-week intervention period (Post) for cyclists performing concurrent endurance and strength training (ES) and cyclists performing endurance training only (E). (a) Maximal aerobic power output, (b) power output at 4 mmol L<sup>-1</sup> [La<sup>-</sup>], (c) angle of peak torque during the pedal stroke (in degrees), and (d) mean power output during the 40-min all-out trial. \*Different from Pre (P < 0.05), #the relative change from Pre is larger than in E (P < 0.05).

earlier peak torque during the pedal stroke ( $r = -0.63$ ,  $P < 0.01$ , Fig. 3) and increases in  $W_{max}$  ( $r = 0.69$ ,  $P < 0.01$ ). A multiple regression analysis showed that these two parameters accounted for 57% of the change ( $R = 0.75$ ,  $P < 0.05$ ) in the 40-min all-out trial ( $P < 0.01$ ). Rating of perceived well-being in the legs after the warm-up to the 40-min all-out trial revealed no differences between groups at neither pre- nor post-test. All cyclists reported *normal* legs at both pre- and post-test, with the mean score across groups and time points being  $5.4 \pm 0.8$  on a 9-point scale, going from 1 = *very good* to 9 = *very very heavy*.

### Discussion

The novel finding of this study was that elite cyclists performing 10-week strength development period

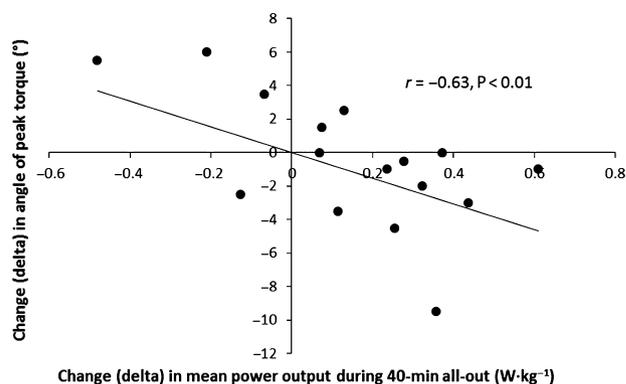


Fig. 3. Correlation between changes (delta) in mean power output during 40-min all-out trial and changes in angle of peak torque during the pedal stroke.

followed by 15-week strength maintenance period achieved superior improvements in  $W_{\max}$  and mean power output during 40-min all-out trial compared with the control cyclists. The improvement in 40-min all-out performance was largely correlated with changes toward earlier peak torque during the pedal stroke. Furthermore, the effect size of the relative improvement in power output at 4 mmol L<sup>-1</sup> [la<sup>-</sup>], peak power output during 30-s Wingate test,  $W_{\max}$ , and mean power output during 40-min all-out trial, revealed a moderate effect of ES training vs E training.

### Strength, lean lower body mass, and power output in Wingate test

Two strength-training sessions per week, as performed during the initial 10 weeks of the intervention, increased leg strength by ~20%. This is in agreement with previous findings on trained to well-trained endurance athletes with a similar strength-training period (Osteras et al., 2002; Rønnestad et al., 2010a; Sunde et al., 2010). Furthermore, the observed maintenance effect is in agreement with observations from cyclists and soccer players showing that one strength training session per week maintains maximal strength developed during a preceding period of strength training (Rønnestad et al., 2010c, 2011b). The 2% increase in lean lower body mass may be interpreted as some of the strength increase is due to increased muscle mass. Measurement of lean mass is not able to distinguish between different muscle groups (and their cross sectional area) in the lower body, and it is therefore possible that the increase in main target muscles of the strength training is even larger or to the contrary lower. Regional differences in muscle cross-sectional area adaptations to strength training have been observed (e.g. Häkkinen et al., 2001), and it has been shown that the largest cross-sectional area of a muscle determines the maximum strength of the muscle (Bamman et al., 2000). That being said, the present increase in lean mass is in agreement with the observation of 3% increase in lean body mass in elite cyclists (Aagaard et al., 2011), and a 4.5% increase in thigh muscle cross-sectional area has been observed in well-trained cyclists (Rønnestad et al., 2010a) due to concurrent strength and endurance training. These minor gains are substantially lower than the ~9–11% increase in cross-sectional area observed in studies employing similar strength training, but without endurance training (Aagaard et al., 2001; McCarthy et al., 2002; Rønnestad et al., 2012a). In the present study, both groups demonstrated a small ~1 kg increase in total body weight from pre- to post-testing. This is likely to be explained by a general tendency toward having a slightly lowered body weight in-season (i.e. at the pre-test) as compared with the beginning of the next competitive season (i.e. post-test). Elite endurance athletes have also previously been

reported to have lower body weight during in the competitive season (Losnegard et al., 2013).

Peak power output usually 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). The observed increase in lean mass in the lower-body and leg strength in ES in the current study may thus explain the observed tendency toward increased peak power output. Correspondingly, the finding of no change in peak power output in E can probably be explained by the lack of change in lean mass in the lower body or leg strength. The effect size showed a moderate practical effect of performing strength training on Wingate peak power output. Evidently, 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<sub>2max</sub>, $W_{\max}$ , power output at 4 mmol L<sup>-1</sup> [la<sup>-</sup>], and pedaling characteristics

The lack of effect of heavy strength training on VO<sub>2max</sub> is in accordance with existing literature (e.g. Aagaard et al., 2011; Osteras et al., 2002; Rønnestad et al., 2010a; Sunde et al., 2010). Due to the elite level of the present cyclists, no change in VO<sub>2max</sub> was expected during the intervention period. Despite no change in VO<sub>2max</sub>, ES increased  $W_{\max}$ , while no changes occurred in E and the effect size revealed a moderate practical effect of ES training on the development of  $W_{\max}$ . This is interesting, since  $W_{\max}$  is considered particularly valuable for distinguishing endurance performance in elite cyclists (Lucia et al., 1998). The importance of  $W_{\max}$  is further underlined by the present finding of a large correlation between changes in  $W_{\max}$  and change in mean power output during the 40-min all-out trial ( $r=0.69$ ,  $P<0.01$ ). In line with these findings in elite cyclists, concurrent endurance and heavy strength training have previously been shown to increase  $W_{\max}$  or time to exhaustion at  $W_{\max}$  in cyclists at lower performance levels (Hickson et al., 1988; Rønnestad et al., 2010a; Sunde et al., 2010). However, this positive effect in cyclists was not observed by using low-resistance explosive strength training (Bastiaans et al., 2001) nor after short-term (6 weeks) strength training (Levin et al., 2009).

Interestingly, there was a tendency toward a moderate correlation between improvements in  $W_{\max}$  and change towards earlier peak torque during the pedal stroke ( $r=-0.47$ ,  $P=0.06$ ).  $W_{\max}$  is influenced by not only VO<sub>2max</sub> and exercise economy, but also incorporate anaerobic capacity and neuromuscular characteristics (Jones & Carter, 2000). Therefore, the findings of increased strength and lean mass in the lower body, in addition to the tendency toward increased Wingate peak

power output, in ES are all likely contributors to the relative increase in  $W_{\max}$ .

Some studies report improved power output at a certain  $[Ia^-]$  of concurrent strength and endurance training (Koninckx et al., 2010; Rønnestad et al., 2010a,c), while others report no effect (Bishop et al., 1999; Sunde et al., 2010; Aagaard et al., 2011). The present study observed increased power output at  $4 \text{ mmol L}^{-1} [Ia^-]$  in ES, and the effect size analysis revealed a moderate practical effect of ES compared with E. The change in power output at  $4 \text{ mmol L}^{-1} [Ia^-]$  correlated largely with a change toward earlier peak torque during the pedal stroke ( $r = -0.50$ ,  $P = 0.05$ ). To our knowledge, this is the first study to investigate the effect of heavy strength training on when peak torque occurs during the pedal stroke in elite cyclists.

It is interesting to note that 25 weeks of combined strength and endurance training led to earlier occurrence of peak torque during the pedal stroke, while endurance training only did not. The effect size of the changes showed that ES had a moderate practical effect. In hypothesis, an earlier peak torque at the standardized submaximal power output might allow for larger blood flow in working muscles by shortening the time frame with relative high force production during each pedal stroke, thus increasing the duration of the blood flow-friendly relaxation phase. Indeed, blood volume in *musculus vastus lateralis* during a pedal stroke is at its lowest during peak torque in the downstroke and at its highest during the upward relaxation phase (Takaishi et al., 2002). In theory, an increased blood flow will lead to increased delivery of  $O_2$  and substrates to working muscles and thus contribute to increased power output at a fixed  $[Ia^-]$ , but not necessarily improved exercise economy. In accordance with our results, Aagaard et al. (2011) hypothesized that a potential explanation for their finding of strength training induced improvement in 45-min all-out performance in elite cyclists was a greater force-time integral (i.e. faster achievement of peak torque) during the pedal stroke. The earlier occurrence of peak torque during the pedal stroke in ES can be argued to be due to increased rate of force development (Aagaard et al., 2011). Concurrent strength and endurance training has also been shown to positively affect muscle-tendon stiffness (Millet et al., 2002), and it might be suggested that a more efficient force transmission due to a more optimal muscle-tendon stiffness could have contributed to the earlier timing of peak pedal stroke torque observed in the present study.

Improved cycling economy, measured as  $VO_2$  at short submaximal power outputs, have been observed after heavy strength training in moderate trained cyclists (Sunde et al., 2010). This might potentially explain the increased power output at  $4 \text{ mmol L}^{-1} [Ia^-]$  observed in ES. However, this was not the case, as cycling economy and gross efficiency did not change significantly in either of the groups. Indeed, when cycling economy is mea-

sured using the traditional method (i.e. short, 3–5 min, submaximal bouts of exercise), it does not seem to be altered by combined heavy strength and endurance training in well-trained and elite cyclists, despite improved performance in all-out trials lasting 40–45 min (present data; Aagaard et al., 2011; Rønnestad et al., 2010c). In agreement with the present findings, it has been reported that gross efficiency and cycling economy in elite cyclists do not vary significantly in a seasonal manner, and the authors suggested that changes in efficiency after training are less evident in elite cyclists (Sassi et al., 2008). The authors did indeed observe individual changes in gross efficiency and suggested that seasonal changes were more likely to occur in cyclists at a lower performance level (Sassi et al., 2008). Seasonal variations were also detected in gross efficiency in trained cyclists (Hopker et al., 2009).

#### 40-min all-out trial

The power output corresponding to a set  $[Ia^-]$  or inflection point obtained during a continuous incremental exercise test is an important determinant of long-term endurance cycling performance (Coyle et al., 1991). Thus, the improved power output at  $4 \text{ mmol L}^{-1} [Ia^-]$  in ES but not in E should arguably be accompanied by a divergence of endurance cycling performance. Accordingly, there was a larger increase in mean power output during the 40-min all-out trial in ES than in E, and the effect size revealed a moderate practical effect of adding strength training. The present finding of ~7% increase in 40-min all-out in ES is in agreement with the previous finding of ~8% increase in mean power output during 45-min all-out cycling in young elite cyclists after 16 weeks of added strength training (Aagaard et al., 2011).

As for power output at  $4 \text{ mmol L}^{-1} [Ia^-]$ , there was a large correlation between the improvement in mean power output during 40-min all-out trial and earlier peak torque during the pedal stroke ( $r = -0.63$ ), suggesting that the parameters are interconnected. Interestingly, Coyle et al. (1991) observed relationship between lean body mass and 1-hour all-out power output in well-trained and elite cyclists, suggesting that improved ability to recruit a relatively large quantity of muscle mass in each pedal stroke was associated with elite performance. This was further related to recruitment of increased amounts of mitochondria, sharing the power production and leading to less metabolic strain at a certain power output. It might thus be speculated that increased lean mass and increased amounts of mitochondria could give a contribution to the findings of the present study. In addition, increased strength might reduce the relative exercise intensity at any particular work load. Another aspect of pedaling characteristic that may affect cycling performance is the phase where negative or retarding crank torque occurs (Hansen et al.,

2012). During the measurement, we did not find any change from pre to post in negative torque in any of the groups. This is in accordance with a previous finding after heavy strength training during prolonged cycling at a standardized submaximal power output (Hansen et al., 2012). However, in Hansen et al. (2012), the negative phase of the pedal stroke was found to be shortened by ~14% and the mean power output was increased by 7% following ES in a 5-min all-out trial following 3 h of prolonged cycling. Unfortunately, in the current study, we did not measure the negative phase in such an all-out setting, but one might speculate that the hip flexion exercise could positively contribute to the observed performance improvement.

It has been suggested that strength training by increasing strength of type I muscle fibers delays their time to exhaustion, thereby delaying activation of the less efficient type II muscle fibers, in turn increasing endurance performance (Rønnestad & Mujika, 2013). Strength training increases maximal force, and therefore peak force or muscle fiber tension developed in each movement cycle at the same absolute exercise intensity decreases to a lower percentage of the maximal values. This might potentially induce less constriction of the blood flow. On the other hand, a recent study on moderately trained cyclists by Barrett-O'Keefe et al. (2012) showed that 8 weeks of heavy strength training improved work economy at a cadence of 60 rpm, reducing muscular blood flow, while maintaining muscular arterial-venous oxygen difference. The latter indicates that improvement in muscular efficiency is an important mechanism behind improved work economy and improved endurance performance.

A cross-sectional study of cyclists with similar  $VO_{2max}$  and  $W_{max}$  reported lower EMG activity in cyclists with higher maximal strength (Bieuzen et al., 2007). Indications of postponed activation of type II muscle fibers have been found in well-trained cyclists. After 12 weeks of strength training, a larger improvement in cycling economy was observed in the strength-training group than in the control group during the last hour of 185-min submaximal cycling (Rønnestad et al., 2011a). This was accompanied by reduced heart rate, RPE,  $[la^-]$ , and

improved performance in a 5-min all-out trial performed immediately following the 185 min of submaximal cycling. One might speculate that in our study, cycling economy was improved in ES during the last part of the 40-min all-out trail, resulting in improved performance. Another potential mechanism contributing to improved long-term endurance performance due to concurrent strength and endurance training could be an increased proportion of the fatigue resistant and relative effective type IIA muscle fibers at the expense of type IIX and/or hybrid IIA/IIX muscle fibers, as previously observed in young elite cyclists (Aagaard et al., 2011).

In conclusion, 25 weeks of concurrent endurance and strength training resulted in larger improvements in cycling performance and performance-related factors, including earlier peak torque during the pedal stroke in elite cyclists.

### Perspectives

Heavy strength training should, based on the results from the present study, be included in training for improve elite cycling performance. The present findings are in agreement with previous findings in moderate to well-trained cyclists (Rønnestad et al., 2010b, 2011a; Sunde et al., 2010). The study of Aagaard et al. (2011) is the only previous study investigating the effects of combining endurance and strength training in elite cyclists. They found superior improvements in cycling performance after concurrent training compared with endurance training only. The present study adds on this knowledge by indicating that the performance improvement in elite cyclists may be related to earlier achievement of peak torque during the pedal stroke.

**Key words:** Aerobic power output, peak power output, concurrent training, weight training, endurance performance.

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### References

- Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Crameri R, Magnusson SP, Kjaer M. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports* 2011; 21: E298–E307.
- Aagaard P, Andersen JL, Dyhre-Poulsen P, Leffers AM, Wagner A, Magnusson SP, Halkjær-Kristensen J, Simonsen EB. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol* 2001; 534: 613–623.
- Aagaard P, Raastad T. Strength training for endurance performance. In: Mujika I, ed. *Endurance training: science and practice*. Spain: Vitoria-Gasteiz, Basque Country, 2012: 51–59.
- Atkinson G, Davison R, Jeukendrup A, Passfield L. Science and cycling: current knowledge and future directions for research. *J Sports Sci* 2003; 21: 767–787.
- Bamman MM, Newcomer BR, Larson-Meyer DE, Weinsier RL, Hunter GR. Evaluation of the strength-size relationship in vivo using various muscle size indices. *Med Sci Sports Exerc* 2000; 32: 1307–1313.
- Barrett-O'Keefe Z, Helgerud J, Wagner PD, Richardson RS. Maximal strength training and increased work efficiency: contribution from the trained muscle

- bed. *J Appl Physiol* 2012; 113: 1846–1851.
- Bastiaans J, Diemen A, Veneberg T, Jeukendrup A. The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists. *Eur J Appl Physiol* 2001; 86: 79–84.
- Bieuzen F, Lepers R, Vercruyssen F, Hausswirth C, Brisswalter J. Muscle activation during cycling at different cadences: effect of maximal strength capacity. *J Electromyogr Kinesiol* 2007; 17: 731–738.
- Bishop D, Jenkins DG, Mackinnon LT, McEniery M, Carey MF. The effects of strength training on endurance performance and muscle characteristics. *Med Sci Sports Exerc* 1999; 31: 886–891.
- Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982; 14: 377–381.
- Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, Abraham LD, Petrek GW. Physiological and biochemical factors associated with elite endurance cycling performance. *Med Sci Sports Exerc* 1991; 23: 93–107.
- Hansen EA, Rønnestad BR, Vegge G, Raastad T. Cyclists' improvement of pedaling efficacy and performance after heavy strength training. *Int J Sports Physiol Perform* 2012; 7: 313–321.
- Hausswirth C, Argentin S, Bieuzen F, Le Meur Y, Couturier A, Brisswalter J. Endurance and strength training effects on physiological and muscular parameters during prolonged cycling. *J Electromyogr Kinesiol* 2010; 20: 330–339.
- Häkkinen K, Pakarinen A, Kraemer WJ, Häkkinen A, Valkeinen H, Alen M. Selective muscle hypertrophy, changes in EMG and force, and serum hormones during strength training in older women. *J Appl Physiol* 2001; 91: 569–580.
- Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol* 1988; 65: 2285–2290.
- Hopker J, Coleman D, Passfield L. Changes in cycling efficiency during a competitive season. *Med Sci Sports Exerc* 2009; 41: 912–919.
- Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 2009; 41: 3–12.
- Izquierdo M, Ibanez J, Hakkinen K, Kraemer WJ, Ruesta M, Gorostiaga EM. Maximal strength and power, muscle mass, endurance and serum hormones in weightlifters and road cyclists. *J Sports Sci* 2004; 22: 465–478.
- Jeukendrup AE, Craig NP, Hawley JA. The bioenergetics of world class cycling. *J Sci Med Sport* 2000; 3: 414–433.
- Jones AM, Carter H. The effect of endurance training on parameters of aerobic fitness. *Sports Med* 2000; 29: 373–386.
- Koninckx E, Van Leemputte M, Hespel P. Effect of isokinetic cycling vs weight training on maximal power output and endurance performance in cycling. *Eur J Appl Physiol* 2010; 109: 699–708.
- Levin GT, McGuigan MR, Laursen PB. Effect of concurrent resistance and endurance training on physiologic and performance parameters of well-trained endurance cyclists. *J Strength Cond Res* 2009; 23: 2280–2286.
- Losnegard T, Myklebust H, Spencer M, Hallén J. Seasonal variations in VO<sub>2</sub>max, O<sub>2</sub>-cost, O<sub>2</sub>-deficit, and performance in elite cross-country skiers. *J Strength Cond Res* 2013; 27: 1780–1790.
- Lucia A, Pardo J, Durantez A, Hoyos J, Chicharro JL. Physiological differences between professional and elite road cyclists. *Int J Sports Med* 1998; 19: 342–348.
- McCarthy JP, Pozniak MA, Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc* 2002; 34: 511–519.
- Millet GP, Jaouen B, Borrani F, Candau R. Effects of concurrent endurance and strength training on running economy and VO<sub>2</sub> kinetics. *Med Sci Sports Exerc* 2002; 34: 1351–1359.
- Osteras H, Helgerud J, Hoff J. Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol* 2002; 88: 255–263.
- Rønnestad BR, Hansen EA, Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *Eur J Appl Physiol* 2010a; 108: 965–975.
- Rønnestad BR, Hansen EA, Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *Eur J Appl Physiol* 2010b; 108: 965–975.
- Rønnestad BR, Hansen EA, Raastad T. In-season strength maintenance training increases well-trained cyclists' performance. *Eur J Appl Physiol* 2010c; 110: 1269–1282.
- Rønnestad BR, Hansen EA, Raastad T. Strength training improves 5-min all-out performance following 185 min of cycling. *Scand J Med Sci Sports* 2011a; 21: 250–259.
- Rønnestad BR, Hansen EA, Raastad T. High volume of endurance training impairs adaptations to 12 weeks of strength training in well-trained endurance athletes. *Eur J Appl Physiol* 2012a; 112: 1457–1466.
- Rønnestad BR, Hansen J, Ellefsen S. Block periodization of high-intensity aerobic intervals provides superior training effects in trained cyclists. *Scand J Med Sci Sports* 2014; 24: 34–42.
- Rønnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. *Scand J Med Sci Sports* 2013; doi: 10.1111/sms.12104.
- Rønnestad BR, Nymark BS, Raastad T. Effects of in-season strength maintenance training frequency in professional soccer players. *J Strength Cond Res* 2011b; 25: 2653–2660.
- Sassi A, Impellizzeri FM, Morelli A, Menaspà P, Rampinini E. Seasonal changes in aerobic fitness indices in elite cyclists. *Appl Physiol Nutr Metab* 2008; 33: 735–742.
- Sunde A, Storen O, Bjerkaas M, Larsen MH, Hoff J, Helgerud J. Maximal strength training improves cycling economy in competitive cyclists. *J Strength Cond Res* 2010; 24: 2157–2165.
- Takaishi T, Sugiura T, Katayama K, Sato Y, Shima N, Yamamoto T, Moritani T. Changes in blood volume and oxygenation level in a working muscle during a crank cycle. *Med Sci Sports Exerc* 2002; 34: 520–528.