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10-weeks of heavy strength training improves performance-related measurements in elite cyclists

Running head: *“Strength training in elite cyclists”*

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Abstract

Elite cyclists have often a limited period of time available during their short preparation phase to focus on development of maximal strength; therefore, the purpose of the present study was to investigate the effect of 10-week heavy strength training on lean lower-body mass, leg strength, determinants of cycling performance and cycling performance in elite cyclists. Twelve cyclists performed heavy strength training and normal endurance training (E&S) while eight other cyclists performed normal endurance training only (E). Following the intervention period E&S had a larger increase in maximal isometric half squat, mean power output during a 30-s Wingate sprint ($p<0.05$) and a tendency towards larger improvement in power output at 4 $mmol \cdot L^{-1}$ [la^-] than E ($p=0.068$). There were no significant difference between E&S and E in changes in 40-min all-out trial (4±6% vs. -1±6%, respectively, $p=0.13$). These beneficial effects may encourage elite cyclists to perform heavy strength training and the short period of only 10-weeks should make it executable even in the compressed training and competition schedule of elite cyclists.

KEYWORDS: Concurrent training; endurance performance; weight training; aerobic power output; peak power output

Introduction

During the last decade, there has been an increased research focus on the effect of strength training on cycling performance (e.g. Aagaard et al., 2011; Bastiaans, van Diemen, Veneberg & Jeukendrup, 2001; Koninckx, Leemputte & Hespel, 2010; Rønnestad, Hansen & Raastad,. 2010a; Rønnestad, Hansen & Raastad 2011 & Sunde, et al. 2010). It has recently been suggested that strength training interventions that have a positive impact on measurements relevant for cycling performance includes heavy strength training with multiple leg exercises and typically lasts 8-12 weeks (Rønnestad & Mujika, 2013).

Most of the studies investigating the effects of adding strength training to the ongoing endurance training in cyclists have been performed on moderate- to well-trained cyclists with maximal oxygen uptake (VO_{2max}) ≤ 66 $ml \cdot kg^{-1} \cdot min^{-1}$. However, there is lacking knowledge about elite cyclists` response to this training. This is natural, since it is very difficult to recruit elite cyclists to participate in intervention studies. To the best of the authors' knowledge, previous studies investigating the effects of combining endurance and strength training in elite cyclists lasts between 16 and 25 weeks (Aagaard et al., 2011; Rønnestad, Hansen, Hollan & Ellefsen, 2015). Interestingly, they reported superior improvements in cycling performance, measured as mean power output during trials lasting 40 to 45 min, when combining endurance and strength training compared with endurance training only. Adding heavy strength training to the normal endurance training is commonly performed during the preparatory period. However, elite cyclists often have a very long race season with a corresponding short preparatory period prior to the beginning of a new race season. Thus, there might often be a minor period to prioritise development of maximal strength.

The purpose of the present study is therefore to investigate the effects of a relatively short period (10 weeks) of combining endurance training with heavy strength training on the lower limbs in elite cyclists. In addition to muscle strength and lean mass in the lower body, important factors for endurance performance like VO_{2max}, power output at a fixed blood lactate concentration ($[la^-]$) and cycling economy will be measured. We hypothesised that combining endurance and strength training would result in superior improvements in both the high and low end of the cyclists' power profile, measured by a 30-s Wingate test and a 40-min all-out trial.

Methods

Participants

Twenty cyclists volunteered for the study, which was approved by the local Ethical Committee of Lillehammer University College and was carried out in accordance with the Declaration of Helsinki. All cyclists signed an informed consent form prior to participation. Twelve cyclists competing at a national (n=5) or international level (n=7) was randomly distributed to perform usual endurance training combined with heavy strength training [E&S; ♂=10,♀=2, mean age 19±2 years, body mass=67±8 kg, height=178±9 cm, VO_{2max}=77±7 $ml\cdot kg^{-1}\cdot min^{-1}$]. The remaining eight cyclists competing at national (n=4) or international level (n=4) performed only usual endurance training only [E; ♂=6, ♀=2, age=20±2 years, body mass=72±9 kg, height=181±10 cm VO_{2max}=72±6 $ml\cdot kg^{-1}\cdot min^{-1}$]. None of the cyclists had performed any strength training during the preceding 6 months. We thought that the risk for withdrawals was largest in the E&S group, therefore we chose to allocate more cyclists to this group. However, none of the cyclists withdrew from the 10-week intervention period. This study is part of a larger study investigating effects the effects of heavy strength training on various aspects of cycling performance (Rønnestad et al. 2015). However, the effects after the first 10 weeks of training on cycling performance and important performance determinants has not been published before. Furthermore, due to no dropouts during this period, the mean baseline values are also now published for the first time. To categorise the cyclists, the physiological criteria suggested by Jeukendrup, Craig and Hawley (2000) were used. All male cyclists fulfilled the VO_{2max} criteria (72-80 $ml \cdot kg^{-1} \cdot min^{-1}$), while two males in both E&S and E approached (5.6 to 5.9 $W \cdot kg^{-1}$) the W_{max} criteria (6.0-7.0 $W \cdot kg^{-1}$) suggested by Jeukendrup et al. (2000) that describes elite cyclists. The VO_{2max} and W_{max} values for the two females in E&S and E were ~65 $ml \cdot kg^{-1} \cdot min^{-1}$ and *5.3* $W \cdot kg^{-1}$ vs. ~63 $ml \cdot kg^{-1} \cdot min^{-1}$ and *5.3* $W \cdot kg^{-1}$, respectively.

Training

The study was initiated two weeks after the racing season ended. Endurance training duration and intensity during the intervention were calculated based on heart rate (HR) recordings. Endurance training was freely organised by the cyclists and their coaches and divided into three HR zones: 1) 60%-72%, 2) 73%-87%, and 3) 88%-100% of maximal HR. The endurance training were performed both outdoor and indoor. Due to the cold climate, most of the training intensity zone 2 and 3 were performed indoor on the cyclists own bike with a mix between individual training and group training with their cycling team. Some of the cyclists in E&S and E trained together. The weekly endurance training volume and intensity distribution were similar between groups during the intervention period (Table 1). Even though there were no significant difference between the groups, the E group performed at weekly basis ~1.5 h more endurance training than the E&S group (p=0.26) resulting in no significant difference between E&S and E when comparing total training duration (included the strength training; p=0.88, Table 1). The cyclists were asked to weekly record their perceived feeling of well-being in the legs in order to look closer on how strength training affected this measurement. Perceived feeling of wellbeing in the legs were recorded using a 9-point scale, going from *very very good* (1) to *very very heavy* (9) with *normal* equals a score of 5 (Rønnestad, Hansen & Ellefsen, 2012). Unfortunately, only seven cyclists in E&S and six cyclists from E provided sufficient data on this measurement. However, the results indicated that E&S had a tendency towards heavier legs than E during the first training week (5.7±0.4 vs. 5.0±0.6, respectively, p=0.06), while there were no difference between groups during the remaining part of the intervention period.

****Insert Table I about here****

The heavy strength training exercises was planned to be performed twice per week and the adherence was high (19.2±0.9 of the planned 20 sessions). Since peak force during pedalling occurs at approximately a 100° knee angle (Coyle et al., 1991), strength-training exercises were performed with a knee angle between 90° and almost full extension. The heavy strength training was performed with maximal effort in the concentric phase (approximately 1 s), while the eccentric was performed more slowly (duration 2-3 s). The performed exercises were: half squat, leg press with one leg at a time, standing one-legged hip flexion and ankle plantar flexion. All cyclists were supervised at all workouts during the first two weeks and thereafter at least once every second week throughout the intervention. The strength-training programme displayed a progressive overload throughout the intervention period. During the first three weeks, cyclists trained with 10 repetitions maximum (RM) sets at the first weekly session and 6RM sets at the second weekly session. During the following three weeks, sets were adjusted to 8RM and 5RM, respectively. During the final four weeks sets were adjusted to 6RM and 4RM, respectively. The number of sets in each exercise was always three with two minute rest in between.

Testing

Testing before and after the intervention was completed as follows: day 1; measurement of lean lower-body mass, day 2; incremental cycle tests for determination of blood lactate profile followed by a VO_{2max} test, day 3; maximal strength test, squat jump (SJ) test, and 30-s Wingate test, and day 4; 40-min all-out trial. The cyclists were instructed to refrain from intense exercise the day preceding testing, to prepare for the trial as they would have done for a competition, and to consume the same type of meal before each test. They were not allowed to eat during the hour preceding a test or trial or to consume coffee or other products containing caffeine during the preceding three hours. All cycling tests were performed under similar environmental conditions (18-21˚C) and at the same time of day. All cycling tests, except the 40-min all-out trial which was performed on their own bike, was performed on the same electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode B. V., Groningen, The Netherlands), which was adjusted according to each cyclist’s preference for seat height, horizontal distance between tip of seat and bottom bracket, and handlebar position. 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.

Lean lower-body mass

Lean lower-body mass was determined by dual-energy x-ray absorptiometry (DXA) using a Lunar Prodigy densiometer (Prodigy Advance PA+302047, Lunar, San Francisco, USA), performed in a highly standardised 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.

Maximal strength and SJ test

The cyclists performed a 10-min warm-up on a cycle ergometer. SJ performance was tested on a force plate (SG-9, Advanced Mechanical Technologies, Newton, Mass., USA, sampling frequency of 1 KHz). The hands were kept on the hips throughout the jump, knees were flexed to 90º, and the participants were instructed to execute a maximal vertical jump from a standing static flexed position. Vertical jumping height was calculated from the impulse from the ground reaction force. Each participant performed four attempts, with one min rest between each jump. The participants were blinded to the results. The best jump from each participant was used in data analysis (CV<3%). Maximal strength was measured as maximal force against a force plate (SG-9, Advanced Mechanical Technologies, Newton, Mass., USA, sampling frequency of 1 KHz) during an isometric half squat. This test was performed 3 min after the last SJ using a custom built rack located over the force plate and bolted to the floor. Three maximal voluntary isometric squats were performed with 1.5 min recovery between each attempt. Each lift was performed for 4 s, and all athletes were given strong verbal encouragement during each lift. The squats were performed with a knee angle between 88º and 92º and a hip angle between 110º and 120º. This variation from person to person was due to limited sensitivity in the adjustments of the height of the bar. However, the identical individual angles at pre- and post-test were ensured by monitoring and marking feet placement and height of the bar during all tests. The best attempt was reported as maximal isometric strength and used for statistical calculations.

Dietary intake

Only the cyclists in the E&S group recorded their daily dietary intake for a 4-day period (Wednesday to Saturday) in the middle of the intervention period by using the weighted food intake method. When participants are not supervised 24 hours a day, the weighted food intake method is recognised as a valid method (Black et al. 1991). The cyclists were given food record journals and digital food weighing scales (Vera 67002, Soehnle-Waagen GmbH & Co, Murrhardt, Germany; precision 1 g). They were also given detailed oral and written guidelines about how to carry out this method. Dietary assessment data were analysed using a nutrient analysis programme (Mat på Data 5.0, The Norwegian Food Safety Authority, Oslo, Norway).

Wingate test

After maximal strength testing, a 15-min warm-up on the Lode cycle ergometer (including 2-3 submaximal sprints) was followed by a 1-min rest before the Wingate test started. The 30-s all-out Wingate test started while pedaling at 60 revolutions per minute (rpm) without braking resistance. Then, following a 3-s countdown, the braking resistance was applied to the flywheel and remained constant throughout the 30-s all-out test. Braking resistance was set to 0.8 $Nm \cdot kg^{-1}$ body mass. 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

This test has been described elsewhere (Rønnestad et al., 2010a). Briefly, the test started without warm-up, with 5 min cycling at 125 W. Cycling continued and power output was increased by 50 W every 5 min. Cyclists initially selected their preferred pedal cadence, which they were required to maintain at the post-test. Blood samples were taken from a finger tip at the end of each 5-min bout and analysed for whole blood $[la^-]$ using a Biosen lactate analyzer (EKF diagnostic GmbH, Barleben, Germany). The test was terminated when a [la$^-$] of 4 mmol·L^{-1} or higher was measured. VO_2, respiratory exchange ratio (RER), and HR (Polar S610i, Polar, Kempele, Finland) were measured during the last 3 min of each bout, and mean values were used for statistical analysis. VO_2 was measured (30 s sampling time) using a computerised metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). The gas analyzers were calibrated with certified calibration gases of known concentrations before every test. The flow turbine (Triple V, Erich Jaeger, Hoechberg, Germany) was calibrated before every test with a 3 l, 5530 series, calibration syringe (Hans Rudolph, Kansas City, USA). Gross efficiency was measured between the 3rd and 5th minute of each submaximal bout during the blood lactate profile test. Gross efficiency was calculated by the measured VO_2 values and their matching RER values to establish the energy expended and divide this by the power output and multiply by 100. Rate of energy expenditure was calculated by using VO_2 values (L·min^{-1}) and their matching RER values according to the Weir method: ([1.1·RER]+3.9)·VO_2 (Weir, 1949). Gross efficiency data are presented from power outputs at 125, 175, and 225 W to ensure that all cyclists utilised only the aerobic energy system and thus avoiding any confounding factors from the anaerobic system. Rate of perceived exertion (RPE) was recorded 4 min and 50 s into each bout, using Borg's 6-20 scale (Borg, 1982). From this continuous incremental cycling test, the power output at 4 mmol·L^{-1} [la$^-$] was calculated from the relationship between [la$^-$] and power output using linear regression between data points.

VO_{2max} test

After termination of the blood lactate profile test, the cyclists recovered for 10 minutes before completing another incremental cycling test for determination of VO_{2max}. This test has been described elsewhere (Rønnestad et al., 2010a). Briefly, the test was initiated with 1 min of cycling at a power output corresponding to 3 W·kg^{-1} (rounded down to the nearest 50 W). Power output was subsequently increased by 25 W every minute until exhaustion. VO_{2max} was calculated as the average of the two highest 30-s VO_2 measurements. W_{max} was calculated as the mean power output during the last minute of the test.

40 min all-out trial

The 40-min all-out trial was performed on the last test day and started after a 20-min individual warm-up, which was concluded by 2-3 submaximal sprints. The cyclists used their own bicycle connected to the same electromagnetically braked roller (Computrainer LabTM, Racer Mate Inc, Seattle, WA, USA) at pre- and post-test. After the first 15-min warm-up, a roll-down resistance determination as prescribed by the manufacturer was performed to quantify and adjust wheel-ergometer rolling resistance to 2.5-3.5 lbs. This procedure was repeated just prior to start of the trial. The cyclists adjusted the power output during the trial with both gearing and pedal frequency in the same manner as riding on the road and were provided feedbacks regarding remaining time and instantaneous power output. 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*.

Statistics

Data in the text, figures, and tables are presented as mean ± standard deviation. Data was analysed with IBM SPSS statistics, version 22.0. We performed the analysis with repeated measures ANOVA with pre and post values as within group factors and group (E&S vs. E) as between group factor. Residuals were checked for normality and homogeneity. All analyses resulting in $p \leq 0.05$ were considered statistically significant. P values <0.1 are described as tendencies.

Results

Comparison of groups at pre-intervention

There were no significant differences between E&S and E at pre-intervention.

Maximal strength, SJ, body mass, lean lower-body mass, and Wingate test

E&S had a larger increase than E in maximal strength in isometric half squat (20±12% vs. 3±3%, respectively; F=18.372, p<0.001) and SJ height (8±8% vs. 0±6%, respectively; F=7.639, p=0.013) during the 10-week strength training period (Figure 1). There were no significant differences between E&S and E in changes in neither overall body mass (1.0±2.5% vs. 0.3±2.2%, respectively; Table II) nor lean lower-body mass (2±2% vs. 1±2%, respectively; Table II). There were no significant differences between E&S and E in changes in peak power output in the 30-s Wingate test (5±5% vs. 1±4%, respectively; Table II). E&S had a larger improvement in mean power output in the 30-s Wingate test compared to E (2±3% vs. -3±5%, F=4.623, p=0.045; Table II).

****Insert Figure 1 about here****

****Insert Table II about here****

VO_{2max}, W_{max}, Power output at 4 mmol·L^{-1} [la^-], and cycling economy

There was no significant change in VO_{2max} or W_{max} from pre- to post-intervention in either of the groups (Table II). There was a tendency towards larger improvements in power output at 4 mmol·L^{-1} [la^-] in E&S than E (2.4±6.3% vs. -3.6±7.3%, respectively;

F=3.783, p=0.068; Figure 2). From pre- to post-intervention there was no difference between E&S and E in change in fractional utilisation of VO_{2max} at the power output at 4 mmol·L^{-1} [la^-] (from 79±3% to 80±4% and from 81±4% to 83±1%, 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 17.1±1.3%, 18.8±1.4%, and 19.6±1.4%, respectively, as mean values across groups and time points of intervention.

****Insert Figure 2 about here****

Power output in the 40-min all-out trial and dietary intake

There was no differences between E&S and E in changes in mean power output during the intervention (3.5±5.5% vs. -0.8±5.7%, respectively; F=2.431, p=0.13; Figure 2). Daily dietary intake of macronutrients during the 5th intervention week in E&S was registered to be 2.2±0.5 g·kg^{-1} body weight·d^{-1} protein, 1.9±0.5 g·kg^{-1} body weight ·d^{-1} fat, and 5.3±1.5 g·kg^{-1} body weight ·d^{-1} carbohydrate constituting an total energy intake of 202±48 kj·kg^{-1} body weight·d^{-1}.

Discussion

The novel finding of the present study was that 10-weeks of concurrent strength and endurance training induces favorable changes in both 30-s sprint and power output at 4 mmol·L^{-1} [la^-] compared to endurance training only in elite cyclists ($p<0.07$).

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

Two strength-training sessions per week during 10 weeks increased leg strength by ~20% and SJ by ~8%. This is in agreement with previous findings on trained- to well-trained endurance athletes with a similar strength-training period (e.g. Millet, Jaouen, Borrani & Candau, 2002; Rønnestad, Kvamme, Sunde & Raastad, 2008; Rønnestad et al., 2010a; Sunde et al., 2010). Although no group differences in changes in lean lower-body mass, the mean ~2% increase in lean lower-body mass in E&S may suggest that some hypertrophy occurred. Another study in elite cyclists observed 3.3% in lean body mass after 16 weeks of similar heavy strength training (Aagaard et al., 2011). Taken together, these two studies indicates that the muscle hypertrophy is lower than expected when untrained persons perform 10 weeks of only heavy strength training, where typical ~9-11% increase in cross-sectional area observed in studies employing similar strength training, but without endurance training (McCarthy, Pozniak & Agre, 2002; Rønnestad et al., 2007; Rønnestad, Hansen & Raastad 2012). This should not be due to inadequate protein intake, since the nutritional data revealed a protein intake within ACSM`s recommendations for endurance- and strength-trained athletes (American College of Sports Medicine, 2009). However, the nutritional data must be carefully interpreted since it is based on only 4 days in the middle of the intervention. Furthermore, regional differences in muscle cross-sectional area adaptations to strength training are not unusual (Häkkinen et al., 2001) and it has been observed that the largest cross-sectional area of a muscle determines the maximum strength of the muscle (Bamman, Newcomer, Larson-Meyer, Weinsier & Hunter, 2000; Klein, Rice & Marsh, 2001). Therefore, it might be suggested that contribution to the increased muscle strength from muscle hypertrophy is somewhat larger than the observed increased in lean lower-body mass. Indeed, in well-trained cyclists we have previously observed ~4.5% increase in cross-sectional area of the thigh muscles (Rønnestad et al., 2010a) after 12 weeks with a similar strength-training programme as used in the present study.

Therefore, the present DXA measurements of the lower body may lack some sensitivity to discover potential small local changes in the emphasised muscles in the thigh.

Power output during a short period of time (seconds) is mainly dependent on the size of the involved muscle mass and maximal leg strength (Izquierdo et al., 2004) and vertical jump performance has been shown to accurately evaluate the ability to develop power in the lower-body (Samozino Morin, Hintzy & Belli, 2008). Therefore, the finding that E&S increased mean power output during the 30-s Wingate sprint to a larger extent than E may be explained by their superior increase in leg strength and SJ performance. 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, Davison, Jeukendrup & Passfield, 2003).

VO_{2max} *and* W_{max}

The finding of neither a positive nor a negative effect of performing heavy strength training on VO_{2max} is in accordance with the existing literature (e.g. Aagaard et al., 2011; Rønnestad et al., 2010a; Sunde et al., 2010). Due to the elite level of the present cyclists, no change in VO_{2max} was expected. The non-significant reduction of ~2% in VO_{2max} in both groups is probably related to the fact that pre-test was performed close to the end of the competition season. The large volume of low exercise intensity during 10 weeks seems not to be very efficient in increasing VO_{2max} or workload at VO_{2max} in well-trained endurance athletes (Enoksen, Shalfawi & Tønnessen, 2011). Furthermore, no significant change in W_{max} was observed in any of the groups. This is in accordance with the findings of no change in W_{max} in a study on elite cyclists with a similar study design as the present (Aagaard et al., 2011). However, simultaneously strength and endurance training have previously been shown to induce ~4% increase in W_{max} after 12 weeks in cyclists at a slightly lower performance level, although well-trained (Rønnestad et al., 2010a).

Power output at 4 mmol·L^{-1} [la^{-}] and 40-min all-out performance

The present study observed a tendency towards larger increase in power output at 4 mmol·L^{-1} [la^{-}] in E&S than E (*p*=0.068). Previous studies present equivocal effects of adding strength training to the ongoing endurance training with some reports on additive effect (Koninckx et al., 2010; Rønnestad et al., 2010a; Rønnestad, Hansen & Raastad, 2010b), while others do not (Aagaard et al., 2011; Bishop, Jenkins, Mackinnon, McEniery & Carey, 1999; Sunde et al., 2010). In theory, should the tendency towards superior improvement in power output at 4 mmol·L^{-1} [la^{-}] lead to favourable adaptations in the 40-min all-out test (Coyle et al. 1991). Even though there was a correlation between the changes in power output at 4 mmol·L^{-1} [la^{-}] and the 40-min all-out test (r=0.74, p<0.01), there were no statistical significant group differences in the changes in 40-min all-out power output (p=0.13). However, although not statistical significant, it can be suggested that ~3.5% increase in 40-min all-out power in E&S and the reduction of ~1% in E may be physiologically relevant, especially when taking into account the high performance level of the present cyclists. This potential relevance of the non-statistical significant ~3.5% increase is underlined by the findings of Paton & Hopkins (2006), who considered the expected range of variation in performance in time trials and suggested that the smallest worthwhile improvement for 40-km mean power was 1.5% in elite cyclists. However, when interpreting the present data, it should be taken into account that the change in E&S is close to the reported coefficient of variation in time trials (CV<3.5%; Jeukendrup, Saris, Brouns & Kester, 1996). Furthermore, there were no statistical significant difference between the groups in endurance training hours or intensity distribution, but the E group performed weekly

~1.5 h more endurance training than E&S, which was similar to the weekly strength training duration in E&S. Therefore, differences in training volume should not explain the present findings E&S. Nevertheless, the present changes in the 40-min all-out trial is smaller than the previous finding of ~8% increase in mean power output during 45-min all-out cycling in elite cyclists (Aagaard et al., 2011). However, the latter study measured performance after 16 weeks of added strength training, while the present study lasted only 10 weeks. The difference in strength training duration can explain some of the difference in performance improvement. The fact that the present study involves cyclists at a very high performance level impairs the methodological approach by making it difficult to recruit and control participants. The relatively few participants may have reduced the statistical power. Furthermore, investigating elite athletes reduces the possibility to optimise and standardise the preparations to testing, like physical training and dietary control before testing. These factors must be taken into account when the present data is interpreted.

Improved cycling economy have been observed after heavy strength training in moderate trained cyclists (Sunde et al. 2010) and this could have explained the observed effect in E&S on power output at 4 $\text{mmol}\cdot\text{L}^{-1}$ [la^{-}]. 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 measured by the traditional method (i.e. short, 3-5 min, submaximal bouts of exercise), it appears there is little change after combining heavy strength training with endurance training in well-trained and elite cyclists, despite improved performance in all-out trials lasting 40-45 min (Aagaard et al., 2011, Rønnestad et al., 2010b, Rønnestad et al., 2015). However, in well-trained cyclists 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, Hansen & Raastad, 2011). The improved economy was accompanied by reduced HR, RPE, [la$^-$], and improved performance in a 5-min all-out trial performed immediately following the 185 min of submaximal cycling. Therefore, it might also be speculated that if the cycling economy had been measured after prolonged cycling and in a more fatigued state, the findings could be different. Unfortunately, although highly relevant, such a prolonged test was impossible to perform in the present study.

In conclusion, performing only 10 weeks of concurrent endurance and strength training resulted in improved 30-s Wingate sprint and a tendency towards superior improvement in power output at 4 mmol·L^{-1} [la$^-$] in elite cyclists. From the present study, 10-weeks is sufficient time to observe improvements in elite cyclists. However, 10-weeks with strength training are not always possible and further studies should look closer into how performance markers change from the onset of strength training. Maybe fewer weeks with strength-training also leads to performance improvements?

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Disclosure statement

There is no conflict of interest.

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Figures

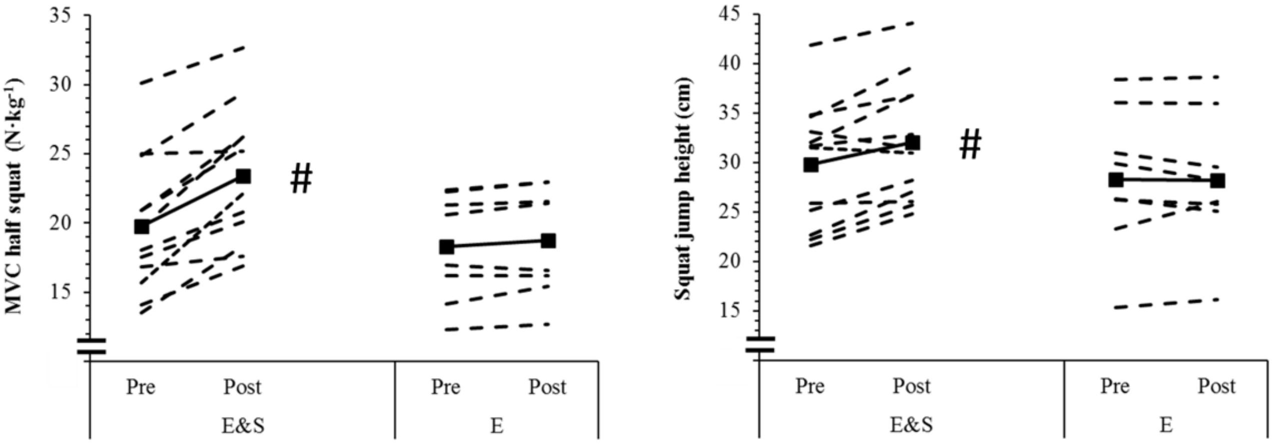

Figure 1 Individual data points and mean values (solid line) for maximal voluntary strength (MVC) in isometric half squat (panel A) and squat jump (SJ) height (panel B) before (Pre) and after (Post) the intervention period for the cyclists performing endurance training and strength training (E&S) and the cyclists performing endurance training only (E). [#]the change from Pre is larger than in E (p<0.01)

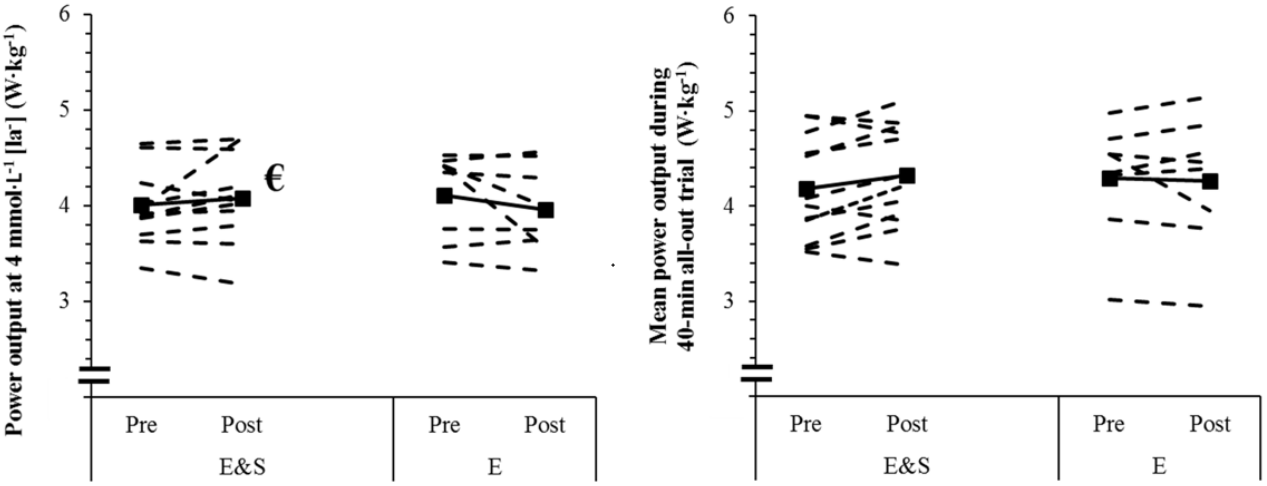

Figure 2 Individual data points and mean values (solid line) before (Pre) and after the intervention period (Post) for the cyclists performing concurrent endurance and strength training (E&S) and the cyclists performing endurance training only (E). Panel A shows power output at 4 mmol·L^{-1} blood lactate ([la^{-}]) and panel B shows mean power output during the 40-min all-out trial. $^{€}$The change from Pre tends to be larger than in E (*p*=0.068)

Table I Duration (in hours per week) of the endurance training performed during the intervention period in the group that performed endurance and strength training (E&S) and the group that performed only endurance training (E).

Intensity zone	E&S	E
Intensity zone I (60%-82% of HR$_{max}$)	8.8 ± 2.3	10.6 ± 2.8
Intensity zone II (83%-87% of HR$_{max}$)	1.2 ± 0.6	1.1 ± 0.6
Intensity zone III (88%-100% of HR$_{max}$)	0.7 ± 0.4	0.6 ± 0.5
Heavy strength training	1.2 ± 0.6	0
Total training time	12.3 ± 1.8	12.3 ± 2.9

Values are mean±SD. HR$_{max}$: maximal heart rate

Table II Body mass, lean lower-body mass, data from the maximal oxygen uptake test and Wingate test before (pre) and after the intervention period (post) in the cyclists that performed both endurance and heavy strength training (E&S) and the cyclists that performed endurance training only (E).

	E&S (n=12)		E (n=8)	
	Pre	Post	Pre	Post
Body mass (kg)	66.5 ± 8.3	67.1 ± 7.8	72.1 ± 9.4	72.3 ± 9.2
Lean lower-body mass (kg)	19.78 ± 3.06	20.15 ± 3.22	20.39 ± 3.01	20.58 ± 4.17
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	77 ± 6	75 ± 8	72 ± 7	70 ± 7
W_{max} ($W \cdot kg^{-1}$)	6.1 ± 0.5	6.1 ± 0.6	5.8 ± 0.5	5.7 ± 0.6
Mean Wingate power ($W \cdot kg^{-1}$)	10.7 ± 1.0	10.9 ± 0.9[#]	10.3 ± 1.1	10.1 ± 1.5
Peak Wingate power ($W \cdot kg^{-1}$)	23.2 ± 2.7	24.3 ± 2.8	22.1 ± 3.2	22.4 ± 4.0

VO_{2max}: maximal oxygen uptake; W_{max}: peak aerobic power output. Values are mean±SD

[#] The relative change from Pre is larger than in E ($p<0.05$).