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The effect of 30-s sprints during prolonged exercise on gross efficiency, electromyography and pedaling technique in elite cyclists

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Original investigation

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Abstract

Background:
Cycling competitions are often of long duration and include repeated high-intensity efforts.

Purpose:
To investigate the effect of repeated maximal sprints during 4 hours of low-intensity cycling on gross efficiency (GE), electromyography patterns (EMG) and pedaling technique compared to work-matched low-intensity cycling in elite cyclists.

Methods:
Twelve elite, male cyclists performed 4 hours of cycling at 50% of VO_{2max} either with 3 sets of 3 x 30-s maximal sprints (*E&S*) during the first 3 h or a work-matched cycling without sprints (*E*) in a randomized order. VO_2, EMG and pedaling technique were recorded throughout the exercises.

Results:
GE was reduced from start to the end of exercise in both conditions (E&S; 19.0±0.2 vs 18.1±0.2, E; 19.1±0.2 vs 18.1±0.2%, both P=0.001), with no difference in change between conditions (condition x time interaction: P=0.8). iEMG increased from start to end of exercise in m.Vastus Lateralis and m.Vastus Medialis (VM; 9.9±2.4, VL; 8.5±4.0 mV, main effect of time: P<0.001 and P=0.03, respectively) and *E*&S increased less than *E* in VM (mean difference -3.3±1.5 mV, main effect of condition: P=0.03, interaction, P=0.06). The mechanical effectiveness only decreased in *E&S* (*E&S;* -2.2±0.7, ES=0.24 vs *E*; -1.3±0.8 percentage points: P=0.04 and P=0.8, respectively). The mean power output during each set of 3x30-s sprints in *E*&S did not differ (P=0.6).

Conclusions:
GE decreases as a function of time during 4 hours of low-intensity cycling. However, the inclusion of maximal repeated sprinting does not affect the GE-changes, and the ability to sprint is maintained throughout the entire session.

Keywords

Elite cyclists
Gross efficiency (GE)
Repeated sprint
Electromyography (EMG)
Pedaling technique

Introduction

The “Classics” in professional cycling are typically ~250 km[1] and performance in these races is mainly determined by maximal oxygen uptake (VO_{2max}), fractional utilization of VO_{2max} and efficiency of movement.[2] However, for tactical reasons, the ability to perform repeated periods of high-intensity efforts are of additional importance.[3] Long-duration sessions with repeated high-intensity efforts are, therefore, important components of cyclists’ competitions and training sessions. However, it is currently unknown whether inclusion of sprints during long-duration sessions affect the quality of sprinting or the cost of the session.

The majority of time (~70%) during one-day races is spent at an intensity below 70% of VO_{2max}.[4] Hours of cycling at such a low intensity gradually increases VO_2 for the same power output (i.e. reduced GE) in well-trained cyclists.[5,6] This increase in VO_2 seems to be intensity-dependent, where higher intensities lead to a greater drift in VO_2 than lower intensity work.[7-10] It could, therefore, be hypothesized that inclusion of short high-intensity efforts performed during prolonged exercise would reduce GE further.

The underlying mechanisms for the observed changes in GE during prolonged exercise, and the possible effects of intensity on this change, are not fully elucidated.[6] Changes in recruitment pattern of motor-units measured by integrated electromyography (iEMG) and median frequency have earlier been reported during high-intensity efforts and prolonged low-intensity cycling, partly explaining the drift in VO_2.[7,11,12] Moreover, changes in pedaling technique might also play a role, since a positive correlation between earlier peak torque during the pedal stroke and improved 40-min TT have been reported.[13] In theory, this could be explained by a reduced time of blood flow obstruction to the working muscles during the downstroke phase, which is highest at peak torque.[14] Furthermore, improved mechanical effectiveness, which means reduced negative torque during the pedaling upstroke, has been reported together with an improved 5-min all-out performance in well-trained cyclists.[15] However, in contrast to would have been expected, reduced negative torque has been associated with increased submaximal VO_2, possibly due to increased hip flexion activity or less efficient flexor muscles in the lower limbs.[15,16] These mechanisms may also be affected by inclusion of high-intensity efforts during long-lasting submaximal work. During the first minutes after high-intensity efforts, the recovery-processes leads to increased energy-consumption, but recovery happens within minutes of rest.[17-20] However, a reduced GE is reported following brief (2 km) all-out efforts and is not restored within 30 min of cycling at 55% of VO_{2max}.[8] To restore GE to baseline values, 45 min of absolute rest may be necessary,[21] but this is not possible during races for elite cyclists. It is therefore suggested that decreased GE affects high-intensity performance later in a race,[22] although the effect of repeated maximal sprinting during prolonged exercise on GE and the following recovery hereof has not earlier been investigated. Therefore, the effects of prolonged submaximal cycling with or without repeated sprints on pedaling technique and GE need further elucidation.

The primary aim of this study was to investigate the effect of performing repeated 30-s maximal sprints during 4 h of low-intensity endurance cycling on GE, EMG patterns and pedaling technique compared to work-matched low-intensity cycling in elite cyclists. Our secondary aim was to examine how the quality of maximal sprints were affected over time.

Methods

Participants

Twelve male cyclists, aged 26.2±6.3 years, were recruited for the study. All cyclists had a history of regular endurance training (cycling or running, 54.9±34.6 h recorded 30 d prior to inclusion) and have been competing in cycling for 5.3±4.1 years. The cyclists were categorized as performance level 4-5 according to De Pauw et al.[23] All participants were accustomed to sprinting on the bike, but did not perform specific sprint-training. Physiological parameters are presented in Table 1.

Before testing, participants were informed of the possible risks and discomforts associated with the study and gave their written, informed consent to participate. The study was approved by the local ethical committee at Lillehammer University College, and performed according to the Declaration of Helsinki.

Insert table 1 here

Experimental design and procedures

Participants visited the lab on four occasions: (1) to perform an initial measurement of their fitness; (2) for familiarization of the study protocol; (3+4) to undertake two experimental conditions. The initial visit consisted of a 30-s all-out sprint (Wingate), a blood lactate profile and an incremental test until exhaustion to determine VO_{2max}. The familiarization to the experimental protocol consisted of a 4 h bout of endurance exercise combined with series of maximal effort sprints (*E&S*). The participants were instructed to refrain from intense exercise, caffeine, beta-alanine and bicarbonate 24 h prior to all testing. Participants were also instructed to record and duplicate food intake and time of consumption 24 h prior to *E&S* and the work-matched endurance protocol (*E*). All testing was performed 4-9 d apart, starting between 8.00-10.00 AM in a controlled environmental condition (16-21°C and 20-35% relative humidity) with a fan ensuring air circulation.

Wingate, blood lactate profile and VO_{2max}

Cycling tests were performed on an electromagnetic braked cycle ergometer, measuring power output at 6 Hz (Lode Excalibur Sport, The Netherlands), which was adjusted to the cyclist and replicated throughout all testing. The *Wingate* modus was used for sprints with the resistance set to 0.8 $nm \cdot kg^{-1}$ body mass. A standardized 20 min warm-up with 3 x 20-s, non-maximal sprints were performed prior to an all-out 30-s Wingate test. Sprints were started from 80 revolutions per minute (RPM), in a seated position with verbal encouragement throughout. Peak power output (PPO) was defined as the highest power output achieved during the Wingate test and mean power output (P_{mean}) was presented as the 30-s average power output sustained throughout the Wingate test.

Participants recovered (~30 min) until the blood lactate concentration [BLa^-] had returned below 1.5 $mmol \cdot L^{-1}$ and thereafter completed a blood lactate profile test as previously described.[24] Blood was sampled from the fingertip and analyzed for [BLa^-] using a lactate analyzer (Biosen C line, 5214 09 0045, EKF Diagnostic, Germany). After 10 min of recovery, participants completed an incremental test to determine VO_{2max}, starting at 200 W with 25 W increments every minute until exhaustion or RPM <60. VO_{2max} was calculated as the moving average of the 12 highest 5-s VO_2-measurements. VO_2 was measured using a computerized metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). W_{max} was calculated as the mean power output during the last minute of the incremental test.

Experimental protocols

The *E&S* protocol consisted of 4 h cycling at a PO equivalent to 50% of VO_{2max} with 3 x 30-s maximal sprints, interspersed by 4 min recovery (1 min completely rest and 3 min cycling at 100 W), 41 min into every hour during the first 3 h. No sprinting was performed during the last hour, equivalent to the *E*-protocol (Figure 1). PO at 50% of VO_{2max} was calculated using interpolation from sub-maximal values from the blood lactate profile together with the VO_{2max}. During the familiarization trial, cyclists consumed water, energy drinks and gels without caffeine (Squeezy Sports Nutrition GmbH, Germany) *ad libitum* to prevent dehydration and glycogen depletion. Consumption was recorded during familiarization and replicated on experimental tests. Participants consumed on average 3.2±0.1 L and 3.2±0.1 L of energy drink and water and 277.3±16.5 g and 273.6±15.2 g carbohydrate in *E&S* and *E*, respectively. The estimated sweat rate, measured as change in body mass and taking into account water consumption and loss of mass from lavatory-visits, during the 4 h of exercise was 1.7±0.2 L and 1.5±0.2 L in *E&S* and *E*, respectively, with no differences between conditions.

Insert figure 1 here

During experimental visits, participants performed, in a randomized order, *E&S* or *E* (4 h without sprints), separated by 6±2 days. The *E*-protocol was work-matched to *E&S* based on the average power output during the familiarization trial, including power output during sprints and rest periods. Due to the 4 min long recovery periods between sprints in *E&S*, the average PO during steady-state periods had to be somewhat higher in the *E&S*-protocol (*E&S;* 186±5 W vs *E;* 182±4 W) in order to work-match the protocols. The average power output of the protocols was therefore 182±4 W and 182±4 W in *E&S* and *E*, respectively.

VO_2, EMG and pedaling technique measurements were recorded from 33rd-35th min and 58th-60th min (6.5 min post sprint) every hour. Participants were instructed to keep the same pedaling frequency during these periods. A 5 min break was allowed every hour for the participants to visit the lavatory and to re-calibrate the metabolic system and the cycle ergometer. The change in VO_2, EMG and pedaling technique measurements were expressed relative to baseline values measured during the first hour from 5th-10th min. Perceived exertion, [BLa^-] and HR was registered throughout the experimental protocols (Figure 1).

Pedaling technique

Pedaling technique measurements were recorded using the Lode Ergometry Manager Software (Lode, version 10.4.5, Netherlands). The torque generated perpendicular to the crank axle was recorded at every 2°. Crank angle was referenced to 0° at the top dead center and 180° at the bottom. Angle of peak torque (in degrees) was recorded as the mean of the highest propulsive torque during the downstroke phase. Mechanical effectiveness was defined as mean of the highest resistive torque during the upstroke phase (force acting negatively on the propulsive force) expressed relative to the mean torque (in percentage).

Gross Efficiency

Gross efficiency (GE), defined as the ratio between the mechanical power output (PO) and the metabolic power input (PI) was calculated from steady-state periods, using the oxygen equivalent[25] and respiratory exchange ratio (RER) by following equation:[26]

$$PI = VO_2\ L{\cdot}s^{-1} \cdot (4{,}840\ J{\cdot}L^{-1} \cdot RER + 16{,}890\ J{\cdot}L^{-1})$$

EMG

To evaluate muscle fiber recruitment during exercise, EMG measurements via a wireless EMG-module (Ergotest Innovation as, Norway) using MuscleLab system (Pantaray Research Ltd. version 10.5.51.4221, Israel) was performed using surface electrodes (DUO-TRODE, Myotronics Inc, Kent, U.S.A) on m. Vastus Lateralis and m. Vastus Medialis placed as recommended by Konrad 2006.[27] Raw EMG-data were captured at 1000 Hz, and smoothed using a moving average with a 20-sample window width, repeated 20 times. iEMG was calculated as the average of the smoothed EMG data over 60 crank cycles, and expressed relative to the baseline (8th – 9th min). The frequency distribution to obtain median frequency was calculated in Matlab (R2016b) using its PSD routine ('periodogram' function) with default settings with a frequency resolution of 1 Hz.

Statistics

Possible differences in physiological variables within and between conditions were evaluated by a marginal-model approach using the SPSS-software version 23 (SPSS, IBM). Time and condition were specified as fixed effects. Repeated effects were specified by subject. A significant main effect or interaction was further evaluated by a multiple-comparison approach with Sidak adjustment. A significance level of 0.05 was applied and *p*-values >0.05 and <0.1 were described as tendencies. Hopkins' effect sizes (ES)[28] using pooled SD was calculated to compare the practical significance of differences in changes between conditions. Interpretations of the magnitude of ES were as follows: <0.2 trivial, 0.2-0.6 small, 0.6-1.2 moderate, 1.2-2.0 large and 2.0-4.0 very large difference.

Results

Physiological responses and rate of perceived exertion

VO_2 and VE increased from baseline (5-10 min) to the end of exercise (238-240 min) in both conditions, with no difference in relative changes (VO_2: 5±1% vs 6±1%, P=0.4 and VE: 9±2% vs 7±2%, P=0.2 in *E&S* and *E*, respectively; Figure 2A and 2B). Due to the higher PO in steady-state periods during *E&S*, there was an effect of condition, with both VO_2 and VE being higher at all time-points for *E&S* compared to *E* (both P<0.001). No change in RER over time was observed in either condition (P=0.8) but *E&*S was lower compared to *E* (mean difference -0.02±0.01, P=0.01; Figure 2C).

There was an effect of time on RPE, which was increased compared to baseline (10 min) after the first set of sprints (54 min) and remained elevated throughout the exercise in *E&S* (P<0.02), whereas *E* was only increased at the end of exercise (234 min, P=0.002; Figure 2D). No difference was observed in RPE at the beginning or at the end of exercise between conditions (P=0.5 and P=0.7). [BLa^-] was increased compared to baseline after the first set of sprints in *E&S* (P<0.001) and remained elevated until the last set of sprints (174 min, P<0.001), whereas [BLa^-] was unchanged in *E* throughout exercise (P=1.0). There were no differences between conditions in [BLa^-] at the beginning but tended to be higher at the end of exercise (P=1.0 and P=0.08). A significant interaction was observed in $\%HR_{max}$ (P=0.02), which increased after the third set of sprints in *E&S* compared to baseline (P<0.001) and was higher compared to *E* during exercise (P<0.006; Figure 2F). However, there was no difference in change from beginning to end of exercise between conditions (*E&S:* 2.6±0.9 vs *E:* 3.1±1.3 percentage points, P=0.5, respectively).

Insert figure 2 here

Gross efficiency and pedaling frequency

GE was in both conditions reduced from baseline (8-10 min) to the end of exercise (238-240 min) (E&S; 19.0±0.2 vs 18.1±0.2, E; 19.1±0.2 vs 18.1±0.2%, pre vs post, respectively, both P=0.001; Figure 3A). There was an overall effect of condition with GE being lower in *E&S* (P=0.002), but there was no interaction between time and condition (P=0.6). Post hoc analysis revealed a difference in GE after the first set of sprints (93-95 min) between *E&S* and *E* (P=0.02). There was no difference in pedaling frequency between conditions in steady-state periods (P=0.2; Figure 3B). During sprints in *E&S* pedaling frequency was increased above baseline (5-10 min) and compared to *E* (P<0.001).

Insert figure 3 here

EMG

An overall effect of time was observed in iEMG in VL (P=0.03), post hoc analysis did not reveal significant differences for either condition from baseline (9-10 min) to the end of exercise (238-239 min, P=1.0 and P=0.8 in *E&S* and *E* respectively) and there was no effect of condition (P=0.3; Figure 4A). A significant effect of time (P<0.001) and condition (P=0.03) and a tendency for a significant interaction (P=0.06) was observed in VM. Post-hoc analysis revealed a temporary small increase (ES = 0.35) compared to baseline in iEMG after the second set of sprints (118-119 min) in *E&S* (P=0.001) which tended to be greater than for *E* (P=0.053; Figure 4B). iEMG in VM was increased the last hour of exercise (213-239 min) compared to baseline in *E* (P=0.008). This increase was considered small (ES=0.46) but was greater than for *E&S* (P=0.02). Median frequency did not change from baseline to any time point during exercise in either condition in VL (*E&S;* -2.9±4.9, P=1.0 vs *E;* -2.3±5.0 Hz, P=1.0) or VM (*E&S*; -2.7±3.4, P=1.0 vs *E;* -1.3±3.4 Hz, P=1.0) and no difference between conditions was observed (P=0.2).

Insert figure 4 here

Pedaling technique

The mechanical effectiveness was decreased by -2.2±0.7 percentage points in *E&S* from baseline (5-10 min) to the end of exercise (238-240 min, P=0.04), while no changes occurred in *E* (-1.3 ± 0.8 percentage points, P=0.8: Table 2). This decrease in mechanical effectiveness was greater in *E&S* compared to *E* (P=0.03). The effect of this decrease was small (ES=0.24) and there was no correlation between the reduction in GE and the change in mechanical effectiveness in either *E&S* (*r*=0.08) or *E* (*r*=0.22). There were no changes in angle of peak torque during the pedal stroke in either condition from beginning to end of exercise (P=0.4 and P=0.2 in *E&S* and *E*, respectively). During sprints in *E&S*, mechanical effectiveness higher compared to baseline and compared to *E* (all P<0.001).

Insert table 2 here

Repeated 30-s maximal sprints

The mean power output during each set of 3 x 30 s sprints in *E&*S did not differ (P=0.6). Set 1, 2 and 3 was 93±1, 92±1 and 91±1%, respectively compared to an all-out Wingate test (Figure 5).

Insert figure 5 here

Discussion

The main finding of this study was that including repeated 30-s maximal sprints during 4 h low-intensity cycling did not affect the reduction in GE from the start to the end of the session, compared to a work-matched constant load cycling in elite cyclists. However, a temporary increase in energy expenditure and a reduction in GE was evident after the first set of sprints in *E&S*, although this temporary decrease in GE diminished and did not affect repeated sprint-ability later during exercise.

GE was reduced from ~19 to ~18% in both conditions, indicating that duration of exercise is mainly responsible for the reduced GE during long-lasting events. This is supported by the findings of earlier studies where prolonged low-intensity exercise (2-3 h) increases VO_2 in untrained to highly trained subjects.[5,6,29] Together with this gradually declining GE, we found an increased VE and RPE during exercise in both conditions, whereas no changes in RER, as an indicator of substrate oxidation, occurred. There are likely multiple explanatory factors for our findings; Increased VE has earlier been calculated to account for a small fraction (12-18%) of the variance in GE[30] and does not fully explain the change in GE found here. Furthermore, an overall effect of time, with increasing iEMG in VL and VM, was found, and indicate a gradual recruitment of additional motor-units simultaneously as there was a reduction in GE. The increasing iEMG may indicate a decreasing efficiency of already recruited fibers, as reported earlier during both low-intensity[12] and supramaximal intensities[7], without indication of change in fiber type recruitment (i.e. increased mean power frequency). However, in our study the maximal effort sprinting only temporarily increased iEMG while the effect on iEMG was small and patterns returned to baseline prior to the next set of sprints. It could be speculated that the short breaks after sprinting (1 min passive rest and 3 min at 100 W) during *E&S* was sufficient to recover the muscles, and therefore demonstrated no effect of time on GE compared to work-matched low-intensity work.

The acute metabolic stress response during and after maximal sprint exercise was evident by the drastically increased [Bla^-] and RPE, which is previously shown to momentarily decrease muscle efficiency[31]. Consequently, energy-consumption in the recovering process increases due to active transportation by Na^+/K^+-ATPase pumps, SERCA-pumps and recovery of metabolic products,[17-19] which may be indicated by the slightly increased HR in this study. This temporary change in homeostasis and consequently increased energy expenditure seems to account for the greater VO_2, VE and HR in *E&S* compared to *E* during this time-period. However, during the ~1 h cycling between sprint-sets, both RPE and [BLa^-] were restored to the same levels as *E*. Despite the rather long recovery between sprints, GE was not restored to baseline levels. The latter is in agreement with the findings in trained cyclists by Groot et al. who showed a reduced GE 30 min after all-out exercise.[8] In line with the present findings, reduced GE has earlier been observed not to affect 30-s sprint performance in competitive cyclists.[22] The present study supports this notion since repeated sprint performance did not seem affected by a reduced GE. Hence, performing sprints early during a prolonged low-intensity exercise does not negatively affect the quality of repeated sprints performed later during the same session.[32] We therefore speculate that including sprints in prolonged low-intensity exercise could benefit both moderately[33] and highly trained cyclists.

As expected, pedaling technique was drastically changed during repeated 30-s maximal sprints. Specifically, RPM was increased and mechanical effectiveness was improved during sprinting compared to low-intensity steady state cycling. Improved mechanical effectiveness has earlier been reported together with an improved 5-min all-out performance in well-trained cyclists.[15] However, in the current study, mechanical effectiveness did not change during submaximal exercise in *E* which is in contrast to previous findings.[34] In the study by Sanderson and Black, competitive cyclists rode on a relative higher power output (80% of maximum power output) to exhaustion, which might explain the differences to our study. Although not different from *E*, the *E&S* group in the current study experienced a slight decrease in mechanical effectiveness from baseline to the end of exercise and temporal increases in energy consumption due to increased RPM.[35] This could in theory contribute to explain the reduced GE, but since there were no differences between conditions, the ES of adding sprints was small and an earlier observation that mechanical effectiveness was not indicative of GE,[16] we find it difficult to relate pedaling technique to the observed reduced GE in *E&S*. A study on combined strength and endurance training in highly-trained cyclists have shown correlations between an earlier occurrence of peak torque during the pedal stroke and improved 40 min TT.[13] An earlier peak torque could hypothetically reduce the time of blood flow obstruction to the working muscle during the downstroke phase, which is highest at peak torque.[14] In the present study, mean angle of peak torque during the down stroke phase did not change during prolonged cycling and did therefore not seem to affect GE. Hence, changes in pedaling technique does not seem to explain the reduction in GE seen during prolonged low-intensity exercise.

Practical applications

Compared to work-matched low-intensity cycling, repeated sprinting does not negatively affect the decrease in GE from the start to the end of 4 hours of low-intensity cycling in elite cyclists. Furthermore, the repeated sprint-ability is not negatively affected by the decreased GE, implying that cyclists can include repeated sprints in their long-duration sessions without interfering the quality of sprinting and without a greater accumulation of fatigue compared to low-intensity cycling. Thus, repeated sprint exercise included in long-duration sessions could be an effective tool for concurrent development of both sprint-ability and endurance performance that should be further explored.[30] In addition, the general reduction in GE over time found here indicates that elite cyclists and coaches should explore the potential for developing training regimes or technical solutions to better maintain GE over time.

Conclusion

GE decreases as a function of time during 4 hours of low-intensity cycling. However, the inclusion of maximal repeated sprinting does not affect the GE-changes compared to work-matched low-intensity cycling. The temporal increases in [BLa^-], as well as the major changes in pedaling technique and muscle activity patterns during and directly after sprints led to a temporarily reduced GE after the initial sets of sprints. However, this did not negatively affect the subsequent repeated sprint performance in elite cyclists.

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Figures

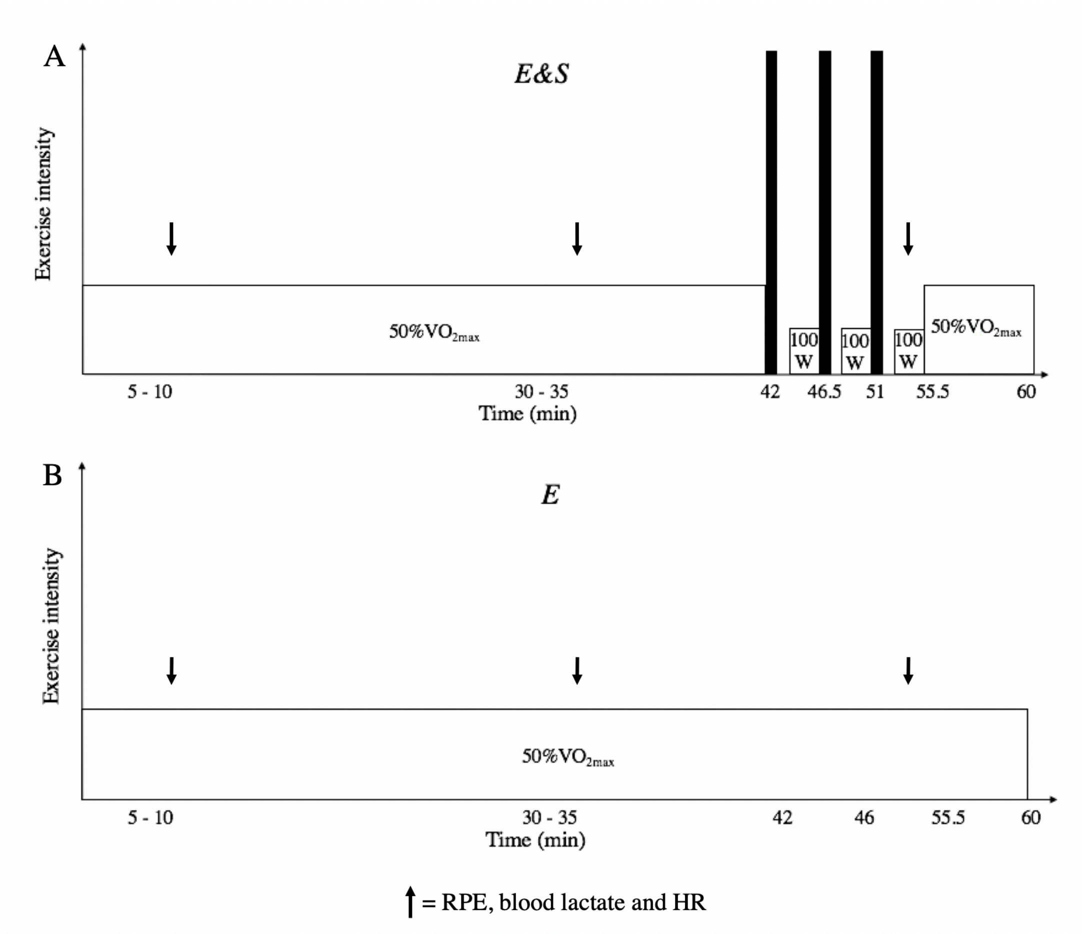

Figure 1: Experimental protocols. Panel A shows the endurance and sprint protocol (E&S) which was repeated three times for the first 3 h followed by 1 h of the E-protocol (panel B). Panel B show the endurance protocol (E) which was a work-matched endurance exercise for 4 h with no sprinting. Oxygen uptake (VO_2) and electromyography (EMG) was recorded for three periods during each hour (5-10 min, 30-35 min and 58-60 min, respectively). Black arrows indicate the time point at which rate of perceived exertion (RPE), blood lactate concentration [BLa^-] and heart rate (HR) was registered.

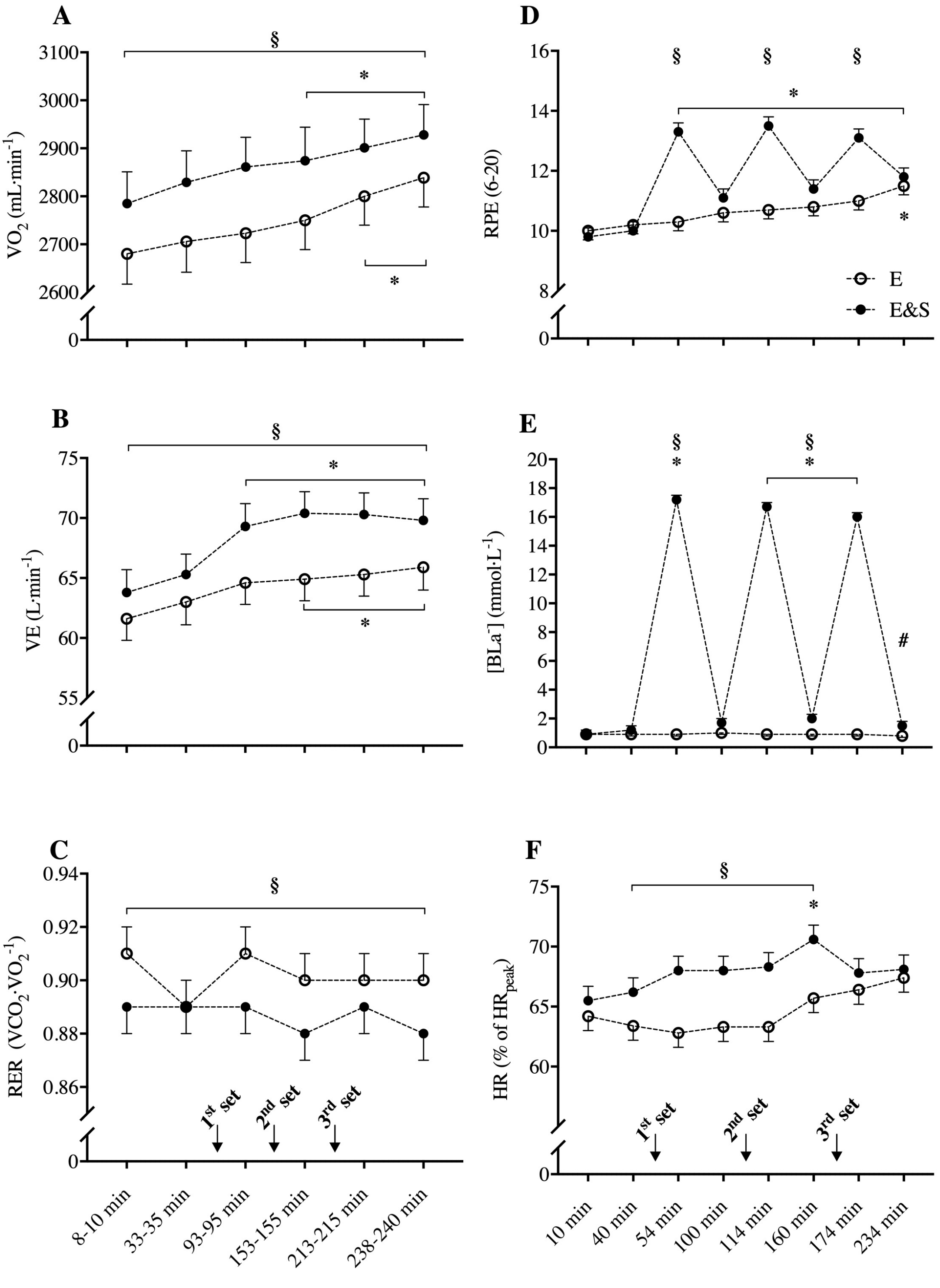

*Figure 2: Panel A: Changes in oxygen consumption (VO_2), panel B: Respiratory exchange ratio (RER), panel C: Ventilation (VE), panel D: Rate of perceived exertion (RPE) on a scale from 6-20, panel E: Blood lactate concentration $[BLa^-]$ and panel F: Relative heart rate ($\%HR_{peak}$) during 4 h of exercise with 9 x 30 s sprint (E&S; •) or without sprints (E; o). Mean ± SE, n = 12, * indicates significantly different ($P<0.05$) from baseline (1^{st} h, 8-10 min), § indicates significant difference $P<0.05$ between conditions, # indicates tendency to difference ($P<0.1$) between conditions.*

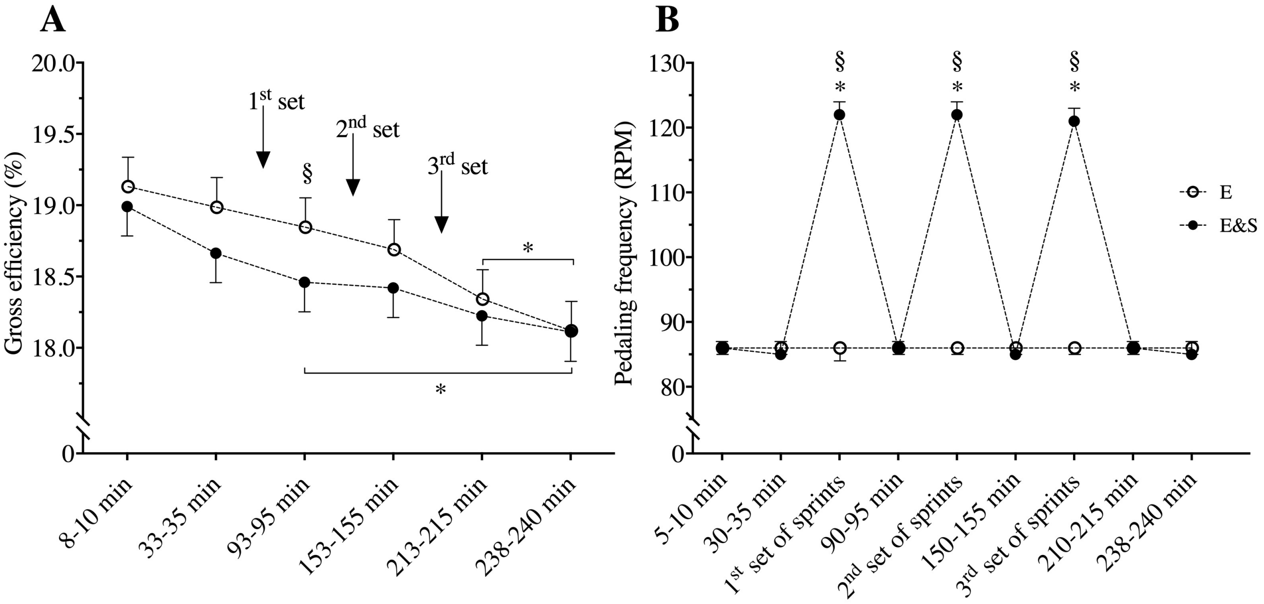

*Figure 3: Panel A: Changes in gross efficiency measured in steady-state periods during 4 h of exercise with 9 x 30 s sprint (E&S; •) or without sprints (E; o). Arrows indicate time of 3 x 30 s sprint during E&S. Panel B: Pedaling frequency (RPM) in steady-state periods and during each set of 3 x 30 s sprints). Mean ± SE, n = 12, * indicates significantly different (P<0.05) from baseline (1st hr 8-10 min), § indicates significant difference (P<0.05) between conditions.*

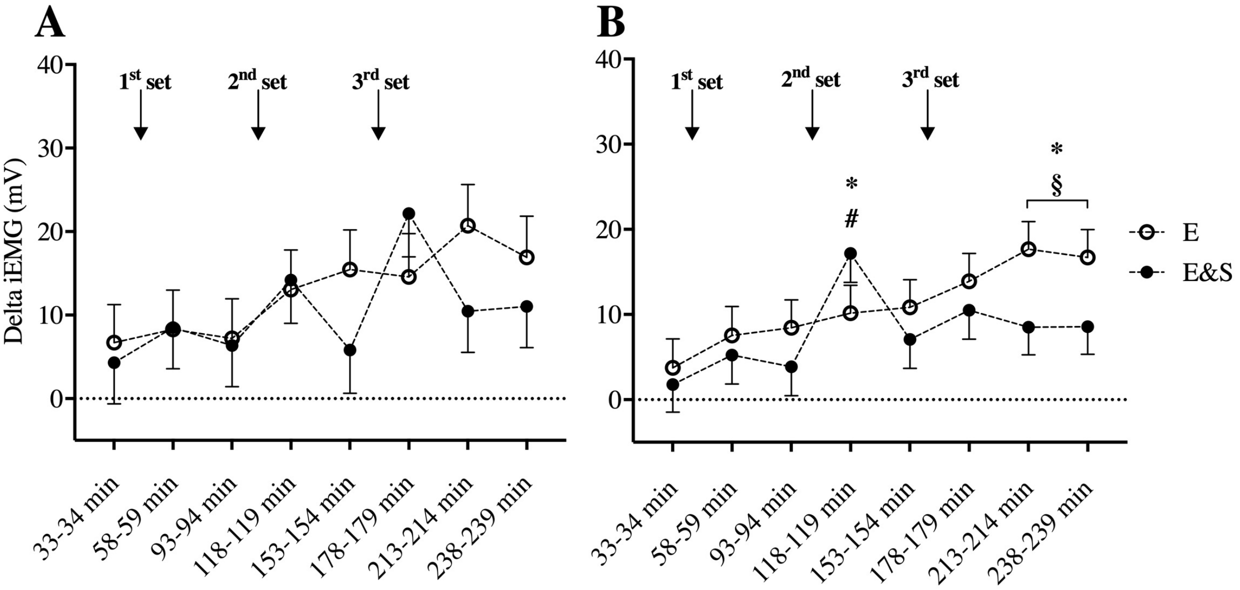

*Figure 4: Absolute changes in integrated electromyography (iEMG) (mV) from baseline (1st h, 9-10 min) during 4 h of exercise with 9 x 30 s sprint (E&S; •) or without sprints (E; o) in A; Vastus Lateralis and B; Vastus Medialis. Filled markers represent E&S, open markers represent E. Arrows indicate time of sprint during E&S. Mean ± SE, n = 12, * indicates significantly different (P<0.05) from baseline (1st h, 9-10 min), § indicates significant difference (P<0.05) between conditions, # indicates tendency (P<0.1) to difference between conditions.*

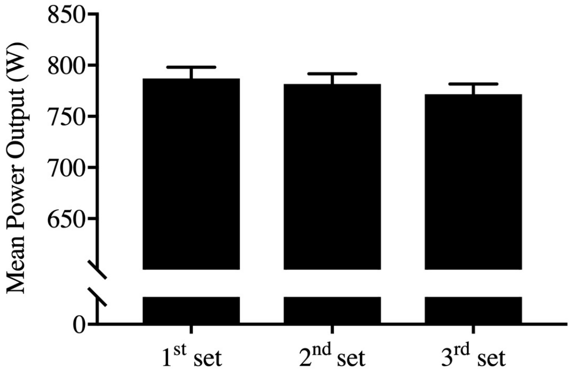

Figure 5: Mean power output of 3 sets of 3 repeated maximal 30-s sprints performed during E&S-protocol. Each set was separated by 1 h of low-intensity cycling at a power equivalent to ~50%VO$_{2max}$ *and each sprint was separated by 4 min recovery. All sprinting was started with a pedaling frequency of 80 RPM. Mean ± SE, n = 12.*

Tables

Table 1: Subject characteristics and physiological parameters of 12 elite male cyclists determined during a Wingate test, incremental lactate profile and incremental maximal exercise test. Values are mean ± SD

Body mass (kg)	76.1 ± 3.2
Height (cm)	183 ± 5
VO_{2max} ($L\cdot min^{-1}$)	5.57 ± 0.35
W_{max} (W)	477 ± 29
Peak power output (W)	1610 ± 235
Mean power output (W)	851 ± 64
Power output at 4 $mmol\cdot L^{-1}$ [BLa^{-1}] (W)	322 ± 40
VO_{2max} ($mL\cdot kg^{-1}\cdot min^{-1}$)	73.4 ± 4.0
W_{max} ($W\cdot kg^{-1}$)	6.3 ± 0.3

VO_{2max}; Maximal oxygen consumption, W_{max}; Maximal power produced the last minute during incremental maximal test, PPO; Peak Power Output during a 30s all-out test.

*Table 2: Mechanical effectiveness and angle at which peak torque is obtained during a revolution (degrees °) during 4 h of exercise with 9 x 30 s sprint (E&S) or without sprints (E) in steady-state periods and during sprints. Power output was kept constant in E during the equivalent "sprint period" in E&S, where a mean of the three 30-s sprints was calculated. Mean ± SE, $n = 10$, * indicates significantly different $P<0.05$ from baseline (1st h, 5-10min), § indicates significant difference $P<0.05$ between conditions.*

		5-10 min	*30-35 min*	*Mean of sprint 1-3 /control*	*90-95 min*	*Mean of sprint 4-7 /control*	*150-155 min*	*Mean of sprint 8-10 /control*	*210-215 min*	*238-240 min*
E&S	Mechanical effectiveness (%)	73.7 ± 1.3	73.0 ± 1.0	96.4 ± 0.7 *§	72.5 ± 1.0	96.8 ± 0.6 *§	72.5 ± 1.1	96.6 ± 0.7 *§	71.5 ± 1.1	71.5 ± 1.0 *
	Angle of peak torque (degrees)	91.9 ± 1.2	92.1 ± 1.2	93.8 ± 3.3	91.5 ± 1.2	91.2 ± 3.2	91.9 ± 1.1	91.1 ± 2.6	91.6 ± 1.0	91.3 ± 0.9
E	Mechanical effectiveness (%)	72.9 ± 1.1	72.4 ± 1.0	72.5 ± 1.0	72.1 ± 1.1	71.8 ± 1.0	71.5 ± 1.0	71.3 ± 1.0	70.9 ± 1.0	71.5 ± 1.1
	Angle of peak torque (degrees)	93.1 ± 1.2	93.1 ± 1.1	92.7 ± 1.1	92.7 ± 1.1	92.2 ± 1.2	92.7 ± 1.0	92.7 ± 1.1	93.1 ± 1.3	92.2 ± 1.3