Eur J Appl Physiol
DOI 10.1007/s00421-011-1957-5

ORIGINAL ARTICLE

# Effects of low and high cadence interval training on power output in flat and uphill cycling time-trials

**Alfred Nimmerichter · Roger Eston · Norbert Bachl · Craig Williams**

Received: 7 February 2011 / Accepted: 31 March 2011


**Abstract** This study tested the effects of low-cadence (60 rev min$^{-1}$) uphill (Int$_{60}$) or high-cadence (100 rev min$^{-1}$) level-ground (Int$_{100}$) interval training on power output (PO) during 20-min uphill (TT$_{up}$) and flat (TT$_{flat}$) time-trials. Eighteen male cyclists ($\dot{V}O_{2\,max}$: 58.6 ± 5.4 mL min$^{-1}$ kg$^{-1}$) were randomly assigned to Int$_{60}$, Int$_{100}$ or a control group (Con). The interval training comprised two training sessions per week over 4 weeks, which consisted of six bouts of 5 min at the PO corresponding to the respiratory compensation point (RCP). For the control group, no interval training was conducted. A two-factor ANOVA revealed significant increases on performance measures obtained from a laboratory-graded exercise test (GXT) ($P_{max}$: 2.8 ± 3.0%; $p < 0.01$; PO and $\dot{V}O_2$ at RCP: 3.6 ± 6.3% and 4.7 ± 8.2%, respectively; $p < 0.05$; and $\dot{V}O_2$ at ventilatory threshold: 4.9 ± 5.6%; $p < 0.01$), with no significant group effects. Significant interactions between group and uphill and flat time-trial, pre- versus post-training on PO were observed ($p < 0.05$). Int$_{60}$ increased PO during both TT$_{up}$ (4.4 ± 5.3%) and TT$_{flat}$ (1.5 ± 4.5%). The changes were −1.3 ± 3.6, 2.6 ± 6.0% for Int$_{100}$ and 4.0 ± 4.6%, −3.5 ± 5.4% for Con during TT$_{up}$ and TT$_{flat}$, respectively. PO was significantly higher during TT$_{up}$ than TT$_{flat}$ (4.4 ± 6.0; 6.3 ± 5.6%; pre and post-training, respectively; $p < 0.001$). These findings suggest that higher forces during the low-cadence intervals are potentially beneficial to improve performance. In contrast to the GXT, the time-trials are ecologically valid to detect specific performance adaptations.

**Keywords** Ecological validity · Training adaptation · Field test · Outdoor cycling · Cadence · SRM

Communicated by Jean-René Lacour.

A. Nimmerichter · R. Eston · C. Williams
College of Life and Environmental Sciences,
Sport and Health Sciences, University of Exeter,
Heavitree Road, Exeter EX1 2LU, United Kingdom

A. Nimmerichter (✉) · N. Bachl
Austrian Institute of Sports Medicine, OEISM,
Auf der Schmelz 6, 1150 Vienna, Austria
e-mail: an242@exeter.ac.uk

N. Bachl
Department of Physiology, Faculty of Sports Science
and University Sport, Auf der Schmelz 6,
1150 Vienna, Austria

## Introduction

The term ‘interval training’ can be characterized as performing repeated bouts of exercise interspersed with recovery periods within a training session. This definition implies that several variables can be modified to describe such training sessions. The modification of number, duration and intensity of the exercise bout, as well as for the recovery phase, affect the impact of the training. The numerous variations of interval-training modalities have been reviewed by Billat (2001).

During cycling, the crank inertial load depends on the moment of inertia of the flywheel or the rear wheel. It has been shown that at the same power output and cadence, crank inertial load is higher during level ground than during uphill cycling because crank inertia increases as a quadratic function of the gear ratio (Fregly et al. 2000). In addition, an increase in crank inertia is accompanied by an increase in peak crank torque and therefore it was suggested that cyclists prefer higher cadences during level-ground cycling to reduce peak crank torque (Hansen et al.

Published online: 11 April 2011

2002). This finding was supported by Lucia et al. (2001) who reported a significantly lower mean cadence during high mountain passes (71.0 ± 1.4 rev min$^{-1}$) than during flat mass start stages (89.3 ± 1.0 rev min$^{-1}$) and time-trials (92.4 ± 1.3 rev min$^{-1}$) in professional cyclists.

During cycling training the pedaling speed or cadence can be manipulated to alter the muscle force applied to the cranks. To change the gear ratio is a unique opportunity for cyclists to influence the force–velocity relationship of the muscular contraction. Depending on the range of the gearshift, a variety of forces and velocities are applicable at constant power output. For example to produce a power output of 300 W with cadences of 60 and 100 rev min$^{-1}$ requires forces of 281 and 169 N, respectively. In a previous study (Paton et al. 2009) performance improvements in maximum power output ($P_{\max}$), $\dot{V}O_{2\max}$ and power output at 4 mmol L$^{-1}$ blood lactate were significantly higher for the low-cadence group (60–70 rev min$^{-1}$) in comparison to the high-cadence group (110–120 rev min$^{-1}$) (6–11 vs. 2–3%), which was attributed to a higher testosterone concentration in response to higher pedal forces in the low-cadence group. Therefore, a training stimulus with the same power output, but different cadences might result in specific adaptations.

The scientific literature offers a variety of studies investigating performance changes (Stepto et al. 1999; Burgomaster et al. 2006; Westgarth-Taylor et al. 1997), metabolic adaptations (Aughey et al. 2007; Burgomaster et al. 2005, 2008) and skeletal muscle adaptations (Gibala et al. 2006) in response to interval training. The vast majority of interval-training studies are conducted on ergometers to control external variables and exercise intensity. However, the differences between laboratory and outdoor cycling have been discussed recently (Jobson et al. 2008a, b) suggesting that the position on the bike, rolling resistance, road gradient, lateral bike movement and fly-wheel inertia induce different physiological demands during laboratory and outdoor cycling. With the use of mobile power meters, exercise intensity can be monitored in the field and therefore can be studied during actual cycling conditions, which improves the ecological validity of the measurements.

Therefore, the purpose of this study was to investigate the effect of a period of interval training applied over 4 weeks during uphill and level-ground cycling at the same relative exercise intensity, but different cadences, on power output during a 20-min uphill and flat time-trial. In addition, the effects on performance measures obtained during laboratory incremental exercise tests were investigated. Following the principle of specificity of training, it was expected that an interval training performed on uphill or flat roads would specifically increase the performance capacity during uphill and flat time-trials. According to the results of Paton et al. (2009) it was hypothesized that performance improvements during the incremental graded exercise tests would be greater for the uphill-training group. Finally, we addressed the question raised in a previous study (Nimmerichter et al. 2010), with regard to whether or not a difference in power output exists between uphill and flat time-trial cycling.

## Methods

### Participants

Eighteen trained cyclists (Table 1) were randomly assigned to one of three groups. Group 1 performed uphill interval training with a cadence of 60 rev min$^{-1}$ ($\text{Int}_{60}$), group 2 performed level-ground interval training with a cadence of 100 rev min$^{-1}$ ($\text{Int}_{100}$). Group 3 (Con) continued their steady training but no interval training was permitted throughout the 4 weeks. One participant of the control group became injured and therefore his data from the pre-tests were excluded from further analyzes. The participants had a training history of at least 5 years and trained for 11.8 ± 2.7 h week$^{-1}$ in the last 12 weeks prior to the study. All participants completed a medical examination prior to the study, were informed of the experimental procedures and provided written informed consent to participate. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki (Harriss and Atkinson 2009) and was approved by the institutional ethics committee.

In a previous study (Nimmerichter et al. 2010), we investigated the test–retest reliability of power output during 20-min time-trials. We found an intraclass correlation coefficient of 0.98 (95% CL 0.95–0.99) and a bias ± random error of—1.8 ± 14 W or 0.6 ± 4.4%. The smallest worthwhile effect for the present study has been set to 15 W. At an estimated power output of 280 W for

**Table 1** Subjects' characteristics (mean ± SD)

| | Group | | |
|---|---|---|---|
| | $\text{Int}_{60}$ ($n = 6$) | $\text{Int}_{100}$ ($n = 6$) | Con ($n = 5$) |
| Age (years) | 30 ± 6.8 | 31 ± 6.9 | 33 ± 5.1 |
| Stature (cm) | 179 ± 3.2 | 177 ± 4.8 | 182 ± 7.0 |
| Body mass (kg) | 70.9 ± 6.4 | 71.5 ± 5.0 | 75.4 ± 4.2 |
| $\dot{V}O_{2\max}$ (mL min$^{-1}$ kg$^{-1}$) | 61.1 ± 5.0 | 58.8 ± 6.0 | 55.4 ± 4.3 |

No significant differences between groups the participants in this study, a change of 15 W (5%) would result in a difference of ±24 s (2%) during a 13-km time-trial. Based on these assumptions, it was calculated that it was necessary to have 6 participants in each group to have a 90% chance of detecting a mean difference of 15 W at an alpha level of 0.05.

## Study design

During the 10 days preceding the start of the intervention, participants performed an incremental graded exercise test in the laboratory (GXT) and two 20-min maximal power time-trials on a flat ($TT_{flat}$) and uphill ($TT_{up}$) road. Both training groups performed two interval-training sessions per week for 4 weeks, whereas no interval training was conducted for the control group. Between the 7th and the 12th day following the last training session, the GXT and the time-trials were repeated. All participants were provided with a PC spreadsheet to record the time and the rating of perceived exertion for each training (session RPE score 6–20) (Foster et al. 2001; Borg 1970) to calculate an integrated training impulse (TRIMP = session RPE × training time) (Foster et al. 2001; Banister and Calvert 1980).

## Laboratory test

The incremental graded exercise test was performed on an electromagnetically braked ergometer (Lode Excalibur, Groningen, The Netherlands) to assess maximal measures of oxygen uptake ($\dot{V}O_{2\,max}$), power output ($P_{max}$), heart rate ($HR_{max}$) and blood lactate concentration ($BL_{max}$). In addition, sub-maximal measures of ventilatory threshold (VT) and respiratory compensation point (RCP) were determined to set the individual exercise intensity for the interval training. After a 5 min warm up at 50 W the work rate was increased by 25 W min$^{-1}$ until exhaustion. If the last work rate was not completed, maximal power was calculated according to the method of Kuipers et al. (1985): $P_{max} = P_L + (t/60 \times P_I)$, where $P_L$ is the last completed work rate ($W$), $t$ is the time for the incomplete work rate (s) and $P_I$ the incremental work rate ($W$). Gas exchange data were collected continuously throughout the test via breath-by-breath open circuit spirometry (Master Screen CPX, VIASYS Healthcare, Hoechberg, Germany). Before each test, flow and volume were calibrated with the integrated system according to the manufacturer. Maximal oxygen uptake ($\dot{V}O_{2\,max}$) was recorded as the highest $\dot{V}O_2$ value obtained for any continuous 30 s period during the test. At least two of the following criteria were required for the attainment of $\dot{V}O_{2\,max}$: a plateau in $\dot{V}O_2$ despite an increase in work rate (Taylor et al. 1955; Howley et al. 1995), a respiratory exchange ratio above 1.10 (Duncan et al. 1997), a heart rate within ±10 b min$^{-1}$ of age-predicted maximum (220 − 0.7 × age) (Gellish et al. 2007). Ventilatory threshold was determined using the criteria of an increase of the ventilatory equivalent of $O_2$ ($\dot{V}E/\dot{V}O_2$) without a concomitant increase of the ventilatory equivalent of $CO_2$ ($\dot{V}E/\dot{V}CO_2$), the first loss of linearity in pulmonary ventilation ($\dot{V}E$) and carbon dioxide ventilation ($\dot{V}CO_2$) (Beaver et al. 1986). RCP was determined using the criteria of an increase in both $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ and the second loss of linearity in $\dot{V}E$ and in $\dot{V}CO_2$ (Wasserman et al. 1999). Two observers determined VT and RCP. In case of disagreement, a third investigator was consulted.

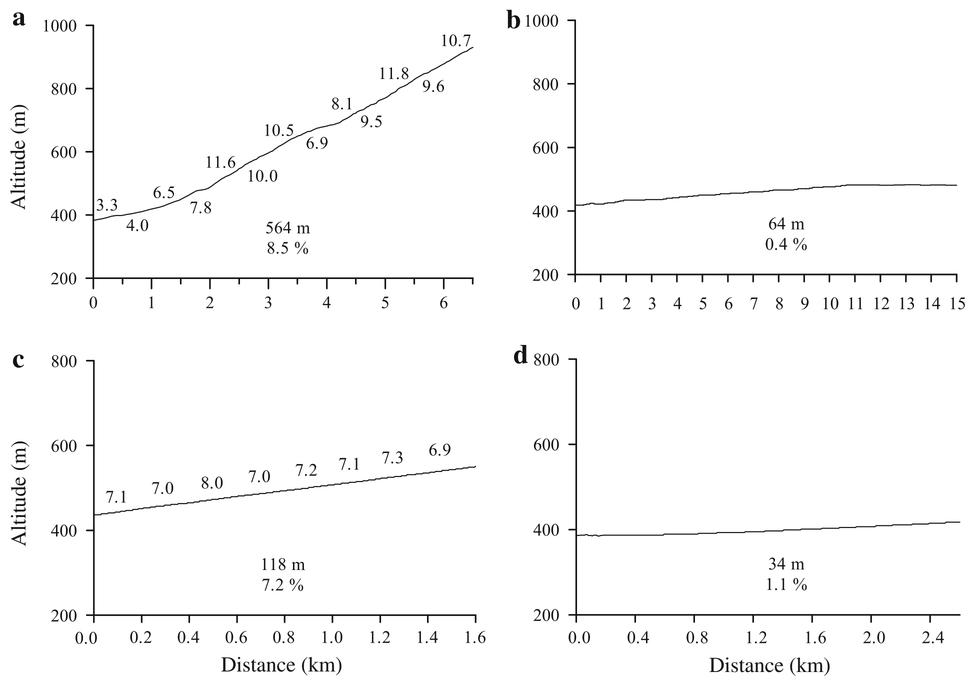
To determine $BL_{max}$ a 20 µl capillary blood sample was obtained from the hyperemic ear lobe 1 min post-exercise and diluted immediately in 1,000 µl glucose system solution. Blood lactate concentration (mmol L$^{-1}$) was measured using an automated lactate analyzer (Biosen S-line, EKF Diagnostic, Barleben, Germany). Heart rate was monitored continuously throughout the test with a 12-lead electrocardiograph (Cardiovit AT 104 PC, Schiller, Baar, Switzerland).

## Time-trials

Two 20-min maximal power time-trials were performed on a flat ($TT_{flat}$) and uphill ($TT_{up}$) road. The route profiles for the time-trials are shown in Fig. 1. The uphill course had a length of 7 km, the altitude at the top was 1,000 m and the average gradient was 8.5%. Since that specific course has been used for cycling competitions before and the ascending time achieved by a world-class cyclist was 19 min, it was assumed that none of the participants in this study would complete the course faster than the required 20 min. The time-trials were separated by at least 1 h. The order of the first time-trial (i.e. uphill or flat) was randomized and counter-balanced within the groups during the pre-tests and reversed at the post-tests. A 30-min standardized warm-up procedure preceded the time-trials. After 15 min at 40–60% of RCP power output, three 1-min efforts at RCP power output separated by 2 min and followed by another 6 min at 40–60% RCP, where performed. After the first time-trial, the athletes cycled for 15 min at a self-selected low intensity before they rested for 30–40 min. A warm up of 15 min at 40–60% of RCP power output preceded the second time-trial.

Power output, heart rate, cadence, and speed were recorded at 1 Hz throughout the time-trials using SRM professional power cranks (Schoberer Rad-Messtechnik, Jülich, Germany). A static calibration procedure was applied on all devices prior to the study according to the

**Fig. 1** Profiles for the uphill (**a**) and flat (**b**) time-trial and uphill (**c**) and flat (**d**) training routes. Numbers for the average gradient of every 500 and 200 m section are shown for the uphill time-trial and training route, respectively




methods of Wooles et al. (2005). Before each trial, the zero offset frequency was adjusted by the investigator according to the manufacturer's instructions. The only information the cyclists received during the time-trials was elapsed time. One minute after completion of each time-trial, a blood sample was obtained from the ear lobe for the determination of blood lactate concentration.

## Interval training

The participants in the training groups substituted two training sessions per week, which usually contained 2–4 h steady rides, with interval training. For 4 weeks, both training groups performed 6 × 5 min intervals at an intensity corresponding to RCP power, interspersed with 5 min at 30–50% of RCP power. It has been shown that four to eight repetitions of aerobic intervals between 4 and 5 min at 80–85% $P_{\max}$ performed over 3–6 weeks is an appropriate stimulus to improve $\dot{V}O_{2\max}$, $P_{\max}$ and time-trial performance in trained cyclists (Lindsay et al. 1996; Stepto et al. 1999; Westgarth-Taylor et al. 1997). The rest period of 5 min was selected to allow the riders to return to the start.

The same warm up procedure as described for the time-trials was used before the training sessions. According to the group, $Int_{60}$ performed intervals on an uphill road with an average gradient of 7% (Fig. 1) and with a cadence of 60 rev min$^{-1}$, whereas participants in the $Int_{100}$ group accomplished their training on a flat road with a cadence of 100 rev min$^{-1}$. All training sessions were recorded with SRM power cranks as described above. During the 1st, 4th, and 8th training sessions, blood samples were taken after each bout for the determination of blood lactate concentration.

## Statistical analyzes

Statistical analyzes were performed with the statistical software package PASW Statistics 18 for Mac OS X (SPSS Inc., Chicago, IL). Descriptive data are shown as mean ± standard deviation (SD) and 95% confidence limits (CL). After the assumption of normality was verified using Kolmogorov–Smirnov's test and Liliefors probability, a three-factor mixed ANOVA was used to analyze power output, cadence, heart rate and blood lactate concentration during the time-trials [Group ($Int_{60}$ vs. $Int_{100}$ vs. Con) × time (pre vs. post) × route ($TT_{up}$ vs. $TT_{flat}$)] and to analyze heart rates and blood lactate concentrations measured during the training [Group ($Int_{60}$ vs. $Int_{100}$) × training (1st vs. 4th vs. 8th) × interval (1–6)]. Results from the incremental graded exercise test before and after the intervention, as well as the weekly training time before and during the intervention, were compared with a two-factor mixed ANOVA [Group ($Int_{60}$ vs. $Int_{100}$ vs. Con) × time (pre vs. post)]. Differences between the groups for TRIMP and RPE scores were assessed with a one-way ANOVA. Significant interactions and main effects were identified with a Tukey's HSD post hoc test. Effect sizes are reported as partial Eta-squared ($\eta_P^2$) and considered as small (0.01), moderate (0.1) and large (0.25) effects (Cohen 1988). Relationships between variables were examined with Pearson's product moment correlations. For all statistical analyses, the level of significance was set at $p < 0.05$.

## Results

### Training records

There was no significant difference in training time between the three groups ($F_{2,14} = 2.1$; $p = 0.15$; $\eta_P^2 = 0.23$; Con: 10.4 ± 2.7 h week$^{-1}$; 7.1–13.8; Int$_{100}$: 13.3 ± 2.0 h week$^{-1}$; 11.2–15.4; Int$_{60}$: 12.8 ± 2.8 h week$^{-1}$; 9.8–15.7). There was a small (0.5 ± 0.4 h week$^{-1}$; 0.15–0.86) but significant ($F_{1,14} = 9.1$; $p < 0.01$; $\eta_P^2 = 0.39$) increase in training time during the intervention in comparison to the 12 weeks before the study with no significant group effects ($F_{2,14} = 1.4$; $p = 0.28$; $\eta_P^2 = 0.17$). The mean session RPE scores were significantly higher ($F_{2,14} = 10.1$; $p < 0.01$; $\eta_P^2 = 0.59$) for Int$_{100}$ (13.7 ± 0.6; 13.0–14.3) and Int$_{60}$ (13.7 ± 0.7; 13.1–14.4) than for Con (11.9 ± 1.0; 10.7–13.1). In addition the TRIMP scores were significantly higher ($F_{2,14} = 6.9$; $p < 0.01$; $\eta_P^2 = 0.5$) for Int$_{100}$ (42,812 ± 6,409; 36,086–49,537) and Int$_{60}$ (40,666 ± 7,370; 32,932–48,399) compared to Con (28,119 ± 7,126; 19,271–36,968).

### Incremental graded exercise test

The results of the incremental exercise tests are presented in Table 2. A significant main effect of time was observed for $P_{max}$ ($F_{1,14} = 14.5$; $p < 0.01$; $\eta_P^2 = 0.51$), power output ($F_{1,14} = 4.8$; $p < 0.05$; $\eta_P^2 = 0.26$) and oxygen uptake ($F_{1,14} = 5.3$; $p < 0.05$; $\eta_P^2 = 0.27$) at RCP and for oxygen uptake at VT ($F_{1,14} = 14.1$; $p < 0.01$; $\eta_P^2 = 0.5$). After the training $P_{max}$, power output and $\dot{V}O_2$ at RCP and $\dot{V}O_2$ at VT increased by 2.8 ± 3.0% (1.2–4.4), 3.6 ± 6.3% (0.3–6.8), 4.7 ± 8.2% (0.5–8.9) and 4.9 ± 5.6% (2.2–7.8), respectively. No significant interactions of group x time ($p = 0.48$–$0.77$; $\eta_P^2 = 0.1$–$0.04$) were observed.

### Time-trials

A significant main effect of the route was found on power output ($F_{1,14} = 25.3$; $p < 0.001$; $\eta_P^2 = 0.64$), cadence

**Table 2** Results from the GXT before and after the training intervention (mean ± SD)

| Measure | | Group | | |
|---|---|---|---|---|
| | | Int$_{60}$ | Int$_{100}$ | Con |
| $P_{max}$ (W)* | Pre | 392 ± 21 | 391 ± 57 | 394 ± 31 |
| 95% CL | | 370–414 | 331–451 | 355–433 |
| | Post | 400 ± 16 | 402 ± 61 | 408 ± 34 |
| | | 383–418 | 338–466 | 365–450 |
| $\dot{V}O_{2max}$ (mL min$^{-1}$ kg$^{-1}$) | Pre | 61.1 ± 5.0 | 58.8 ± 6.0 | 55.4 ± 4.3 |
| 95% CL | | 55.9–66.4 | 52.5–65.1 | 50.1–60.7 |
| | Post | 60.8 ± 3.3 | 60.1 ± 7.7 | 57.2 ± 5.2 |
| | | 57.3–64.3 | 52.0–68.1 | 50.7–63.7 |
| RCP (W)* | Pre | 297 ± 11 | 304 ± 55 | 298 ± 36 |
| 95% CL | | 286–308 | 246–361 | 253–342 |
| | Post | 311 ± 21 | 316 ± 59 | 301 ± 37 |
| | | 289–333 | 255–378 | 256–347 |
| RCP (mL min$^{-1}$ kg$^{-1}$)* | Pre | 50.4 ± 4.8 | 48.6 ± 6.3 | 45.2 ± 5.2 |
| 95% CL | | 45.3–55.4 | 41.9–55.2 | 38.7–51.7 |
| | Post | 51.5 ± 5.0 | 51.6 ± 6.6 | 47.2 ± 3.7 |
| | | 46.3–56.8 | 44.7–58.5 | 42.6–51.8 |
| VT (W) | Pre | 190 ± 21 | 199 ± 38 | 187 ± 21 |
| 95% CL | | 168–212 | 160–239 | 160–213 |
| | Post | 198 ± 11 | 200 ± 36 | 187 ± 26 |
| | | 186–209 | 162–238 | 155–219 |
| VT (mL min$^{-1}$ kg$^{-1}$)* | Pre | 35.7 ± 3.1 | 35.3 ± 5.2 | 30.7 ± 3.8 |
| 95% CL | | 32.5–38.9 | 29.9–40.8 | 26.1–35.4 |
| | Post | 37.4 ± 3.6 | 36.4 ± 4.5 | 32.9 ± 3.8 |
| | | 33.6–41.2 | 31.7–41.0 | 28.1–37.6 |

*P* power output, $\dot{V}O_2$ oxygen uptake, *RCP* respiratory compensation point, *VT* ventilatory threshold, *CL* confidence limit

* $p < 0.05$; main effect of time (post > pre)

($F_{1,14} = 651.5$; $p < 0.001$; $\eta^2_P = 0.98$), heart rate ($F_{1,14} = 57.1$; $p < 0.001$; $\eta^2_P = 0.8$) and blood lactate concentration ($F_{1,14} = 17.5$; $p < 0.001$; $\eta^2_P = 0.56$). Power output was significantly higher during uphill time-trials, which was accompanied by significantly higher heart rates and blood lactate concentrations (Table 3). ANOVA revealed a significant main effect of time on heart rate ($F_{1,14} = 8.5$; $p < 0.05$; $\eta^2_P = 0.38$) (post < pre). There were no significant main effects for group ($p = 0.39$–$0.88$; $\eta^2_P = 0.13$–$0.02$).

Significant time × route × group interactions on power output were observed ($F_{2,14} = 6.2$; $p < 0.05$; $\eta^2_P = 0.47$). These indicate that both interval-training groups increased power output after the training during $TT_{flat}$ ($Int_{100}$: 2.6 ± 6.0%; −3.7–8.9 and $Int_{60}$: 1.5 ± 4.5%; −3.2–6.2) in contrast to the control group (−3.5 ± 5.4%; −10.1–3.2). Power output during $TT_{up}$ was increased after the training for $Int_{60}$ (4.4 ± 5.3%; −1.2–9.9) and Con (4.0 ± 4.6%; −1.7–9.8), but not for $Int_{100}$ (−1.3 ± 3.6%; −5.1–2.4). All three groups showed higher power outputs before the intervention during $TT_{up}$ (Con: 3.4 ± 6.6%; −4.8–11.6, $Int_{100}$: 5.4 ± 5.8%; −0.7–11.5 and $Int_{60}$: 4.4 ± 6.7%; −2.7–11.4). Post training the difference to $TT_{flat}$ increased for $Int_{60}$ (7.2 ± 4.9%; 2.0–12.3). In addition, the control group increased the difference between the uphill and the flat time-trial (11.4 ± 4.6%; 5.7–17.1). However, this was the result of both an increase and decrease in power output during $TT_{up}$ and $TT_{flat}$, respectively. Finally, the $Int_{100}$ group reduced the difference between the uphill and the flat time-trial (1.3 ± 2.0%; −0.8–3.4). This was attributed to an increase and decrease in power output during the $TT_{flat}$ and $TT_{up}$ conditions, respectively. The changes in power output during the uphill and the flat time-trials are presented in Fig. 2.

Power outputs during the pre- and post-training uphill time-trials were strongly correlated with $P_{max}$ ($r = 0.92$ and 0.91; $p < 0.001$) and RCP ($r = 0.9$ and 0.85; $p < 0.001$). In addition, the velocities during the pre- and post-training uphill time-trials were strongly correlated with $P_{max}$ ($r = 0.71$ and 0.74; $p < 0.001$), $\dot{V}O_{2\,max}$ ($r = 0.8$ and 0.88; $p < 0.001$), RCP ($r = 0.85$ and 0.72; $p < 0.001$ and 0.01) and $TT_{up}$ power output ($r = 0.71$ and 0.74; $p < 0.01$). For the pre- and post-training flat time-trials, strong correlations between power outputs and $P_{max}$ ($r = 0.86$ and 0.88; $p < 0.001$) and RCP ($r = 0.84$ and 0.88; $p < 0.001$) were observed. The correlations between velocities and performance measures were non-significant or moderate for the pre-training time-trials ($r = 0.36$; $p = 0.14$ for $P_{max}$; $r = 0.38$; $p = 0.14$ for $\dot{V}O_{2\,max}$; $r = 0.53$; $p < 0.05$ for RCP; and $r = 0.52$; $p < 0.05$ for $TT_{flat}$ power output). However, post training these correlations were stronger for $P_{max}$ ($r = 0.76$; $p < 0.001$), $\dot{V}O_{2\,max}$ ($r = 0.76$; $p < 0.001$), RCP ($r = 0.82$; $p < 0.001$) and $TT_{flat}$ power output ($r = 0.79$; $p = 0.001$).

### Interval training

As the assumption of sphericity was violated for the factor interval (Mauchly's test: $\chi^2$ (14) = 71.4; $p < 0.001$), the degrees of freedom were adjusted (Greenhouse-Geisser: ε = 0.26). A significant main effect of interval was

**Table 3** Power output and physiological measures during the time-trials before and after the training intervention (mean ± SD)

| Measure | | Group | | | | | |
|---|---|---|---|---|---|---|---|
| | | $Int_{60}$ | | $Int_{100}$ | | Con | |
| | | $TT_{up}$ | $TT_{flat}$ | $TT_{up}$ | $TT_{flat}$ | $TT_{up}$ | $TT_{flat}$ |
| $P$ (W)* | Pre | 307 ± 14 | 295 ± 15 | 314 ± 47 | 299 ± 48 | 302 ± 29 | 292 ± 18 |
| 95% CL | | 292–322 | 280–310 | 265–363 | 248–349 | 266–339 | 269–315 |
| | Post | 321 ± 20 | 300 ± 25 | 310 ± 49 | 306 ± 49 | 314 ± 26 | 283 ± 30 |
| | | 299–342 | 274–326 | 259–361 | 255–357 | 281–347 | 245–320 |
| HR (b $min^{-1}$)* | Pre | 180 ± 8 | 178 ± 13 | 177 ± 7 | 174 ± 7 | 177 ± 10 | 174 ± 10 |
| 95% CL | | 171–189 | 164–191 | 169–185 | 166–181 | 164–189 | 161–186 |
| | Post | 179 ± 8 | 174 ± 8 | 176 ± 7 | 173 ± 8 | 173 ± 8 | 168 ± 9 |
| | | 171–187 | 165–182 | 168–183 | 164–181 | 163–183 | 157–178 |
| BL (mmol $L^{-1}$)* | Pre | 10.0 ± 2.7 | 9.7 ± 2.5 | 9.2 ± 2.3 | 8.1 ± 2.3 | 9.1 ± 2.7 | 8.4 ± 0.9 |
| 95% CL | | 6.3–13.6 | 7.1–12.2 | 6.8–11.6 | 5.6–10.5 | 5.8–12.5 | 7.3–9.5 |
| | Post | 11.2 ± 2.6 | 9.5 ± 2.8 | 8.9 ± 2.1 | 7.9 ± 2.0 | 10.3 ± 1.6 | 7.6 ± 1.4 |
| | | 8.4–13.9 | 6.6–12.4 | 6.7–11.1 | 5.8–10.0 | 8.4–12.3 | 5.8–9.4 |

*P* power output, *HR* heart rate, *BL* blood lactate concentration

* $p < 0.001$; main effect of route (uphill > flat)

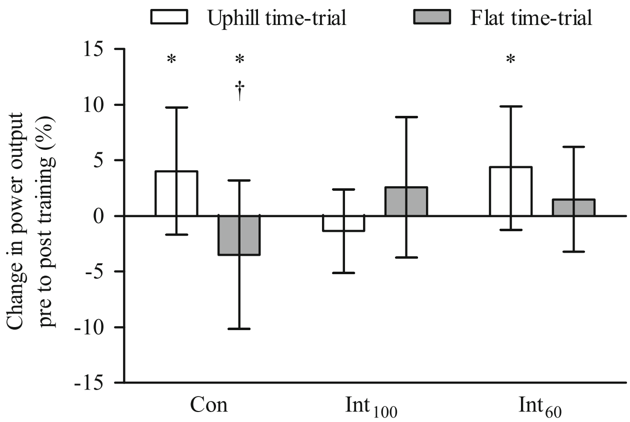



**Fig. 2** Pre- to post-training changes in power output during the uphill and flat time-trials. *Error bars* represents 95% CL. *Significantly different from $Int_{100}$ at $p < 0.05$; †significantly different from $Int_{60}$ at $p < 0.05$

observed for heart rate ($F_{1.3,13.1} = 16.3$; $p < 0.001$; $\eta_P^2 = 0.62$). Heart rate significantly increased during the intervals (Fig. 3). No significant main effect of interval was found for the blood lactate concentration ($F_{1.3,12.7} = 1.1$; $p = 0.36$; $\eta_P^2 = 0.09$) (Fig. 3). In addition, no significant main effects of group ($p = 0.68$–$0.95$; $\eta_P^2 = 0.04$–$0.01$), training ($p = 0.23$–$0.83$; $\eta_P^2 = 0.13$–$0.04$) and interactions of group x training x interval ($p = 0.39$–$0.99$; $\eta_P^2 =$ 0.1–0.01) were observed. The coefficients of variation (CV) of power output and cadence between the training sessions ($n = 8$) were 1.1 ± 0.3 and 1.6 ± 0.3% for $Int_{60}$ and 1.5 ± 0.3 and 1.2 ± 0.2% for $Int_{100}$. Between the intervals ($n = 48$), the CVs of power output and cadence were 1.5 ± 0.6 and 2.4 ± 1.1% vs. 2.4 ± 1.0 and 1.5 ± 0.5% for $Int_{60}$ and $Int_{100}$, respectively.

## Discussion

To the best of our knowledge, this was the first study that investigated the effects of aerobic interval training at different terrains and cadences in the field, on performance during incremental graded exercise tests and time-trials. The new findings indicate that substituting two continuous endurance training sessions per week over 4 weeks with interval training on a level-ground or uphill course, has no additional benefit on performance measures obtained from a GXT in well-trained cyclists. However, the magnitude of changes in power output during uphill and flat time-trials significantly differed between the training groups. This suggests that specific field-tests should be favored to reveal adaptations to a specific training strategy. In addition, it was shown that power output during a 20-min uphill time-trial was higher compared to a flat time-trial.

In the present study, we observed no significant differences in the performance improvements assessed during a GXT between the two interval-training groups and the control group. Although the control group averaged approximately 2 h less training per week than both interval groups, the total training time as well as the increase during the intervention was not significantly different between the groups. The TRIMP and the session RPE scores were significantly higher for the interval groups. This finding indicates the importance of training volume as a main stimulus for endurance athletes (Jobson et al. 2009; Nimmerichter et al. 2011) and that an increase of exercise intensity does not necessarily enhance performance gains. This is in accordance with previous studies that have also shown similar performance gains after short-term sprint interval versus traditional endurance training in active, but untrained subjects (Burgomaster et al. 2008; Gibala et al. 2006).

While several studies have reported the physiological and performance adaptations in response to various interval-training modes, the effects of cadence during such intervals remained to be shown. We are aware of only one study that compared the effects of low cadence (60–70 rev $min^{-1}$) and high cadence (110–120 rev $min^{-1}$) during 30 s sprint interval training on performance (Paton et al. 2009). In the latter study, the performance gains (i.e. $P_{max}$, $\dot{V}O_{2\,max}$ and power output at 4 mmol $L^{-1}$ blood lactate) were higher for the low-cadence group (6–11%) in comparison to the high-cadence group (2–3%), which was attributed to a higher testosterone concentration in response

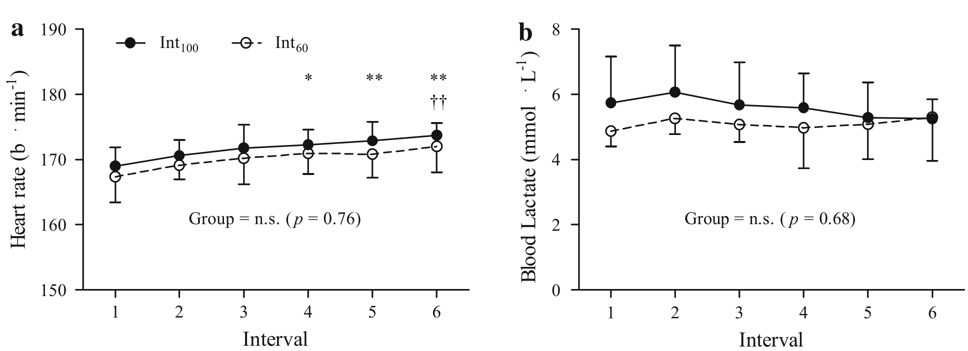



**Fig. 3** Heart rate (**a**) and blood lactate (**b**) profiles during the interval trainings. *Error bars* represents 95% CL. *Significantly different from interval 1 at $p < 0.05$ and **at $p < 0.01$; ††significantly different from interval 2 at $p < 0.01$; *n.s.* not significant

to higher pedal forces in the low-cadence group (Paton et al. 2009).

In contrast to the results of the GXT in the present study, a significant interaction of time × route × group was observed for time-trial power output. According to Bertucci et al. (2005, p 1008), who concluded that *"…it appears necessary to train in specific conditions (uphill road cycling and level ground, low and high cadences) in order to develop these specific muscular adaptations…"*, the two interval-training groups in our study showed higher performance improvements on the terrain where the interval-training sessions were performed ($Int_{100}$: 2.6 ± 6.0 and −1.3 ± 3.6% for $TT_{flat}$ and $TT_{up}$, respectively; $Int_{60}$: 4.4 ± 5.3 and 1.5 ± 4.5% for $TT_{up}$ and $TT_{flat}$, respectively). The magnitude of the improvements and the fact that the $Int_{60}$ group increased power output during both, uphill and flat time-trials supported the results of Paton et al. (2009), that low-cadence interval training is potentially superior to high-cadence intervals. This was emphasized by a longitudinal study of elite cyclists where the training time spent to improve strength (i.e. intervals of 2–20 min at 40–60 rev min$^{-1}$) was strongly correlated with the classification of the riders ($r = -0.86$; $p < 0.01$) and the improvement of 20-min time-trial power output during the season ($r = 0.83$; $p < 0.05$) (Nimmerichter et al. 2011). In addition, the intensity of these intervals was related to 20-min time-trial power output ($r = 0.88$; $p < 0.01$) and $\dot{V}O_{2\,max}$ ($r = 0.89$; $p < 0.01$) (Nimmerichter et al. 2011). Although the underlying mechanisms are not entirely clear, possible explanations are: (1) at any given power output, low cadences require higher forces which (2) increases neuromuscular fatigue, as indicated by an increase of root mean-square EMG in the vastus lateralis and gluteus maximus muscles at high power outputs (i.e. >300 W) (Lucia et al. 2004). To generate and sustain higher forces suggests (3) an additional recruitment of type II fibers which have been shown to be more efficient at higher contraction velocities than type I fibers (Sargeant 1994) and (4) increases in testosterone (Paton et al. 2009) and human growth hormone (Lafortuna et al. 2003) concentrations.

It might be argued that low-cadence training does not comply with observations from recent studies (Lucia et al. 2004; Vercruyssen and Brisswalter 2010) that have shown freely chosen cadences between 90 and 100 rev min$^{-1}$ in trained cyclists at high power outputs. However, we would like to emphasize that a low-cadence strategy during some high-intensity intervals and the associated benefits, is not contrary to a higher freely chosen cadence. Moreover, this observation underpins a basic training principle that taxing a physiological system during exercise is necessary to improve performance. It should be noted that the control group also increased power output during $TT_{up}$ by 4.0 ± 4.6%, but not during $TT_{flat}$ (−3.5 ± 5.4%). Even after revisiting the diaries, we have no explanation for this adaptation in the control group.

This study also showed for the first time, that trained cyclists are able to produce significantly higher power outputs during uphill than flat time-trials of the same duration. This was observed in both the pre- and post-training conditions (4.4 ± 6.0 and 6.4 ± 5.6%, respectively). The higher power outputs were accompanied by higher cardiovascular and metabolic responses and indicate a higher physiological strain during uphill time-trials (Padilla et al. 2000). These results extend a recent study (Nimmerichter et al. 2010) where flat time-trial power output was strongly correlated with GXT measures ($p < 0.001$) and not significantly different from the power output at RCP ($p = 0.97$). The strong correlations between uphill and flat time-trial power outputs and GXT measures observed in the present study are in agreement with previous studies (Balmer et al. 2000; Nimmerichter et al. 2010). The velocities during the uphill time-trials were strongly related to GXT measures and $TT_{up}$ power outputs, whereas the relationships between flat time-trial velocities and performance measures are much more variable (Jobson et al. 2009). This indicates that velocity, especially on flat terrain, is largely influenced by external conditions (e.g. aerodynamics, rolling resistance) and therefore should be used with caution as a performance measure especially in repeated measure study designs.

Finally, the low CVs observed for power output and cadence between 8 training sessions and 48 intervals indicate that the 12 participants completed the required task accurately. This observation shows that well-trained cyclists are able to control both variables within a narrow range despite the fact that nine of our athletes had no prior experience with mobile power meters. The cardiovascular and metabolic response was slightly but not significantly higher for the $Int_{100}$ compared to the $Int_{60}$ training group. This finding is supported by Vercruyssen et al. (2005) who reported significantly lower heart rates and blood lactate concentrations at lower cadences in triathletes, but in contrast to Lucia et al. (2004) who reported the opposite in professional cyclists. It was concluded, that the higher efficiency at a high cadence is one of the main adaptations of professional cyclists (Lucia et al. 2004).

The present study is not without limitations. By design, the study aimed to replicate an outdoor cycling interval-training situation, which is usually completed on a certain route in an out-and-back direction. Consequently, the rest periods between the intervals were longer than in comparable studies with a laboratory set-up (Stepto et al. 2001; Weston et al. 1997). The current study had a limited number of SRM devices and therefore it was not possible to complete the entire study at exactly the same time of the year for all athletes. Data sampling was conducted from May to August in three stages. Although two riders of each group were allocated to the three stages, we cannot eliminate the possibility that a small seasonal performance change may have affected the results (Nimmerichter et al. 2011).

In conclusion, this study has shown that interval training on level-ground or uphill roads, at high or low cadences, leads to similar significant performance gains during a GXT as those, which may be observed after a continuous aerobic endurance training intervention. However, the performance improvements during uphill and flat 20-min time-trials have shown specific adaptations in response to the interval-training sessions and indicate the ecological validity of the time-trials. The magnitude of these improvements suggests that the application of higher pedaling forces via low cadences provides a potentially higher training stimulus with a crossover effect to flat time-trials. High-cadence intervals on level ground are more likely to enhance flat time-trial power output with no crossover to uphill time-trials. When evaluating power output data or prescribing training zones, it is important to note that trained cyclists are able to produce higher power outputs during uphill compared to flat time-trial conditions.

**Acknowledgments** The authors acknowledge the commitment of the participants in this study. This research was not sponsored by any funding body external to the University of Exeter. The authors declare that they have no conflict of interest.

## References


Aughey RJ, Murphy KT, Clark SA, Garnham AP, Snow RJ, Cameron-Smith D, Hawley JA, McKenna MJ (2007) Muscle Na + -K + -ATPase activity and isoform adaptations to intense interval exercise and training in well-trained athletes. J Appl Physiol 103(1):39–47

Balmer J, Davison RC, Bird SR (2000) Peak power predicts performance power during an outdoor 16.1-km cycling time trial. Med Sci Sports Exerc 32(8):1485–1490

Banister EW, Calvert TW (1980) Planning for future performance: implications for long term training. Can J Appl Sport Sci 5(3):170–176

Beaver WL, Wasserman K, Whipp BJ (1986) A new method for detecting anaerobic threshold by gas exchange. J Appl Physiol 60(6):2020–2027

Bertucci W, Grappe F, Girard A, Betik A, Rouillon JD (2005) Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling. J Biomech 38(5):1003–1010

Billat LV (2001) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. Sports Med 31(1):13–31

Borg G (1970) Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med 2(2):92–98

Burgomaster KA, Hughes SC, Heigenhauser GJ, Bradwell SN, Gibala MJ (2005) Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. J Appl Physiol 98(6):1985–1990

Burgomaster KA, Heigenhauser GJ, Gibala MJ (2006) Effect of short-term sprint interval training on human skeletal muscle carbohydrate metabolism during exercise and time-trial performance. J Appl Physiol 100(6):2041–2047

Burgomaster KA, Howarth KR, Phillips SM, Rakobowchuk M, Macdonald MJ, McGee SL, Gibala MJ (2008) Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. J Physiol 586(1):151–160

Cohen J (1988) The concepts of power analysis. In: Statistical power analysis for the behavioural sciences, 2nd edn. Lawrence Erlbaum Associates, Hillsdale, pp 8–14

Duncan GE, Howley ET, Johnson BN (1997) Applicability of $VO_{2max}$ criteria: discontinuous versus continuous protocols. Med Sci Sports Exerc 29(2):273–278

Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P, Dodge C (2001) A new approach to monitoring exercise training. J Strength Cond Res 15(1):109–115

Fregly BJ, Zajac FE, Dairaghi CA (2000) Bicycle drive system dynamics: theory and experimental validation. J Biomech Eng 122(4):446–452

Gellish RL, Goslin BR, Olson RE, McDonald A, Russi GD, Moudgil VK (2007) Longitudinal modeling of the relationship between age and maximal heart rate. Med Sci Sports Exerc 39(5):822–829

Gibala MJ, Little JP, van Essen M, Wilkin GP, Burgomaster KA, Safdar A, Raha S, Tarnopolsky MA (2006) Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. J Physiol 575(3):901–911

Hansen EA, Jorgensen LV, Jensen K, Fregly BJ, Sjogaard G (2002) Crank inertial load affects freely chosen pedal rate during cycling. J Biomech 35(2):277–285

Harriss DJ, Atkinson G (2009) International Journal of Sports Medicine—ethical standards in sport and exercise science research. Int J Sports Med 30(10):701–702

Howley ET, Bassett DR, Welch HG (1995) Criteria for maximal oxygen uptake: review and commentary. Med Sci Sports Exerc 27(9):1292–1301

Jobson SA, Nevill AM, George SR, Jeukendrup AE, Passfield L (2008a) Influence of body position when considering the ecological validity of laboratory time-trial cycling performance. J Sports Sci 26(12):1269–1278

Jobson SA, Woodside J, Passfield L, Nevill AM (2008b) Allometric scaling of uphill cycling performance. Int J Sports Med 29(9):753–757

Jobson SA, Passfield L, Atkinson G, Barton G, Scarf P (2009) The analysis and utilization of cycling training data. Sports Med 39(10):833–844

Kuipers H, Verstappen FT, Keizer HA, Geurten P, van Kranenburg G (1985) Variability of aerobic performance in the laboratory and its physiologic correlates. Int J Sports Med 6(4):197–201

Lafortuna CL, Marinone PG, Ottolini S, Sartorio A (2003) GH responses to a near-maximal exercise training session on-the-field in cyclists. J Endocrinol Invest 26(8):12–14

Lindsay FH, Hawley JA, Myburgh KH, Schomer HH, Noakes TD, Dennis SC (1996) Improved athletic performance in highly trained cyclists after interval training. Med Sci Sports Exerc 28(11):1427–1434

Lucia A, Hoyos J, Chicharro JL (2001) Preferred pedalling cadence in professional cycling. Med Sci Sports Exerc 33(8):1361–1366

Lucia A, San Juan AF, Montilla M, CaNete S, Santalla A, Earnest C, Pérez M (2004) In professional road cyclists, low pedaling cadences are less efficient. Med Sci Sports Exerc 36(6):1048–1054

Nimmerichter A, Williams C, Bachl N, Eston R (2010) Evaluation of a field test to assess performance in elite cyclists. Int J Sports Med 31(3):160–166

Nimmerichter A, Eston R, Bachl N, Williams C (2011) Longitudinal monitoring of power output and heart rate profiles in elite cyclists. J Sports Sci (in press)

Padilla S, Mujika I, Orbananos J, Angulo F (2000) Exercise intensity during competition time trials in professional road cycling. Med Sci Sports Exerc 32(4):850–856

Paton CD, Hopkins WG, Cook C (2009) Effects of low- vs. high-cadence interval training on cycling performance. J Strength Cond Res 23(6):1758–1763

Sargeant AJ (1994) Human power output and muscle fatigue. Int J Sports Med 15(3):116–121

Stepto NK, Hawley JA, Dennis SC, Hopkins WG (1999) Effects of different interval-training programs on cycling time-trial performance. Med Sci Sports Exerc 31(5):736–741

Stepto NK, Martin DT, Fallon KE, Hawley JA (2001) Metabolic demands of intense aerobic interval training in competitive cyclists. Med Sci Sports Exerc 33(2):303–310

Taylor HL, Buskirk E, Henschel A (1955) Maximal oxygen intake as an objective measure of cardio-respiratory performance. J Appl Physiol 8(1):73–80

Vercruyssen F, Brisswalter J (2010) Which factors determine the freely chosen cadence during submaximal cycling? J Sci Med Sport 13(2):225–231

Vercruyssen F, Suriano R, Bishop D, Hausswirth C, Brisswalter J (2005) Cadence selection affects metabolic responses during cycling and subsequent running time to fatigue. Br J Sports Med 39(5):267–272

Wasserman K, Hansen JE, Sue DY, Casaburi R, Whipp BJ (1999) Physiology of exercise. In: Principles of exercise testing and interpretation, 3rd edn. Lippincott Williams & Wilkins, Philadelphia, pp 30–32

Westgarth-Taylor C, Hawley JA, Rickard S, Myburgh KH, Noakes TD, Dennis SC (1997) Metabolic and performance adaptations to interval training in endurance-trained cyclists. Eur J Appl Physiol Occup Physiol 75(4):298–304

Weston AR, Myburgh KH, Lindsay FH, Dennis SC, Noakes TD, Hawley JA (1997) Skeletal muscle buffering capacity and endurance performance after high-intensity interval training by well-trained cyclists. Eur J Appl Physiol Occup Physiol 75(1):7–13

Wooles A, Robinson A, Keen P (2005) A static method for obtaining a calibration factor for SRM bicycle power cranks. Sports Eng 8(3):137–144