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ORIGINAL ARTICLE

Influence of road incline and body position on power–cadence relationship in endurance cycling

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Abstract In race cycling, the external power–cadence relationship at the performance level, that is sustainable for the given race distance, plays a key role. The two variables of interest from this relationship are the maximal external power output ($P_{\max}$) and the corresponding optimal cadence (C_{opt}). Experimental studies and field observations of cyclists have revealed that when cycling uphill is compared to cycling on level ground, the freely chosen cadence is lower and a more upright body position seems to be advantageous. To date, no study has addressed whether $P_{\max}$ or C_{opt} is influenced by road incline or body position. Thus, the main aim of this study was to examine the effect of road incline (0 vs. 7%) and racing position (upright posture vs. dropped posture) on $P_{\max}$ and C_{opt}. Eighteen experienced cyclists participated in this study. Experiment I tested the hypothesis that road incline influenced $P_{\max}$ and C_{opt} at the second ventilatory threshold ($P_{\max}^{\mathrm{VT}_2}$ and $C_{\mathrm{opt}}^{\mathrm{VT}_2}$). Experiment II tested the hypothesis that the racing position influenced $P_{\max}^{\mathrm{VT}_2}$, but not $C_{\mathrm{opt}}^{\mathrm{VT}_2}$. The results of experiment I showed that $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ and $P_{\max}^{\mathrm{VT}_2}$ were significantly lower when cycling uphill compared to cycling on level ground ($P < 0.01$). Experiment II revealed that $P_{\max}^{\mathrm{VT}_2}$ was significantly greater for the upright posture than for the dropped posture ($P < 0.01$) and that the racing position did not affect $C_{\mathrm{opt}}^{\mathrm{VT}_2}$. The main conclusions of this study were that when cycling uphill, it is reasonable to choose (1) a lower cadence and (2) a more upright body position.

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Introduction

It is well known that cyclists choose a lower cadence when cycling uphill compared to cycling on level ground even if they had gear ratios available to hold the same cadence as during cycling on level ground (Hansen et al. 2002; Lucia et al. 2001; Rodriguez-Marroyo et al. 2008; Sassi et al. 2009; Vogt et al. 2008). In those studies, different conjectures were proposed to explain this phenomenon. Hansen et al. (2002), for example, speculated that cyclists may increase the cadence on level ground to compensate for the higher peak crank torque that accompanies cycling with high compared to low crank inertial load (CIL). However, currently, it is unknown whether the lower cadence chosen when cycling uphill is advantageous from a performance-related point of view.

In race cycling, a major aim is to maximize the cycling speed sustainable for a given distance. This cycling speed is influenced by a variety of physiological, biomechanical, mechanical, and environmental factors (Atkinson et al. 2003; Faria et al. 2005a, b; Jeukendrup and Martin 2001). The two main factors influencing cycling speed are: the external power output of the cyclist (P_{ext}) and the resistive forces acting on the bicycle (Fig. 1). The resistive forces are caused mainly by aerodynamic drag, grade resistance, rolling resistances, and bearing resistances. The factors influencing the resistive forces are called external factors, whereas internal factors are defined as factors influencing P_{ext}. Most of these internal and external factors that influence the cycling performance are given at the

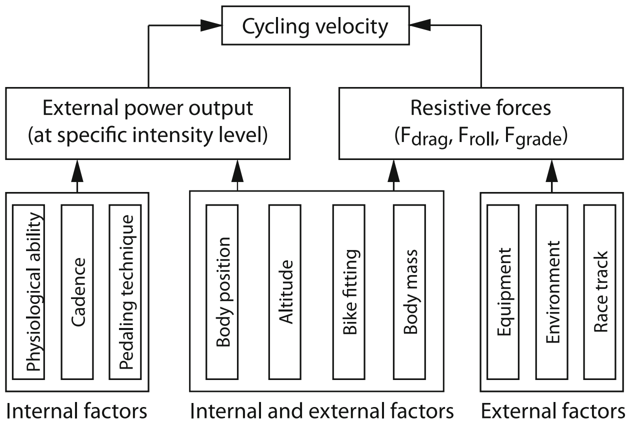

Fig. 1 Diagram showing various factors that can influence cycling velocity. The factors influencing external power output are called internal factors. The factors influencing the resistive forces are called external factors. Some factors act both as internal and as external factor

beginning of a race and cannot be altered during a race, but two parameters that the cyclist can adjust during a race are cadence and body position.

The influence of cadence on P_{ext} for endurance cycling was analyzed in a previous study (Emanuele and Denoth 2011), which reported a quadratic P_{ext}–cadence relationship at different endurance performance levels. The two variables of interest from P_{ext}–cadence relationships are the maximal power output at the specific performance level (P_{max}) and the corresponding optimal cadence (C_{opt}) (Fig. 2). P_{max} is defined as the apex of the P_{ext}–cadence relationship at a specific performance level and C_{opt} is defined as the specific value at which P_{max} occurs (Dorel et al. 2005, 2010; Emanuele and Denoth 2011; Hintzy et al. 1999; Martin et al. 1997). It is clear that the longer the given race distance, the lower the sustainable P_{max}, respectively, the sustainable performance level will be (di Prampero 2003; Ferretti et al. 2011). Thus, P_{max} in a short-term sprint cycling performance is by a multiple greater than P_{max} in an endurance cycling performance. Concurrently C_{opt} is also increasing with increasing P_{max} (Kohler and Boutellier 2005; MacIntosh et al. 2000). Furthermore P_{max} and C_{opt} are depending on several internal factors influencing the P_{ext}–cadence relationships. It has been shown that crank length (Martin and Spirduso 2001), fiber type composition of the cyclist (Hautier et al. 1996), muscle temperature (Sargeant 1987), and fatigue (MacIntosh et al. 2004; MacIntosh and Fletcher 2011) influence P_{max} and C_{opt} in short-term sprint cycling. To our knowledge, no study has compared the P_{ext}–cadence relationship, P_{max}, and C_{opt} at any performance level between cycling on level ground and cycling uphill. Therefore, the assumption that C_{opt} is lower when cycling uphill compared to cycling on level ground lacks the support of scientific evidence.

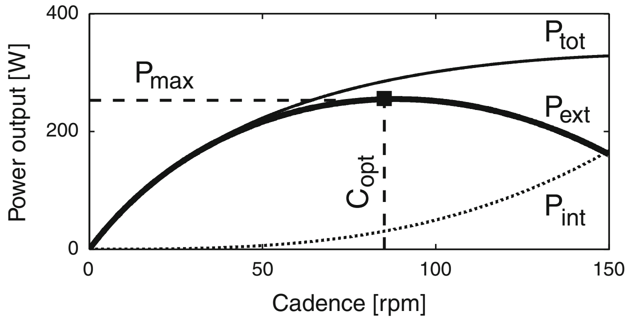

Fig. 2 The power–cadence relationships simulated with the cycling model described in Emanuele and Denoth (2011). The total muscular power output (P_{tot}) is represented by the *thin solid line*. The internal power output (P_{int}) is shown by the *dotted line*. The difference in these two curves defines the power–cadence relationship of the mechanical external power output (P_{ext}; *thick solid line*). P_{max} is identified as the apex of the P_{ext}–cadence relationship and C_{opt} corresponds to the specific value at which P_{max} occurs

In field observations it can be noted that the cyclists not only decrease their freely chosen cadence (FCC) when cycling uphill, but often also adopt a more upright body position when cycling uphill. Body position acts both as an external factor and an internal factor. As an external factor, body position affects the drag area (Jeukendrup and Martin 2001). From this point of view, an upright posture is clearly detrimental. On the other hand, as an internal factor, body position can influence the P_{ext}–cadence relationship by altering the power-generating capacity of some muscles. Some studies have suggested that more power can be produced with a more upright body position (Ashe et al. 2003; Grappe et al. 1998; Jobson et al. 2008; Welbergen and Clijsen 1990), but no study has addressed whether the influence of body position on P_{ext} was independent of the used cadence. To really compare P_{max} between two conditions, the P_{ext}–cadence relationship at the specific performance level has to be analyzed. This was also stated by Martin and Spirduso (2001) who determined the influence of crank length on maximal power output in sprint cycling: “In contrast, in the present investigation, the inertial load method was used to determine the apex of the power/pedaling rate relationship, and thus, our values truly represent maximum cycling power for each crank length.” To the best of our knowledge, the effect of body position on P_{max} and C_{opt} at any performance level has not been analyzed.

The main aim of the present study was to compare the P_{ext}–cadence relationships in an upright posture between cycling on level ground (0% slope) and cycling uphill (7% slope). 7% road inclination corresponds to the mean gradient of several high mountain ascents during Giro d’Italia, Tour de France, and Vuelta a España (Lucia et al. 2001; Rodriguez-Marroyo et al. 2008; Vogt et al. 2008). Our main hypothesis (experiment I) was that road incline would influence both $P_{\max}$ and C_{opt} at VT_2 ($P_{\max}^{\mathrm{VT}_2}$ and $C_{\mathrm{opt}}^{\mathrm{VT}_2}$, respectively). The second aim of the present study (experiment II) was to compare the P_{ext}–cadence relationship between cycling in an upright posture (hands on the top portion of the handlebars and arms fully extended) and cycling in a dropped posture (hands on the lower parts of the handlebars and arms fully extended). The hypothesis for this experiment was that racing position would influence $P_{\max}^{\mathrm{VT}_2}$, but not $C_{\mathrm{opt}}^{\mathrm{VT}_2}$. These hypotheses were tested in an experimental approach based on the method to determine the P_{ext}–cadence relationship introduced in a previous study (Emanuele and Denoth 2011).

Methods

Subjects

Eighteen well-trained male amateur cyclists that competed at the national level volunteered to participate in this study. The mean (±standard deviation, SD) age, height, and weight were 30 ± 5 years, 180.7 ± 4.7 cm, and 74.2 ± 6.8 kg, respectively. Twelve cyclists participated in experiment I and six in experiment II. Before giving written consent to participate, each participant was informed of the nature of the study and the possible risk and discomfort associated with the experimental procedures. The ethical committee of ETH Zurich approved the study experimental design (no. 2008-49 and no. 2009-44).

Experiment I

Subjects cycled on a treadmill for four test sessions. In two sessions, they were cycling on level ground (0% road incline) and in two sessions they were cycling uphill (7% road incline). All tests were carried out in the same body position (upright posture): hands on the top portion of the handlebars and arms fully extended.

Experimental design

The subjects were asked to attend the four test sessions within a 4-week period with at least 2 days between single test days. To improve the reliability of the ventilatory measurements, participants were requested to control a number of variables. They were instructed to consume a normal diet during the 48 h prior to each test session; to refrain from ingestion of caffeine for at least 4 h prior to testing; to perform workouts of similar duration and intensity on the day prior to each session; and to not perform prior exercise on the test days. To minimize variation due to circadian rhythms, each test session was conducted at the same time of day. Each test session consisted of four parts, during which, heart rate (HR), oxygen uptake ($\dot{V}\mathrm{O}_2$), carbon dioxide output ($\dot{V}\mathrm{CO}_2$), minute ventilation ($\dot{V}_{\mathrm{E}}$), and breathing frequency (BF) were continuously recorded. The first and third test sessions consisted of the following parts: (1) 3-min rest on the bicycle; (2) unloaded cycling; (3) cycling at constant power outputs; and (4) a ramp exercise test at FCC. The second and fourth test sessions consisted of the following parts: (1) 3-min rest on the bicycle; (2) unloaded cycling; (3) a first ramp exercise test at either FCC−10 rpm or at FCC + 10 rpm; and (4) a second ramp exercise test at either FCC + 10 rpm or at FCC−10 rpm. The three ramp exercise tests were performed at three different cadences to determine the P_{ext}–cadence relationships at VT_2 and assess $P_{\max}^{\mathrm{VT}_2}$ and $C_{\mathrm{opt}}^{\mathrm{VT}_2}$. The other tests were a part of our test session, but the results are not presented in this paper.

The ramp exercise tests started at 100 W and increased linearly at a rate of 0.14 W s^{-1}. On the first and third test days, the ramp exercise test was performed until volitional fatigue of the subject. On the second and fourth test days, the ramp exercise tests were performed until the test was terminated by the tester. The test was terminated 3 min after a clear second ventilatory threshold was observed by the tester in the real-time display of ventilatory parameters. After cessation of the first ramp test, subjects completed a cool down for 10 min at 100 W, followed by a resting period of 30 min before the second ramp test was performed at a different cadence.

For each ramp exercise test, the ventilatory data were analyzed to determine the first and second ventilatory thresholds (VT_1 and VT_2, respectively) by identifying deflection points in the $\dot{V}_{\mathrm{E}}$, $\dot{V}_{\mathrm{E}}/\dot{V}\mathrm{O}_2$, and $\dot{V}_{\mathrm{E}}/\dot{V}\mathrm{CO}_2$ (Wasserman et al. 1973). Each of these three variables was plotted against the power output, and a computerized linear regression analysis was used to fit each plot with three components. The intersection of the second and third regression lines gave the VT_2 (Beaver et al. 1986). For each road incline condition, the power outputs at VT_2 were then plotted against the cadences used. A quadratic regression that was constrained to pass through the origin was then fitted to the plot to assess $P_{\max}^{\mathrm{VT}_2}$ and $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ (Emanuele and Denoth 2011).

Equipment

A standard racing bicycle was used in the experiments. The bicycle was adjusted for each subject so that the vertical and horizontal positions of the saddle and the handlebars that were related to the crank axis matched each subject's own bicycle. The standard racing bicycle was equipped with a professional (8 strain gages) SRM PowerMeter

(Schoberer Rad Messtechnik, Jülich, Germany) and mounted on a treadmill (Woodway, Weil am Rhein, Germany). Level ground cycling was performed at 30 km h^{-1}, and uphill cycling was performed at 15 km h^{-1}. On the treadmill, the fork of the bicycle was fixed to a sliding carriage, which allowed a horizontal bicycle translation relative to the laboratory. The power output was adjusted by changing the mass of a weight magazine. This magazine was connected to a wire that ran over a pulley placed behind the treadmill and was then tied to the back of the bicycle (Coleman et al. 2007; Hansen et al. 2002). During the tests, the ventilatory variables were continuously recorded with the Oxycon Mobile system (Viasys Healthcare, Höchberg, Germany). Prior to each test session, the gas concentration and flow were calibrated according to the manufacturer's specifications.

Experiment II

Subjects cycled on an ergometer for four test sessions. In two sessions, they were cycling in an upright posture with the hands on the top portion of the handlebars and arms fully extended. In the other two sessions, they were cycling in a dropped posture with hands on the lower portion of the handlebars and arms fully extended.

Experimental design

The experimental design was the same as the design used in experiment I, with the following modifications. All four of the test sessions consisted of the following four parts: (1) measurement of resting values; (2) unloaded cycling; (3) a first incremental exercise test; and (4) a second incremental exercise test. The four tested cadences were: 70, 80, 90, and 100 rpm. The incremental exercise tests were started at 100 W with an increase of 25 W every 3 min, until the subject indicated that he would not be able to finish the next higher stage.

For each incremental exercise test, the VT_2 was determined with a semi-computerized analysis. The ventilatory parameters, $\dot{V}_\mathrm{E}$, $\dot{V}_\mathrm{E}/\dot{V}\mathrm{O}_2$, and $\dot{V}_\mathrm{E}/\dot{V}\mathrm{CO}_2$ were averaged over the last 1 min of each bout and then plotted against power output. These plots were fitted with two linear regressions, and the intercept of the two lines represented VT_2 (Beaver et al. 1986). The first regression line was fit to the data from 100 W to the visually identified deflection point in the data. The second regression line was fit to the remaining data. For each body position, the power outputs at VT_2 were then plotted against the cadences used, and a quadratic regression that was constrained to pass through the origin was then fitted to assess the $P_{\max}^{\mathrm{VT}_2}$ and $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ (Emanuele and Denoth 2011).

Equipment

An electronically braked cycle ergometer (ergo bike, Daum Electronic, Fürth, Germany) was used for the incremental exercise tests. Ventilatory variables were continuously recorded with the Oxycon Mobile system (Viasys Healthcare, Höchberg, Germany). Prior to each test session, the gas concentration and flow were calibrated according to the manufacturer's specifications.

Statistics

All statistical analyses were performed with SPSS Statistics 17 (SPSS Inc., Chicago, USA). The level of significance was set at $P < 0.05$. Regression lines were fitted to data with the least-squares method. The power output and cadence measured for each subject were normalized to their estimated individual $P_{\max}^{\mathrm{VT}_2}$ and corresponding individual $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ to assess the validity of the quadratic regression constrained to pass through the origin. The residuals of the quadratic fit were normalized to the corresponding fitted power outputs and analyzed in a modified Bland–Altman plot (Gardner et al. 2007). The SD of these residuals (residual SD) was calculated to estimate the variability (coefficient of variation, CV) in the determination of single threshold power outputs. The precision (CV) for assessing individual $P_{\max}^{\mathrm{VT}_2}$ and $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ was calculated with the model-based residual bootstrapping method for regression, based on the estimated CV for the determination of single threshold power outputs. All parameter values were compared between the two road inclines and the two body positions with the student's *t* test. Variables were summarized with descriptive statistics (mean ± SD).

Results

Experiment I

Power output and cadence from all subjects normalized to their estimated individual $P_{\max}^{\mathrm{VT}_2}$ and corresponding individual $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ were well fitted by a quadratic regression constrained to pass through the origin ($R^2 = 0.91$; $P < 0.001$; Fig. 3a). The normalized residuals were displayed in the modified Bland–Altman plot (Fig. 3b). The residual SD was 0.3% and the estimated CV for single threshold power outputs was 0.5%. The residual bootstrap based on this CV yielded a precision (CV) for assessing individual $P_{\max}^{\mathrm{VT}_2}$ and $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ of 0.5 and 1.5%, respectively.

The assessed individual $P_{\max}^{\mathrm{VT}_2}$ in the upright posture was significantly higher ($P < 0.05$) for level ground cycling

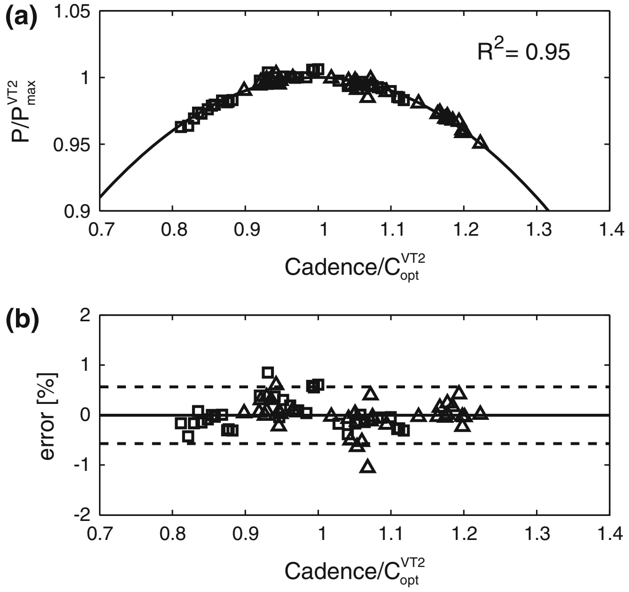

Fig. 3 **a** Power output at the second ventilatory threshold (VT_2) in relation to cadence for level ground and uphill cycling. Power outputs at VT_2 for the three tested cadences (FCC−10 rpm, FCC, and FCC + 10 rpm) were measured for all subjects while cycling on level ground (*open squares*) and uphill (*open triangles*). Power outputs and cadences from each subject were normalized relative to their estimated individual maximal power output at VT_2 ($P_{max}^{VT_2}$) and individual optimal cadence ($C_{opt}^{VT_2}$) for each corresponding road condition. The quadratic regression was constrained to pass through the origin ($R_2 = 0.95$; $P < 0.001$). **b** Modified Bland–Altman plot of the normalized residuals (error %) of the quadratic power–cadence fit. Data for uphill cycling (*open triangles*) and cycling on level ground (*open squares*) are shown. The *solid line* represents the mean error % (0.0%). The *dashed lines* indicate the 95% limits of agreement (0.0 ± 0.6%)

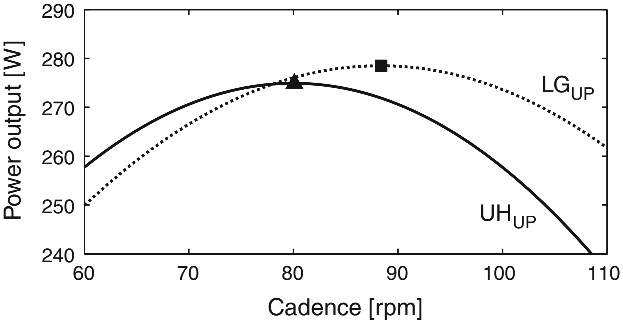

Fig. 4 The power–cadence relationships for level ground cycling and for uphill cycling. The maximal power outputs at second ventilatory threshold and the corresponding optimal cadences are shown for cycling on level ground in the upright body position (*filled square*) and for cycling uphill in the upright body position (*filled triangle*). The corresponding second-order polynomial regressions for cycling on level ground (LG_{UP}; *dotted line*) and for cycling uphill (UH_{UP}; *solid line*) were fitted to the data points

(278.5 ± 34.4 W) than for uphill cycling (274.9 ± 32.5 W) (Fig. 4). $P_{max}^{VT_2}$ for cycling on level ground was 1.2 ± 1.3% higher than that for cycling uphill. The corresponding individual $C_{opt}^{VT_2}$ was also significantly higher ($P < 0.01$) for level ground cycling (88.3 ± 2.3 rpm) than for uphill cycling (80.3 ± 1.4 rpm). $C_{opt}^{VT_2}$ for cycling on level ground was 9.0 ± 2.7% higher than that for cycling uphill.

Experiment II

As in experiment I power output and cadence from all subjects normalized to their estimated individual $P_{max}^{VT_2}$ and corresponding individual $C_{opt}^{VT_2}$ were well fitted by a quadratic regression constrained to pass through the origin ($R^2 = 0.9$; $P < 0.001$; Fig. 5a). The normalized residuals were displayed in the modified Bland–Altman plot (Fig. 5b). The residual SD was 1.0% and the estimated CV for single threshold power outputs was 1.4%. The residual bootstrap based on this CV yielded a precision (CV) for assessing individual $P_{max}^{VT_2}$ and $C_{opt}^{VT_2}$ of 0.9 and 2.2%, respectively.

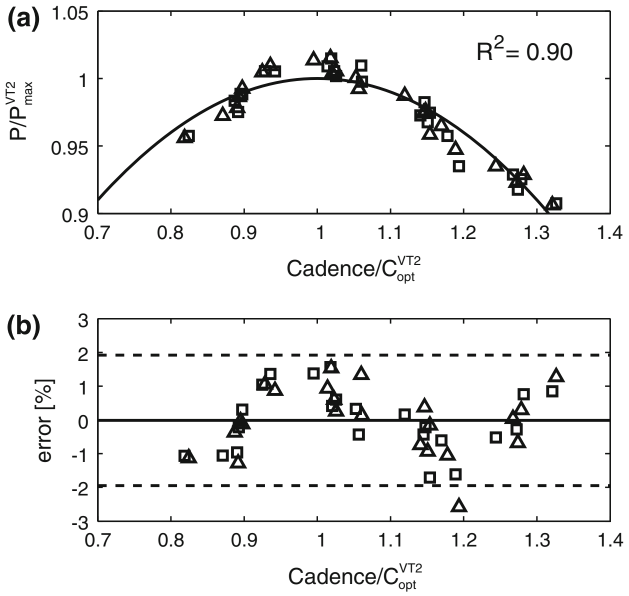

Fig. 5 **a** Power output at second ventilatory threshold (VT_2) in relation to cadence for the upright and the dropped body position. Power outputs at VT_2 for the four tested cadences (70, 80, 90, and 100 rpm) were measured for all subjects while cycling in the upright posture (*open triangles*) and in the dropped posture (*open squares*). Power outputs at VT_2 and cadences from each subject were normalized relative to their estimated individual maximal power output at VT_2 ($P_{max}^{VT_2}$) and individual optimal cadence ($C_{opt}^{VT_2}$) for each corresponding body position. The quadratic regression was constrained to pass through the origin ($R^2 = 0.90$; $P < 0.001$). (**b**) Modified Bland–Altman plots of the normalized residuals (error %) of the quadratic power–cadence fit. Data are shown for the upright posture (*open triangles*) and for the dropped posture (*open squares*). The *solid line* represents the mean error % (0.0%). The *dashed lines* indicate the 95% limits of agreement (0.0 ± 1.9%)

The assessed individual $P_{\max}^{\mathrm{VT}_2}$ was significantly higher ($P < 0.01$) for the upright posture (262 ± 25 W) than for the dropped posture (255 ± 24 W). The $P_{\max}^{\mathrm{VT}_2}$ in the upright posture was 2.6 ± 1.4% higher than that for the dropped posture. The corresponding individual $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ was not different between the two body positions (79.0 ± 3.2 and 79.4 ± 3.3 rpm for upright and dropped postures, respectively).

Discussion

Taken together, the results of experiment I and experiment II suggest, that from a performance-related point of view under real cycling conditions it is advantageous to use (1) a lower cadence and (2) a more upright body position when cycling uphill compared to cycling on level ground. Thus, under real cycling conditions C_{opt} and $P_{\max}$ have to be compared between uphill cycling in the upright posture and level ground cycling in the dropped posture. The results of this study led to the conclusion that $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ is lower and $P_{\max}^{\mathrm{VT}_2}$ is higher for uphill cycling in the upright posture compared to level ground cycling in the dropped posture (Fig. 6). The reason for the lower $C_{\mathrm{opt}}^{\mathrm{VT}_2}$ during uphill cycling is the increased energy dissipation, which is also called internal power output (Emanuele and Denoth 2011). The reduction of aerodynamic drag as a consequence of the lower cycling speed allows to use a more upright body position, which is more powerful. The detailed mechanisms of the mentioned factors are discussed below. Beyond which slope inclination of the road, the upright position is more advantageous than the dropped position for obtaining maximal cycling speed depends on body mass, effective frontal area, and external power outputs. Furthermore, in real cycling conditions the cyclist can not only chose between two different positions of the upper body but can also adopt lots of different upper body positions. The best position to reach maximal cycling speed at a given road inclination is an individual characteristic depending on body mass, effective frontal area, and external power outputs. The results of the present study suggest that for the normally used range of body positions, the steeper the road incline the more upright the best body position should be.

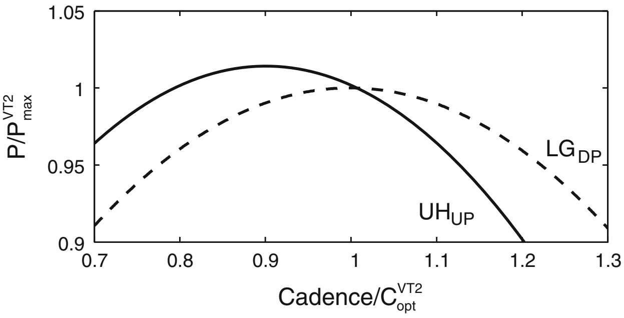

Fig. 6 The power–cadence relationships at the second ventilatory threshold (VT_2) for level ground cycling and for uphill cycling. Relationships are shown for level ground cycling in the dropped posture ($\mathrm{LG_{DP}}$; *dashed line*) and uphill cycling in the upright posture ($\mathrm{UH_{UP}}$; *solid line*). These power outputs at VT_2 and cadences were normalized relative to the maximal power output at VT_2 ($P_{\max}^{\mathrm{VT}_2}$) and the corresponding optimal cadence ($C_{\mathrm{opt}}^{\mathrm{VT}_2}$) for level ground cycling in the dropped posture ($\mathrm{LG_{DP}}$)

Influence of road incline

So far scientific evidence from experimental or theoretical studies, that road incline affects $P_{\max}$ and/or C_{opt} at any performance level, has not been provided. This is the first study to show that from a performance-related point of view it is advantageous to decrease the cadence during uphill cycling.

The lower C_{opt} observed when cycling uphill may be explained by two mechanisms involving the oscillations in crank angular velocity within a single crank cycle. These oscillations are much more pronounced when cycling uphill compared to cycling on level ground, due to the different CIL (Emanuele and Denoth 2008; Emanuele et al. 2011b); CIL is a function of the static and rotating masses of bicycle + rider times the square of the gear ratio (Fregly et al. 1996; Hansen et al. 2002). The magnitude of these oscillations affects the internal mechanical power output (P_{int}) and the total muscular power output (P_{tot}) produced at a constant mean cadence.

With increased oscillations, the sinusoidal changes of the joint angular velocities and of the body segments accelerations are affected. The change of these intracyclic patterns in turn could influence the P_{int}–cadence relationship. P_{int} includes mainly three parts: (1) dissipation of kinetic energy of wobbling masses (kinetic part); (2) power output needed against the frictional/viscous resistance of joint cartilage, ligaments, and other extramuscular structures of the joints (viscous part); and (3) the concomitant agonist–antagonist activation (coordination part). The studies, which calculated P_{int} based on kinematic or metabolic measurements reported that P_{int} increases significantly as a power function of the velocities (Bonjour et al. 2010; Foss and Hallen 2004; Francescato et al. 1995; Hansen et al. 2004; Minetti et al. 2001, 2011). Thus, from a theoretical point of view each of the three parts of P_{int} could be significantly affected by the changed intracyclic pattern as discussed in Francescato et al. (1995). As mentioned in Emanuele and Denoth (2011) the P_{int}–cadence relationship is an important factor determining the P_{ext}–cadence relationship. The consequence of the changed P_{int}–cadence relationship could be a decreased $P_{\max}$ and

C_{opt} of the P_{ext}–cadence relationship. This hypothesis is supported by the lower $P_{max}^{VT_2}$ that corresponded to the lower $C_{opt}^{VT_2}$ observed in experiment I of this study.

The increased oscillations in crank angular velocity affect also the sinusoidal changes of the velocity of contraction of the single muscles within a single crank revolution. The change of these intracyclic velocity patterns in turn influences the P_{tot}–cadence relationship (Emanuele and Denoth 2011). The consequence is a further slight reduction of C_{opt}.

Recently, Sassi et al. (2009) and Leirdal and Ettema (2009) showed that cycling speed significantly affected FCC. In both studies it was surmised that CIL played a key role in modulating FCC. Taken together, the past and present studies suggest that both FCC and C_{opt} are affected by CIL or rather cycling speed. On the other hand some theoretical studies based on the force–velocity relationship of the muscles (Kohler and Boutellier 2005; MacIntosh et al. 2000; Sargeant 1994) were not able to explain the lower C_{opt} or FCC at any given performance level with decreasing CIL or rather with decreasing cycling speed. These models are too simplistic to simulate the influence of road incline or rather cycling speed on C_{opt}. Thus a more complex cycling model has to be considered to explain the influence of road incline on C_{opt}. Two important factors that have to be included in such a cycling model are the oscillations in crank angular velocity within a single crank cycle and P_{int}.

Influence of body position

The results of the $P_{max}^{VT_2}$ and $C_{opt}^{VT_2}$ determinations showed that the increased power output for the upright posture was independent of the selected cadence within the commonly used range of 70–100 rpm. $P_{max}^{VT_2}$ was significantly greater for the upright posture than for the dropped posture. $C_{opt}^{VT_2}$ seemed to be unaffected by the tested change in body position. These results supported those of Jobson et al. (2008), who reported a significant increase in power output with a more upright position in a time trial. The mean power output in those time trials was 266 W in the upright position versus 251 W in the aerodynamic position. The greater difference in power output observed in that study compared to the present study could be explained by the fact that they used a greater difference in body positions. The FCC in that study was nearly identical for the two analyzed positions (91.7 vs. 89.4 rpm). Assuming that the cyclists freely chose a cadence near the optimal cadence, it could be concluded that the C_{opt} in that study would not have differed between the two analyzed body positions.

The higher $P_{max}^{VT_2}$ observed when cycling in the upright posture may be explained by changes in the operating region on the force–length relationship for the hip muscles, or rather for the sarcomeres of the hip muscles (Emanuele et al. 2011a). This has been hypothesized also in past studies analyzing the effect of body position on power output and/or on metabolic variables (Gnehm et al. 1997; Jobson et al. 2008). This assumption is based on the well-known force–length relationship of muscles with a force maximum at an intermediary length of about 1.05 times the "rest length." In conceptual work, different authors have demonstrated that the force of the contractile element is a product relationship between the two phenomena of force–length and force–velocity (Abbott and Wilkie 1953; Bahler 1968; Winters 1990). The altered operating region on the sarcomere force–length relationship caused by the change in body position should not affect the optimal shortening velocity of the fibers (Edman 1979) because, as noted above, the force of the fiber is a product relationship between its force–length and force–velocity relationships. Furthermore, the sliding filament theory underlying Huxley's muscle model (Huxley 1957) also postulates, that the shortening velocity at zero load and the optimal shortening velocity are independent of the number of myosin cross bridges that are able to interact with the thin filament. Thus, if we look at the muscular level, the gain in power output resulting from the altered operation region on the sarcomere force–length relationship should not affect $C_{opt}^{VT_2}$, which is in agreement with our experimentally assessed $C_{opt}^{VT_2}$.

Conclusion

The results of this study showed that the external power–cadence relationship at a performance level corresponding to the second ventilatory threshold was influenced by road incline and body position.

The two variables of interest from this relationship, the maximal external power output and the corresponding optimal cadence were significantly lower during uphill cycling (7% slope) compared to cycling on level ground in the same body position. The observed larger oscillations caused by the lower CIL during uphill cycling lead to a reduction of the maximal external power output and of the corresponding optimal cadence by increasing the dissipation of energy. These results are the first to provide a scientific basis for the decreased cadence during uphill cycling reported in field observations of cyclists.

The change in body position from a dropped posture to an upright posture significantly increased the maximal external power output without an effect on the corresponding optimal cadence. This led to the conclusion that the reduction in FCC seen in field observations of cyclists is (1) advantageous from a performance-related point of view, and (2) caused entirely by the road incline. The concomitant change to a more upright body position with increasing road incline is (1) advantageous from a performance-related point of view, and (2) does not affect the FCC.

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