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Laboratory predictors of uphill cycling performance in trained cyclists

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ABSTRACT

This study aimed to assess the relationship between an uphill time-trial (TT) performance and both aerobic and anaerobic parameters obtained from laboratory tests. Fifteen cyclists performed a Wingate anaerobic test, a graded exercise test (GXT) and a field-based 20-min TT with 2.7% mean gradient. After a 5-week non-supervised training period, 10 of them performed a second TT for analysis of pacing reproducibility. Stepwise multiple regressions demonstrated that 91% of TT mean power output variation (W kg^{-1}) could be explained by peak oxygen uptake (ml $kg^{-1} \cdot min^{-1}$) and the respiratory compensation point (W kg^{-1}), with standardised beta coefficients of 0.64 and 0.39, respectively. The agreement between mean power output and power at respiratory compensation point showed a bias ± random error of 16.2 ± 51.8 W or 5.7 ± 19.7%. One-way repeated-measures analysis of variance revealed a significant effect of the time interval (123.1 ± 8.7; 97.8 ± 1.2 and 94.0 ± 7.2% of mean power output, for epochs 0–2, 2–18 and 18–20 min, respectively; $P < 0.001$), characterising a positive pacing profile. This study indicates that an uphill, 20-min TT-type performance is correlated to aerobic physiological GXT variables and that cyclists adopt reproducible pacing strategies when they are tested 5 weeks apart (coefficients of variation of 6.3; 1 and 4%, for 0–2, 2–18 and 18–20 min, respectively).

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KEYWORDS
Power output; field test; VO_{2max}; pacing strategy; self-paced exercise

Introduction

While test conditions can be easily standardised in the laboratory setting, it may be impractical to implement laboratory-based performance tests into the athletes' training routines, preventing some of them, from taking part in scientific projects. But despite the existence of several validated field-based performance tests within the cycling literature (Gonzalez-Haro, Galilea, Drobnic, & Escanero, 2007; Karsten, Jobson, Hopker, Stevens, & Beedie, 2015; Nimmerichter, Williams, Bachl, & Eston, 2010; Padilla, Mujika, Cuesta, Polo, & Chatard, 1996; Pinot & Grappe, 2014), relatively few experimental studies have utilised them within their methods (Karlsen et al., 2015; Klika, Alderdice, Kvale, & Kearney, 2007; Nimmerichter, Eston, Bachl, & Williams, 2012; Racinais, Periard, Karlsen, & Nybo, 2015). Recently, Nimmerichter et al. (2010) investigated the validity and reproducibility of a field-based 20-min time-trial (TT) on a flat course as a performance predictor for common laboratory parameters measured during a graded exercise test (GXT). The study demonstrated high test–retest reproducibility of the field-based 20-min TT (0.6 ± 4.4%; bias ± random error) and strong agreement between TT mean power output with power output at the second lactate turn point (LTP2; 0.02 ± 13%), and the respiratory compensation point (RCP; −0.3 ± 14.3%). The data from Nimmerichter et al. (2010) thereby suggest that a field-based 20-min TT could be used for performance monitoring and field-based assessment of power output at approximately LTP2/RCP.

However, cycling is a sport in which riders are often required to cycle uphill for a prolonged period of time (Atkinson, Davison, Jeukendrup, & Passfield, 2003; Jeukendrup, Craig, & Hawley, 2000). Therefore, it is important to consider not just flat, but also uphill TT efforts when assessing rider performance capabilities. Indeed, Nimmerichter et al. (2012) have demonstrated that an uphill 20-min TT effort produces higher mean power output when compared to an effort over a flat course. Therefore, this raises questions about the relationship between uphill TT performance expressed as mean power output, and physiological parameters obtained from laboratory-based tests using simulated flat TT courses in the lab (Amann, Subudhi, & Foster, 2006; Bentley & McNaughton, 2003; Bentley, McNaughton, Thompson, Vleck, & Batterham, 2001; Bishop, Jenkins, & Mackinnon, 1998; Lamberts, Lambert, Swart, & Noakes, 2012), and flat TT courses in the field (Balmer, Davison, & Bird, 2000; Nimmerichter et al., 2010; Smith, 2008; Tan & Aziz, 2005).

To the present date, a handful of studies have attempted to address the predictive ability of laboratory parameters on uphill TT performance (Anton et al., 2007; Costa et al., 2011; Davison, Swan, Coleman, & Bird, 2000; Heil, Murphy, Mattingly, & Higginson, 2001; Tan & Aziz, 2005). However, to the author's knowledge, only 1 study has assessed the influence of both aerobic and anaerobic variables (Davison et al., 2000), although performance tests were conducted on an inclined treadmill that limits the ecological validity of the findings. Hence, the first aim of this study was to identify whether the proposed GXT aerobic predictors of performance (e.g., RCP

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proposed by Nimmerichter et al. (2010)), still hold during a field-based, uphill 20-min TT, and whether the inclusion of anaerobic variables improves prediction capability.

One factor that has been shown to affect cycling performance, and therefore the ability to predict the TT performance, is pacing strategy (Atkinson et al., 2003). It is generally accepted that on a flat course and under stable environmental conditions (e.g., wind), an even pacing strategy represents the best work distribution for optimum cycling TT performance (Atkinson, Peacock, St Clair Gibson, & Tucker, 2007). However, not only even (Thomas, Stone, Thompson, St Clair Gibson, & Ansley, 2012a), but also variable (Billat, Wesfreid, Kapfer, Koralsztein, & Meyer, 2006; Lander, Butterly, & Edwards, 2009) and parabolic (Ham & Knez, 2009; Thomas, Stone, St Clair Gibson, Thompson, & Ansley, 2013) pacing strategies have all been linked to optimal TT performance. Since pacing strategy in the field is also affected by fluctuations in gradient and wind, which consequently result in a more variable power distribution (Atkinson & Brunskill, 2000; Cangley, Passfield, Carter, & Bailey, 2011), it is important to consider this variable when investigating the nuances of field-based performance tests.

To our knowledge, the only study that has systematically studied changes in power distribution across repeated trials was conducted within a laboratory environment (Thomas, Stone, Thompson, St Clair Gibson, & Ansley, 2012b). Thus, there is a need to investigate power distribution and reliability of pacing strategies used in outdoor real-world TTs. Accordingly, the second aim of this work was to describe the pacing strategy employed by cyclists and its reproducibility in a field-based, uphill 20-min TT.

Methods

Fifteen trained cyclists, including 1 female (mean ± *s*; age: 30.8 ± 4.8 years; height: 176.5 ± 8.0 cm; body mass: 78.9 ± 14.5 kg), were recruited from local cycling clubs. The inclusion criteria were at least 2 years of cycling experience with a minimum of 4 sessions and 7 h of training per week. Verbal and written explanations were given to all participants about the nature of the study, of all associated risks, and of their right to withdraw at any time, before they provide written informed consent. The study protocol followed the guidelines laid down by the World Medical Assembly Declaration of Helsinki and was granted approval by the University's research ethics committee.

Study design

During the first visit to the laboratory, participant's height and body mass were assessed and a Wingate anaerobic test was performed. At the second visit, participants performed a GXT and, at the third visit, they performed a field-based, uphill TT. Approximately 5 weeks after the initial test sessions, a subset of 10 participants completed an additional TT on the same course to assess pacing reproducibility. During the 5-week period between tests, participants were asked to continue their normal training regime (not supervised by the research team). Testing sessions were separated by at least 48 h. Cyclists were instructed to avoid vigorous exercise, alcohol and caffeine consumption in the last 24 h, and any food in the last 2 h, before testing.

Wingate anaerobic test

The Wingate anaerobic test (Bar-Or, Dotan, & Inbar, 1977) was applied using a mechanically braked cycle ergometer (Biotec2100, Cefise, Nova Odessa, Brazil) adapted with clipless pedals and a powermeter crank (Professional, SRM, Jülich, Germany). To ensure accuracy and reliability of power measurement, the crank was calibrated by the manufacturer prior to the study, and zero offset procedure was performed prior to each test according to the manufacturer's recommendations. Initially, cyclists warmed up for 10 min at a self-selected intensity, and, at the fifth minute, they performed a 5-s familiarisation sprint. The test commenced from unloaded pedalling followed by a 30 s all-out effort at a resistance of 0.075 kg kg^{-1} body mass. Cyclists were required to remain seated and were verbally encouraged throughout the test. The anaerobic peak power output (PPO) and the anaerobic capacity were considered as the highest 5- and 30-s mean power output, respectively (Beneke, Pollmann, Bleif, Leithauser, & Hutler, 2002).

Graded exercise test

The GXT was undertaken on a cycling rig (Computrainer ProLab, RacerMate, Seattle, USA) using the cyclists' own bikes. The protocol consisted of initial load of 70 W with subsequent 25 W min^{-1} increments, each minute until exhaustion. Cyclists were verbally encouraged and exhaustion was defined as the moment when the cyclist could not maintain a minimum pedal cadence of 70 rev min^{-1} for more than 5 s (Lucia et al., 2004). Power output and cadence were monitored continuously throughout the test using a mobile powermeter (PowerTap, Saris, Madison, USA). Prior to each test, the powermeter zero offset procedure was performed according to the manufacturer's recommendations. The highest 1-min mean power output was considered the aerobic PPO (Balmer et al., 2000; Smith, 2008).

Oxygen consumption (VO_2) was continuously measured on a breath-by-breath basis, by an open circuit spirometer ($K4b^2$, Cosmed, Rome, Italy) which was calibrated before each test using ambient air samples and a gas sample with known O_2 and CO_2 concentrations. The bidirectional turbine (flow meter) was calibrated by a 3 L syringe (Cosmed, Rome, Italy). Data were averaged over a 30-s mean and peak oxygen uptake (VO_{2peak}) was deemed the highest mean value registered during the test. The ventilatory threshold (VT) was identified by (1) an increase on ventilatory equivalent of O_2 (VE/VO_2) with no change in ventilatory equivalent of CO_2 (VE/VCO_2), (2) an increase on the end-tidal PO_2 with no fall in end-tidal PCO_2 and (3) a departure from linearity of pulmonary ventilation (VE) (Wasserman, 1987; Wasserman et al., 2012). The RCP was determined by (1) an increase of both VE/VO_2 and VE/VCO_2, (2) a decrease of the end-tidal PCO_2 and (3) a second slope increase on the curve between VE and mechanical workload (Wasserman, 1987; Wasserman et al., 2012). The cyclist's heart rate was continuously monitored (RS800CX, Polar Electro, Kempele, Finland), and their ratings of perceived exertion were asked in the last 10 s of each stage, using the 6–20 Borg scale (Borg, 1982).

Uphill twenty-minute time-trial

Participants used their own bikes for the TT, equipped with the same powermeter used in the GXT and equally calibrated before each test. Cyclists were asked to ride the greatest distance possible during the 20-min TT with only elapsed time as feedback. As previously used by Costa et al. (2011), the outdoor course consisted of a 10-km uphill stretch with a mean gradient of 2.7% (Figure 1). Prior to the TT, participants warmed up for 20 min at a self-selected intensity. Participants were supervised during each TT, verbally encouraged, and could stand ride. Heart rate was continuously monitored throughout the TT by the same device used during the GXT.

In all tests, powermeter data were logged by a cycle computer (Edge 510, Garmin, Olathe, USA) at 1 Hz sampling rate and subsequently analysed using specific software (WKO+ 3.0, Peaksware, Boulder, USA).

Data analysis

The descriptive results are presented as mean ± *s*. Initially, data were assessed for normality using the Shapiro-Wilk test. Pearson's product-moment correlations were used to determine the relationship between laboratory variables and TT performance quantified by mean power output. When laboratory and TT data were scaled to body mass, partial correlations were used. The variables VO_{2peak}, aerobic PPO, RCP and anaerobic capacity were chosen for the multiple stepwise linear regression analysis in order to identify significant laboratory predictors of the TT mean power output. Bland–Altman plots and 95% limits of agreement were applied to assess the agreement between the TT mean power output and the RCP (Bland & Altman, 1986). To quantify bias and random error in percentages, data were previously log transformed (Hopkins, 2000a). In addition, the typical error of estimate and 95% confidence limits (CL) were used to describe the predictive accuracy between TT mean power output and RCP. Nimmerichter et al. (2012) demonstrated that the mean power output was roughly 5.4% higher when the TT was performed in an uphill course rather than a level ground course. Based on this finding, we analysed also the agreement between 94.6% of the TT mean power output and the RCP.

For TT pacing analysis and reproducibility, a parabolic shape of the power distribution curve was assumed and 3 time intervals were determined, in accordance with the published literature: 0–2; 2–18; 18–20 min (i.e., 0–10; 10–90; 90–100% TT distance) (Roelands, De Koning, Foster, Hettinga, & Meeusen, 2013). The mean power output from each epoch was percentage normalised to the total TT mean power output, with statistical differences between each interval from the first TT assessed via a one-way repeated-measures analysis of variance (ANOVA) (n = 15). Pacing reproducibility was assessed via the use of a two-way repeated-measures ANOVA (TT × time interval; n = 10). Following ANOVA, Bonferroni pairwise comparisons were used to identify where significant differences existed within the data. Pacing reproducibility was also assessed using coefficients of variation from log transformed normalised power data and 95% CL. The difference in the mean power output between the 2 TTs was verified by a paired *t*-test. Statistical significance was set at $P \leq 0.05$. The SPSS statistical package (20.0, IBM, Armonk, USA) and an online published spreadsheet (Hopkins, 2000b) (Excel 2010, Microsoft, Redmond, USA) were used for the statistical analysis.

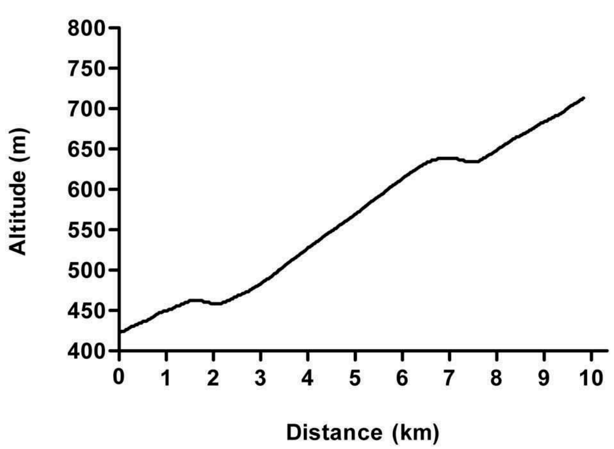

Figure 1. Time-trial course altimetry.

Results

Tables 1 and 2 describe laboratory variables and TT variables, respectively. There was a significant correlation between the

Table 1. Laboratory testing results (n = 15).

Win_{peak} (W)	906 ± 146
Win_{mean} (W)	674 ± 97
Win_{peak} (W kg^{-1})	11.55 ± 0.98
Win_{mean} (W kg^{-1})	8.63 ± 0.83
PPO (W)	341 ± 42
PPO (W kg^{-1})	4.38 ± 0.49
VO_{2peak} (L·min^{-1})	4.37 ± 0.68
VO_{2peak} (ml kg^{-1}·min^{-1})	56.1 ± 7.7
RCP (W)	276 ± 43
RCP (W kg^{-1})	3.58 ± 0.64
VT (W)	174 ± 29
VT (W kg^{-1})	2.27 ± 0.49
HR_{peak} (beats·min^{-1})	185 ± 6
RER_{peak}	1.15 ± 0.07
RPE_{peak}	19.1 ± 0.6

Win_{peak}: anaerobic peak power output; Win_{mean}: anaerobic capacity; PPO: aerobic peak power output; VO_{2peak}: peak oxygen uptake; RCP: respiratory compensation point; VT: ventilatory threshold; HR_{peak}: peak heart rate; RER_{peak}: peak respiratory exchange ration; RPE_{peak}: peak rating of perceived exertion.

Table 2. Uphill 20-min time-trial results (n = 15).

Distance (m)	8164 ± 896
PO_{mean} (W)	293 ± 48
PO_{mean} (W kg^{-1})	3.75 ± 0.51
PO_{mean} (%PPO)	85.6 ± 5.6
Cadence (rev·min^{-1})	81 ± 5
HR_{mean} (beats·min^{-1})	180 ± 7

PO_{mean}: mean power output from the time-trial; PPO: aerobic peak power output; HR_{mean}: mean heart rate from the time-trial.

Table 3. Correlations between laboratory test results and performance from the time-trial expressed either as absolute (Pearson's product-moment) and relative units (partial correlations) (n = 15).

		Win_{peak} (W)	Win_{mean} (W)	PPO (W)	VO_{2peak} (L·min^{-1})	RCP (W)	VT (W)
PO_{mean} (W)	r	0.72	0.73	0.94	0.94	0.84	0.57
	Sig.	0.002	0.002	0.001	0.001	0.001	0.027
		Win_{peak} (W kg^{-1})	Win_{mean} (W kg^{-1})	PPO (W kg^{-1})	VO_{2peak} (ml kg^{-1}·min^{-1})	RCP (W kg^{-1})	VT (W kg^{-1})
PO_{mean} (W kg^{-1})	r	0.25	0.34	0.86	0.89	0.80	0.59
	Sig.	0.378	0.232	0.001	0.001	0.001	0.024

PO_{mean}: mean power output from the time-trial; Win_{peak}: anaerobic peak power output; Win_{mean}: anaerobic capacity; PPO: aerobic peak power output; VO_{2peak}: peak oxygen uptake; RCP: respiratory compensation point; VT: ventilatory threshold.

distance covered and the TT mean power output expressed relative to the cyclists' body mass (r = 0.92; P < 0.001), but not when considering the mean power output in absolute values (r = 0.38; P = 0.156). Moreover, a significant correlation was evident between the TT mean power output and the cyclists' body mass (r = 0.69; P = 0.004). Table 3 presents the correlation values between laboratory parameters and TT performance quantified either as absolute and relative mean power output.

Using guidance from endurance performance theoretical models (Di Prampero, 2003; Joyner & Coyle, 2008) and based on strength of correlations between TT mean power output and laboratory variables, VO_{2peak}, aerobic PPO, RCP and anaerobic capacity were selected for inclusion within the regression analyses. Considering variables expressed as absolute values, multiple stepwise linear regression analysis produced the final equation (n = 15):

$$PO_{mean} = -35.583 + 48.612 \cdot VO_{2peak} + 0.419 \cdot RCP \quad (1)$$

(Adjusted r^2 = 0.95; SEE = 10.34; P < 0.001; β_1 = 0.68; P < 0.001; β_2 = 0.37; P = 0.001)

where PO_{mean} is the TT mean power output, VO_{2peak} is the peak oxygen uptake and RCP is the respiratory compensation point.

Even if a hierarchical regression method was used to control the influence of body mass on the TT mean power output values, the coefficient of determination was not improved, nor were other variables included within the final equation.

When considering variables expressed as relative values, the regression analysis produced 2 similar equations, though their coefficient of determination were smaller (n = 15):

$$PO_{mean} = 0.302 + 0.061 \cdot VO_{2peak} \quad (2)$$

(Adjusted r^2 = 0.83; SEE = 0.20; P < 0.001; β_1 = 0.92; P < 0.001)

$$PO_{mean} = 0.196 + 0.043 \cdot VO_{2peak} + 0.317 \cdot RCP \quad (3)$$

(Adjusted r^2 = 0.91; SEE = 0.14; P < 0.001; β_1 = 0.64; P < 0.001; β_2 = 0.39; P = 0.003)

Bland–Altman plot between the TT mean power output and RCP showed a bias±random error of 16.2 ± 51.8 W or 5.7 ± 19.7% (Figure 2) and 0.4 ± 49.7 W or –0.1 ± 19.7% when agreement was assessed between 94.6% of the TT mean power output and RCP. The typical error of estimate was 24.4 W (CL: 17.7 – 39.3 W) or 9% (CL: 6.4 – 14.9%).

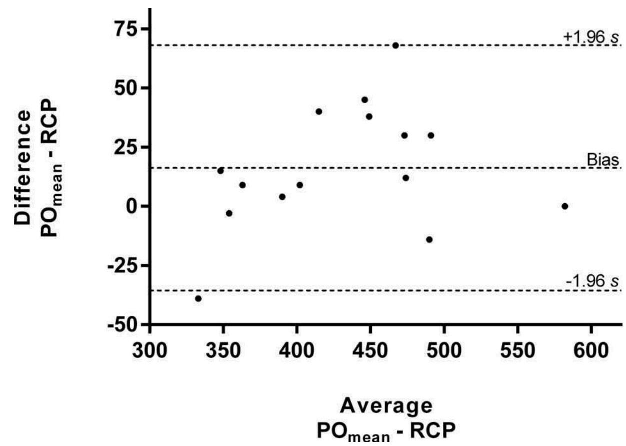

Figure 2. Bland–Altman plot from the difference between time-trial mean power output (PO_{mean}) and respiratory compensation point (RCP) *vs.* the average between time-trial mean power output and respiratory compensation point (n = 15).

Repeated measures one-way ANOVA revealed an effect of the time interval (F = 72.4; P < 0.001) on the normalised mean power output from each TT epoch (123.1 ± 8.7; 97.8 ± 1.2 and 94.0 ± 7.2% of the mean power output from epochs 0–2, 2–18 and 18–20 min, respectively). *Post hoc* pairwise comparisons demonstrated a significantly higher normalised mean power output from the interval 0–2 compared to the intervals 2–18 and 18–20 min. Analysis of data from the subset of 10 cyclists who completed the second uphill TT demonstrated no significant main effect of the TT (F = 3.02; P = 0.116), nor any kind of interaction (F = 0.76; P = 0.433; Figure 3).

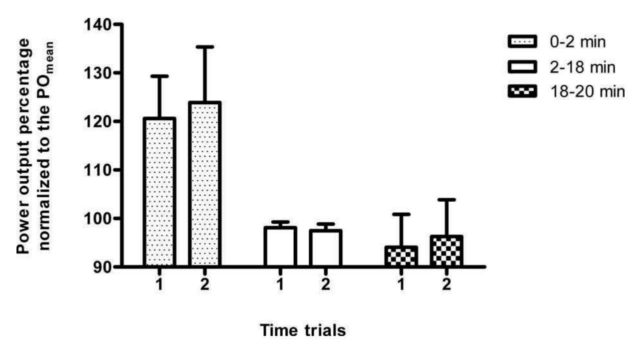

Figure 3. Mean and standard deviation from the mean power output from each time-trial epoch, percentage normalised to the total time-trial mean power output (PO_{mean}) (n = 10; first and second time-trial).

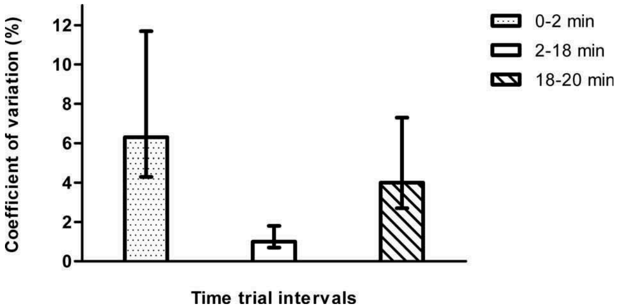

Figure 4. Reproducibility of the pacing adopted: coefficient of variation and 95% confidence limits of the mean power output, percentage normalised to the total time-trial mean power output, from each time epoch (n = 10).

Mean power output was also not significantly different between the 2 TTs (t = 0.2; P = 0.845; 301 ± 49 and 302 ± 52 W; first and second TT, respectively). Differences in the normalised mean power output of 3.33% (CL: −4.07–10.73%), −0.65% (CL: −1.59–0.30%) and 2.23% (CL: −1.49–5.95%) were found between the TTs, for the first (0–2 min), the second (2–18 min) and the third (18–20 min) time epoch, respectively. Figure 4 exhibits the coefficient of variation of log transformed normalised power output data from each time epoch and their 95% CL (6.3%, CL: 4.3–11.7%; 1%, CL: 0.7–1.8%; 4%, CL: 2.7–7.3%; epochs 0–2, 2–18 and 18–20 min, respectively).

Discussion

The aim of this study was to assess which laboratory variables would predict cyclist's performance during a field-based, uphill 20-min TT. Data suggest that 91% of TT mean power output variation (W kg^{-1}) could be explained by physiological parameters VO$_{2peak}$ (ml kg^{-1}·min^{-1}) and RCP (W kg^{-1}). However, cyclists' anaerobic capacity was not correlated with TT performance when data were scaled to body mass. In addition, performing the TT in an ascent premises a 94.6% adjustment of the mean power output in order to improve its agreement with RCP power output, although due to a random error of approximately 50 W, it potentially limits their interchangeable use in some instances. Finally, it was demonstrated that cyclists typically adopt a highly reproducible positive pacing strategy when 2 tests are applied in an outdoor uphill course.

The results of this study demonstrated a significant correlation between distance covered and TT mean power output relative to body mass (r = 0.92), which was not apparent when absolute power output values were considered (r = 0.38). Unsurprisingly, the differences in the strength of correlation can be explained by the considerable influence of the body mass on uphill performance, since gravity is the main resistive force to be overcome (Fonda & Šarabon, 2012; Heil et al., 2001; Swain, 1994). The current findings are similar to previous studies, which rather than distance covered, have assessed completion time of an uphill course (r = −0.82 to −0.95) (Costa et al., 2011; Davison et al., 2000; Tan & Aziz, 2005). Therefore, to compare uphill performance among cyclists of different body masses, it is necessary to express mean power output as relative values (W kg^{-1}). Further, our results indicate that even small gradients (2.7%) can be critical to the ability to predict TT performance from laboratory variables.

When evaluating the relationship between laboratory variables and TT mean power output, the strength of correlations were higher when data were expressed as absolute values (except for VT). The present study sample was composed of a heterogeneous group of cyclists in relation to their body mass. Consequently, it is not surprising that there was a large variability in TT mean power output (209–388 W), and its significant correlation with body mass (r = 0.69) (Jeukendrup et al., 2000). Thus, the fact that most variables were strongly correlated with TT mean power output expressed as absolute values (r = 0.57–0.94), actually denotes the high degree of collinearity between them, and not just their physiological relationship. It is therefore possible to question the correlations presented by previous studies which quantified TT performance by the mean power output (Amann et al., 2006; Balmer et al., 2000; Bentley & McNaughton, 2003; Bentley et al., 2001; Bishop et al., 1998; Jacobs et al., 2011; Lamberts et al., 2012; Nimmerichter et al., 2012, 2010; Smith, 2008; Tan & Aziz, 2005).

The results of the current study clearly demonstrated the importance of VO$_{2peak}$ as a primary determinant of endurance performance. Eighty-three percent of TT performance variation was attributed to differences in participants' VO$_{2peak}$. In support of the findings of the current study, Costa et al. (2011) demonstrated a correlation of r = 0.80 between VO$_{2peak}$ and TT mean power output on an uphill 10-km course; both variables normalised to body mass. Similarly, Heil et al. (2001) reported correlations between VO$_{2peak}$ (ml kg^{-1}.min^{-1}) and mean cycling speed from a 12.5- and a 6.2-km TTs of r = 0.89 and 0.84, respectively.

PPO from the laboratory GXT was also strongly correlated to the TT mean power output (r = 0.85), albeit not being included within the equations derived from the regression analysis. The absence of PPO can be explained by its intimate relationship with VO$_{2peak}$ (Hawley & Noakes, 1992; Jacobs et al., 2011; Lamberts et al., 2012), thereby, not contributing for improvements on the explanatory power of the model. The correlation between aerobic PPO and TT mean power output has been previously reported by many studies and, in agreement with our investigation, r values ranging from 0.81 to 0.97 have been cited in most of them (Amann et al., 2006; Balmer et al., 2000; Bishop et al., 1998; Costa et al., 2011; Jacobs et al., 2011; Lamberts et al., 2012; Nimmerichter et al., 2012, 2010; Smith, 2008; Tan & Aziz, 2005). Therefore, if gas exchange data are not available, aerobic PPO could be used as a TT performance predictor with reasonable confidence.

Although a high VO$_{2peak}$ is a basic prerequisite for success on endurance modalities (Bassett & Howley, 2000; Joyner & Coyle, 2008), it does not represent performance per se (Levine, 2008). Equations (2) and (3) attested an 8% enhancement of the predictive capacity of the TT mean power output when the RCP was included within the formula. Moreover, significant correlations between TT mean power output and both RCP and VT (normalised to body mass) were found. These results confirm that no single variable encompass all the physiological factors that interact to determine endurance performance.

The oxidative capacity of the skeletal muscle, typically estimated by the RCP and the VT, determines the rate of aerobic metabolism that can be maintained during a prolonged performance bout (Bassett & Howley, 2000; Joyner & Coyle, 2008).

Unexpectedly, cyclists' anaerobic PPO and anaerobic capacity were not correlated with TT mean power output (data expressed as relative units), and neither parameter was included in the TT performance prediction equation. These results do not support those from Davison et al. (2000) who found that anaerobic capacity (W kg^{-1}) was the best individual predictor of simulated hill climb mean speeds, using steeper gradients (12 and 6 *vs.* 2.7%) and shorter tests (~4 and ~16 *vs.* 20 min) than that of the current study. In their discussion, Davison et al. (2000) stated that several cyclists chose to ride out of the saddle in an attempt to complete the TT distance in the quickest time, which in turn would allow them to increase power output during short-term accelerations, and thus the potential for anaerobic energy contribution (Millet, Tronche, Fuster, & Candau, 2002). The 2.7% mean gradient used in the current study was possibly not steep enough to force cyclists out of the saddle and, therefore, the utilisation of the anaerobic energy system is likely to have played a minor role in the TT performance. It is also possible that the shorter test durations in the study of Davison et al. (2000) contributed to the significant correlations between performance and anaerobic variables found in their study. The findings of the current study are however similar to those of Storen, Ulevag, Larsen, Stoa and Helgerud (2013), who failed to find a significant correlation between both Wingate anaerobic parameters and the time to complete a laboratory-based, flat TT of 15 km.

Nimmerichter et al. (2010) demonstrated that the intensity adopted by cyclists in a flat 20-min TT is similar to that of the RCP obtained from a GXT (−0.4 ± 49 W or −0.3 ± 14.3%; bias ± random error) which contrasts to our results that show 16.2 ± 51.8 W or 5.7 ± 19.7%. After the current study's TT mean power output was adjusted to 94.6%, in accordance with the findings of Nimmerichter et al. (2012), the bias was reduced to 0.4 W (−0.1%), indirectly confirming that cyclists are able to produce higher mean power outputs when riding uphill (Nimmerichter et al., 2012). However, the random error of 49.7 W (19.7%) and the typical error of estimate of 24.4 W (9%) mean there are potential limitations on the predictive validity of the uphill 20-min TT for identification of RCP power output and *vice versa* (Nimmerichter et al., 2010).

A further finding of the current study was that a positive pacing strategy was identified. This positive pacing strategy contrasts to studies that have shown parabolic pacing profile from laboratory-based TTs of 20 (Albertus et al., 2005; Kenefick, Mattern, Mahood, & Quinn, 2002; Mattern, Kenefick, Kertzer, & Quinn, 2001; Thomas et al., 2012a, 2012b), 30 (Ham & Knez, 2009) and 40 km (Nikolopoulos, Arkinstall, & Hawley, 2001). This result also contrasts to data presented by Nimmerichter et al. (2010), as cyclists in their study produced significant higher mean power outputs on the first and the last minute of the TT, with an even intensity distribution during the middle portion. Thus, it can be speculated that the higher random error between TT mean power output and RCP from this study might be due to poor pacing strategy adopted by cyclists. After a 5-week non-supervised training period, a subset of 10 cyclists performed a second TT, which demonstrated similar pacing strategies to the first TT. This finding is in accordance with the research of Thomas et al. (2012b), who found good repeatability of the intensity distribution during 3 laboratory-based 20-km TTs. Taken together, those results indicate that cyclists are able to adopt similar pacing strategies when performing TTs of approximately 20–30 min, even if they might not choose an optimal one.

It is important to mention that this study is not without limitations. It could be argued that the regression analysis model used in this study lacks statistical power due to the few number of participants (*n* = 15). The small sample size could have also increased the random error between TT mean power output and RCP, if any of the cyclists did not perform well during the TT. Therefore, future work with larger samples should try to address these issues.

Conclusions

In summary, the present study demonstrated that in a heterogeneous group of trained cyclists, the mean power output from a field-based, uphill 20-min TT could be explained mainly by the laboratory parameters of VO_{2peak} and RCP. Unexpectedly, cyclists' anaerobic variables were not correlated with TT performance. Moreover, the agreement between TT mean power output and RCP can be improved by a 94.6% adjustment of the mean power output; although a random error of approximately 50 W is expected, potentially limiting their use interchangeably in some instances. In this study, cyclists adopted a positive pacing strategy which was highly reproducible across TTs. Taken together, this information indicates that an uphill, 20-min TT-type performance is strongly correlated to GXT physiological variables and that cyclists are able to adopt similar pacing strategies when they are tested 5 weeks apart. Future work should investigate the reliability of uphill TT performance. Together with our results, it can support scientists and athletes with a practical test for performance monitoring.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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