

## Consistency of perceptual and metabolic responses to a laboratory-based simulated 4,000-m cycling time trial

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Received: 8 October 2010 / Accepted: 24 December 2010 / Published online: 11 January 2011  
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**Abstract** Although pacing-related research is widely reported, no studies have described the consistency of pacing strategies or their associated energetic contributions. This study aimed to investigate the consistency of pacing and energetic outlay by establishing the typical within and between trial variations during simulated 4,000 m time trials. Fifteen well-trained male cyclists performed three, 4,000 m time trials with 3–7 days separating each trial. Power output, cadence, heart rate, respiratory exchange and iEMG of the vastus lateralis were recorded continuously throughout each trial. To examine within-trial variability, the data were assigned to 10% bins. Rating of perceived exertion and affective response were recorded every 400 m and a capillary blood sample was collected and assayed for blood lactate concentration every 800 m. Mean typical error across trials 1–3 for all variables was low (range 2.1–6.3%) and lower between trials 2–3 for all variables with the exception of cadence. There were no between-trial differences in pacing strategy; however, typical error for each 10% bin was lower between trials 2–3 than trials 1–2. Anaerobic contribution to power was greatest during the first and last 10% of each trial ( $p > 0.05$ ). In conclusion, well-trained cyclists demonstrated a high degree of consistency in terms of the pacing strategy they adopted which coincided with similar levels of energy distribution and perceived exertion. A laboratory

simulated 4-km cycling trial is a reliable test that may be used to monitor performance and pacing strategy.

**Keywords** Reliability · Pacing · Exercise · EMG · Cardiorespiratory · Perceptual

### Introduction

The term ‘pacing strategy’ relates to the pattern by which energetic resources, mechanical power output or speed is distributed during a bout of exercise. The pacing strategy adopted during a time trial competition involving athletes of similar ability can play an important role in determining the final race standings (Hettinga et al. 2006). Negative, all-out, positive, even, parabolic shaped or variable pacing strategies have been broadly identified. Descriptions of these terms as well as advice pertaining to the optimal pacing strategies for varying competitive scenarios have been explained elsewhere (Abbiss and Laursen 2008).

Computer simulation and observations of elite competitors concur that a fast start followed by a transition to an even pacing strategy represents the optimal race profile for a 4,000-m cycling time trial (Corbett 2009; de Koning et al. 1999). The high intensity starting strategy is believed to expedite the rate of  $\dot{V}O_2$  kinetics, thus sparing the finite ‘anaerobic capacity’, with this energy being made available later in the exercise bout (Bishop et al. 2002; Jones et al. 2008). The subsequent even or gradually declining work rate precludes an untimely depletion of anaerobic energy supplies, but should also ensure that anaerobic resources are fully exhausted upon completion of the race (Foster et al. 2003).

Previous studies with trained cyclists have reported a coefficient of variation (CV) as low as 0.9% for power

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Communicated by Toshio Moritani.

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output between test and retest in laboratory simulated 40-km cycling time trials (Laursen et al. 2003) and 1.9% in laboratory simulated 20-km time trials (Sporer and McKenzie 2007). In both of these studies, the CV was higher between trials 1–2 than 2–3 suggesting the existence of a learning effect following the first trial. However, despite growing evidence that 4,000 m cyclists favour a fast start strategy, there are currently no data available detailing the consistency of this pacing strategy and associated distribution of energetic resources during self-paced cycling exercise, and there is scarce data detailing the reproducibility of cardiorespiratory or perceptual responses to self-paced exercise. A few studies have reported the reproducibility in performance and physiological measurements at the end of the trial (Smith et al. 2001; Zavorsky et al. 2007), but have not taken regular measurements within trials to establish the variability in pacing strategy.

Reproducible tests are needed to enable coaches and researchers to systematically evaluate observed pacing strategies against a predicted optimal, and to establish the usefulness of a strategy or intervention designed to manipulate the pacing strategy. Furthermore, it is important to establish the usefulness of the test by calculating the smallest worthwhile change, to distinguish whether real changes have occurred over time for subsequent testing periods (Hopkins 2000). To date, pacing-related studies have not reported the smallest worthwhile change.

The main aim of the present study was therefore to document the pattern of physiological and perceptual responses to self-paced exercise. Secondary aims were to assess the consistency of the pacing strategy and associated distribution of energetic resources and perceptual responses during a laboratory-simulated 4,000-m cycling time trial; and to calculate the magnitude of effect that represents a worthwhile change in both overall performance, and pacing strategies in well-trained cyclists.

## Methods

### Participants

Fifteen well-trained male cyclists volunteered to take part in the study. Mean age ( $\pm$ SD) of the participants was 35.9 (7.9) years, stature 1.81 (0.06) m, body mass 78.4 (11.2) kg, body fat 14 (5.7)%, peak oxygen uptake ( $\dot{V}O_{2\text{peak}}$ ), 4.85 (0.48) L min<sup>-1</sup> and power output at  $\dot{V}O_{2\text{peak}}$  ( $P\dot{V}O_{2\text{peak}}$ ), 331.8 (20.7) W. The institutional ethics committee approved the project. All participants were fully informed of the nature of the research provided written informed consent and completed a physical activity readiness questionnaire prior to participation.

### Design

A repeated measures design was administered to examine the consistency of power output and distribution of energetic resources and perceptual responses during a laboratory simulated 4,000-m cycling time trial. After preliminary testing, each participant undertook three, self-paced 4,000-m cycling time trials. Intra-participant testing was conducted at the same time of day to minimize circadian variation, with 3–7 days between test sessions. Participants were instructed to maintain their normal diet throughout the experiment and to refrain from strenuous exercise and the consumption of caffeine or alcohol in the 24 h preceding each laboratory testing session.

Testing was conducted on an electromagnetically braked cycle ergometer (Velotron Racer mate, Seattle, USA), which has previously been shown to produce valid and reliable indices of power output (McDaniel et al. 2005; Sporer and McKenzie 2007). The ergometer was adjusted to fit each participant based on their own measurements; this included fitting their own pedals and saddle. These adjustments were replicated for all subsequent trials.

Expired breath-by-breath respiratory gas exchange parameters ( $\dot{V}O_2$  and  $\dot{V}CO_2$ ) were measured continuously using an automated online metabolic cart (Cortex, Metalyzer, Leipzig, Germany), which has been shown to be a valid and reliable instrument for the measurement of gaseous exchange during exercise (Meyer et al. 2005). Aerobic ( $P_{\text{aer}}$ ) and anaerobic ( $P_{\text{anaer}}$ ) contributions to total power output were calculated according to the methods previously described (de Koning et al. 1999) using efficiency estimated during cycling at 150 W during the warm up. The gas analyser and flow turbine were calibrated before each test using certified standard gases (15.00% O<sub>2</sub>, 5% CO<sub>2</sub>) and a 3-L syringe (Hans Rudolph, Kansas City, USA). Heart rate was recorded using short-range telemetry (Polar Electro Oy, Kempele, Finland) interfaced with the Cortex software.

### Preliminary testing session

On their first visit to the laboratory, participants performed a submaximal exercise test, and a standard incremental test to maximal exertion for the determination peak oxygen uptake ( $\dot{V}O_{2\text{peak}}$ ). Following a 10-min self-paced warm-up, power output was set at 150 W and increased by 25 W every 4 min. Oxygen uptake was averaged during the final minute of each stage and a capillary blood was sampled and analysed for blood lactate concentration ([La-]b). The submaximal exercise test was terminated after a second sharp rise in [La-]b was observed. Subsequently, the power output was adjusted to 200 W and continuously increased by 5 W every 15 s until volitional fatigue. The highest  $\dot{V}O_2$

averaged over a 30-s period was defined as  $\dot{V}O_{2\text{speak}}$ . The linear relationship between power output and oxygen uptake was extrapolated for the estimation of the lowest power output which elucidated  $\dot{V}O_{2\text{speak}}$  ( $P\dot{V}O_{2\text{speak}}$ ).

### Time trial

Before the 4,000-m time trial participants performed a standardised warm-up which consisted of cycling for 5 min at 150 W and then a further 5 min at 70% of  $P\dot{V}O_{2\text{speak}}$ , after which they were given 5 min to relax and prepare themselves for the subsequent time trial. A flat 4,000-m time trial profile was created using the Velotron Coaching Software (RacerMate Inc., Seattle, USA) and was used for all trials. Participants were instructed to complete the 4,000-m distance in as short a time as possible. During the time trial, no visual feedback was available to the participant, but verbal feedback on the distance covered was given every 400 m. The gear ratio was the same at the start of each time trial, but participants were permitted to adjust the gear ratio throughout the trial to reflect their preferred cadence.

Electrical activity of the vastus lateralis (VL) was recorded using a surface electromyography (EMG) system (Powerlab, ADInstruments, NSW, Australia) for seven participants. It has previously been suggested that the VL is the most appropriate muscle to monitor in the lower limb when studying the causes of fatigue in cycling trials (Hettinga et al. 2006). The skin over the muscle was shaved, abraded and then cleaned with ethanol. Two electrodes 10-mm apart were placed on the belly of the muscle. The raw EMG signal was relayed to an online computer (Chart Software ADInstruments, NSW, Australia) at a sample rate of 1 kHz and was filtered to reduce extraneous activity using band-pass filters with cut-off frequencies set at 20 and 400 Hz (Clancy et al. 2002). The EMG signal was rectified, and the high frequencies that were present in the rectified EMG were smoothed by integration. Integrated EMG (iEMG) was normalised to iEMG during cycling at 70%  $P\dot{V}O_{2\text{speak}}$  during the warm up, and expressed as a percentage of  $P\dot{V}O_{2\text{speak}}$ .

At 400-m intervals, participants were asked to report their rating of perceived exertion (Borg 1982) and their affective perceptions of the work rate using an 11-point bipolar scale (+5 [very good] to -5 [very bad]) with verbal anchors at two-point intervals (Rejeski 1985). A 5- $\mu$ l fingertip capillary blood sample was obtained at 800-m intervals, and assayed for B[La] concentration (Biosen, EKF Diagnostic, Barleben, Germany).

### Data analysis

Typical error and coefficient of variation were established using a spreadsheet (Hopkins 2000). Statistical analyses

were conducted using SPSS 16.0 (Chicago, IL, USA). Data are presented as mean ( $\pm$ SD). Data from the cycle ergometer and cardiorespiratory system were averaged and interpolated over 1-s intervals and time aligned. Intra-participant consistency of whole trial performance and physiological parameters was established using the coefficient of variation (CV) derived from the log-transformed data. Uncertainty in the difference between successive trials was expressed as 90% confidence limits (Hopkins 2000). A one-way ANOVA with three repeated measures was conducted to investigate differences in these variables and a fully factorial  $3 \times 10$  (trial versus distance covered) ANOVA was implemented to investigate differences in pacing strategy. Significant main effects were followed by a Bonferroni's post hoc test. Significance was accepted at  $P < 0.05$ . To describe the variability in the pacing strategy between trials, the power output data were assigned to 'bins' representing each 10% of the distance completed for each trial. Unbiased typical error (90% confidence limits) and change in the mean was calculated for each 10% segment from the raw scores.

### Results

Mean ( $\pm$ SD) power for trials 1, 2 and 3 was 335 (26) W; 336 (33) W and 335 (31) W, respectively. The CV for power was 2.3% (90% CL 1.7–3.3%) between trials 1–2 and 1.9% (90% CL 1.5–2.8%) between trials 2–3. There were no significant between trial main or interaction effects for any of the performance, physiological or perceptual parameters recorded (Table 1). Mean typical error across trials 1–3 for all variables was low (range 2.1–6.3%) and lower between trials 2–3 for all variables with the exception of cadence (Table 2). A reverse J-shaped pacing strategy was adopted for all three trials. The serial patterns of power output and speed across trials 1–3 are shown in Fig. 1. Typical error for each 10% bin was higher between trials 1–2 than 2–3, and typical error was greatest during the first and last 10% bins for both sets of trials (Fig. 2).

There were significant within trial differences for power output ( $F = 5.869$ ,  $p = 0.000$ ), ( $F = 5.773$ ,  $p = 0.00$ ),  $P_{\text{aer}}$  ( $F = 169$ ,  $p = 0.00$ ) and  $P_{\text{anaer}}$  ( $F = 42.243$ ,  $p = 0.00$ ). Pairwise comparisons revealed that power output was significantly greater at 100% than at 40 (90% CI 8.1–52.4), 50 (90% CI 9.6–50.4), 60 (90% CI 8.2–48.1), 70 (90% CI 12.7–50.1), 80 (90% CI 13.3–49.6) and 90% of the total distance (90% CI 8.2–46.6). Speed was significantly greater at 100% than 40 (90% CI 0.2–2 km h<sup>-1</sup>), 50 (90% CI 0.4–1.9 km h<sup>-1</sup>), 60 (90% CI 0.4–1.8 km h<sup>-1</sup>), 70 (90% CI 0.5–1.9 km h<sup>-1</sup>) 80 (90% CI 0.6–1.9 km h<sup>-1</sup>) and 90% of the total distance (90% CI 0.4–1.7 km h<sup>-1</sup>). Oxygen uptake was significantly

**Table 1** Mean (SD) for trials 1, 2 and 3 for all whole trial performance and physiological parameters

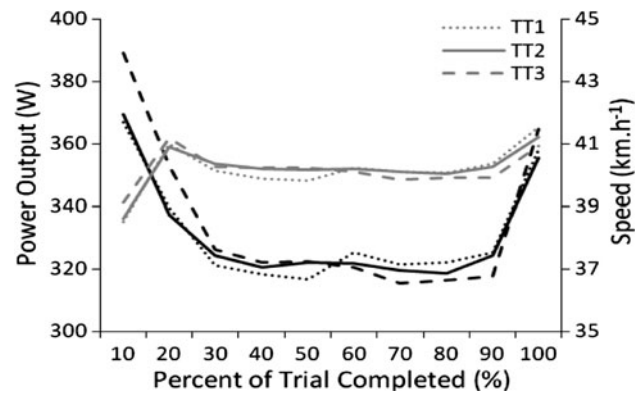
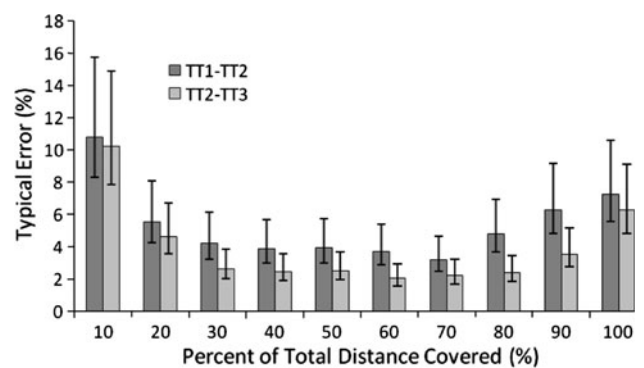
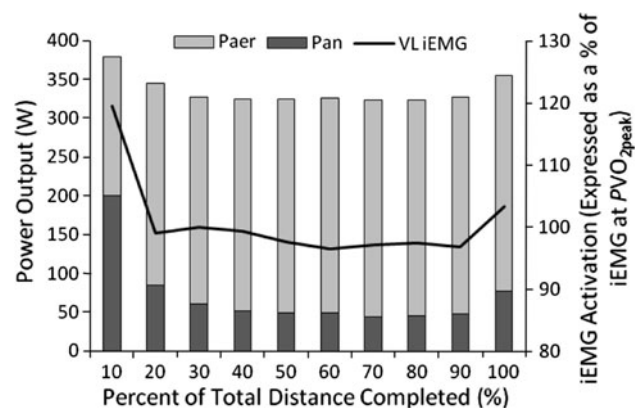
	Trial 1	Trial 2	Trial 3
Time to completion (S)	360.9 (10.1)	360.5 (12.9)	360.7 (11.8)
Speed	40.2 (1.1)	40.2 (1.4)	40.2 (1.3)
Power (W)	335 (26)	336 (33)	335 (31)
Cadence (RPM)	108 (7.4)	108 (8.2)	107 (10.3)
$\dot{V}O_2$ (L min <sup>-1</sup> )	4.44 (0.54)	4.41 (0.46)	4.40 (0.50)
Peak $\dot{V}O_2$ (L min <sup>-1</sup> )	4.79 (0.56)	4.75 (0.54)	4.80 (0.52)
$\dot{V}CO_2$ (L min <sup>-1</sup> )	4.96 (0.58)	5.01 (0.44)	4.94 (0.48)
RER	1.12 (0.06)	1.13 (0.06)	1.12 (0.04)
HR (BPM)	168 (10)	168 (11)	167 (12)
[La-]b (mmol L <sup>-1</sup> )	7.4 (1.7)	7.8 (1.7)	7.4 (1.9)
Peak lactate (mmol L <sup>-1</sup> )	10.8 (2.8)	11.1 (2.0)	10.6 (2.2)
RPE	16 (1)	17 (2)	16 (1)
Affect	-1 (2.0)	-1 (2.3)	-1 (2.1)
VL iEMG (%)	101.8 (6.5)	100.5 (8.4)	99.5 (7.9)

**Table 2** Typical error (%) based on the log-transformed data (90% confidence limits) for trials 2–1 and 3–2 and as a mean for whole trial performance and physiological parameters

	Trial 2–1	Trial 3–2
Time to completion	0.9 (0.7–1.4)	0.8 (0.6–1.2)
Speed	0.9 (0.7–1.3)	0.7 (0.6–1.1)
Power	2.3 (1.7–3.3)	1.9 (1.5–2.8)
Cadence	2.7 (2.1–3.9)	3.7 (2.9–5.5)
$\dot{V}O_2$	5.2 (4.0–7.7)	3.3 (2.5–4.8)
Peak $\dot{V}O_2$	5.1 (3.8–8.0)	2.4 (1.8–3.8)
$\dot{V}CO_2$	8.0 (6.1–11.9)	3.8 (2.9–5.6)
RER	4.2 (3.2–6.2)	2.9 (2.2–4.3)
HR	1.8 (1.4–2.6)	1.5 (1.2–2.3)
[La-]b	5.9 (4.5–8.7)	7.0 (5.3–10.4)
Peak [La-]b	16.2 (12.2–24.4)	9.6 (7.3–14.3)
RPE	7.3 (5.6–11.1)	6.0 (4.6–9.1)
VL iEMG	4.7 (3.26–9.04)	5.2 (3.6–10.0)

lower at 10 (90% CI 1.1–2 L min<sup>-1</sup>) and 20% (90% CI 0.08–0.5 L min<sup>-1</sup>) than at 100% of the total distance.

The serial pattern of RPE, affective response and [La-]b concentration during each time trial is shown in Fig. 3. There were significant within trial main effects for RPE ( $F = 85.387$ ,  $p = 0.00$ ), [La-]b ( $F = 71.911$ ,  $p = 0.00$ ) and affective responses ( $F = 17.070$ ,  $p = 0.00$ ). Pairwise comparisons revealed significant, cumulative increases at each 'bin' for both RPE and [La-]b. Affective response was significantly lower at 60 (90% CI 0.2–3.5), 70 (90% CI

**Fig. 1** Serial pattern of power output and speed during the first, second and third time trial**Fig. 2** Typical error (90% confidence limits) in the pacing strategy for trials 2–1 and 3–2 for each 10% of the trial**Fig. 3** Mean (trials 1–3) pattern of aerobic and anaerobic contributions to total power output and iEMG ( $n = 7$ )

0.3–3.7), 80 (90% CI 0.4–4.1) and 90% (90% CI 0.4–4.7) when compared with 10% of the total distance.

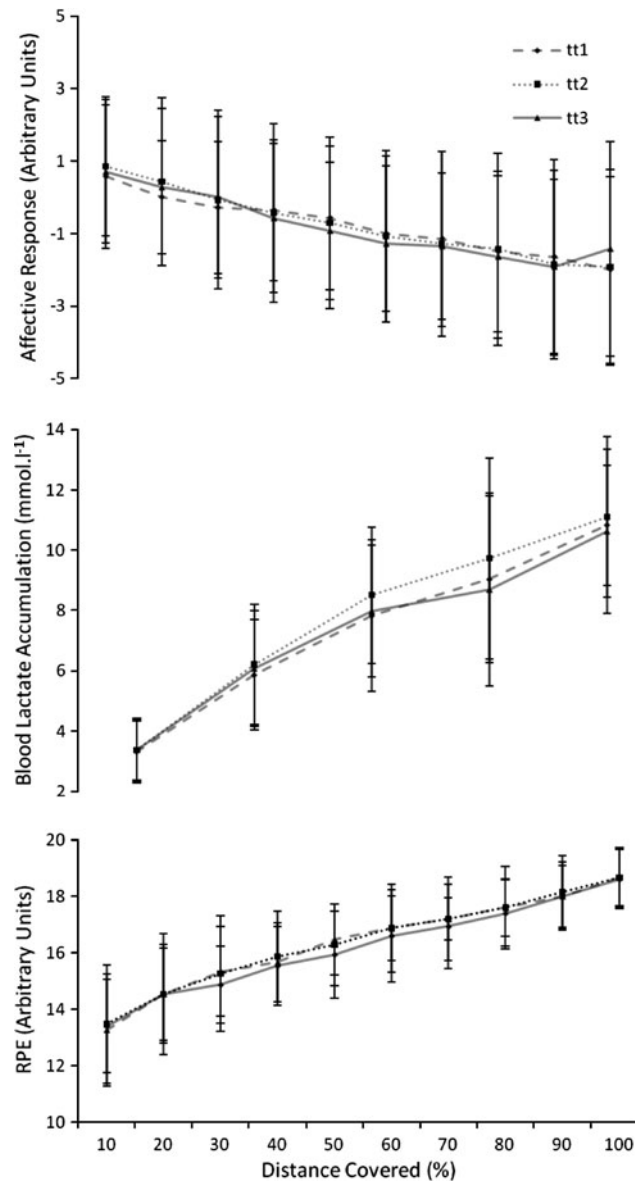
Mean iEMG and power output profiles for the remaining seven participants are shown in Fig. 3. A  $10 \times 3$  ANOVA with repeated measure revealed no between- or within-trial differences in iEMG.

## Discussion

This is the first study to have established the consistency of pacing strategies and their associated energetic and perceptual responses during simulated time trial competition. The main findings were that pattern of power output profile was consistent between trials that the variability in heart rate was low between trials ( $CV < 2\%$ ) and that the between trial variability in iEMG, cadence,  $\dot{V}O_2$ ,  $\dot{V}CO_2$ , RER and RPE were moderate ( $CV = 3\text{--}10\%$ ). These data suggest that trained cyclists are able to perform consistently in self paced trials, despite some individual variation between test and retest in perceptual and cardiorespiratory responses to self-paced exercise and choice of gear. The typical error scores for 10% bins showed that there was a reduction in variability between trials 2–3 compared with trials 1–2, indicating that there is a learning effect due to task familiarisation. It is therefore recommended that researchers monitoring pacing strategies across successive trials include a habituation trial to minimise systematic changes in pacing strategy between trials.

Coefficient of variation for both time to completion and speed were small when compared with power output; however, researchers should apply caution if evaluating these variables to make inferences concerning a change in exercise intensity between 4,000-m cycling time trials performed on the track. In track cycling where gradient, wind speed, ambient temperature, barometric pressure, altitude and riding surface remain stable, aerodynamic drag is the foremost resistance to movement (Atkinson et al. 2003), and the relationship between speed and the resulting drag force is exponential (Martin et al. 2006). Calculations of speed based on the modelling incorporate coefficients for aerodynamic drag and for the frontal area of the cyclist (Martin et al. 2006); however the development of fatigue is known to impair technical ability in cycling (Bini et al. 2010) and this reduction in technical ability might cause postural changes which increase frontal area, and are therefore less aerodynamically efficient. These changes in aerodynamics might alter performance time or speed on the track, but cannot currently be accounted for during stationary, laboratory-based cycle ergometry. Accordingly, the measurement of power output is advocated as the most valid parameter for monitoring changes in exercise intensity, rather than speed or time to completion.

Blood lactate concentration rose linearly during each trial, despite fluctuations in power output (Fig. 4). The low test–retest reproducibility of peak [La-]b ( $CV = 13.2\%$ ) reflects the sensitivity of [La-]b to the power output immediately preceding the measurement. The pattern by which cyclists rated their perceptual response to exercise was also consistent across trials. Perceived exertion



**Fig. 4** Serial pattern of RPE, affect response and blood lactate concentration during trials 1–3

increased linearly, and the final RPE reported at 4,000 m, was consistent with maximal effort ( $18.57 \pm 0.14$ ). This linear increase in RPE occurred regardless of changes in power output or cardiorespiratory parameters, and is consistent with the previous observations of the pattern of RPE in 20-km cycling time trials (Albertus et al. 2005). In the present study, there was a negative linear relationship between self-reported affect and distance covered. To date, the relationship between perceived exertion and the emotional response to exercise and pacing have received not much attention and further research is warranted.

In contrast to our findings, a previous study by Corbett et al. (2008) reported that whilst there were no changes in

performance between successive 2,000-m cycling time trials, pacing strategy in the second and third trials differed from the first in that power output was lower during the first quarter of the trial, enabling participants to retain an anaerobic energy reserve for use later in the trial. The discrepancy between studies could be explained by the use of well-trained participants in the present study, rather than recreational volunteers as used in the previous study. An alternative explanation is that the change in pacing strategy which was observed in the previous study could have been representative of the large variability which we have now shown exists at the start of a trial. This high typical error could be explained by a degree of uncertainty in the demands of the task early in the trial, which is resolved as the bout progresses (Lambert et al. 2005; Tucker 2009).

The high reproducibility of mean power output in the present study is comparable to a previous investigation into the reproducibility of 20-km cycling time trial where continuous feedback was given (Sporer and McKenzie 2007). Furthermore, the low CV between trials is comparable to that expected during actual performance in elite athletes (Paton and Hopkins 2006). Smallest worthwhile change in performance (1.8%) was similar to typical error between trials 2 and 3 (1.9%) therefore this test is rated as 'ok' (Pyne 2003). An improvement of 2% (>6 W) would be regarded as a meaningful change in performance as the difference is greater than both the CV and smallest worthwhile change. Hopkins (2000) has shown that the sample size requirements for a study using a particular protocol can be estimated from knowledge of the typical error and smallest worthwhile change. Using the equation described by Hopkins, the data presented in the current study indicate a minimum sample size requirement of ten participants to detect 80% power in a crossover or simple test-retest design. If a control group is used, then the minimum requirement is 38 participants.

Observations of the race profiles of elite individual pursuit cyclists have shown that following an initial all-out start, speed progressively deteriorates throughout the trial (Corbett 2009). In contrast, the pattern of power output distribution in the present study shows that participants adopted a reverse J-shaped pacing strategy for all three trials, which is characterised by an all-out start and a marked increase in power output towards the end of trial (Abbiss and Laursen 2008). Corbett et al. (2008) reported a similar observation amongst recreationally trained participants completing a 2,000-m cycling time trial, and our finding is also consistent with the previous observations of the pacing strategy selected by trained cyclists in longer duration cycling events (Tucker et al. 2004). Participants in the present study, although well trained, were not specialist 4,000 m individual pursuit competitors, which could account for the suboptimal pacing strategy.

An alternative explanation for the end spurt is that pacing strategy is centrally mediated in such a way that changes in power output occur secondary to changes in motor unit recruitment, in order to optimise performance whilst preventing catastrophic disturbances in homeostasis (St Clair Gibson et al. 2006). According to this model, the brain predetermines the optimal power output which can be maintained throughout the trial, and this power output is continuously monitored to avoid catastrophic failure of any physiological system, and to optimise performance (Noakes et al. 2005). The presence of an end spurt would, therefore, represent a miscalculation between perceived optimal performance and actual available motor reserve. Accordingly, towards the end of the bout a greater number of motor units become available and mechanical power can increase (Tucker et al. 2004).

Our finding that iEMG of the VL tracked the increase in power output towards the end of the trial seems consistent with this explanation. However, in a recent paper by Hettinga et al. (2006) during which a high-power output was enforced during the first half of a 4,000 m time trial, and the second half of the time trial was self paced, it was reported that iEMG in the VL increased significantly towards the end, even though power output decreased. This contradictory finding could be explained in part by differences in the anaerobic contribution towards power output. In the present study, anaerobic power significantly increased during the final 10% of the trial, suggesting that the cyclists monitored their energetic resources throughout the trial and maintained an anaerobic reserve. However, in the data reported by Hettinga et al. (2006), there was neither end spurt nor presence of increased anaerobic contribution to total power output. This is probably because the first half of the trial was not self paced; therefore, participants could not maintain an anaerobic reserve. This might suggest that the pattern of motor unit recruitment was largely attributable to changes in  $P_{\text{anaer}}$  rather than overall power output. This interpretation is consistent with the previous suggestions that possible mechanisms for pacing lie within the anaerobic energy system (Corbett et al. 2008; Foster et al. 2004; Hettinga et al. 2006).

It has previously been suggested that a mechanical power output at the start of the event exceeding that which is sustained for the rest of the trial might signify a mismatch between the anticipatory pacing strategy and the ability of the participant (Corbett et al. 2008; Foster et al. 2004). However, in the present study, we found that despite a significantly higher power output during the first 400 m than at any point later in the trial, mean speed was still lower at 400 m than at any other point during the trial. There was marginally higher speed at 800 m, but speed otherwise remained relatively constant throughout the trial. The proportion of mechanical power output required to

overcome rolling resistance decreases with increasing speed (Martin et al. 2006), Therefore, the high power output observed during the first 400 m is most likely due to the relatively high proportion of mechanical power needed to overcome the rolling resistance, and to quickly reach an optimal speed. In addition, there is evidence that a high power output at the start of the race is beneficial to overall race performance. Using an energy flow model, de Koning et al. (1999) have shown that the fastest time achievable for a 4,000-m cycling time trial requires a high initial mechanical power output followed by a constant power output after 12 s; and Jones et al. (2008) reported that the increase in  $\dot{V}O_2$  kinetics in trials associated with a high-initial mechanical power output spares endogenous phosphocreatine stores, enabling a greater anaerobic contribution throughout the remainder of the trial, which ultimately allows improved performance.

In conclusion, we have shown that cyclists are able to perform self-paced time trials consistently, despite small variations in the perceptual and cardiorespiratory response to the exercise between trials. Therefore, a laboratory-based, simulated 4,000 m time trial provides a reliable test of pacing strategy, performance, perception and cardiorespiratory parameters during exercise. Finally, a habituation trial is recommended to minimise systematic error in 4,000-m self-paced trials. In our study with well-trained male participants, a 2% improvement in performance would signify a real and worthwhile change in performance.

**Acknowledgments** The authors would like to thank the English Institute of Sport for supporting this project.

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