Respiratory frequency is strongly associated with perceived exertion during time trials of different durations

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Abstract

In order to provide further insight into the link between respiratory frequency (f_R) and the rating of perceived exertion (RPE), the present study investigated the effect of exercise duration on perceptual and physiological responses during self-paced exercise. Nine well-trained competitive male cyclists (23±3 yrs) performed a preliminary incremental ramp test and three randomized self-paced time trials differing in exercise duration (10, 20 and 30 min). Both RPE and f_R increased almost linearly over time, with a less pronounced rate of increase when absolute exercise duration increased. However, when values were expressed against relative exercise duration, no between-trial differences were found either in RPE or f_R. Conversely, between-trial differences were observed for minute ventilation ($\dot{V}_E$), $\dot{V}O_2$ and heart rate (HR), when values were expressed against relative exercise duration. Unlike the relationship between RPE and both $\dot{V}_E$ and HR, the relationship between RPE and f_R was not affected by exercise duration. In conclusion, respiratory frequency, but no other physiological parameter, shows a strong relationship to RPE and a similar time course, irrespective of exercise duration. These findings indicate that f_R is the best correlate of RPE during self-paced exercise, at least among the parameters and for the range of durations herein investigated.

Introduction

It is commonly recognized that perceived exertion plays a crucial role in regulating workload during self-paced exercise, even though different models have been developed to explain how the brain regulates pacing during exercise (de Koning et al., 2011; Marcora, 2010; Tucker, 2009). Both in time trial (TT) and time to exhaustion (TTE) protocols, the rating of perceived exertion (RPE) increases almost linearly over time, reaches nearly maximal values at the end of exercise, and shows a less pronounced rate of increase when absolute exercise duration increases (Eston, 2012). This progressive increase in RPE during exercise is a major feature of fatigue (Enoka & Stuart, 1992; Noakes, 2004). Interestingly, it has been observed that RPE shows scalar properties, i.e. in trials differing in exercise duration, similar RPE values are reported when RPE is expressed against relative exercise duration (Eston, 2012; Faulkner, Parfitt, & Eston, 2008; Joseph et al., 2008). This holds true, when some experimental interventions affecting TTE are administered, i.e. glycogen depletion (Noakes, 2004), prior exercise-induced fatigue (Eston, Faulkner, Gibson, Noakes, & Parfitt, 2007) or muscle damage (Davies, Rowlands, & Eston, 2009), and exposure to different ambient temperatures (Crewe, Tucker, & Noakes, 2008). However, it has been reported that RPE may not scale with time when protocols with considerably different exercise durations are compared, or when some deception strategies are used (Swart et al., 2009).

It has been recently reported that respiratory frequency (f_R), but no other physiological parameter, has a strong link with RPE during self-paced maximal-effort exercise, irrespective of the intermittent or continuous nature of the protocol (Nicolò, Bazzucchi, Haxhi, Felici, & Sacchetti, 2014). In addition, in that study a very good relationship between the two parameters was found in all the conditions tested (Nicolò, Bazzucchi, Haxhi et al., 2014). A strong link between RPE and f_R is even supported by the experimental interventions that attempted to dissociate ventilatory response from perceived exertion (Robertson, 1982). Similarly to RPE, f_R shows a progressive almost linear increase over time and reaches nearly maximal values at the end of exercise in a variety of exercise paradigms (Kift & Williams, 2007; Nicolò, Bazzucchi, Haxhi et al., 2014; Nicolò, Bazzucchi, Lenti et al., 2014). Moreover, f_R and RPE respond in a similar way to some experimental interventions that affect performance, such as prior exercise-induced muscle fatigue (Marcora, Bosio, & de Morree, 2008) or damage (Davies et al., 2009), and increases in body temperature (Hayashi, Honda, Ogawa, Kondo, & Nishiyasu, 2006).

Investigating the effect of exercise duration on perceptual and physiological responses may provide further insight into the link between f_R and RPE. To this end, in the present study three time trials differing in exercise duration (10 min, 20 min and 30 min) were compared. A time trial paradigm was used since RPE is recognized as playing a crucial role in regulating workload during self-paced exercise (de Koning et al., 2011; Marcora, 2010; Tucker, 2009). Besides, we avoided adopting a TTE protocol because it would have confounded the effect of exercise duration on physiological responses, since duration is a function of exercise intensity in a TTE paradigm. We hypothesized that during self-paced exercise of different durations, respiratory frequency, but no other physiological parameter, would have a similar time course as well as a strong relationship to RPE.

Methods

Participants

Nine male participants (mean ± SD: age 23±3 years, stature 1.77 ± 0.03 m, body mass 69 ± 6 kg) volunteered to participate in this study. All participants gave their written informed consent according to the declaration of Helsinki. The experimental protocols were approved by the Ethics Committee of the University of Rome Sapienza (243/14). All the participants were well-trained competitive cyclists (De Pauw et al., 2013) with a minimum of 4 years' cycling experience and 250 km training per week. They were asked to refrain from strenuous exercise, consumption of alcohol and caffeine for at least 24 h before each test.

Experimental overview

All testing was completed in the laboratory with a room temperature of 19–21°C and at the same time of day (± 2h). Participants reported to the laboratory on 4 separate occasions over a three-week period, with visits separated by at least 48 hours. In the first visit, participants performed a preliminary ramp incremental exercise test, followed by a familiarization trial. In the following visits, they performed in a random order three self-paced cycling time trials differing in exercise duration, i.e. 10 min, 20 min and 30 min. All the protocols were performed on an electromagnetically-braked cycle ergometer (Lode Excalibur Sport, Groningen, the Netherlands), whose setting was adjusted and recorded for each participant during the first visit to be reproduced in the following visits. Performance, physiological and perceptual responses were measured during all tests.

Preliminary test and familiarization trial

Before the incremental test was performed, the Borg 6–20 Rating of Perceived Exertion scale was presented to participants, and appropriate instructions about the scale were given according to established recommendations (Borg, 1998). Briefly, participants were asked to rate overall perceived exertion, which depends on both leg and respiratory effort. During the incremental test, they rated their perceived exertion every minute during exercise and immediately after exhaustion. Perceived exertion data obtained from this test served for familiarization purposes and were not used for further analysis.

The ramp incremental test to exhaustion was preceded by a 5 min warm-up at 100 W, 3 min of rest and 3 min pedalling at 20 W. The test consisted of a continuous ramped increase in work rate of 30 W*min^{-1}, starting from 20 W. Preferred pedalling cadence (95 ± 2 rpm) was selected by each participant and was kept constant throughout the test, which terminated when cadence fell by more than 10 rpm, despite strong verbal encouragement. During the test, pulmonary gas exchange was measured breath-by breath as described below. The maximal power output of the test (Pmax) was defined as the highest power output achieved at exhaustion, registered to the nearest 1 W, and the $\dot{V}O_2$max as the highest value of a 30-s average. Breath-by-breath data were averaged over 10 s and the gas exchange threshold (GET) was determined from a cluster of measures including 1) the first disproportionate increase in carbon dioxide output ($\dot{V}CO_2$) from visual inspection of individual plots of $\dot{V}CO_2$ versus $\dot{V}O_2$, 2) an increase in $\dot{V}_E$/ $\dot{V}O_2$ with no increase in $\dot{V}_E$/ $\dot{V}CO_2$, and 3) an increase in end-tidal O_2 tension with no fall in end-tidal CO_2 tension (Whipp, 2007). The power output value corresponding to the GET was estimated with account taken of the mean response time of the $\dot{V}O_2$ response, which was assumed to approximate

40 s (Whipp, 2007). After recovering from the incremental exercise test, participants were familiarized with the linear mode of the ergometer used in the time trials. In particular, participants were asked to vary cadence so as to understand the positive exponential relationship between power output and cadence proper of the linear mode (torque is linearly related to cadence, while power output is exponentially related to cadence). In other terms, participants experienced that small changes in cadence resulted in relatively important changes in power output.

Time trials

In visits 2-4, participants performed 3 time trials differing in exercise duration, i.e. 10 min (TT10), 20 min (TT20) and 30 min (TT30). In each trial, participants were asked to self-regulate the workload so as to achieve the maximal mean power output even possible. The time trials were performed with the ergometer set in the linear mode, also called rpm-dependent mode. For TT20 and TT30, the α linear factor of the ergometer (indicating the slope of the relationship between torque and cadence) was selected according to a previous study where a TT30 was performed by well trained competitive cyclists (Nicolò, Bazzucchi, Haxhi et al., 2014). Briefly, the α linear factor was set for each participant considering the 50% Δ (the power output halfway between the GET and Pmax, expressed in W) and the preferred cadence, according to the formula: $\alpha = 50\%\ \Delta/\text{preferred cadence}^2$. Since a TT10 lies within the severe intensity domain (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010) and a relatively high power output was expected, a slightly different formula was used to obtain the α linear factor for this trial: $\alpha = (50\%\ \Delta/\text{preferred cadence}^2) + 0.001$. In other terms, the slope of the relationship between torque and cadence was increased by 0.001, compared to the slope used for the other two time trials.

Before the time trials, a standardized warm up consisting of 3 min at 100 W, 6 min at 50% of Pmax, 1 min at 60% of Pmax, and 1 min at 100 W was performed. Three minutes of rest and 3 min pedalling at 20 W preceded the time trials.

With the exception of elapsed time and time to be completed, no feedback on performance or physiological measurements and no encouragement was given to participants during the time trials, to minimize external factor influence (Currell & Jeukendrup, 2008). Power output, and all the physiological parameters were measured continuously during exercise, while RPE was collected every minute.

Measurements

Pulmonary gas exchange, ventilatory parameters (f_R, minute ventilation and tidal volume) and heart rate were measured breath-by-breath using open-circuit indirect calorimetry (Quark b2, Cosmed, Rome, Italy). Appropriate calibration procedures were performed following the manufacturer's instructions.

Data analysis

When expressing physiological parameters against relative exercise duration, values were averaged over 1, 2 and 3 min for TT10, TT20 and TT30, respectively. Data averaged in this way were also used to relate f_R, minute ventilation ($\dot{V}_E$) and HR with RPE. Since RPE was measured at discrete points in time (every minute during exercise), values collected every 1, 2 and 3 min for TT10, TT20 and TT30, respectively, were considered to express RPE values as a % of total duration of exercise, to calculate mean values, and to obtain the relationship between RPE and the three above cited physiological parameters.

For all the physiological parameters reported in table 1 and all the time trials, the peak value was defined as the highest value obtained from a 30 s average. The same analysis was used to obtain physiological parameters maximum values from the incremental test.

Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics 20 (SPSS Inc, Chicago, Illinois, USA). A one-way repeated-measures ANOVA was used to analyze mean and peak values of performance, physiological parameters and RPE for the three time trials. In case of a significant effect of trial, the Bonferroni test was used as follow up analysis. Partial eta squared (η_p^2) effect sizes for the effect of trial were calculated. An effect of $\eta_p^2 \geq 0.01$ indicates a small, $\eta_p^2 \geq 0.059$ a medium and $\eta_p^2 \geq 0.138$ a large effect, respectively (Cohen, 1988). A two-way repeated-measures ANOVA (trial x time) was used to analyze the effect of trial on performance, physiological and perceptual parameters as a function of relative exercise duration. When the sphericity assumption was violated, the Greenhouse-Geisser adjustment was performed. Partial eta squared (η_p^2) effect sizes for the trial x time interaction and for the main effects of trial and time were calculated. In case of a significant interaction, a one-way repeated-measures ANOVA was used to test simple main effects of trial at different time points, with subsequent follow-up Bonferroni test performed in case of significant simple main effect. In case of a significant main effect of trial, the Bonferroni test was used as follow-up analysis. Within-subjects correlation coefficients (r) were computed for the correlations between RPE/f_R, RPE/ $\dot{V}_E$ and RPE/HR, using a previously described method (Bland & Altman, 1995). Briefly, this method adjusts for repeated observations within participants, by using multiple regression with "participant" treated as a categorical factor using dummy variables. A correlation coefficient and a P value were obtained considering the three time trials together, as well as for each time trial separately. A P value < 0.05 was considered statistically significant in all analyses. The results are expressed as mean (±SD).

Results

The $\dot{V}O_2max$ and the Pmax measured during the ramp incremental test were 4437 ± 472 mL*min^{-1} (65 ± 8 mL*kg^{-1}*min^{-1}) and 439 ± 34 W, respectively. $\dot{V}O_2$ and power output corresponding to the GET were 2842 ± 325 mL*min^{-1} and 210 ± 31 W, respectively.

Table 1 reports mean and peak values of performance and physiological parameters for the three time trials. An effect of trial ($P < 0.031$, $\eta_p^2 > 0.354$) was found for all the parameters reported in the table, except for RPE, f_R and HR_{peak}. Although HR_{mean} and $\dot{V}_{Epeak}$ showed a main effect of trial ($P = 0.023$, $\eta_p^2 = 0.375$ and $P = 0.030$, $\eta_p^2 = 0.355$, respectively), follow-up tests (Bonferroni) only indicated a statistical trend ($P = 0.080$ for TT10 vs. TT20 and $P = 0.084$ for TT10 vs. TT30, for HR_{mean} and $\dot{V}_{Epeak}$, respectively). In addition, no differences were found between f_{Rpeak} values from the 3 time trials and f_R maximum value registered during the incremental exercise test (60 ± 6).

No interaction, but significant main effects both of trial ($P < 0.001$, $\eta_p^2 = 0.954$) and time ($P < 0.003$, $\eta_p^2 = 0.504$) were observed for absolute power output values expressed against relative exercise duration (figure 1, panel A). Symbols in the figure show results of the Bonferroni follow-up analysis for the main effect of trial. The main effect of trial disappeared when power output values were normalized for the average power output of each trial (figure 1, panel B).

Figure 2 reports RPE and f_R responses as a function of absolute (panel A and C) and relative (panel B and D) duration of exercise. While both parameters showed an almost linear increase over time with a less pronounced rate of increase with absolute exercise duration, neither interaction effect nor main effect of trial were observed when expressing values against relative exercise duration. Conversely, a significant main effect of time ($P < 0.001$, $\eta_p^2 > 0.883$) was found for both RPE and f_R. Contrary to RPE and f_R, the parameters reported in figure 3, i.e. $\dot{V}O_2$, HR, $\dot{V}_E$ and tidal volume (V_T) all showed a main effect of trial ($P < 0.024$, $\eta_p^2 > 0.374$), time ($P < 0.001$, $\eta_p^2 > 0.801$) as well as an interaction ($P < 0.001$, $\eta_p^2 > 0.298$), when expressed against relative exercise duration (panel B, D, F and H). Symbols in the figure show results of the Bonferroni follow-up analysis.

Rating of perceived exertion was significantly related ($P < 0.001$) with f_R (r = 0.89), $\dot{V}_E$ (r = 0.80) and HR (r = 0.81) when the three time trials were considered together. Significant correlations (all P levels < 0.001) were also observed between RPE and the three physiological parameters in all the time trials considered separately, i.e. f_R (TT10 = 0.94; TT20 = 0.88 and TT30 = 0.90), $\dot{V}_E$ (TT10 = 0.91; TT20 = 0.83 and TT30 = 0.84), and HR (TT10 = 0.89; TT20 = 0.83 and TT30 = 0.80). These relationships are represented in figure 4, which shows that only f_R is linearly related with RPE across the entire duration of exercise, since the relationships between RPE/ $\dot{V}_E$ and RPE/HR are better described by a non linear function (parabolic). The figure also shows that RPE/ $\dot{V}_E$ and RPE/HR relationships - but not RPE/f_R relationship – are affected by exercise duration.

Discussion

The main original finding of the present study is that during time trials of different durations, respiratory frequency, but no other physiological parameter, shows a strong relationship and a similar time course to RPE. This indicates that f_R is the best correlate of RPE during self-paced exercise, at least among the parameters and for the range of durations herein investigated (10 min to 30 min). Since the increase in RPE during exercise is recognized as being a major feature of fatigue (Enoka & Stuart, 1992; Noakes, 2004), as well as playing a pivotal role in regulating pacing during exercise (de Koning et al., 2011; Eston, 2012; Marcora, 2010; Tucker, 2009), the present findings suggest that f_R is an important physiological parameter to be monitored during self-paced exercise.

Similarly to RPE, we found a progressive almost linear increase of f_R in all the trials, maximal f_R values reached at the end of exercise, and a decline in the rate of increase in f_R with the increase in absolute exercise duration. These data corroborate findings from previous studies that reported similar f_R responses during various exercise paradigms, i.e. continuous TTE (Davies et al., 2009; Kift & Williams, 2007), continuous TT (Wuthrich, Eberle, & Spengler, 2014), intermittent TTE (Nicolò, Bazzucchi, Lenti et al., 2014) and intermittent TT (Nicolò, Bazzucchi, Haxhi et al., 2014). However, very few studies, limited to the investigation of TTE protocols, reported f_R values expressed against relative exercise duration (Davies et al., 2009; Pires et al., 2011). Among these, Davies et al. (2009) pointed out that the effect of exercise-induced muscle damage on f_R response disappeared when f_R values were expressed against the % of TTE. In fact, these authors reported a similar response also for V_E and HR, being the between-trial difference in exercise duration too small, albeit significantly different (Davies et al., 2009).

This is the first study that systematically investigated, using a time trial paradigm, the effect of exercise duration on the relationship between RPE and the physiological parameters supposed to predominantly mediate perceived exertion. We found that f_R was better related to RPE than any other physiological parameter, and that the exercise duration did not affect the relationship between RPE/f_R, but it did affect the relationships between RPE/ $\dot{V}_E$ and RPE/HR. Our data also show that only f_R has a strong linear relationship with RPE across the entire duration of exercise. The relationships between RPE and both $\dot{V}_E$ and HR were better described by a non linear function, particularly when considering the entire duration of exercise.

While the majority of evidence linking HR with RPE is derived from correlational data, several experimental interventions managed to dissociate the two parameters (Robertson, 1982). Conversely, previous studies attempting to dissociate the respiratory response from RPE found in fact a strong link (Robertson, 1982). Notably, the link between $\dot{V}_E$ and RPE is primarily determined by f_R, but not V_T (Robertson et al., 1986). In the present investigation this is particularly evident with the manipulation of exercise duration. Indeed, since V_T, but not f_R, significantly decreased with exercise duration, $\dot{V}_E$ decreased accordingly, and the relationship between $\dot{V}_E$ and RPE was in turn affected. In this view, it is interesting to report that in a previous investigation $\dot{V}_E$ and RPE response did not dissociate when a continuous and different intermittent self-paced protocols - with the same exercise duration - were compared (Nicolò, Bazzucchi, Haxhi et al., 2014).

Importantly, the strong relationship found between f_R and RPE is consistent with our current understanding of the role of central command in the regulation of ventilation and perceived exertion during exercise. Central command is defined as the activity of premotor and motor areas of the brain related to voluntary muscle contraction (de

Morree, Klein, & Marcora, 2012). The corollary discharge of central command to the locomotor muscles projects both to medullary respiratory centres contributing to drive ventilation during exercise (Paterson, 2014), and to sensory areas of the brain generating perceived exertion (Berchicci, Menotti, Macaluso, & DiRusso, 2013; de Morree et al., 2012; de Morree, Klein, & Marcora, 2014; Enoka & Stuart, 1992; Marcora, 2009). Specifically, this corollary discharge is the sensory signal of the leg effort component of overall perceived exertion (Stendardi, Grazzini, Gigliotti, Lotti, & Scano, 2005). Since it has been reported that f_R, but not V_T, responds to central command to the locomotor muscles (Bell & Duffin, 2006; Thornton et al., 2001), a first neurophysiological link between f_R and perceived exertion is evident. Furthermore, the corollary discharge of central command to the respiratory muscles projects to sensory areas of the brain generating respiratory effort (de Morree & Marcora, 2015; Laviolette & Laveneziana, 2014; O'Donnell et al., 2007), another major component of overall perceived exertion (Marcora, 2009; Stendardi et al., 2005). This corollary discharge constitutes a second neurophysiological link between f_R and RPE. Within such neurophysiological framework, the strong association observed between f_R and RPE in the present and previous studies is unlikely to be spurious.

The strong correlation with RPE indicates that f_R is a valid physiological measure of effort during self-paced exercise. This confirms and extends previous findings that, among physiological parameters classically supposed to reflect physiological strain, f_R was the only parameter associated with RPE during both continuous and intermittent self-paced exercise (Nicolò, Bazzucchi, Haxhi et al., 2014). As suggested by these authors (Nicolò, Bazzucchi, Haxhi et al., 2014), monitoring f_R may have some advantages over RPE. Respiratory frequency is an objective physiological parameter that can be measured continuously during exercise. Conversely, RPE relies on self-report and can only be collected at discrete points in time.

Interestingly, we found that the power output values of the three time trials were virtually superimposed when data were normalized for the average power output of each trial. These results suggest that well-trained competitive cyclists use a similar pacing strategy across time trials of different durations. Although these findings may not apply to time trials with durations outside the range here investigated, normalized power output data similar to those observed in the present study have been reported for time trials around 1 h of duration (Skorski et al., 2015). However, it has to be acknowledged that these findings may not be generalized to recreational cyclists or untrained individuals.

Conclusions

The present study point out, for the first time, that during time trials of different durations, respiratory frequency, but no other physiological parameter, shows a strong relationship and a similar time course to RPE. This indicates that f_R is the best correlate of RPE during self-paced exercise, at least among the parameters and for the range of durations herein investigated. Since the increase in RPE over time is recognized as being a major feature of fatigue (Enoka & Stuart, 1992; Noakes, 2004) as well as playing a pivotal role in regulating pacing during exercise (de Koning et al., 2011; Eston, 2012; Marcora, 2010; Tucker, 2009), the present findings suggest that f_R is an important physiological parameter to be monitored during self-paced exercise. The mechanisms underlying the strong link between respiratory frequency and perceived exertion deserve further investigation.

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Figure captions

Fig. 1 Time course of absolute (A) and normalized (B) power output expressed as a function of relative exercise duration for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Values are mean ± SD. Letters indicate results of follow-up tests for the main effect of trial. (a) $P < 0.05$ vs. TT20; (b) $P < 0.05$ vs. TT3

Fig. 2 Perceived exertion and respiratory frequency expressed as a function of absolute (A and C) and relative (B and D) duration of exercise for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Values are mean ± SD

Fig. 3 $\dot{V}O_2$, HR, $\dot{V}_E$ and V_T expressed as a function of absolute (A, C, E and G) and relative (B, D, F and H) duration of exercise for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Values are mean ± SD. When expressed against relative duration of exercise, a significant interaction was observed for all parameters. Letters indicate results of follow-up tests. (a) $P < 0.05$ vs. TT20; (b) $P < 0.05$ vs. TT30

Fig. 4 Relationships between RPE/f_R, RPE/ $\dot{V}_E$ and RPE/HR for TT10 (closed circles), TT20 (open circles) and TT30 (closed triangles). Each symbol represent the mean value of all participants at each time point.

Fig 1.

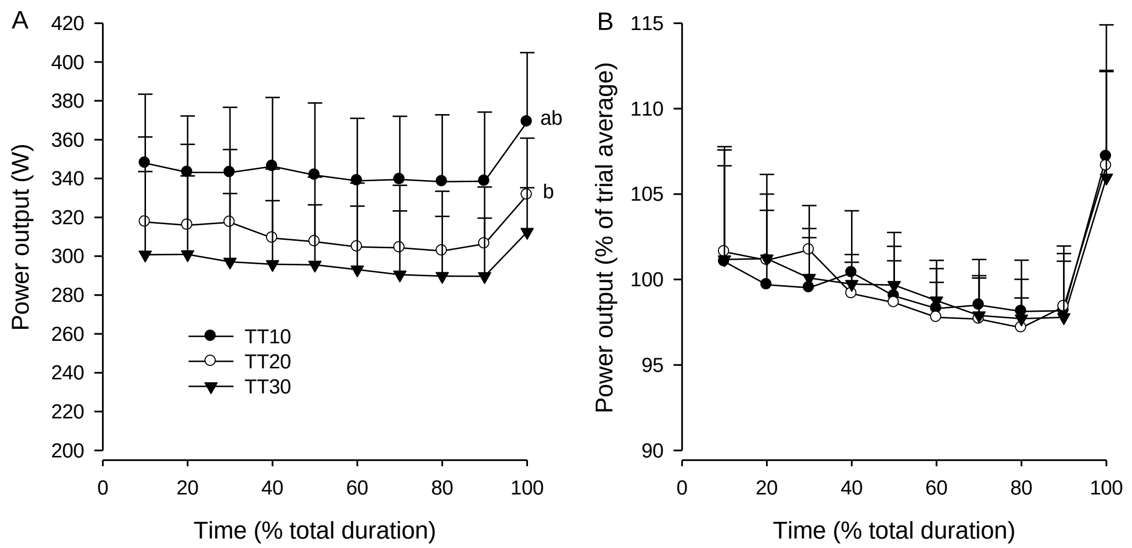

A
B
Power output (W)
Power output (% of trial average)
Time (% total duration)
Time (% total duration)
ab
b
TT10
TT20
TT30

Fig. 2

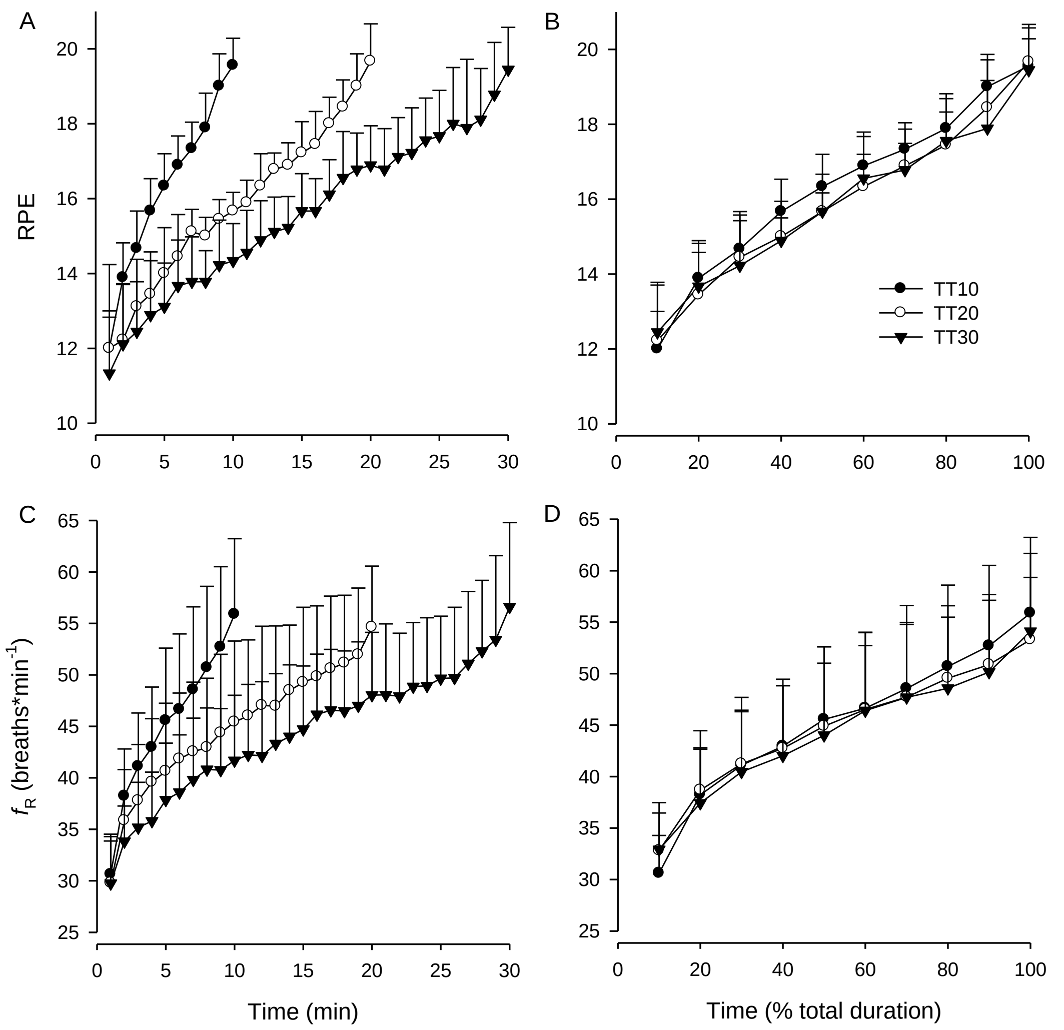

A
B
C
D
RPE
f_R (breaths*min^{-1})
TT10
TT20
TT30
Time (min)
Time (% total duration)

Fig. 3

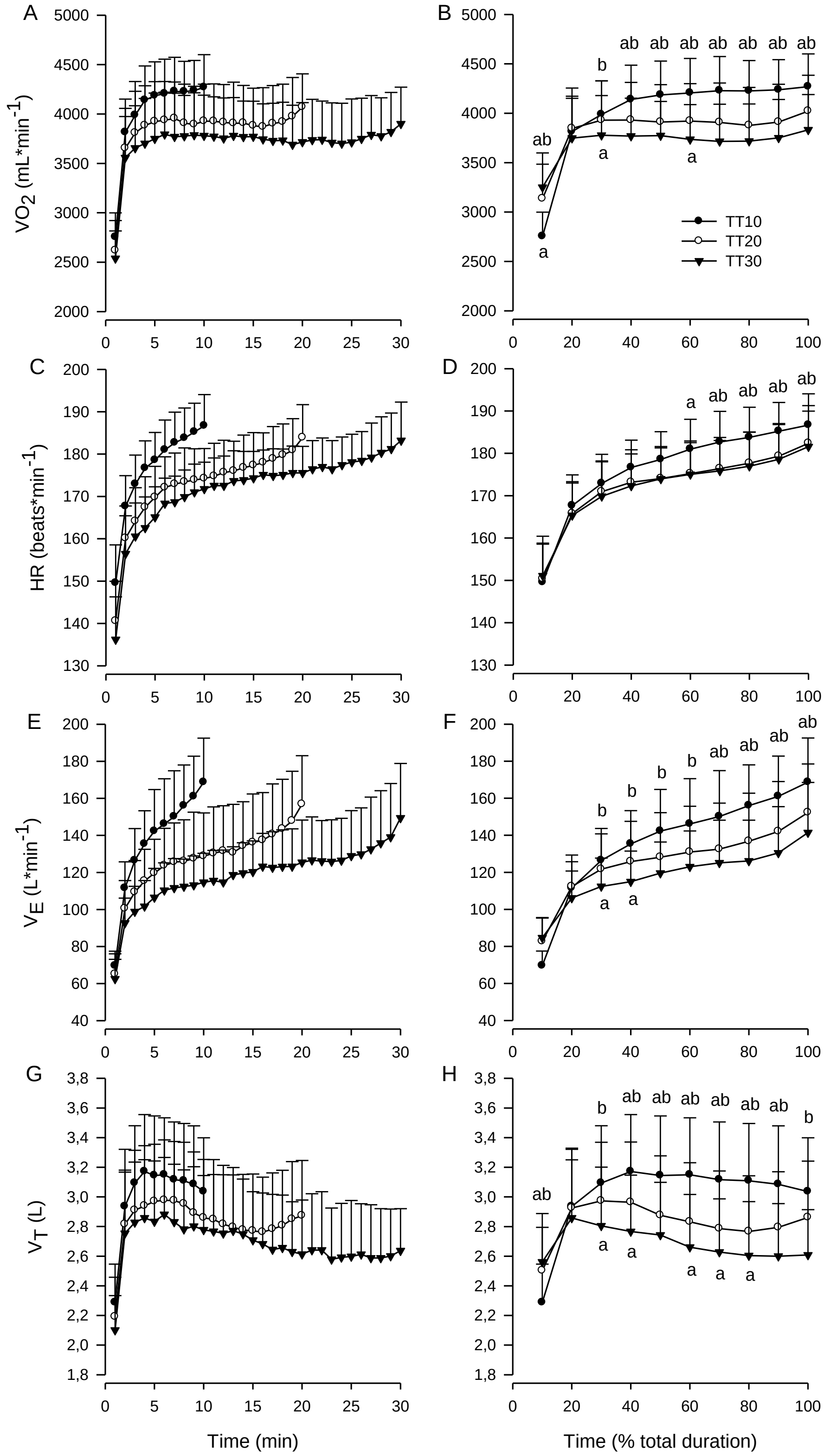
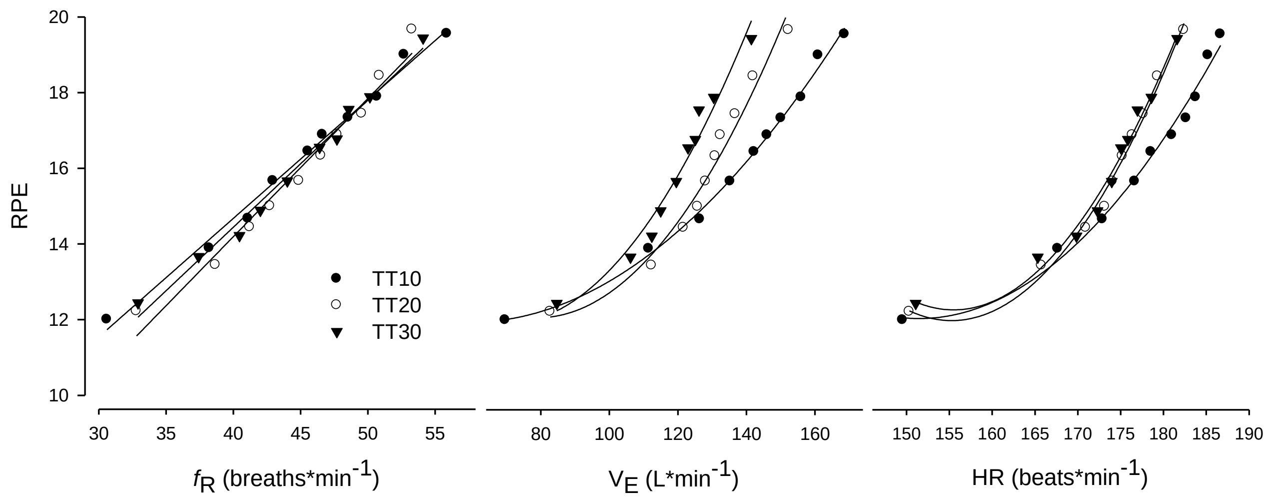

A
B
C
D
E
F
G
H
VO2 (mL*min-1)
HR (beats*min-1)
VE (L*min-1)
VT (L)
TT10
TT20
TT30
ab
b
a
Time (min)
Time (% total duration)

Fig. 4


RPE
20
18
16
14
12
10
TT10
TT20
TT30
30 35 40 45 50 55
fR (breaths*min-1)
80 100 120 140 160
VE (L*min-1)
150 155 160 165 170 175 180 185 190
HR (beats*min-1)