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ORIGINAL ARTICLE

Prediction of performance reduction in self-paced exercise as modulated by the rating of perceived exertion

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Abstract
Purpose Rating of perceived exertion (RPE) is a scale of exercise difficulty and has been hypothesized to be a regulator of work rate during self-pacing. The goal of this work was to develop a dynamic prediction of RPE and to characterize the control strategy employed to reduce work rate during self-paced exercise using RPE as feedback.
Methods Training and test data were acquired from the literature to develop a linear regression of RPE as a function of four physiological variables: core temperature, mean-weighted skin temperature, metabolic rate, and integral of relative oxygen consumption ($R^2 = 0.85$). A thermoregulatory model was used to predict core and mean-weighted skin temperature. Utilizing self-paced cycling and running data from the literature, we characterized reductions in work rate with a proportional-derivative control algorithm with RPE as feedback.
Results Bland–Altman analysis revealed the necessity to parameterize RPE equations for untrained and endurance-trained individuals. Afterwards, dynamic predictions of RPE were accurate for a wide range of activity levels and air temperatures for walking, running, and cycling (LoA and bias of 2.3 and −0.03, respectively). For self-paced exercise, the control algorithm characterized the trend and magnitude of work rate reductions for cycling and running, and showed regulated RPE to be less conservative for shorter vs. longer duration exercise.
Conclusions A novel methodology to characterize self-paced work intensity, based upon dynamic physiologic response, is provided. The complete model is a useful tool that estimates performance decrements during self-paced exercise and predicts tolerance time for exhaustive fixed-rate exercise.

Keywords Self-pacing · Rating of perceived exertion · Exercise performance · Thermoregulation · Dynamic control

Abbreviations

HR	Heart rate
K_d	Derivation controller gain
K_p	Proportional controller gain
LoA	Limits of agreement
MET	Metabolic equivalent of task
MR	Metabolic rate
RMSD	Root mean square deviation
RPE	Rating of perceived exertion
RPE_{reg}	Regulated RPE
SD	Standard deviation
T_{core}	Core temperature
$\overline{T}_{sk}$	Mean-weighted skin temperature
TRM	Thermoregulatory model
$\dot{V}O_{2,max}$	Maximum volumetric oxygen consumption

Introduction

Understanding the impact of physiological constraints and environmental stressors on exercise performance is

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important in both military and civilian sectors. For military leaders it is important to quantify performance limitations to properly plan missions and to assess physiological limitations for military personnel. For competitive sports it is important to understand how athletes can achieve peak performance while ensuring that physiological injury does not occur; in some industrial occupations, high metabolic demands and extreme conditions require an understanding of the physiological demands of the work to develop appropriate safety guidelines.

Fixed-rate and self-paced activity are common experimental models employed to assess exercise performance (Schlader et al. 2011c). For exhaustive fixed-rate exercise, the main measure of performance is the observed time to exhaustion. In most real world applications, however, exercise does not occur at a fixed rate; instead an overall activity is prescribed and conducted at a self-selected work rate (i.e., self-paced activity). For self-paced activities, performance is measured as either the time to complete the task or the amount of work that is generated during the task. Performance reductions have been observed in both fixed- and self-paced exercises with increased air temperature (Galloway and Maughn 1997; Peiffer and Abbiss 2011). Fixed-rate exercise has been correlated to a critical core temperature when exercising in the heat (González-Alonso et al. 1999; Maughan et al. 2012). In contrast to fixed-rate exercise, self-pacing permits the subject to reduce their work rate in hotter conditions and is likely an attempt to limit the adverse effects of exercise in the heat, to ensure that the task is completed before reaching deleterious physiological limits (Tatterson et al. 2000; Tucker et al. 2004). Self-pacing has been suggested to be a spontaneously occurring protective mechanism to limit physiological strain (Schlader et al. 2011c). Studies have shown that reductions in work output can occur early on during exercise before dangerous levels of thermal strain are indicated (Tucker et al. 2004; Périard et al. 2011).

How the work rate in self-paced exercise is chosen has been debated in the literature (Périard et al. 2012; Tucker et al. 2006; Pageaux 2014). Tucker et al. (2006) have hypothesized that an 'anticipatory' response in work rate is modulated by body heat storage rate while Périard et al. (2011) have hypothesized that the power output reductions seen in hot conditions are instigated by cardiovascular strain. It has been shown across studies that exercise in hot conditions is associated with significant increases in skin temperatures when compared with temperate conditions, and it has been postulated that the increased cardiovascular demands associated with elevated skin temperatures mediate the reduction in power output seen in hot conditions (Périard et al. 2011). It has also been suggested that power output selectivity may be related to the rise in core temperature (Peiffer and Abbiss 2011; Tatterson et al. 2000) or the rate of rise of core temperature (Peiffer and Abbiss 2011). Another hypothesis is that work rate reductions occur in the heat to improve heat exchange between the body and environment (Schlader et al. 2011d). Additionally, a psychobiological model has also been postulated where exercise is regulated by physiological and psychological factors (Pageaux 2014).

Another possible influence on selected self-paced work rate is perceived exertion (Tucker 2009). Manipulation of work rate via perceived exertion unifies aspects of the above theories since perceived exertion has been found to be highly correlated to thermal physiological measures and exercise intensity (Pandolf et al. 1972). In general, perceived exertion is an integration of various afferent feedbacks from peripheral (related to working muscle/joints), metabolic, cardio-respiratory, thermal, and central nervous system (CNS) components, and is also affected by psychological factors (Borg 1982; Eston 2012; Morgan 1973; Noble et al. 1973). Previous multivariable regression analysis have shown that physiological variables including skin temperature, core temperature, and oxygen consumption ($\dot{V}O_2$) explained between 75 and 84 % of the variance in perceived exertion in hot conditions (Noble et al. 1973). In this study, they concluded that perceived exertion is comprised of sensations that are the outcome of physiological processes, which are incorporated by the subconscious brain.

Perceived exertion can be quantified using the rating of perceived exertion (RPE) scale which is a perceptual-based rating scale of exercise difficulty. The most commonly used RPE scale is the 15-point Borg rating, which measures exercise difficulty on a scale from 6 to 20, with 6 being the lightest and 20 being the hardest rating (Borg 1982). RPE has been shown to rise during exercise and reach maximum levels at exercise termination; thus, it is one of the main indicators of exercise intolerance (Crewe et al. 2008; Eston et al. 2007; Horstman et al. 1979a). The rate of change of RPE has been shown to be a sensitive predictor of time to exhaustion, and is similar between experimental interventions when expressed as a percentage of total exercise time (Crewe et al. 2008; Eston et al. 2007; Horstman et al. 1979a; Noakes 2004).

It has been suggested that RPE is more than an indicator of exercise exertion; it is also a regulator of work rate during self-paced activity to ensure that RPE does not reach near-maximum levels before exercise completion (Tucker 2009; Tucker et al. 2004; de Koning et al. 2011). This is backed by self-paced studies that show little difference in RPE response for widely varying work outputs between control and experimental interventions such as changes in ambient temperature, muscle glycogen, and oxygen content (Tucker 2009). Furthermore, in a study by de Koning et al. (2011), the probability of altering velocity during nine different competitive running and cycling performances was highly correlated to the current RPE and percentage of remaining event duration.

The primary aim of this study was to characterize and implement a control strategy that modulated work rate during self-paced exercise. The major hypothesis was that alterations in work rate could be solely controlled using RPE as a feedback variable. It was also hypothesized that RPE would be highly correlated to a minimum amount of measurable physiological variables related to thermoregulation (core and mean-weighted skin temperature) and exercise (metabolic rate and integral of $\%\dot{V}O_{2,\max}$) enabling a dynamic prediction of RPE. The model developed here characterizes adaptations in work output during whole body self-paced exercise for various intensities and environmental conditions.

Methods

A dynamic prediction of RPE was developed as a correlation of various physiological variables (core temperature, mean-weighted skin temperature, metabolic rate, and integral of $\%\dot{V}O_{2,\max}$) using multivariable linear regression analysis. To characterize the reductions in work rate utilizing RPE as feedback, a proportional-derivative (PD) control strategy was determined.

Thermoregulation model overview

The dynamic core and mean-weighted skin temperatures in the RPE calculation were predicted from an anatomical physics-based Thermoregulation Model (TRM), which was developed by the authors. The TRM is primarily based on the past efforts of Fiala et al. (2001) and Stolwijk (1971) and includes passive (i.e., internal conduction) and active (i.e., sweating and vasomotor control) components that govern heat exchange within the human body and with the environment. Predictions of core temperature and mean-weighted skin temperature were shown to be accurate for a wide range of air temperatures (10–45 °C), activity levels (2.6–8.8 METs, where 1 MET equals 58.2 W/m^2) and clothing (minimal to 2.4 clo). A full description of the TRM and validation results is provided in the supplementary materials.

RPE prediction algorithm

Previous work (Noble et al. 1973) has shown that RPE can be linearly regressed as a function of physiological variables, thus requiring a set of training data for development of the RPE prediction. It was hypothesized that core temperature, mean-weighted skin temperature, and activity level would have a large effect on RPE based on the work of Noble et al. (1973). Therefore, fixed-rate and self-paced exercise studies that reported the activity level and time response of core temperature, mean-weighted skin temperature, and Borg 15-point scale RPE were chosen (Castle et al. 2012; Hasegawa et al. 2005; Janse De Jonge et al. 2012; Lee et al. 2008; Mündel et al. 2007; Ping et al. 2011; Pivarnik et al. 1992; Watson et al. 2004; Oliver et al. 2009). Cycle ergometer exercise datasets were identified with the exception of two treadmill datasets (Oliver et al. 2009; Ping et al. 2011). The training datasets were limited to subjects with a hydration status of less than 2 % body weight to minimize dehydration effects (Saunders et al. 2005). Training data also included women exercising in follicular and luteal phases (Janse De Jonge et al. 2012; Pivarnik et al. 1992). Experiments that involved supplementations (e.g., caffeine ingestion and carbohydrate replacement) were excluded as they have been shown to affect the RPE response (Backhouse et al. 2011; Carter et al. 2005; Casal and Leon 1985; Doherty and Smith 2005; Kang et al. 1996; Utter et al. 1997, 1999). The training data utilized subjects who were healthy and active but not endurance trained.

Parametric analysis showed that RPE was highly correlated to four variables: (1) change in core temperature (ΔT_{core}), (2) change in mean-weighted skin temperature ($\Delta\overline{T}_{\text{sk}}$), (3) metabolic rate (MR), and (4) the integral of $\%\dot{V}O_{2,\max}$ $\left(\int \%\dot{V}O_{2,\max}\right)$:

$$\text{RPE} = 5.65 + 1.21 \times \Delta T_{\text{core}} + 0.72 \times \max(\Delta\overline{T}_{\text{sk}}, 0) + 0.0048 \times \text{MR} + 9.74 \times 10^{-4} \int \%\dot{V}O_{2,\max} \times \text{d}t \quad (1)$$

Other predictor variables including heart rate (HR) were considered but ultimately eliminated from the final equation. The variables ΔT_{core} and HR explained much of the variance in RPE ($R^2 = 0.74$); however, MR along with ΔT_{core} explained slightly more of the variance in RPE ($R^2 = 0.75$) than ΔT_{core} and HR, and HR was essentially redundant with the inclusion of MR. The combination of ΔT_{core}, $\Delta\overline{T}_{\text{sk}}$, and MR alone explained a high amount of variance in RPE ($R^2 = 0.81$), but tended to underestimate RPE near the end of exercise. The response of variables such as ΔT_{core} and $\Delta\overline{T}_{\text{sk}}$ eventually plateau, especially during compensable heat stress, meaning an RPE prediction using these variables alone would also plateau. However, due to the continuously increasing nature of RPE response during exercise, it was hypothesized that there is a gradual increase in RPE due to exercise magnitude and duration. Thus, the $\int \%\dot{V}O_{2,\max}$ was included in the final prediction, which explained more of the variance in RPE when included with ΔT_{core}, $\Delta\overline{T}_{\text{sk}}$, and MR ($R^2 = 0.85$) than when not included. In the final equation, it was also assumed that a mean-weighted skin temperature below its thermoneutral temperature would not subtract from RPE. The predictor variables were tested for multicollinearity by calculating variance inflation factors (VIF). For each predictor variable, VIF was less than 10, which indicated that multicollinearity did not significantly influence the least squares estimate (Kutner et al. 2004).

Verification of the RPE prediction algorithm

Additional datasets were acquired to provide an independent test of the RPE correlation prediction's accuracy and applicability. For this purpose, exercise studies that reported environmental conditions, quantified activity level, and provided the time response of RPE were acquired from the literature. The test data included studies that provided the time response of core temperature, but not mean-weighted skin temperature, and also included studies that did not provide any body temperature traces. The average environmental, activity level, clothing, and subject conditions reported in the studies were input into the TRM to determine core and mean-weighted skin temperatures responses, which were then used to calculate RPE response using Eq. (1). Root mean square deviation (RMSD) between model predicted and observed core temperature (if available) and RPE response were also calculated to assess model accuracy (Haslam and Parsons 1994):

$$\mathrm{RMSD} = \left[\left(\sum_{i=1}^{n} (X)_i^2 \right) \Big/ n \right]^{1/2}$$

where X is the difference between the measured and predicted variable for n data points. Since core temperature is an input for the RPE prediction, it was important to assess its agreement using RMSD calculation as well as RPE itself. It has been suggested that RMSDs below 0.5 °C for core temperature indicate useful predictions (Wissler 1988), and this criteria was used to assess TRM agreement with experimental data. For RPE, maximum standard deviations reported in the literature were typically around 2, so an RMSD below this value was assumed to be acceptable.

Additionally, Bland–Altman plots were also constructed to further determine the limits of agreement (LoA) and bias between predicted and observed RPE (Bland and Altman 1999) and to characterize weaknesses in Eq. (1). LoA, calculated as $\pm 1.96 \times$ SD of the differences between predicted and observed, determines the range of error that 95 % of predictions should fall within. It has been previously suggested that Bland–Altman plots are not useful for perceptual-based measures; however, this is in regards to the reliability of repeated measurements with scales that do not feature decimal values (Garcin et al. 2003). For this study, however, Bland–Altman plots were useful in comparing predicted and measured values, especially since the predicted RPE is continuous (i.e., has decimals).

Pacing control algorithm

An algorithm was developed to characterize a control strategy that governed work rate reductions during self-paced exercise, using the previously described RPE prediction (see "RPE prediction algorithm") as a feedback variable. As shown below in the frequency domain, we assumed standard proportional-derivative corrective action with metabolic rate (ΔMR in W) was taken to control RPE as follows:

$$\Delta \mathrm{MR} = \left[K_{\mathrm{p}} \left(\mathrm{RPE}_{\mathrm{reg}} - \mathrm{RPE} \right) + K_{\mathrm{d}} s \left(\mathrm{RPE}_{\mathrm{reg}} - \mathrm{RPE} \right) \right] \frac{1}{5s + 1} \quad (2)$$

where $\mathrm{RPE}_{\mathrm{reg}}$ is the regulated RPE value assumed to be constant, ΔMR is the change in metabolic rate (only negative changes were allowed), K_{p} is a proportional gain equal to 250 (W/RPE units), and K_{d} is the derivative gain equal to 3,750 (W min/RPE units). The control gains and $\mathrm{RPE}_{\mathrm{reg}}$ were fitted from self-paced exercise data acquired from the literature. In particular, self-paced cycling and running studies that provided the time response of RPE and cycling power output or running speed were obtained. The environmental, clothing, and subject conditions from these studies were used to simulate the TRM to determine core and mean-weighted skin temperatures for the RPE prediction. For self-paced cycling and running, the initial power output or running speed provided by the studies was used at the start of the simulation. Afterwards, the control algorithm drove the power output or running speed as described above. For cycling, metabolic rate was calculated from power output by assuming a net mechanical efficiency of 20 % (Caretti 1994; Bijker et al. 2001). For running, speed was converted to metabolic rate using an equation developed by Givoni and Goldman (1971). Comparisons of model vs. data were made to assess the agreement of RPE, power output, and running speed responses.

Values for $\mathrm{RPE}_{\mathrm{reg}}$ were fitted for each experimental case to best match the observed work rate reductions, whereas the fitted control gains were constrained to be the same values across experimental cases. Some of the self-paced studies consisted of cases where work rate remained level or slightly increased; these cases were included in the analysis to characterize when controlled reductions in work rate should NOT be taken. In these cases, the lowest values for $\mathrm{RPE}_{\mathrm{reg}}$ resulting in no reduction in work rate (using the same control gains) were determined. Additionally, a single pole, low pass filter with unity gain and a time constant of 5 min was applied to better match the data as shown in Eq. (2). The need for the filter generally indicated that the self-pacing data exhibited lags in the metabolic rate changes relative to the error.

One often seen characteristic of pacing exercise during performance trials is a final end-spurt before exercise completion (Tucker 2009; Abbiss and Laursen 2008). We did

Table 1 Air temperature (T_{air}), relative humidity (rh), exercise intensity as a percentage of $\dot{V}O_{2,max}$, and RMSDs (between predicted and observed RPE) for exercise test data that provided core temperature but not mean-weighted skin temperature responses

References	Exercise mode	T_{air} (°C)	rh (%)	$\%\dot{V}O_{2,max}$	RMSD		
					T_{core} (°C)	RPE[a]	RPE[b]
Ansley et al. (2008)	Cycling	29	50	75	0.051	2.71	–
Beis et al. (2011)[c]	Running	10	69	60	0.11	1.98	0.98
Carter and Gisolfi (1989)[c]	Cycling	32	22	59	0.54	3.93	1.07
Carter et al. (2005)[c]	Cycling	35	30	58	0.30	2.36	1.08
Coles and Luetkemeier (2005)	Cycling	21–23	40	70	0.45	3.33	–
Hobson et al. (2013)	Cycling	30	30	55	0.27	0.40	–
Ishijima et al. (2009)	Cycling	28	50	55	0.24	0.93	–
Mündel et al. (2006)	Cycling	34	28	68	0.13	0.93	–
Muñoz et al. (2012)[c]	Running	33	30	30	0.21	2.45	1.41
Sheffield-Moore et al. (1997)[c]	Cycling	35	21–35	60	0.35	2.20	0.54
Sheffield-Moore et al. (1997)[c]	Cycling	35	70	60	0.088	1.10	1.46
Smolander et al. (1990)	Walking	21	43	31	0.24	1.47	–
Smolander et al. (1990)	Walking	30	80	31	0.10	1.31	–
Smolander et al. (1990)	Walking	40	20	31	0.18	1.12	–
Strachan et al. (2004)	Cycling	32	60	60	0.33	0.90	–
Tyler et al. (2010)	Running	30	53	60	0.29	1.26	–

[a] Predicted RPE was calculated from Eq. (1)

[b] Predicted RPE includes corrections for endurance-trained individuals (Eq. (3))

[c] Studies with endurance-trained subjects

not attempt to predict the work rate changes seen during the end-spurt focusing on performance decrement only. However, prior to an end-spurt, a plateau in work rate was typically observed, which was assumed to occur because the end of exercise was near and subjects gauged that further reductions in work rate were not needed. To model this plateau, the derivative gain was reduced continuously to zero starting 15 min prior to exercise completion. This reduction in derivative gain was assumed to occur only if distance or time feedback was provided to the subjects. A number of studies have shown that an end-spurt occurred only when distance feedback was provided (Abbiss and Laursen 2008; Micklewright et al. 2010).

Results

RPE prediction test

The RPE prediction algorithm (Eq. 1) was evaluated against a dataset that provided RPE and core temperature traces, and was shown to be accurate for the majority of data (10 of 16 RMSD values below 2), see Table 1. The prediction greatly underestimated the observed RPE response for the study by Coles and Luetkemeier (2005) but is likely the result of the experiment being conducted at high altitude as discussed later. The prediction overestimated the observed RPE response for the Carter and Gisolfi (1989), Carter et al. (2005), Muñoz et al. (2012), and Sheffield-Moore et al. (1997) studies and can be attributed to the fitness level as all subjects were trained endurance athletes. The Ansley et al. (2008) study analysis (RMSD of 2.71) still fell within the experimental standard deviation for all data points. Core temperature RMSDs were all below 0.5 °C except for one study (Carter and Gisolfi 1989), which was not far outside the limit.

A second test dataset was acquired to further assess the validity of the RPE prediction and was comprised of exercise studies that provided RPE traces but no core temperature or mean-weighted skin temperature traces. See Table 2 for boundary conditions and RMSDs of RPEs. The RPE predictions were accurate for 19 of the 27 cases analyzed (RMSD values below 2), including a study comprised of all female subjects Loftin et al. (2009). However, as with the previous dataset, the prediction significantly overestimated RPE for another five cases involving endurance-trained athletes, a trend that was also seen for the previous test dataset and will be analyzed in the next section.

Correction to the RPE prediction for endurance-trained persons

Bland–Altman plots were used to show the necessity to account for training in predicting RPE accurately. Bland–Altman plots for all test data [excluding Coles and Luetkemeier (2005) due to the possible effects of high altitude] were constructed to determine the LoA, the percentage of predicted RPE values within the acceptable ±2 range, and the bias associated with the prediction. When using Eq. (1), 68 % of the predicted values fell within the acceptable range with a majority overshooting the test data (Fig. 1); and the LoA and bias of the RPE prediction was 3.6 and 0.95, respectively. However, when data

Table 2 Air temperature (T_{air}), relative humidity (rh), exercise intensity as a percentage of $\dot{V}O_{2,max}$, and RMSDs (between predicted and observed RPE) for exercise test data that did not provide any body temperature responses

References	Exercise mode	T_{air} (°C)	rh (%)	$\%\dot{V}O_{2,max}$	RMSD	
					RPE[a]	RPE[b]
Backhouse et al. (2005)[c]	Cycling	20[d]	40[d]	70	3.29	0.41
Backhouse et al. (2007)[c]	Running	20	47	70	3.69	1.09
Backhouse et al. (2011)[c]	Cycling	21	52	73	2.68	0.35
Below et al. (1995)[c]	Cycling	31	54	21	0.91	1.36
Casal and Leon (1985)[c]	Running	20[d]	40[d]	73	0.59	1.39
Corbett et al. (2009)	Running	20	50	NR	0.64	–
Glass et al. (1994)	Cycling	18	60	80	1.30	–
Glass et al. (1994)	Cycling	25	50	80	1.32	–
Glass et al. (1994)	Cycling	31	55	80	0.72	–
Kang et al. (1996)[c]	Cycling	20[d]	40[d]	70	4.07	0.80
Loftin et al. (2009)	Running	22	25	68	0.83	–
Loftin et al. (2009)[e]	Running	22	25	76	0.68	–
Minniti et al. (2011)[c]	Running	30	53	60	1.65	0.27
Peltier et al. (2011)[c]	Running	20[d]	40[d]	67	3.82	0.74
Perry et al. (2001)	Cycling	20[d]	40[d]	32	0.13	–
Perry et al. (2001)	Cycling	20[d]	40[d]	38	1.00	–
Perry et al. (2001)	Cycling	20[d]	40[d]	45	1.07	–
Pires et al. (2011)	Cycling	23–25	40[d]	60	1.62	–
Potteiger and Weber (1994)	Cycling	14	50	82	0.67	–
Potteiger and Weber (1994)	Cycling	22	50	82	0.69	–
Potteiger and Weber (1994)	Cycling	30	50	82	0.77	–
Steed et al. (1994)	Running	21	50	76	2.56	–
Steed et al. (1994)	Running	21	50	88	0.37	–
Steed et al. (1994)	Running	21	50	92	1.71	–
Utter et al. (1997)[c]	Running	24	52	77	3.24	0.58
Vallier et al. (2005)[c]	Cycling	20–21	50	58	2.74	1.44
Wilson et al. (2010)[c]	Running	19–21	50–60	64	0.90	0.32

NR not reported

[a] Predicted RPE was calculated from Eq. (1)

[b] Predicted RPE includes corrections for endurance-trained individuals (Eq. 3)

[c] Studies with endurance-trained subjects

[d] Value not reported; so standard room conditions (20 °C, 40 % humidity) were assumed for the simulations

[e] Exercise performed by women

from endurance-trained subjects were excluded from the Bland–Altman plot, 89 % of predicted values fell within the acceptable range (see Fig. 2) and the LoA and bias were 2.4 and −0.14, respectively. Additionally, Eq. (1) had similar accuracy for lower RPE values (<12) and higher RPE values (>12) when the endurance-trained cases were excluded. Thus, it was evident that Eq. (1) was accurate for healthy active persons, but needed to be adjusted for endurance-trained persons. Therefore, the coefficients of MR and the integral of $\%\dot{V}O_{2,max}$ were refit from Eq. (1) to better match the endurance-trained subject data as follows,

$$\mathrm{RPE} = 5.65 + 1.21 \times \Delta T_{core} + 0.72 \times \max(\Delta \overline{T}_{sk}, 0) + 0.0041 \times \mathrm{MR} + 4.52 \times 10^{-4} \int \%\dot{V}O_{2,max} \times \mathrm{d}t \quad (3)$$

which assumed that core and mean-weighted skin temperature contributions to RPE are the same for untrained and endurance-trained individuals.

A Bland–Altman plot constructed using Eq. (3) (Fig. 3) showed great improvement, with 93 % of predicted values falling within the acceptable range and the LoA and bias of the corrected RPE prediction were 2.3 and −0.03, respectively. RMSDs were re-calculated for the endurance-trained cases as shown in the last columns of Tables 1 and 2. Using the corrected RPE prediction improved the RMSD score for 14 out of 17 cases involving the endurance trained. Furthermore, RMSDs were below 2 for all 17 endurance-trained cases (compared to just 5 previously). For the endurance-trained cases only, Eq. (3) resulted in an improved LoA and bias of 2.0 and 0.1, respectively, whereas the uncorrected prediction, Eq. (1), resulted in a less accurate LoA and bias of 3.0 and 2.3, respectively.

Self-pacing algorithm test

The self-paced data for cycling and running exercise is described in Table 3, providing information including air temperature (T_{air}), exercise duration, performance objectives, and distance/time feedback. The values of RPE_{reg}

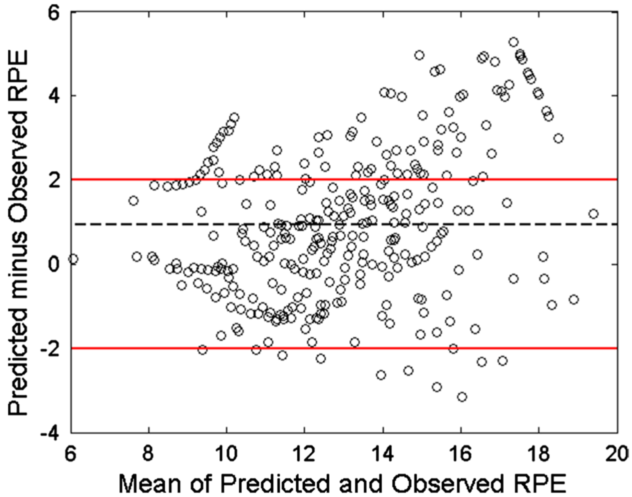

Fig. 1 Bland–Altman plots for RPE prediction using Eq. (1) showing all test data. The *solid lines* show the acceptable bound for RPE prediction of ±2. The *dashed line* shows the bias of the RPE prediction, which is the average of the RPE differences (predicted minus observed). The LoA and bias of the RPE prediction was 3.6 and 0.95, respectively

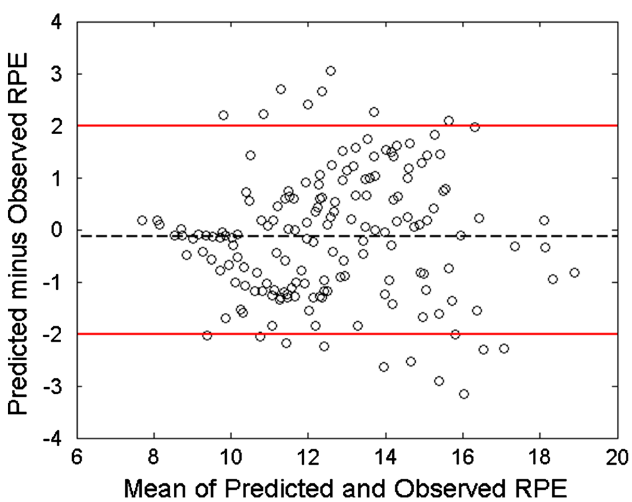

Fig. 2 Bland–Altman plots for RPE prediction using Eq. (1) excluding test data of endurance-trained subjects. The *solid lines* show the acceptable bound for RPE prediction of ±2. The *dashed line* shows the bias of the RPE prediction. The LoA and bias were 2.4 and −0.14, respectively

used in the simulations are also shown in Table 3. The experimental cases were conducted in air temperatures ranging from 17 to 35 °C.

A comparison of the modeled and observed power output and the RPE response for eight cycling performance trials showed good agreement (Fig. 4a, b). The modeled and observed running speeds and RPE responses for two performance trials are compared in Fig. 5a, b, respectively. The simulations and data did not include the end-spurt portion

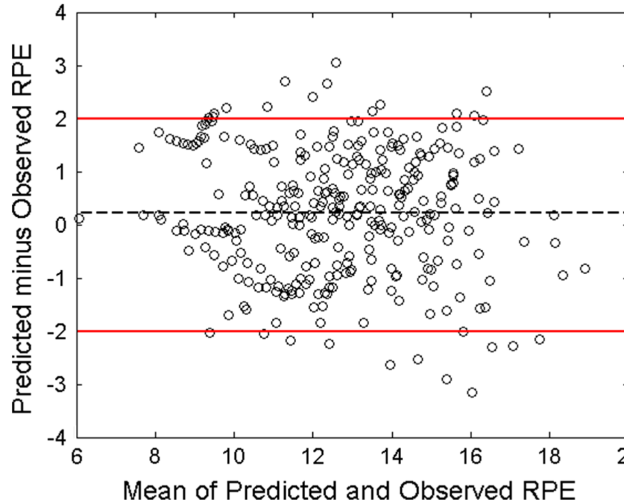

Fig. 3 Bland–Altman plots for RPE prediction with correction factors for endurance-trained subjects for all test data. The *solid lines* show the acceptable bound for RPE prediction of ±2. The *dashed line* shows the bias of the RPE prediction. The LoA and bias of the corrected RPE prediction were 2.3 and −0.03, respectively

(since we did not attempt to model positive changes in work rate). As shown in Table 3, most performance objectives involved cycling or running as hard as possible with exercise feedback regarding the duration, time, or amount of work performed. There was only one case (Barwood et al. (2008)) where the subjects were not provided any distance or time feedback. Therefore, in this case, the derivative gain was held constant throughout the exercise, resulting in a continuous decline in speed near the end of the exercise (see Fig. 5a). For Byrne et al. (2011), Castle et al. (2012), and the 23 °C case of Tatterson et al. (2000), the lowest value for RPE_{reg} resulting in no reductions in work output was determined as explained in the Methods. For all other experimental cases, RPE_{reg} was fitted to best match the reductions in work rate. For cycling and running cases that showed self-paced reductions in work rate, the control algorithm accurately characterized the time of occurrence, magnitude, and overall shape of the drop in work output as shown in Figs. 4a and 5a. Also, predicted RPE was generally in good agreement with the observed (see Figs. 4b, 5b). The values of RPE_{reg} used in the simulations for all experimental cases are presented in Table 3. For cases with exercise duration greater than 45 min, RPE_{reg} ranged from 15 to 16, while for exercise durations of 30 min, RPE_{reg} ranged from 17.5 to 19.3, indicating that RPE_{reg} is likely dependent on exercise duration.

Discussion

In this work, we have shown that self-paced reductions in work rate can be characterized with a

Table 3 Description of self-paced data for cycling and running exercise including the reference, air temperature (T_{air}), exercise duration, value of RPE_{reg} used in the simulation, performance objective, and distance/time feedback provided to subjects

References	T_{air} (°C)	Duration (min)	RPE_{reg}	Performance objective	Distance/time feedback
Byrne et al. (2011)	33	30	19.3	Cycle as far as possible in 30 min	Exercise time and distance were continuously available
Carter et al. (2004)	17	61	15.3	Perform 914 kJ of work as fast as possible on a cycle ergometer	Subjects were only aware of the amount of work completed
Castle et al. (2012)	31	30	17.5	Complete a 30 min cycling time trial	Not stated in article
Périard et al. (2011)	20	60	15.2	Complete a 40 km cycling trial at highest sustainable work rate	Subjects were informed of every elapsed 5 km but not time
Périard et al. (2011)	35	64	16	Same as previous	Same as previous
Robinson et al. (1995)	20	60	15.5	Cycle as far as possible in 1 h	Exercise time was available
Tatterson et al. (2000)	23	30	17.5	Complete as much work as possible in a 30-min cycle	Exercise time was available
Tatterson et al. (2000)	32	30	18.5	Same as previous	Same as previous
Barwood et al. (2008)	30	90	15.0	Run as far as possible in 90 min	No feedback whatsoever was provided
Bertuzzi et al. (2006)	28–30	45	15.5	Run 10 km as fast as possible	Subjects knew of every elapsed 400 m

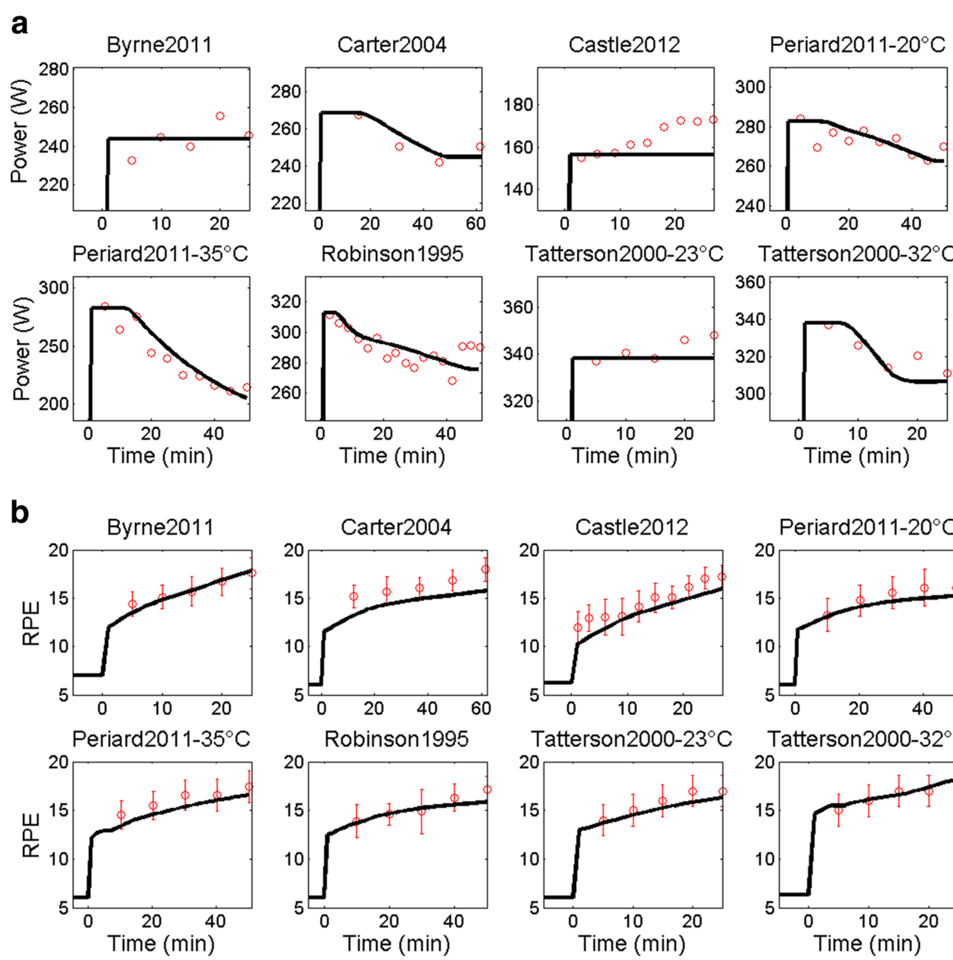

Fig. 4 Resultant **a** power output (W) and **b** RPE response (*solid lines*) vs. data (*circular points*) for cycling exercise. RPE plots also include the standard deviation at each data point. For Périard et al. (2011), the performance trials for two different air temperatures (20 and 35 °C) are shown. Likewise, for Tatterson et al. (2000), performance trials at two different air temperatures (23 and 32 °C) are shown. The simulations do not include the end-spurt portion

proportional-derivative control algorithm utilizing only RPE as feedback. This provided further evidence that RPE is not just an indicator of exercise difficulty but is integral in the regulation of work rate during self-paced activity. We have also shown that it is possible to accurately predict the dynamic response of RPE using only four measurable physiological variables, but the prediction required different parameterization for healthy active subjects and for

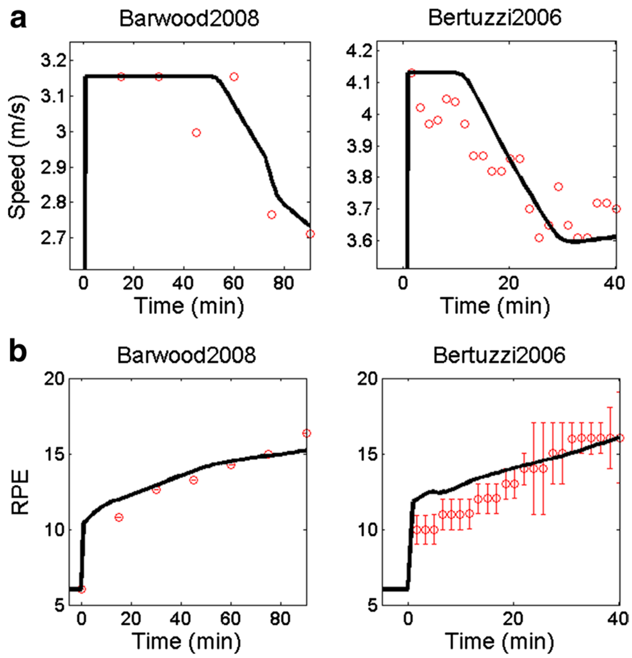

Fig. 5 Resultant **a** speed (m/s) and **b** RPE response (*solid lines*) vs. data (*circular points*) for running exercise. RPE plots also include the standard deviation at each data point when reported

endurance-trained subjects. Overall, the self-pacing control algorithm with RPE prediction can be utilized to estimate reductions in work rate for motivated performers during cycling and running exercise for a range of environmental conditions.

RPE relation to physiological variables

Previously, RPE response was found to be highly correlated to variables core temperature, skin temperature, and exercise intensity using a multivariate analysis of variance (Pandolf et al. 1972), but only one previous study attempted to develop a RPE regression using these types of physiologic variables (Noble et al. 1973). The RPE prediction developed here utilized four physiological variables: core temperature, mean-weighted skin temperature, metabolic rate, and the integral of $\%\dot{V}O_{2,max}$ which explained 85 % of the variance in RPE. This formulation improves upon a previous multiple regression analysis, which explained between 75 and 84 % of the variance in RPE in hot conditions, utilizing variables such as skin temperature, core temperature, and oxygen consumption ($\dot{V}O_2$) (Noble et al. 1973).

Core temperature or skin temperature alone has been shown to have a strong linear relationship with RPE during exercise (Crewe et al. 2008; Muñoz et al. 2012). Interventions that decrease or increase pre-exercise core temperature have been shown to attenuate or enhance RPE with respect to control values, respectively (González-Alonso et al. 1999). Additionally, changes in skin temperature alone have been shown to alter RPE (Noble et al. 1973; Pandolf et al. 1972). Particularly, increases in skin temperature increase RPE (Pivarnik et al. 1988), whereas reductions in skin temperature alone have been shown to reduce RPE even without differences in core temperature (Muñoz et al. 2012). Elevations in skin temperature may directly increase RPE via enhanced thermal perception (Schlader et al. 2011b); or alternatively, elevations in skin temperature could indirectly alter RPE due to its cardio-respiratory consequences. It has been suggested that increases in skin temperature enhance blood pooling in the periphery resulting in cardio-respiratory limitations that may be reflected in conscious RPE, which could elicit reductions in work output (Ely et al. 2010).

For the RPE prediction, metabolic rate was used to determine the initial RPE at the onset of exercise. A linear relationship between workload and RPE has been previously observed (Pandolf et al. 1972). Additionally, Crewe et al. (2008) observed a significantly higher initial RPE at an exercise intensity of 70 % peak power output (PPO) when compared to exercise at 65 % PPO. We utilized an absolute criterion for work, metabolic rate, instead of a relative one, because it resulted in a higher adjusted R^2. However, we conducted a similar analysis of the RPE prediction using a relative work rate criterion, and the results were not significantly affected (data not shown). Furthermore, heart rate was essentially found to be redundant with the inclusion of metabolic rate in the RPE prediction. Heart rate can reflect the level of activity and has been shown to be highly correlated to RPE for incremental exercise (Borg 1982) but breaks down for constant load exercise to exhaustion (Garcin et al. 1998). Pandolf et al. (1972) also found that heart rate was not related to RPE for 30-min constant load exercise in hot air temperatures.

The integral of $\%\dot{V}O_{2,max}$ was included in the final prediction to more accurately calculate ending RPE values for longer duration exercise. Core temperature and mean-weighted skin temperature alone could not explain the progressively increasing nature of RPE, especially during compensable heat stress where these variables tend to plateau. The integral of $\%\dot{V}O_{2,max}$ represents the total energy due to aerobic metabolism, which increases with exercise duration (Péronnet and Thibault 1989). In predicting RPE and associated performance decrement, we were mainly concerned about exercise for durations of 30 min or longer. For exhaustive whole body exercise with time to fatigue greater than 30 min, the aerobic contribution dominates the anaerobic contribution in regards to the production of power (Péronnet and Thibault 1989). Since ATP is derived from energy stores such as muscle glycogen and blood glucose during aerobic metabolism, the integral of $\%\dot{V}O_{2,max}$ is essentially tracking the consumption of these substrates.

Reduced muscle glycogen levels have been shown to have an adverse effect on RPE (Baldwin et al. 2003) and exercise performance (Johnson et al. 2006; Rauch et al. 2005) and have been suggested to be a primary limiter during exercise in the cold (Pitsiladis and Maughan 1999). Additionally, carbohydrate feedings during exercise have been shown to attenuate the rise in RPE (Carter et al. 2005; Kang et al. 1996; Utter et al. 1997, 1999); therefore, the RPE prediction would be conservative when carbohydrate feeding occurs. It should be noted that the RPE prediction algorithm presented here is likely not applicable to exercise with a considerable anaerobic component, which has been shown to manipulate RPE via peripheral mechanisms (Pandolf et al. 1972).

Applicability of RPE prediction

The RPE prediction was found to be applicable for the untrained active population and the endurance-trained population but required different parameterizations for these groups due to the overestimation of the RPE response for the latter. Perceived exertion has been found to be lower in trained individuals compared with untrained individuals doing treadmill walking in the heat while wearing semi-permeable protective clothing (Selkirk and McLellan 2001; Tikuisis et al. 2002). Ekblom and Goldbarg (1971) found RPEs at the same relative $\dot{V}O_{2,\max}$ to be lower in trained individuals in comparison to untrained individuals, which was corroborated by Berry et al. (1989) and Hill et al. (1987). These findings support the idea that the coefficient for the integral of $\%\dot{V}O_{2,\max}$ should be lower for endurance-trained individuals. Also, untrained and endurance-trained subjects reach similar levels of RPE at exhaustion (Tikuisis et al. 2002). These two results may partially explain why subjects of lower fitness terminate exercise at a lower core temperature than their fitter counterparts (Selkirk and McLellan 2001). The reduced coefficient of the integral of $\%\dot{V}O_{2,\max}$ may to some extent reflect an increased starting pool of energy substrates. Endurance-trained athletes typically consume high carbohydrate diets, and thus have higher baseline muscle glycogen levels than their untrained counterparts (Gollnick et al. 1973). While not accounted for in this model, it is worth noting that psychological differences between trained and untrained subjects could also lead to differences in RPE response. Trained individuals are typically more motivated and more accustomed to high intensity exercise, and thus may perceive exertion to be lower than untrained individuals.

The RPE prediction was analyzed for a small subset of female data and compared against an equivalent demographic (e.g., age, fitness) of male data. In general, there seems to be no gender-related differences in RPE for equal relative intensity exercise (Springer and Pincivero 2010). RPE has been found to be higher for females than males performing exercise at the same absolute oxygen uptake, but no gender differences in RPE were observed for work occurring at the same percentage of $\dot{V}O_{2,\max}$ (Garcin et al. 2005; Robertson et al. 2000). Overall, the RPE prediction performed well for all cases exclusively involving female subjects. In particular, studies by Pivarnik et al. (1992) and Janse De Jonge et al. (2012), which tested only female subjects, were used to train the RPE prediction. A study by Loftin et al. (2009) utilizing all female subjects provided test data for the RPE prediction (see Table 2). Loftin et al. (2009) also tested a separate all male group, and the RPE prediction was accurate for both male and female groups running on a treadmill for 1-h at marathon pace. However, due to the small female dataset, the RPE prediction requires further testing to ensure that is applicable to the general healthy female population. Furthermore, data for endurance-trained women needs to be analyzed before concluding that the RPE equation can be applied for endurance-trained women.

The RPE prediction, trained almost exclusively with cycling data, was found to be applicable for walking, running, and cycling exercise for the test data used in this study by accounting for exercise mode differences in $\dot{V}O_{2,\max}$ and mechanical efficiency. Differences in RPE and physiological responses have been observed between the different modes of exercise. For a given $\dot{V}O_2$, Ekblom and Goldbarg (1971) found RPE to be higher for cycling than running for healthy individuals. Berry et al. (1989) found RPE for walking to be higher than running at a given $\dot{V}O_2$ for highly fit individuals. Additionally, McArdle et al. (1973) found a lower $\dot{V}O_{2,\max}$ for walking than running for highly fit individuals. Similarly, Horstman et al. (1979a) also found $\dot{V}O_{2,\max}$ to be lower in walking than running but in a group of healthy volunteers. Interestingly, subsequent constant load exercise showed no difference in RPEs when work intensity was prescribed as a percentage of $\dot{V}O_{2,\max}$ specific to the exercise mode (Horstman et al. 1979a). This indicates that it is important to use the exercise specific $\dot{V}O_{2,\max}$ in the RPE prediction. Additionally, our thermoregulatory model takes into account the difference in net mechanical efficiency between exercise modes when determining the heat generation in working muscles. In regards to the three mentioned exercise modes, mechanical efficiencies are lowest in cycling, higher in walking, and the highest in running (Bijker et al. 2001; Caretti 1994; Luhtanen et al. 1990). For a given absolute $\dot{V}O_2$ (or exercise intensity), exercise modes with lower efficiency result in higher heat generation, and hence higher core temperature, which will further increase RPE in our model. Thus, our model would support the studies that found RPE responses to be higher in walking and cycling than in running for an absolute work criterion. Overall, our results indicate that the RPE prediction is applicable to cycling and running exercise. However, while the RPE prediction performed well for walking, care should be taken for this application since the amount of validation data was limited.

The RPE prediction developed here can be used to predict performance limits for single bouts of fixed-rate exercise. From previous studies, there is considerable evidence that RPE could be used to predict the time to exercise termination for fixed-rate exercise (Eston et al. 2007; Faulkner et al. 2008). A number of studies have observed linearity in the response of RPE along with scalar time-based properties for fixed-rate exercise (Crewe et al. 2008; Horstman et al. 1979a; Noakes 2004). In the work of González-Alonso et al. (1999) exhaustion occurred at the same core temperature (roughly 40 °C) regardless of the starting core temperature; although, the idea of a critical core temperature has been disputed since core temperatures above 40 °C have been noted without exhaustion (Ely et al. 2009). However, an interesting observation from González-Alonso et al. (1999) was that similar RPE values were obtained at exercise termination for different starting core temperatures. Other fixed-rate exercise studies have shown similar RPE values at exercise termination between control and experimental interventions involving neck cooling, exercise intensity, ambient temperature, relative humidity, carbohydrate ingestion, muscle glycogen levels, and drink water temperature (Baldwin et al. 2003; Carter et al. 2003; Crewe et al. 2008; Lee et al. 2008; Maughan et al. 2012; Pitsiladis and Maughan 1999). Therefore, the RPE prediction developed here may be useful for estimating tolerance limits in fixed-rate exercise which would be reached at maximal levels of RPE. Typically, subjects may only reach an RPE of 18 or 19 at volitional exhaustion (Faulkner et al. 2008), so a maximal value in this range could be used as termination criterion.

Limitations of RPE prediction

The training datasets used for the RPE prediction minimized secondary effects that can significantly alter RPE response such as head cooling, caffeine ingestion, antecedent fatiguing exercise, and pre-exercise mental fatigue occur (Ansley et al. 2008; Backhouse et al. 2011; Casal and Leon 1985; Doherty and Smith 2005; Eston et al. 2007; Marcora et al. 2009; Mündel et al. 2007). Therefore, the RPE prediction may not be accurate when these effects are introduced. Additionally, the RPE prediction is applicable to a single bout of exercise which assumes that there is a sufficient amount of rest and recovery prior to the exercise. To expand the prediction beyond a single bout of exercise may require a more complex model that tracks consumption and replenishment of peripheral energy stores and blood glucose.

The RPE prediction may not be applicable for manipulations that alter arterial oxygen saturation (e.g., hypoxia and altitude) during exercise testing, as they have been shown to affect RPE response and performance (Allen and Pandolf 1977). The RPE response predicted from the algorithm was severely underestimated for the Coles and Luetkemeier (2005) data, most likely because this exercise test was performed at high altitude. However, $\dot{V}O_{2,max}$ is reduced for acute exposures to high altitude (Horstman et al. 1979b), so it is possible that the RPE prediction could be accurate if the altitude specific $\dot{V}O_{2,max}$ is used in the equation.

The RPE prediction developed in this study may not be accurate for cases where subjects are deceived of the task duration unless the effects of duration expectation on RPE are mediated with oxygen consumption. Overall, RPE represents the integration of multiple physiological and psychological factors (Eston 2012). Task duration deception has been shown to affect RPE response (Baden et al. 2004; Rejeski and Ribisl 1980). However, expectation of task duration appears to influence muscular efficiency, and thus may alter RPE via its effect on metabolic rate (Vidacek and Wishner 1971).

The training and test dataset were limited to cases where dehydration was less than 2 % body weight; therefore, caution should be taken when using the RPE prediction for applications where dehydration is significant. Dehydration has been shown to have an adverse effect on RPE (Below et al. 1995; Ishijima et al. 2009; Vallier et al. 2005), however, it is unclear if dehydration has a direct effect on RPE and/or an indirect effect via its alteration of thermoregulatory mechanisms. Progressive dehydration, measured by body weight loss, has been shown to augment core temperature by reducing skin blood, and possibly by reducing the sweat rate at a given thermal drive flow (Montain and Coyle 1992). Therefore, it is possible that the overall effect of dehydration is accounted for in the RPE prediction with the inclusion of core temperature as a predictor variable.

Lastly, there are many indices for core temperature, which could cause discrepancies in the prediction of RPE. However, the most common laboratory indices, rectal and esophageal, have been shown to have an LoA of around 0.58 °C (Buller et al. 2013), which would indicate that these discrepancies would be minimal. Additionally, mean-weighted skin temperature is affected by the number of measurement sites. However, a commonly used four-site measurement equation, which was utilized for all the training data, has been shown to be accurate when compared to mean-weighted average skin temperature calculations using more sites (Ramanathan 1964).

Control of work rate with RPE feedback

We found that RPE as the feedback variable for modulating work rate could be used to explain performance reductions during self-paced activity. This is based on the idea that RPE is not just an indicator of exercise exertion, but is a main regulator of work rate during self-paced activity so that near-maximum RPE levels are not reached before exercise completion (Tucker 2009; Tucker et al. 2004). de Koning et al. (2011) gave further credibility to this theory by showing that the probability of altering velocity during competitive self-paced performance trials was related to the current RPE and percentage of remaining event duration. Altareki et al. (2009) also suggested that exercise intensity was regulated using RPE to maintain thermoregulatory homeostasis during exercise, and recently, Barwood et al. (2012) suggested that RPE is the primary marker of pacing. Our model was able to accurately characterize reductions in work rate using RPE as the sole feedback variable, further lending evidence that RPE can be one of the main regulators of exercise performance.

The thermo-physiological variables utilized in our RPE prediction as modulators of pacing have been identified as major contributors. Self-paced performance has been shown to be improved after pre-cooling either core or skin temperatures (Byrne et al. 2011; Duffield et al. 2010; Schlader et al. 2011a). Based on their cycling performance study, Tatterson et al. (2000) suggested that power output was altered relative to the change in core temperature. A strong association has been identified between the rate of core temperature rise and mean power output in 40-km cycling trials performed in 17–32 °C air (Peiffer and Abbiss 2011). It has also been suggested that skin temperature is an input to a brain mediated anticipatory model of exercise regulation (Schlader et al. 2011a).

In controlling RPE, we assumed a standard proportional-derivative control algorithm where only negative changes in work rate were allowed. Also a single pole, low pass filter with unity gain was included in the control structure to account for a lag in the initiation of work rate change for self-paced activity (St. Clair Gibson et al. 2006). An integral component was not incorporated, since qualitatively RPE did not appear to approach a constant value with minimal steady-state error (Franklin et al. 2009). Therefore, the developed self-pacing model could not currently predict work rate reductions for exercise performed at a fixed RPE, which would require an integral component in the control structure. Previous studies involving exercise at fixed RPE showed a gradual reduction in power output that was steeper with greater thermal strain or heat perception (Schlader et al. 2011b; Tucker et al. 2006). In relation to our model, this reduction in work rate would be required to counteract the increase in RPE due to rises in core temperature, skin temperatures, and energy consumption to maintain exercise at a constant RPE.

The implemented proportional-derivative control algorithm was designed to capture observed behavior between performance reduction and RPE. The derivative component of the control algorithm was implemented based upon observation that the rate of RPE rise is a likely feedback variable in the control of work rate during exercise (Albertus et al. 2005). With the use of a derivative component in the control algorithm, control action could still be taken even when RPE was below RPE_{reg}, if the rate of change of RPE was high enough. A general observation in work rate response was a plateau near the end of exercise. The control algorithm modeled this component by progressively decreasing the derivative gain to zero 15 min before exercise completion, but only if distance or time feedback was provided. Most likely, this plateau near the end of exercise (which is often proceeded with an end-spurt) is the result of a subject's understanding that the exercise is ending soon and no more negative adjustments in work rate are needed (Abbiss and Laursen 2008; Micklewright et al. 2010). The amount of performance neglected by not including the end-spurt is likely minimal since a near maximal effort could not be maintained for a long time; but it would also depend on the duration of the exercise and knowledge of time/distance remaining. If distance or time feedback was not provided, we would not be neglecting any part of the performance since an end-spurt would not occur. For longer duration exercise of known time/distance, we would be neglecting lesser of the performance as the end-spurt comprises a lower percentage of the overall activity.

Characterizing the pacing control strategy established that RPE_{reg} was generally larger for shorter duration exercises; therefore, RPE_{reg} reflects how conservatively the trial was performed. Thus, for longer duration exercise, a more conservative work profile typically occurred, which resulted in a lower RPE response up to the end-spurt. In some cases, the end-spurt resulted in near-maximum ending RPE values, which likely would not have occurred without the end-spurt. A more conservative approach for longer duration exercise is likely because there is more uncertainty in the quantification of required work intensity, which poses a bigger threat to homeostasis (Tucker 2009). Conversely, for shorter duration exercise, subjects are more able to better quantify the work intensity needed to optimize performance within the body's physiological constraints.

The self-pacing model proposed here indicated that early reductions in work rate were largely explained by the rate of change in core temperature and increases in skin temperature. This type of regulation becomes critical to self-preservation particularly in hot conditions to minimize dangerous levels of physiological strain (Périard et al. 2011; Tucker et al. 2004; Schlader et al. 2011c). Our model was able to explain an early reduction of power output for cycling data collected in hot 35 °C air (Périard et al. 2011) through rate of rise in core temperature and increases in skin temperature. In cooler conditions, for example the

20 °C air Robinson et al. (1995) case, early reductions in work output were due mainly to the rate of rise in core temperature with negligible effect from skin temperature. In the case of Robinson et al. (1995), subjects started the exercise at a very high power output, which resulted in a relatively high rate of core temperature change along with a high initial RPE. The control algorithm was sensitive enough to this rate of change in core temperature (and hence, RPE) to elicit work rate reductions while the current RPE was still below RPE_{reg}, though the enhanced RPE response (due to the high exercise intensity) also lowered the threshold needed by the derivative control component to initiate these reductions in power output. Similarly, others have shown that alterations in power output during cycling performance trials are related to changes in core temperature or rate of change in core temperature in cool to hot conditions (Peiffer and Abbiss 2011; Tatterson et al. 2000). Our results suggest that the rate of change in core temperature mediated the early declines in work rate in hot and cool conditions; it also suggests that the role of skin temperature is minimal in cool conditions, but increasingly influential with hotter conditions. Changes in skin temperature may influence the selection of work intensity via its effect on thermal perception (Schlader et al. 2011b).

Conclusion

We have developed a novel methodology to predict self-pacing strategy using a standard proportional-derivative control algorithm with RPE as the feedback variable. The successful use of RPE as a feedback variable in the control scheme provides further evidence that RPE is not just an indicator of exercise exertion, but is a regulator of work rate during self-paced activity. It was also shown that the dynamic response of RPE is highly correlated to measurable physiological variables, which corroborates observations that have shown an influence of core and skin temperature on the modulation of self-paced work rate, but should be differentiated between healthy active and endurance-trained subjects due to the difference in response of perceived exertion between the two groups. This algorithm can predict self-paced work for a spectrum of conditions from cool to extreme heat and low to high intensity levels for moderate durations up to 90 min. The RPE prediction has broad applicability and can be successfully applied to walking, running, and cycling aerobic exercise. The complete model, including the RPE prediction, pacing control algorithm and thermoregulatory simulator, is a useful tool that estimates performance reductions during self-paced exercise and could also be used to predict tolerance time for exhaustive fixed-rate exercise.

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Conflict of interest The authors declare that they have no conflict of interest.

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