

A new method for self-paced peak performance testing on a treadmill

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Summary

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Purpose Self-paced maximal testing methods may be able to exploit central mediation of function-limiting fatigue and therefore have potential to generate more valid estimates of peak oxygen uptake. The aim of this study was to investigate the feasibility of a new method for self-paced peak performance testing on treadmills and to compare peak and submaximal performance outcomes with those obtained using a non-self-paced ('computer-paced') method employing predetermined speed and slope profiles.

Methods The proposed self-paced method is based upon automatic subject positioning using feedback control together with an exercise intensity which is driven by a predetermined, individualized work-rate ramp.

Results Peak oxygen uptake was not significantly different for the computer-paced (CP) versus self-paced (SP) protocols: 4.38 ± 0.48 versus 4.34 ± 0.46 ml min⁻¹, $P = 0.42$. Likewise, there were no significant differences in the other peak and submaximal cardiopulmonary parameters, viz. peak heart rate, peak respiratory exchange ratio and the first and second ventilatory thresholds. Ramp duration for CP was longer than for SP: 494.5 ± 71.1 versus 371.3 ± 86.0 s, $P = 0.00072$. Concomitantly, the peak rate of work done against gravity was higher for CP: 264.8 ± 40.8 versus 203.8 ± 53.4 W, $P = 0.0021$.

Conclusions The self-paced approach was found to be feasible for estimation of the principal performance outcomes: the method was technically implementable, it was acceptable to the subjects and it showed good responsiveness. Further investigation of the self-paced method, with adjustment of the target ramp-phase duration or modification of the work-rate calculation equations, is warranted.

Introduction

There has recently been substantial interest in the development and evaluation of 'self-paced' maximal exercise testing protocols; this is a family of methods whereby exercise intensity is set according to the subject's volition. It has been observed that, during normal exercise outwith the formal testing environment, self-paced mechanisms naturally come into play through optimized central mediation of muscle recruitment which is presumed to have the goal of avoidance for as long as possible of catastrophic function-limiting fatigue (Lander et al., 2009). Self-paced maximal testing therefore has the potential of generating more valid, that is, higher, peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) values.

Various self-paced testing methodologies have been proposed and compared with different implementations of

'standard/traditional' protocols, but the outcomes have, as yet, proven broadly inconclusive. A novel self-paced approach based on the subject's self-controlled rating of perceived exertion (RPE), involving five-two-minute RPE stages, was put forth by Mauger & Sculthorpe (2012). During maximal exercise testing using a cycle ergometer, these authors found higher average $\dot{V}O_{2\text{peak}}$ with the self-paced approach, compared to a standard protocol (Mauger & Sculthorpe, 2012). Chidnok et al. (2013), in contrast, found no differences in $\dot{V}O_{2\text{peak}}$ between the Mauger self-paced approach and two standard protocols, albeit the self-paced and standard tests were administered on different models of cycle ergometer.

The same RPE-based self-paced method has been implemented in various forms for treadmill testing, but, again, broad consensus is not yet evident regarding $\dot{V}O_{2\text{peak}}$ outcomes. Mauger et al. (2013) reported higher self-paced

$\dot{V}O_{2\text{peak}}$, but the self-paced and standard protocols which were compared were evaluated on different treadmills: the self-paced protocol used a non-motorized treadmill where the subject was able to freely choose running speed, whereas the standard protocol was evaluated with a motorized treadmill. This confounding factor was eliminated in a subsequent study from the Mauger group (Hogg et al., 2015). That work used a single 2.5-m-long motorized treadmill and a zoning approach where the subject indicated to the experimenter the need, or otherwise, to change speed or slope to achieve each of the five prescribed two-minute duration RPE levels; that is, the subject self-positioned on the treadmill surface to self-control RPE, while the experimenter was required to manually adjust speed or slope according to the subject's indicative position. It was found that a self-paced protocol which primarily used slope to influence RPE gave higher $\dot{V}O_{2\text{peak}}$ than either a self-paced speed-driven approach or a standard protocol. An alternative treadmill implementation of the Mauger self-paced protocol did not, however, demonstrate a significant difference in $\dot{V}O_{2\text{peak}}$ (Faulkner et al., 2015). In that study, slope was kept constant (1%) and, in the self-paced protocol, speed was self-regulated by the subject manually pressing the speed button on the treadmill control panel. Finally, a fully manual form of self-paced testing, where no RPE-clamping was required, was investigated (Sperlich et al., 2015). There, subjects had to manually adjust speed and slope using the control panel with the aim of reaching exhaustion in 8–12 min. No differences were found between self-paced $\dot{V}O_{2\text{peak}}$ and those obtained using three conventional forms of incremental testing.

The studies highlighted in the foregoing review all required some form of manual intervention by the subject and/or the experimenter during the self-paced protocol, but the need for the subject to either self-position within some zone on the treadmill surface or to interact with the control panel might be a significant distractor: fully automated approaches which allow the subject to self-pace without the need to manually interact in any way with the treadmill, and which inherently provide safe positioning on the treadmill belt, therefore warrant investigation. A study from Schedler & Devor (2015) implemented just this approach, but it was found that $\dot{V}O_{2\text{peak}}$ was significantly lower with self-pacing compared to a 'traditional' incremental protocol. Technically, that study used a heuristic control algorithm for automated positioning: position was continuously measured using an ultrasound sensor; the treadmill surface was divided into 10 acceleration/deceleration zones, with the magnitude of speed correction being higher for zones further from a central, neutral zone; and the subject was then allowed to self-select running speed in order to self-control RPE during five-two-minute stages (i.e. the Mauger RPE-based self-pacing approach was implicit in this implementation); slope was kept constant at 8%. In contrast, the traditional protocol employed a constant speed and a slope profile which had increases of 2% every 2 min. Thus, the way in which speed and slope were combined was quite different for the self-paced (constant slope, variable speed) and

traditional (constant speed, variable slope) protocols, thus introducing an additional unaccounted-for factor into the comparative analysis. The feedback control approach to automatic positioning employed in the aforementioned study is reminiscent of techniques that have been widely used in other fields of investigation, notably in locomotion, virtual environment and gait research (Minetti et al., 2003; Lichtenstein et al., 2007; Sloot et al., 2014, 2015; Plotnik et al., 2015).

A novel algorithm for self-paced peak performance testing on treadmills is set out in the sequel. In common with the approach of Schedler & Devor (2015), the technical implementation herein also includes automatic positioning by feedback control, but the incremental exercise intensity is driven by a predetermined and individualized work-rate ramp. The method incorporates simultaneous changes in both speed and slope, and the subject is free to arbitrarily and freely vary running speed without any need for manual interaction. Based on the self-selected speed and the work-rate ramp, slope is automatically computed and set on a continuous basis. Thus, the subject is required neither to interact manually with the control unit, nor is he required to control his position on the treadmill belt, nor to self-control to meet the incrementally increasing exercise-intensity target. The self-paced (SP) protocol is compared to a non-self-paced method, termed 'computer-paced' (CP), where the speed and slope profiles are predetermined according to the same work-rate ramp. This has the advantage, for comparative purposes, that the CP approach implemented here also combines simultaneous changes in speed and slope according to the same governing equation for the rate of work done against gravity that is used for SP testing.

The aim of this study was to investigate the feasibility of this new method for self-paced peak performance testing on treadmills and to compare peak and submaximal performance outcomes with those obtained using a non-self-paced method employing predetermined speed and slope profiles.

Methods

Subjects and study design

For the comparison of the CP and SP protocols, a convenience sample of 10 healthy male subjects was recruited (Table 1). Subjects were not required to have any experience of treadmill running; persons with any cardiovascular, respiratory or musculoskeletal complaints were excluded.

Table 1 Subject characteristics.

	Mean \pm SD	Range
Age/(y)	23.4 \pm 2.9	19–29
Body mass/(kg)	76.9 \pm 9.6	65.0–96.0
Height/(m)	1.80 \pm 0.05	1.72–1.88
BMI/(kg m ⁻²)	23.6 \pm 2.4	21.5–29.0

n = 10, all male.

SD, standard deviation; BMI, body mass index (mass/height²).

Each subject attended three sessions, with sessions separated by at least 48 h. The first session was a familiarization where subjects were acquainted with the breath-by-breath system, the treadmill and with the CP and SP test protocols.

The second and third sessions were the formal CP/SP test measurements. The study design was counterbalanced by sequentially changing the order of presentation of each test condition for each subject, that is CP then SP versus SP then CP, and by random assignment of subjects upon recruitment; thus, for the 10 subjects, there were five cases of CP then SP and five cases of SP followed by CP.

All formal CP/SP peak performance tests had six stages: a three-minute period of recorded rest with the subject standing quietly on the treadmill; a five-minute warm-up of running at 1.4 m s^{-1} (5 km h^{-1}) and zero slope; a further 3 min of recorded rest; 3 min of walking at 0.6 m s^{-1} (2 km h^{-1}) and zero slope; a ramp phase, where work rate increased linearly until the subject's limit of tolerance was reached; and a cool-down of 5 min walking at 0.6 m s^{-1} and zero slope. All 20 formal exercise tests were terminated at the subjects' own volition by them indicating via a hand signal that they had reached their peak exertion.

Ramp test protocols

For both the CP and SP test protocols, work rate (power) was characterized as the rate of work done against gravity in moving the body mass up the treadmill slope using

$$P(t) = mgv_t(t) \sin(\theta(t)), \quad (1)$$

where m is body mass, g is gravitational field strength (9.81 N kg^{-1}), v_t is treadmill speed and θ is the treadmill angle (treadmill slope is related to θ as $\text{slope} = \tan \theta \cdot 100\%$). During the ramp phase of both protocols, the rate of work done against gravity increased linearly with time; the gradient of the ramp was set individually for each subject such that their predicted peak work rate would be reached in 10 min; predicted peak work rate was obtained using a methodology detailed elsewhere (Saengsuwan et al., 2016).

For the CP protocol, to obtain the specified individual ramp work rate, speed and slope were preprogrammed to simultaneously increase in a nonlinear, equally smooth fashion according to the algorithm proposed by (Hunt, 2008; Jamieson et al., 2008), which is based upon the governing equation for the rate of work done against gravity, Eq. (1).

For the SP protocol, the individualized linear-ramp work-rate profiles, with the aim of reaching predicted peak work rate in 10 min, were the same as those used for CP, but subjects were allowed to self-select their running speed during the ramp phase. Thus, with respect to Eq. (1), the rate of work done against gravity P was prespecified, speed v_t was self-selected by the subject, and Eq. (1) was continuously resolved in real time to obtain the required treadmill angle and slope, viz.

$$\theta(t) = \arcsin\left(\frac{P(t)}{mgv_t(t)}\right), \quad \text{slope}(t) = \tan(\theta(t)) \cdot 100\%. \quad (2)$$

Automatic positioning controller for self-paced testing

To enable the subject to self-select running speed, denoted v_r , and therefore to facilitate self-paced performance testing, an automatic positioning controller was implemented (Fig. 1). This controller has the task of keeping the subject close to a target position x^* relative to a reference point at the front of the treadmill; here, x^* was set to 0.7 m. To achieve this, treadmill speed v_t is automatically and continuously updated by a feedback controller transfer function $C(s)$ based on the difference between target position x^* (a constant) and real-time measurement of actual position x . The treadmill speed v_t thus computed by the position controller is also used as described above to update the treadmill angle/slope in real time, Eq. (2), Fig. 1.

Thus, the overall self-paced strategy has two independent inputs: the self-selected running speed v_r and the individual predetermined work-rate profile P . Volitional changes in v_r lead to transient deviations of position x from the target x^* ; the resulting position error $e = x^* - x$ feeds into the dynamic compensator function $C(s)$ resulting in an updated treadmill speed v_t which in turn serves to reduce the position error; treadmill angle/slope is also continuously adjusted using the speed variable $v_t(t)$ and work rate $P(t)$ according to Eq. (2).

The parameters of the compensator $C(s)$ were determined using an analytical control design procedure based on established feedback system principles (Åström & Murray, 2008). $C(s)$ was chosen to be a linear, time-invariant, strictly proper transfer function:

$$C(s) = \frac{g_1 s + g_0}{s(s + h_0)}, \quad (3)$$

where s is the Laplace-transform complex variable. The real controller parameters g_1 , g_0 and h_0 were computed to give position control performance with a satisfactory speed of response (closed-loop bandwidth). Integral action was included via the factor $1/s$, thus ensuring zero steady-state position error. The same compensator parameters were used for all subjects.

Control design used a dynamic model derived from the underlying equations of motion for runner position: position x is simply the integral of the difference between the speeds of the treadmill and the runner (see Fig. 1), expressed in the time and frequency domains as

$$x(t) = \int (v_t(t) - v_r(t)) dt \longleftrightarrow x(s) = \frac{1}{s} (v_t(s) - v_r(s)). \quad (4)$$

Here, the double arrow denotes forward and inverse Laplace transformation.

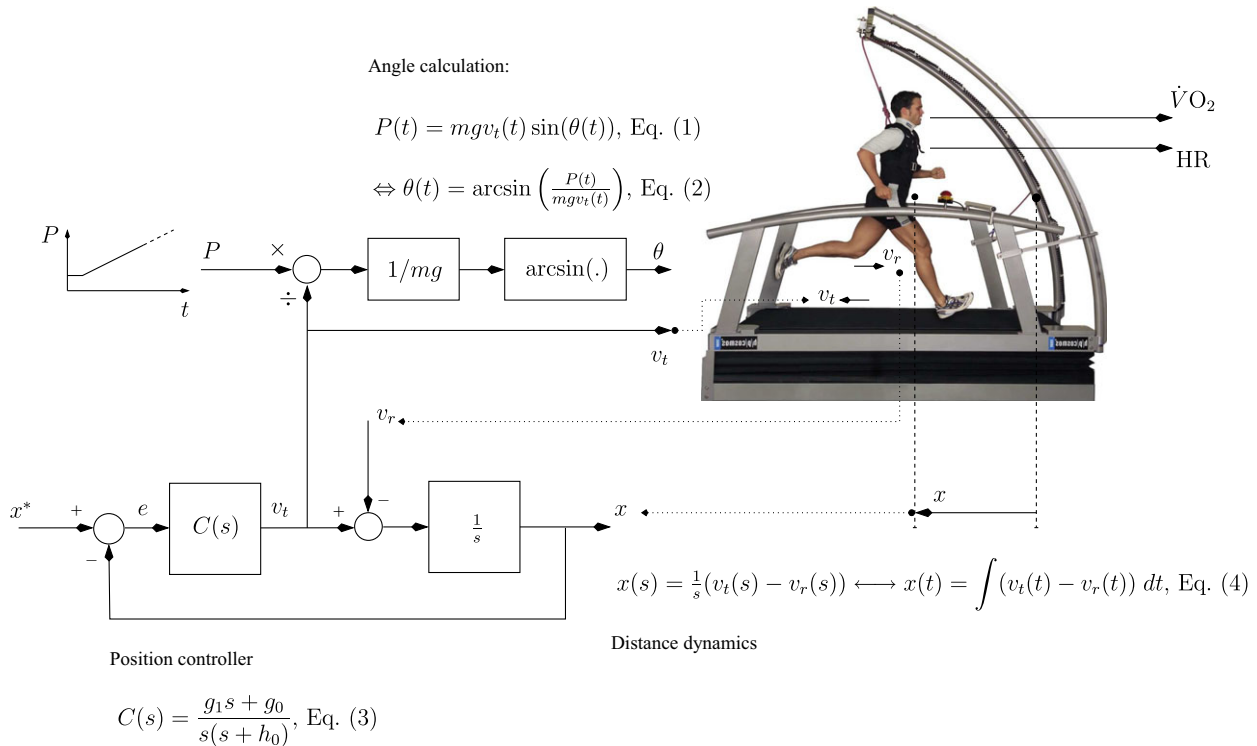


Figure 1 Self-paced (SP) protocol and automatic position control structure. Continuous, real-time determination of treadmill speed v_t and angle θ , driven by self-selected running speed v_r and work-rate profile P . [Colour figure can be viewed at wileyonlinelibrary.com]

Equipment

Gas exchange variables and heart rate were recorded breath-by-breath using a cardiopulmonary monitoring system (Metamax 3B; Cortex Biophysik GmbH, Leipzig, Germany) and analysed using the proprietary software associated with this device (Metasoft, version 3.9.9 SR5). Prior to each test, volume and gas concentrations were calibrated using a 3-l syringe and a precision gas mixture (15% O₂, 5% CO₂). Heart rate was recorded using a chest belt (T34; Polar Electro Oy, Kempele, Finland).

The CP and SP protocols were both executed on a motorized, computer-controlled treadmill (model Venus, h/p/cosmos Sports and Medical GmbH, Nussdorf-Traunstein, Germany) connected via an RS-232 serial communication link to a personal computer. For the CP protocol, the speed and slope profiles were preprogrammed and implemented in real time in the Metasoft software on the PC. The SP protocol, incorporating the automatic position control system, was implemented in the PC using Matlab/Simulink with the Real-Time Workshop (The Mathworks Inc., Natick, Massachusetts, USA); for SP, slope was updated in real time using Eq. (2), based on the preprogrammed work-rate profile and the treadmill speed, the latter having been determined as a function of the subject's self-selected speed using the automatic positioning controller described above (Section Automatic positioning controller for self-paced testing, Fig. 1).

For automatic positioning control in the SP strategy, continuous feedback of the subject's position x was obtained using a

wire draw encoder (Ecoline BCG08-L1KM03PP; Sick AG, Waldkirch, Germany) mounted at the front of the treadmill and connected to the subject via a side release buckle attached to a waist belt. The analogue sensor signal was read into the Matlab/Simulink control program in real time using a data acquisition card (PCI-6024E; National Instruments Corp., Austin, Texas, USA).

Outcome measures

The outcomes comprised four peak performance parameters, two submaximal thresholds and ramp duration; their definition, notation, units and method of determination are given as follows.

Peak performance outcomes:

- 1 Peak oxygen uptake, $\dot{V}O_{2\text{peak}}$ [l min^{-1}]: the highest value of a 15-breath moving average of $\dot{V}O_2$.
- 2 Peak heart rate, HR_{peak} [bpm]: the highest value of heart rate.
- 3 Peak respiratory exchange ratio, RER_{peak} [dimensionless]: the value of a 15-breath moving average of RER at the time of occurrence of $\dot{V}O_{2\text{peak}}$, where $\text{RER} = \dot{V}CO_2 / \dot{V}O_2$.
- 4 Peak rate of work done against gravity, P_{peak} [W]: the value of the rate of work done against gravity at the time of occurrence of $\dot{V}O_{2\text{peak}}$, calculated using Eq. (1).

The submaximal outcomes comprised two thresholds which were obtained by analysis of gas exchange variables. For simplicity, these are referred to here as the first and second ventilatory thresholds, VT1 and VT2, but a range of alternative

terms have been used elsewhere. The methodology summarized below for determination of VT1 and VT2 follows Binder et al. (2008) where a review of the diverse terminology employed for VT1 and VT2 can also be found.

Submaximal performance outcomes:

1 Oxygen uptake at the first ventilatory threshold, $\dot{V}O_{2VT1}$ [l min^{-1}]: VT1 was determined by: (i) visual inspection of the point where $\dot{V}E/\dot{V}O_2$ reaches its minimum or starts to increase without an increase in $\dot{V}E/\dot{V}CO_2$; (ii) visual inspection of the point at which $P_{ET}O_2$ reaches a minimum or starts to increase without a decline in $P_{ET}CO_2$ and (iii) calculation of the point of deflection of $\dot{V}CO_2$ versus $\dot{V}O_2$ (V-slope method).

2 Oxygen uptake at the second ventilatory threshold, $\dot{V}O_{2VT2}$ [l min^{-1}]: VT2 was obtained by: (i) visual inspection of the point where $\dot{V}E/\dot{V}CO_2$ has its minimum value or starts a non-linear increase; (ii) visual inspection of the point where $P_{ET}CO_2$ starts to decline and (iii) calculation of the point of deflection of $\dot{V}E$ versus $\dot{V}CO_2$.

The thresholds were estimated independently by two experienced raters (JS and KJH) using the above criteria; the definitive values were then set by mutual agreement.

The duration of the ramp phase, denoted t_{ramp} [s] and defined as the time from ramp onset until the time at which $\dot{V}O_{2\text{peak}}$ was deemed to have occurred, was also recorded.

Criteria for feasibility assessment

The criteria employed for assessment of the feasibility of the new self-paced method were as follows (Bowen et al., 2009): (i) implementation (technical feasibility of self-paced approach), (ii) acceptability (was the testing methodology tolerable?) and (iii) responsiveness (were the principal peak and submaximal performance outcomes able to be identified?).

Statistical analysis

A comparison of means was carried out for all seven outcome variables to test for any differences between the CP and SP protocols. Before the hypothesis testing was carried out, normality

of the sample differences was checked using the Kolmogorov–Smirnov test with Lilliefors correction. Paired two-sided t-tests were employed for normal data and Wilcoxon signed-rank tests otherwise. The null hypothesis for each paired comparison was that no difference existed and the significance level was set to $\alpha = 0.05$. Statistical analysis was performed using the Matlab Statistics and Machine Learning Toolbox (The Mathworks Inc.).

Results

Mean peak oxygen uptake was not significantly different (mean difference 0.04 ml min^{-1}) for the computer-paced and self-paced protocols: $\dot{V}O_{2\text{peak}}$ was 4.38 ± 0.48 versus $4.34 \pm 0.46 \text{ ml min}^{-1}$, CP versus SP ($P = 0.42$; Table 2, top row; Fig. 2a). Likewise, there were no significant differences in the other peak and submaximal cardiopulmonary parameters, viz. HR_{peak} , RER_{peak} , $\dot{V}O_{2VT1}$ and $\dot{V}O_{2VT2}$ (Table 2; Figs 2b,c and 3a,b).

The first ventilatory threshold, VT1, was successfully determined for all 10 subjects for both protocols. As noted in Table 2, for one subject VT2 could not be determined for both the CP and SP protocols, therefore $n = 9$ for the $\dot{V}O_{2VT2}$ comparison.

The ramp duration for CP was substantially and significantly longer (mean difference $123.2 \text{ s} \equiv 2 \text{ min}, 3.2 \text{ s}$) than for SP: t_{ramp} was 494.5 ± 71.1 versus $371.3 \pm 86.0 \text{ s}$, CP versus SP ($P = 0.00072$; Table 2, bottom row; Fig. 4b). In 2 of 10 cases for SP, t_{ramp} was outwith (below) the desirable ramp duration range of 5–26 min (see Section Discussion), whereas for CP, no case was outside this range (Fig. 4b). Concomitantly (for ramp protocols, work rate is directly proportional to time), the peak rate of work done against gravity, P_{peak} , was significantly higher (mean difference 61.0 W) for CP than for SP: 264.8 ± 40.8 versus $203.8 \pm 53.4 \text{ W}$, CP versus SP ($P = 0.0021$, Table 2, Fig. 4a).

Discussion

The aim of this study was to investigate the feasibility of a new method for self-paced peak performance testing on treadmills and to compare peak and submaximal performance

Table 2 Outcome measures for paired comparisons and P-values for comparison of means (see also Figs 2–4).

	Mean \pm SD		MD (95% CI) CP–SP	P-value
	CP	SP		
$\dot{V}O_{2\text{peak}}/(\text{l min}^{-1})$	4.38 ± 0.48	4.34 ± 0.46	$0.04 (-0.07, 0.15)$	0.42
$HR_{\text{peak}}/(\text{bpm})$	188.1 ± 10.2	190.5 ± 9.7	$-2.4 (-9.9, 5.1)$	1.0
RER_{peak}	1.16 ± 0.05	1.14 ± 0.09	$0.02 (-0.04, 0.07)$	0.48
$P_{\text{peak}}/(\text{W})$	264.8 ± 40.8	203.8 ± 53.4	$61.0 (28.6, 93.4)$	0.0021
$\dot{V}O_{2VT1}/(\text{l min}^{-1})$	2.15 ± 0.39	2.24 ± 0.44	$-0.09 (-0.27, 0.08)$	0.26
$\dot{V}O_{2VT2}/(\text{l min}^{-1})$	3.66 ± 0.72	3.58 ± 0.70	$0.08 (-0.27, 0.43)$	0.61
$t_{\text{ramp}}/(\text{s})$	494.5 ± 71.1	371.3 ± 86.0	$123.2 (67.7, 178.7)$	0.00072

$n = 10$, except $\dot{V}O_{2VT2}$ ($n = 9$).

CP, computer-paced; SP, self-paced; MD, mean difference, CP–SP; SD, standard deviation; 95% CI, 95% confidence interval for the mean difference; P-values are: paired two-sided t-tests, except for HR_{peak} (two-sided Wilcoxon signed-rank test).

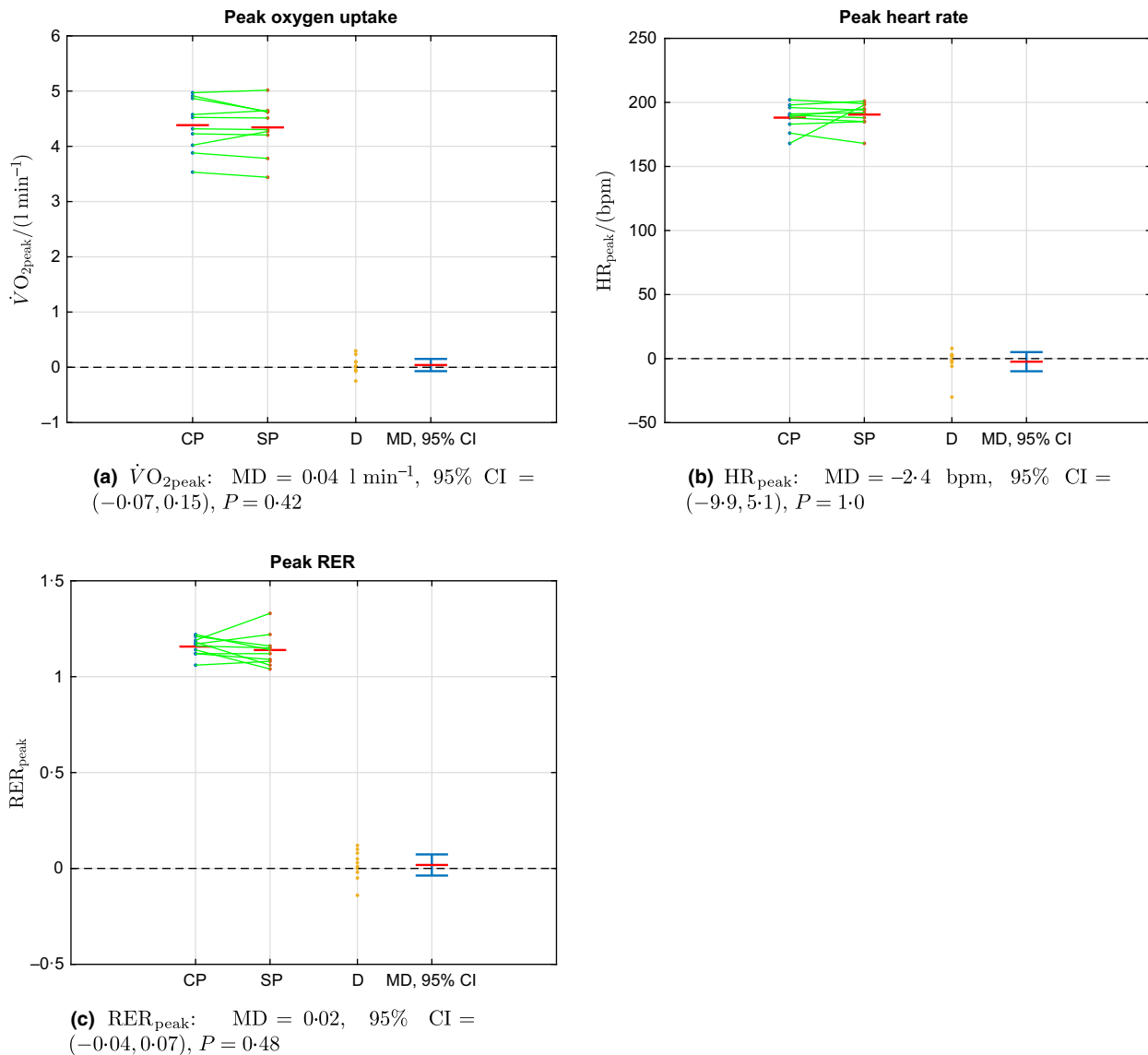


Figure 2 Peak cardiopulmonary performance outcomes: samples for all 10 subjects for computer-paced (CP) and self-paced (SP) tests (see Table 2); the green lines link the sample pairs from each subject; the red horizontal bars depict mean values. D is the difference between the paired samples: D = CP-SP. MD is the mean difference (red horizontal bar), with its 95% confidence interval (CI) in blue. Inclusion of the value 0 within the 95% CIs signifies non-significant differences between the means; this conforms with $P > 0.05$ for each of these variables (Table 2). [Colour figure can be viewed at wileyonlinelibrary.com]

outcomes with those obtained using a non-self-paced method employing predetermined speed and slope profiles. The proposed self-paced method is based upon automatic subject positioning using feedback control together with an exercise intensity which is driven by a predetermined, individualized work-rate ramp.

The mean ramp-phase duration of 6.2 min (371.3 s) for the self-paced protocol was significantly shorter than for the computer-paced approach [8.2 min (494.5 s)], but was still within contemporary guidelines for incremental test duration (Midgley et al., 2008): there, Midgley et al. critically reviewed available evidence and concluded that, to elicit valid peak $\dot{V}O_2$ values, incremental treadmill tests should last between 5 and 26 min. This conclusion challenged a widely adopted

recommendation from Buchfuhrer et al. (1983) that test duration should be between 8 and 12 min – the latest guidelines from the American College of Sports Medicine still recommend 8–12 min for clinical exercise testing (Pescatello et al., 2014; p. 126) – but the Buchfuhrer study included only five subjects and has been criticized elsewhere as being underpowered to an ‘unacceptable’ degree (Yoon et al., 2007). The authors of Buchfuhrer et al. (1983) later refined their recommended duration to between 8 and 10 min, while adding that ‘tests as short as 6 min are acceptable’ (Wasserman et al., 2004, p. 149).

Despite the difference in ramp-phase duration, both protocols gave similar values for all peak and submaximal cardiopulmonary parameters. This lends further support to the concept that short-duration incremental tests can elicit valid

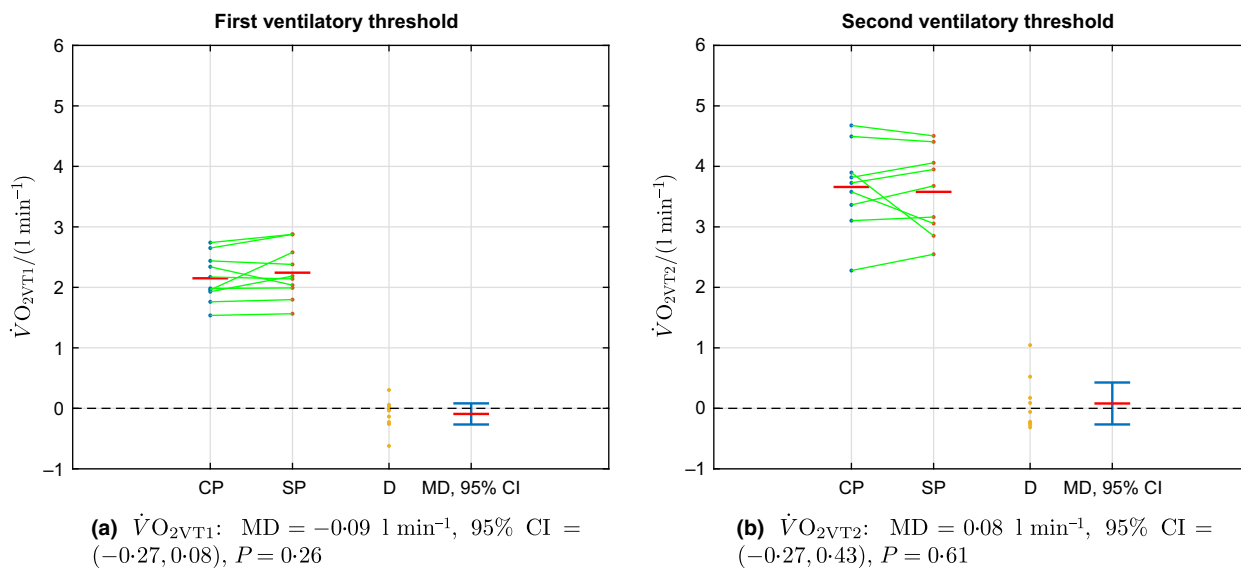


Figure 3 Submaximal performance outcomes: samples for all 10 subjects for computer-paced (CP) and self-paced (SP) tests (see Table 2); the green lines link the sample pairs from each subject; the red horizontal bars depict mean values. D is the difference between the paired samples: $D = CP - SP$. MD is the mean difference (red horizontal bar), with its 95% confidence interval (CI) in blue. Inclusion of the value 0 within the 95% CIs signifies non-significant differences between the means; this conforms with $P > 0.05$ for each of these variables (Table 2). [Colour figure can be viewed at wileyonlinelibrary.com]

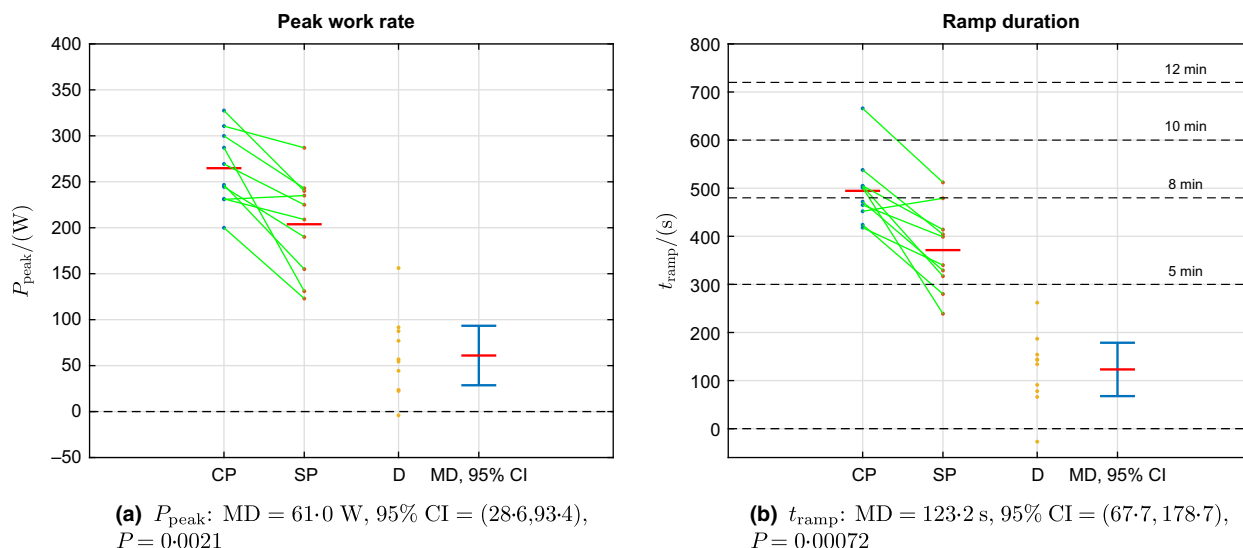


Figure 4 Peak rate of work done against gravity and ramp duration: samples for all 10 subjects for computer-paced (CP) and self-paced (SP) tests (see Table 2); the green lines link the sample pairs from each subject; the red horizontal bars depict mean values. D is the difference between the paired samples: $D = CP - SP$. MD is the mean difference (red horizontal bar), with its 95% confidence interval (CI) in blue. The value 0 is out-with the 95% CIs in both cases, marking a significant difference between the means; this conforms with $P < 0.05$ for these variables (Table 2). The thick, horizontal, black-dashed lines in (b) indicatively mark durations of 5, 8, 10 and 12 min (see Section Discussion). [Colour figure can be viewed at wileyonlinelibrary.com]

outcomes in some populations. This overall outcome is also consistent with several studies reviewed in the Introduction which did not show that self-pacing made a difference to the measured physiology.

The significantly lower peak rate of work done against gravity with the self-paced protocol is directly correlated with the difference in ramp-phase duration because, for both protocols, the work-rate ramp increased linearly with respect to time. It

may seem surprising that, despite the apparent difference in the peak rate of work done against gravity, both protocols gave similar peak $\dot{V}O_2$ values. Closer analysis reveals, however, that the maximum (self-determined) speed for self-pacing was substantially higher than for the conventional (preprogrammed) profile (Fig. 5); in fact, the maximum SP-speed was higher than the maximum CP-speed for all 10 subjects. Conversely, the maximum treadmill slope for SP was lower than for CP. It

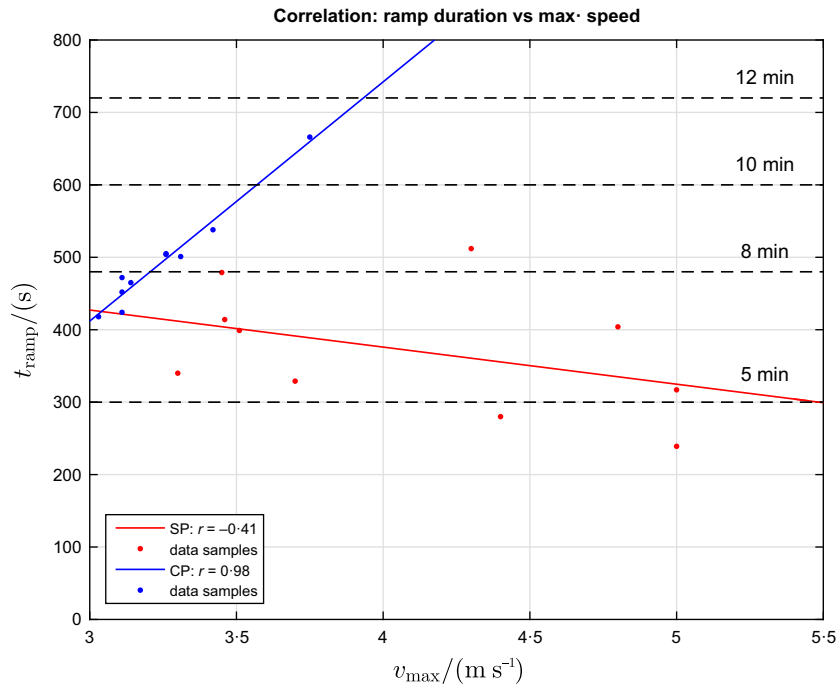


Figure 5 Correlation between ramp duration and maximum running speed. For the self-paced (SP) protocol, there is a moderate negative linear correlation with $r = -0.41$, $P = 0.24$ (red line and samples). For the computer-paced (CP) protocol, there is a very strong (almost perfect) positive linear correlation: $r = 0.98$, $P = 5.3 \times 10^{-7}$, blue line and samples. The horizontal black-dashed lines indicatively mark durations of 5, 8, 10 and 12 min. [Colour figure can be viewed at wileyonlinelibrary.com]

follows that the unmeasured component of work performed, that is the baseline work rate associated with running on-the-level at a given speed, will have been substantially higher for SP than for CP. That is, the total rate of work actually attained during the exercise, comprising the sum of this unmeasured power and the rate of work done against gravity according to Eq. (1), is likely to have been similar for the two protocols. This is reflected in the similar values for peak $\dot{V}O_2$. The observed moderate and negative linear correlation between maximum speed and ramp duration for the SP protocol (Fig. 5) is consistent with this hypothesis.

Future studies investigating the potential of the proposed self-paced approach to generate more valid peak $\dot{V}O_2$ values should be carefully designed to control for the observed tendency for self-pacing to result in higher running speeds, lower slopes and concomitantly shorter test durations: the purpose of the present study was to do a head-to-head comparison with only a single factor, viz. self-paced versus computer-paced; it is known, however, that ramp duration influences peak oxygen uptake, see Midgley et al. (2008), therefore the (significantly different) test duration emerged unwittingly as a second, unaccounted-for factor.

A simple way to attempt to balance ramp-phase durations for both protocols would be to use the ratio of the t_{ramp} values observed here to scale the target peak work rates. This could be done in one of two ways: by extending the target durations for SP to match those of CP or by reducing the target durations of CP to match those of SP.

A second option would be to augment the equation for work rate, Eq. (1), to include a term which explicitly predicts the on-the-level work rate. Such a term could be derived from an estimate of the total metabolic cost (total $\dot{V}O_2$) of running, such as the widely employed equation described in Deschenes & Ewing Garber (2014). That equation includes three terms: one related to the cost of on-the-level running, which is linearly proportional to speed; one involving gravity, including both speed and slope; and the baseline (resting) cost. The modified work-rate equation, augmented using the first of these terms, would then be

$$P(t) = mgv_t(t) \sin(\theta(t)) + k_v v_t(t), \quad (5)$$

where the constant of proportionality k_v can be obtained using an estimate of the oxygen cost of the work done during level treadmill running (Saengsuwan et al., 2016). The corresponding expression for the treadmill angle is [cf. Eq. (2)]

$$\theta(t) = \arcsin\left(\frac{P(t) - k_v v_t(t)}{mgv_t(t)}\right). \quad (6)$$

Employment of these modified expressions would potentially even out differences in test duration between the CP and SP protocols: for a given total work rate P , a higher running speed would give a higher on-the-level work-rate contribution $k_v v_t(t)$ [the second term on the right-hand side of Eq. (5)] which would necessarily be compensated for by a lower contribution from the gravitational component $mgv_t(t) \sin(\theta(t))$, resulting in turn in a lower angle and slope.

Conclusions

The new self-paced approach was found to be a feasible method for estimation of peak and submaximal performance parameters during incremental treadmill testing: the method was technically implementable (implementation aspect), it was well tolerated by the subjects (acceptability) and cardiopulmonary performance outcomes were identifiable and found to be similar to those obtained using a conventional protocol (responsiveness). Further investigation of the proposed self-paced method, with adjustment of the target ramp-phase duration or modification of the work-rate calculation equations, is warranted.

Authors' contributions

KJH and JS designed the study. PA and JAL did the data acquisition. PA, JAL, JS and KJH contributed to the analysis and interpretation of the data. KJH wrote the manuscript; JS, PA and JAL revised it critically for important intellectual content. All authors read and approved the final manuscript.

References

- Åström KJ, Murray RM. *Feedback Systems* (2008). Princeton University Press, Princeton, NJ, USA and Oxford, UK.
- Binder RK, Wonisch M, Corra U, et al. Methodological approach to the first and second lactate threshold in incremental cardiopulmonary exercise testing. *Eur J Cardiovasc Prev Rehabil* (2008); **15**: 726–734.
- Bowen DJ, Kreuter M, Spring B, et al. How we design feasibility studies. *Am J Prev Med* (2009); **36**: 452–457.
- Buchfuhrer MJ, Hansen JE, Robinson TE, et al. Optimizing the exercise protocol for cardiopulmonary assessment. *J Appl Physiol Respir Environ Exerc Physiol* (1983); **55**: 1558–1564.
- Chidnok W, Dimenna FJ, Bailey SJ, et al. $\dot{V}O_{2max}$ is not altered by self-pacing during incremental exercise. *Eur J Appl Physiol* (2013); **113**: 529–539.
- Deschenes M, Ewing Garber C. General principles of exercise prescription. In: *ACSM's Guide-Lines for Exercise Testing and Prescription* (Chap. 7), 9th edn (eds Pescatello, LS, Arena, R, Riebe, D, Thompson, PD) (2014), pp. 162–193. Lippincott, Williams and Wilkins, Philadelphia.
- Faulkner J, Mauger AR, Woolley B, et al. The efficacy of a self-paced $\dot{V}O_{2max}$ test during motorized treadmill exercise. *Int J Sports Physiol Perform* (2015); **10**: 99–105.
- Hogg JS, Hopker JG, Mauger AR. The self-paced $\dot{V}O_{2max}$ test to assess maximal oxygen uptake in highly trained runners. *Int J Sports Physiol Perform* (2015); **10**: 172–177.
- Hunt KJ. Treadmill control protocols for arbitrary work rate profiles combining simultaneous nonlinear changes in speed and angle. *Biomed Signal Process Control* (2008); **3**: 278–282.
- Jamieson LP, Hunt KJ, Allan DB. A treadmill control protocol combining nonlinear, equally smooth increases in speed and gradient: exercise testing for subjects with gait and exercise limitations. *Med Eng Phys* (2008); **30**: 747–754.
- Lander PJ, Butterly RJ, Edwards AM. Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. *Br J Sports Med* (2009); **43**: 789–795.
- Lichtenstein L, Barabas J, Woods RL, et al. A feedback-controlled interface for treadmill locomotion in virtual environments. *ACM Trans Appl Percept* (2007); **4**: 7.
- Mauger AR, Sculthorpe N. A new $\dot{V}O_{2max}$ protocol allowing self-pacing in maximal incremental exercise. *Br J Sports Med* (2012); **46**: 59–63.
- Mauger AR, Metcalfe AJ, Taylor L, et al. The efficacy of the self-paced $\dot{V}O_{2max}$ test to measure maximal oxygen uptake in treadmill running. *Appl Physiol Nutr Metab* (2013); **38**: 1211–1216.
- Midgley AW, Bentley DJ, Luttikholt H, et al. Challenging a dogma of exercise physiology: does an incremental exercise test for valid $\dot{V}O_{2max}$ determination really need to last between 8 and 12 minutes? *Sports Med* (2008); **38**: 441–447.
- Minetti AE, Boldrini L, Brusamolin L, et al. A feedback-controlled treadmill (treadmill-on-demand) and the spontaneous speed of walking and running in humans. *J Appl Physiol* (2003); **95**: 838–843.
- Pescatello LS, Arena R, Riebe D eds, et al. *ACSM's Guide-Lines for Exercise Testing and Prescription*, 9th edn (2014). Lippincott, Williams and Wilkins, Philadelphia.
- Plotnik M, Azrad T, Bondi M, et al. Self-selected gait speed - over ground versus self-paced treadmill walking, a solution for a paradox. *J Neuroeng Rehabil* (2015); **12**: 20.
- Saengsuwan J, Nef T, Hunt KJ. A method for predicting peak work rate for cycle ergometer and treadmill ramp tests. *Clin Physiol Funct Imaging* (2016); doi: 10.1111/cpf.12344.
- Scheidler CM, Devor ST. $\dot{V}O_{2max}$ measured with a self-selected work rate protocol on an automated treadmill. *Med Sci Sports Exerc* (2015); **47**: 2158–2165.
- Sloot LH, van der Krogt MM, Harlaar J. Self-paced versus fixed speed treadmill walking. *Gait Posture* (2014); **39**: 478–484.
- Sloot LH, Harlaar J, van der Krogt MM. Self-paced versus fixed speed walking and the effect of virtual reality in children with cerebral palsy. *Gait Posture* (2015); **42**: 498–504.

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Disclosure statement

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in this study in regard to the human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards: the study protocol was reviewed and approved by the Ethics Committee of the Swiss Canton of Bern (Ref. KEK-Nr. 106/14). Informed consent was obtained from all individual participants included in the study.

- Sperlich PF, Holmberg H-C, Reed JL, et al. Individual versus standardized running protocols in the determination of $\dot{V}O_{2\max}$. *J Sports Sci Med* (2015); **14**: 386–393.
- Wasserman K, Hansen JE, Sue DY, et al. *Principles of exercise testing and interpretation*, 4th edn (2004). Lippincott, Williams and Wilkins, Philadelphia, USA.
- Yoon B-K, Kravitz L, Robergs R. $\dot{V}O_{2\max}$, protocol duration, and the $\dot{V}O_2$ plateau. *Med Sci Sports Exerc* (2007); **39**: 1186–1192.