The sustainability of VO_{2max}: effect of decreasing the workload

Véronique Billat, Hélène Petot, Jason R. Karp, Guillaume Sarre, R. Hugh Morton & Laurence Mille-Hamard

European Journal of Applied Physiology

ISSN 1439-6319

Eur J Appl Physiol
DOI 10.1007/s00421-012-2424-7

Springer

Eur J Appl Physiol
DOI 10.1007/s00421-012-2424-7

ORIGINAL ARTICLE

The sustainability of VO_{2max}: effect of decreasing the workload

Véronique Billat · Hélène Petot · Jason R. Karp · Guillaume Sarre · R. Hugh Morton · Laurence Mille-Hamard

Received: 6 September 2011 / Accepted: 8 May 2012

Abstract The study examined the maintenance of VO_{2max} using VO_{2max} as the controlling variable instead of power. Therefore, ten subjects performed three exhaustive cycling exercise bouts: (1) an incremental test to determine VO_{2max} and the minimal power at VO_{2max} (PVO_{max}), (2) a constant-power test at PVO_{max} and (3) a variable-power test (VPT) during which power was varied to control VO_2 at VO_{2max}. Stroke volume (SV) was measured by impedance in each test and the stroke volume reserve was calculated as the difference between the maximal and the average 5-s SV. Average power during VPT was significantly lower than PVO_{max} (238 ± 79 vs. 305 ± 86 W; $p < 0.0001$). All subjects, regardless of their VO_{2max} values and/or their ability to achieve a VO_{2max} plateau during incremental test, were able to sustain VO_{2max} for a significantly longer time during VPT compared to constant-power test (CPT) (958 ± 368 s vs. 136 ± 81 s; $p < 0.0001$). Time to exhaustion at VO_{2max} during VPT was correlated with the power drop in the first quarter of the time to exhaustion at VO_{2max} ($r = 0.71$; $p < 0.02$) and with the stroke volume reserve ($r = 0.70$, $p = 0.02$) but was not correlated with VO_{2max}. This protocol, using VO_{2max} rather than power as the controlling variable, demonstrates that the maintenance of exercise at VO_{2max} can exceed 15 min independent of the VO_{2max} value, suggesting that the ability to sustain exercise at VO_{2max} has different limiting factors than those related to the VO_{2max} value.

Keywords Cycling · Endurance · Plateau · Performance · Stroke volume

Communicated by David C. Poole.

V. Billat (✉) · H. Petot · G. Sarre · L. Mille-Hamard
INSERM U902, University Genopole Evry, ZAC Bras de Fer,
3 bis impasse Christophe Colomb, 91000 Evry, France
e-mail: veronique.billat@wanadoo.fr

J. R. Karp
RunCoachJason.com, San Diego, CA, USA

R. H. Morton
School of Sport and Exercise, Massey University,
Palmerston North, New Zealand

Introduction

For generations of physiologists, VO_{2max} has been considered the defining characteristic of the O_2 transport system. However, animals and humans rarely, and then only fleetingly, exercise at VO_{2max} (Poole 2008). Maybe this is the reason why the endurance at VO_{2max} has not been investigated as VO_{2max} itself which is considered as the gold standard parameters of the cardiorespiratory system's maximal ability to deliver oxygen and of aerobic muscle metabolism since one century (Hill and Lupton 1923; Howley 2007). Indeed, the concept of a maximal plateau in oxygen uptake with increasing intensity of independent, continuous, fixed-power exercises was central to Hill and Lupton's (Hill and Lupton 1923) description of maximal oxygen uptake (VO_{2max}). Since then, VO_{2max} and its associated power (PVO_{max}) have been considered, while a plateau in VO_2 at the end of an incremental exercise test is used as an important criterion to validate that VO_{2max} has been achieved (di Prampero et al. 1986), the duration that subjects can sustain that plateau has largely been ignored. In contrast, endurance at some fraction of VO_{2max} has achieved much attention, as it has been shown to have important performance ramifications (Aunola and Rusko 1984; Dempsey et al. 1984).

Research over the last 15 years has examined the time limit at the minimal power eliciting VO_{2max} (PVO_{max}) in incremental power protocols (Billat et al. 2000, 2009). This time limit at PVO_{max} (Tlim@PVO_{max}), while reproducible, is highly variable between subjects (3–8 min) (Billat et al. 1994). Furthermore, Tlim@PVO_{max} is negatively correlated with PVO_{max} and VO_{2max}, and positively correlated with the maximal oxygen deficit, an index of the ability to generate energy from anaerobic metabolism (i.e., anaerobic capacity) (Billat et al. 2000). It has been shown that VO_{2max} is reached and maintained during constant-load exercise performed until exhaustion within 3–10 min (between 90 and 105 % of PVO_{max}) (Day et al. 2003; Hawkins et al. 2007; Morton and Billat 2000; Rossiter et al. 2006). A power eliciting a longer VO_{2max} plateau has been proposed as a "critical power at VO_{2max}" (Dempsey et al. 1984) and shown to be between the lactate threshold and PVO_{max} (Morton and Billat 2000). However, the determination of individual endurance at VO_{2max} requires a series of at least four such exhaustive exercise bouts, which is impractical in a systematic approach to endurance at VO_{2max}. Furthermore, past research exercise protocols have been based on power as the controlling factor in the model, making examination of the fatigue response at a VO_{2max} plateau difficult, as it is confounded by a mechanical and/or neuromuscular fatigue limitation (McKenna and Hargreaves 2008; Place et al. 2007). While there is still debate concerning the central versus peripheral limiting factors of VO_{2max} (Bergh et al. 2000; Ekblom 2009), the limiting factors of VO_{2max} and of the ability to sustain VO_{2max} remain to be investigated independently of PVO_{max}.

The purposes of this study were to (1) examine the maintenance of VO_{2max} using VO_{2max} as the controlling variable instead of the power associated with VO_{2max} and (2) examine the association between the cardiovascular factors that determine VO_{2max} and the ability to sustain $VO_{2max.}$ We hypothesized that VO_{2max} can be sustained for a longer duration when exercise is controlled by maintenance of VO_{2max}, and that the limiting cardiovascular factors of endurance at VO_{2max} are unrelated to its value.

Methods

Subjects

Ten (7 males, 3 females) healthy, active subjects who were familiar with cycling exercise volunteered to take part in the study (Table 1). Before participation, subjects were verbally explained the nature of the study, including the risks associated with performing a maximal physical effort, and gave their written voluntary informed consent. The present study conformed to the standards set by the Declaration of Helsinki, and all the procedures were approved by the Local Research Ethics Committee.

Table 1 Subject characteristics

Subjects characteristics

S #	Gender	Age (years)	Height (cm)	Weight (kg)	Sport
1	F	37	163	45	Triathlete
2	F	30	160	52	Triathlete
3	M	37	171	68	Cyclist
4	M	37	177	78	Cyclist
5	M	29	177	78	Cyclist
6	M	35	170	63	Cyclist
7	M	35	170	65	Cyclist
8	M	37	178	78	Triathlete
9	F	31	167	62	Triathlete
10	M	35	179	89	Triathlete
Mean	–	34	171	68	–
SD	–	3	6	13	–

Experimental design and exercise protocols

After familiarization with the laboratory and procedures, each subject performed three exercise tests to exhaustion: (1) an incremental test to determine maximal oxygen consumption (VO_{2max}), (2) a constant-power exercise bout at PVO_{max} (CPT) and (3) an exercise bout during which power was varied to maintain VO_2 at VO_{2max} (VPT). All tests were performed at least 2 h postprandial and were separated by at least 72 h. Subjects were asked to refrain from caffeine intake on the days of testing.

Maximal oxygen consumption (VO_{2max}) test

Each subject performed an incremental exercise test to exhaustion on an electronically braked cycle ergometer (ERGOLINE 900, Hellige, Markett, Bitz, Germany). The VO_{2max} test was used to determine VO_{2max}, the minimal power that elicited VO_{2max} (PVO_{max}), and the power associated with the lactate threshold (pLT), The lactate threshold was determined from the relationship between blood lactate concentration and power output and was defined as a non-linear increase in the lactate concentration of at least 1 mM (3) (Table 2). The test began at 50 W for 6 min and increased 50 W every 3 min until exhaustion.

Constant-power test

The second test was a CPT at PVO_{max}. Subjects warmed up for 15 min at 50 % of PVO_{max}, rested for 5 min until VO_2 returned to its resting value, and then cycled at PVO_{max}

Table 2 Individual maximal values measured in the incremental test

Values of incremental test

S #	VO_{2max} (mL kg^{-1} min^{-1})	pLT (W)	PVO_{max} (W)	pPeak (W)	HRmax (bpm)	SVmax (mL)	COmax (L min^{-1})	Lacmax (mmol L^{-1})
1	46	150	200	200	161	94	15.1	9
2	45	150	200	200	166	88	17.2	8
3	70	250	350	400	193	179	34.6	13
4	58	300	400	400	177	133	22.1	10
5	63	300	400	450	191	150	33.3	16
6	49	150	250	300	195	126	28.3	8
7	51	200	300	300	191	123	22.3	13
8	60	350	400	450	191	189	30.1	10
9	42	150	200	200	170	115	20.1	10
10	52	250	350	400	201	176	33.8	12
Mean	53.6	225	305	330	184	137	15.1	11
SD	8.9	75	86	103	19	35	7.0	2

Values are mean ± SD. VO_{2max} is the maximal oxygen uptake achieved in the incremental test

pLT power associated with the lactate threshold. PVO_{max} power associated with VO_{2max}, *pPeak* maximal power reached by the subject during the incremental test, HR_{max} maximal heart rate achieved in the incremental test, SV_{max} maximal stroke volume achieved in the incremental test, CO_{max} maximal cardiac output achieved in the incremental test, *Lacmax* maximal blood lactate concentration measured at the end of incremental test

until volitional exhaustion. Each subject's time to exhaustion was recorded.

Variable-power test

The third test was a variable-power test (VPT) in which the power was modulated for maintaining VO_2 at VO_2 as long as possible. Indeed, once the subjects reached their VO_{2max}, we applied a VO_{2max} controlled protocol by modulation of the power. This test was exactly identical to CPT before the subject reached VO_{2max} (as measured with the incremental test). At this time, power was decreased from PVO_{max} to pLT with different individual patterns while maintaining a VO_{2max} plateau during the longest time possible. During the first second of the VO_{2max} plateau, the first power decreased by 19 ± 9 W/10 s on average. Then, the power continuously adjusted by stage of 5 or 10 W, so that the power was at its lowest point possible. In the same way, in this case VO_2 declined lower than 95 % VO_{2max}, the power was increased by the same procedure by stage of 5 or 10 W. The test stopped when the subject did not support the VO_{2max}, any longer, or when the subject stopped the test by himself.

Data collection procedures

Oxygen uptake was measured breath-by-breath during each test using a Cosmed Quark b^2 (Rome, Italy), with expired gas concentrations averaged every 5 s. Before each test, the Quark b^2 was calibrated according to the manufacturer's instructions, the turbine flow-meter being calibrated using a 3-L syringe (Quinton Instruments, USA).

During all three tests, stroke volume (SV) and heart rate (HR) were recorded beat-by-beat by a non-invasive cardiac output measurement using analysis of thoracic electrical bioimpedance signals (Lab 1, Physioflow, Manatec Type PF05L1, Strasbourg, France). Cardiac output (CO) was calculated from HR and SV values. Then, HR, SV and CO were averaged every 5 s.

The theoretical basis for this device and its validity during rest and exercise testing have been previously published (Teo et al. 1985; Bernstein 1986; Charloux et al. 2000; Lepretre et al. 2004; Richard et al. 2001, 2004; Tordi et al. 2004).

The VO_2 and CO values were synchronized over 5 s intervals to obtain the arterio-veinous difference (Da-VO_2). The oxygen blood saturation (SaO_2) was recorded every 2 min and the end of VO_{2max} during both tests with a non-invasive pulse oximeter placed at the fingertip (Oxypleth, Novametrix Medical System, Wallingford, USA).

The lactate blood concentration was measured with lactate pro® (lactate pro, ARKRAY.Inc, Kyoto, Japan). During the incremental test blood lactate was measured at the end of each power stage during the incremental protocol and every 2 min of the VO_{2max} plateau, at the end and 2 and 4 min of CPT and VPT protocols.

The subjects were given strong verbal encouragement to exercise until volitional fatigue, but were not given progress feedback. The rating of perceived exertion (RPE) was recorded at the end of each power stage, every 2 min during VO_{2max} plateau and at the end of the test with RPE Borg scale (Borg 1982).

Data analysis

The attainment of VO_{2max} was confirmed by the following criteria: (1) a plateau in VO_2 ($\Delta VO_2 < 10$ ml min^{-1} W^{-1}); (2) a respiratory exchange ratio greater than 1.10, (3) a heart rate > 95 % of the theoretical age-predicted maximal HR (Howley et al. 1995; Poole et al. 2008b), (4) an RPE > 16, and (5) a blood lactate concentration above 8 mM. If a VO_{2max} plateau was not identified, all other criteria needed to be met to validate the attainment of VO_{2max}. The duration of the VO_{2max} plateau was calculated as the time sustained at a VO_2 >95 % of VO_{2max} acknowledging its experimental and biological variability (Katch et al. 1982) and the minimal duration for considering a VO_{2max} plateau was 1 min (Day et al. 2003; Doherty et al. 2003). Time to attain VO_{2max} (Tatt) was calculated as the total exercise time to exhaustion (Tlim test) minus the time at VO_{2max}.

VO_{2max} and maximum stroke volume were identified as the highest averaged 30-s value. In the CPT, the stroke volume reserve was calculated as the sum of successive 5-s intervals difference between the maximal SV and the current SV.

Statistical analysis

Normality of the data and the equality of the variances were verified using commercially available software (SigmaStat, Jandel Scientific, Chicago, IL, USA). Given normality and equality of the variances, a one-way analysis of variance (ANOVA) was performed to test for a protocol effect on the differences in time to exhaustion at VO_{2max} between the incremental test, the CPT, and the VPT (Staview 5.5, StatSoft, Berkeley, CA, USA). A post hoc test (PLSD of Fischer) was then applied to test the difference in time to exhaustion between the constant-power and VPTs. Correlations between Fick equation and respiratory factors, including SV, CO, HR, Da-VO_2, VE, and the time to exhaustion at PVO_{max} and VO_{2max} plateau were determined using Pearson's product moment correlation coefficient.

p values are included for all tests, and statistical and practical significances are discussed on a case-by-case basis. Results are presented as mean ± SD.

Results

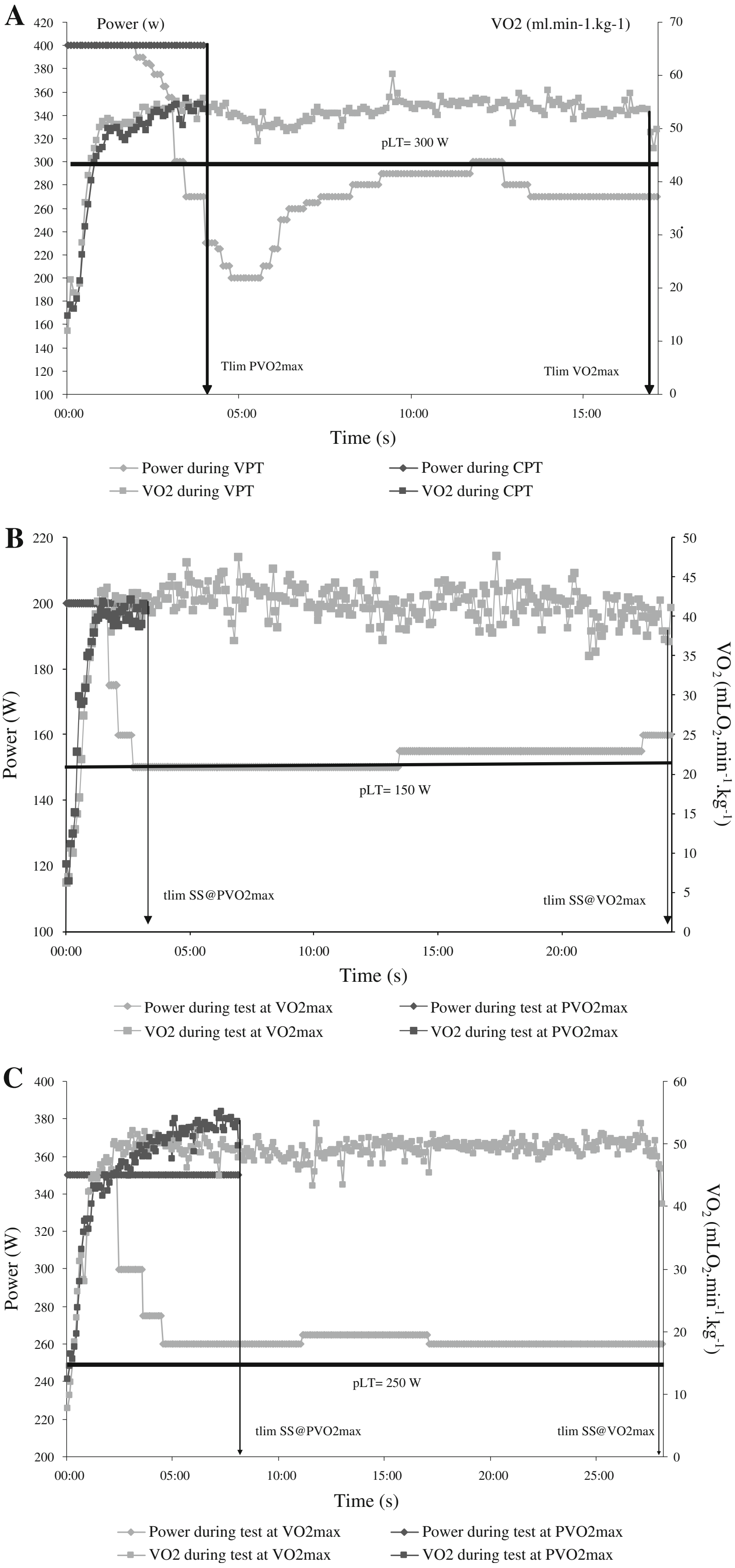
A long VO_{2max} plateau can be observed in all subjects when exercise is controlled by maintenance of VO_{2max} instead of PVO_{max}

According to our first hypothesis, once the subjects had reached VO_{2max} (in 71 ± 19 s), it is even possible, while maintaining VO_{2max} at an average power output which is not significantly above power at the lactate threshold (77 ± 6 vs. 74 ± 7 % of PVO_{2max} for the minimal power during VPT vs. pLT, $p = 0.08$). This submaximal power variation controlled by VO_{2max} allowed, then, the subject to sustain a long VO_{2max} plateau. Indeed, all subjects, regardless of their VO_{2max} and/or their ability to achieve a VO_{2max} plateau at the end of the incremental test maintained a much longer VO_{2max} plateau during the VPT compared to the CPT (15 min 58 s ± 6 min 8 s vs. 2 min 16 s ± 1 min 21 s; $p < 0.0001$, Tables 2, 3). Indeed, in VPT, only all the subjects but two sustained VO_{2max} for more than 10 min and among them, three subjects were even able to sustain it for longer than 20 min. In contrasts, in CPT, only three subjects sustained it for longer than 3 min (Table 3). The VO_{2max} steady state was maintained with the power fluctuated between the power at the lactate threshold (pLT) and at VO_{2max} (PVO_{max}) (Fig. 1a–c). Furthermore, the average power of VPT was not significantly different from pLT (77.4 ± 6.3 vs. 73.2 ± 7.1 % of PVO_{max}, $p = 0.08$, Fig. 2). While VO_{2max} was at a steady state, cardiorespiratory parameters, blood lactate concentration and RPE increased significantly until the maximal values registered in CPT and the incremental test (Fig. 3).

Table 3 Time at VO_{2max} during each of the tests (min; s): incremental test (Inc), constant-power test (CPT) and variable power test (VPT)

Time at VO_{2max} during each test (s)			
S #	Inc test	CPT	VPT
1	0 min 40 s	1 min 35 s	20 min 20 s
2	1 min 15 s	1 min 40 s	16 min 05 s
3	1 min 55 s	3 min 15 s	16 min 50 s
4	1 min 40 s	3 min 00 s	16 min 10 s
5	0 min 20 s	0 min 20 s	07 min 10 s
6	0 min 15 s	0 min 25 s	14 min 50 s
7	1 min 25 s	2 min 30 s	08 min 50 s
8	0 min 40 s	3 min 05 s	10 min 05 s
9	1 min 00 s	2 min 05 s	23 min 15 s
10	1 min 20 s	4 min 45 s	26 min 00 s
Mean	1 min 03 s	2 min 16 s	15 min 58 s
SD	0 min 33 s	1 min 21 s	06 min 08 s

Fig. 1 Pattern of power variation (W) and VO_2 (mL kg^{-1} min^{-1}) during variable-power test and constant-power test of 3 subjects with low, medium, and long endurance at VO_{2max} plateau. pLT (W) is the power associated with the lactate threshold. **a** Subject S4 with time to exhaustion at VO_{2max} during constant-power test at 3 min 00 s and during TlimVO_{2max} at 16 min 10 s. **b** Subject S9 with to exhaustion at VO_{2max} during constant-power test at 2 min 05 s and during TlimVO_{2max} at 23 min 15 s. **c** Subject S10 with TlimVO_{2max} during constant-power test at 4 min 45 s and during variable-power test at 26 min 00 s



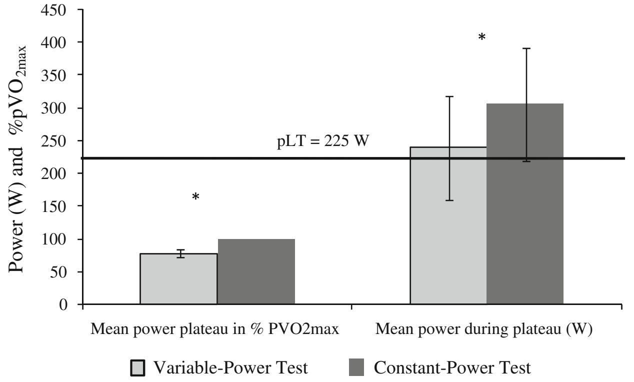


Fig. 2 Mean power of plateau in %PVO_{2max} and mean power of plateau (W) during variable-power test and constant-power test. pLT (W) is the power associated with the lactate threshold

Limiting factors of endurance at VO_{2max} during variable-power test versus constant-power test

According to our second hypothesis, endurance at VO_{2max} (TlimVO_{2max}) was not correlated with VO_{2max} ($r = 0.05$, $p = 0.84$) (Table 4). Furthermore, despite the similitude of maximal physiological responses, TlimVO_{2max} was not associated with the same cardiorespiratory parameters than VO_{2max} (Table 5). Indeed, while VO_{2max} was correlated with maximal values of SV and Da-VO_2, TlimVO_{2max} was correlated with average values of HR, CO and SV expressed in percentage maximal values HR_{max}, CO_{max}, SV_{max}. TlimVO_{2max} was also correlated with the percentage PVO_{2max} (Table 5). Therefore, while VO_{2max} was correlated with the maximal SV, TlimVO_{2max} was correlated with cardiac and power reserves (Table 5). Furthermore, TlimVO_{2max} was correlated with amplitude of the power drop in the first quarter of the VO_{2max} (expressed in Watts; $r = 0.71$, $p < 0.02$). This decrease of power output for the same oxygen uptake (i.e. VO_{2max}) induced an increase of the oxygen cost per watt which was significantly higher in the VPT versus CPT test at pTlimVO_{2max} (2 min 16 s ± 1 min 21 s) (11 ± 2 vs. 16 ± 5 W, $p < 0.01$). Furthermore, this difference of oxygen cost at TlimPVO_{max} between VPT and CPT, was correlated with TlimVO_{2max} ($r = 0.76$, $p < 0.01$). It was, therefore, possible, but only with 58 % (r^2) of determination to estimate the TlimVO_{2max} once the subject reached its TlimPVO_{max} (at 2 min 16 s ± 1 min 21 s).

TlimVO_{2max} was also correlated with the difference of RPE at TlimPVO_{max} ($r = 0.73$, $p = 0.01$). However, this difference of RPE was not correlated with the difference of power output at TlimPVO_{max} ($r = 0.38$, $p = 0.29$). Therefore, the difference of RPE does not directly covariates with the difference of power output at TlimPVO_{2max} in VPT versus CPT.

Discussion

According to our hypothesis: (1) it was possible for all subjects to sustain their VO_{2max} about 20 min in half the subjects when the power output is controlled by VO_{2max}, (2) The ability to sustain VO_{2max} is independent of VO_{2max} suggesting that there are different limiting factors between VO_{2max} and the ability to sustain it.

Here we showed that a long maintenance of VO_{2max} even appeared in subjects who did not demonstrate a plateau in VO_2 at the end of the incremental test. Indeed, despite only a 40 % occurrence of a VO_{2max} plateau during

Fig. 3 The power output (%PVO_{2max}) at 25, 50, 75 and 100 % of TlimVO_{2max} and the physiological variables in VPT. On *left y* axis: heart rate (HR, bpm), respiratory frequency (Rf, cycle min^{-1}), and on *right y* axis: RPE, blood lactate concentration (mM) ($p < 0.01$ for all with an ANOVA for repeated measurements)

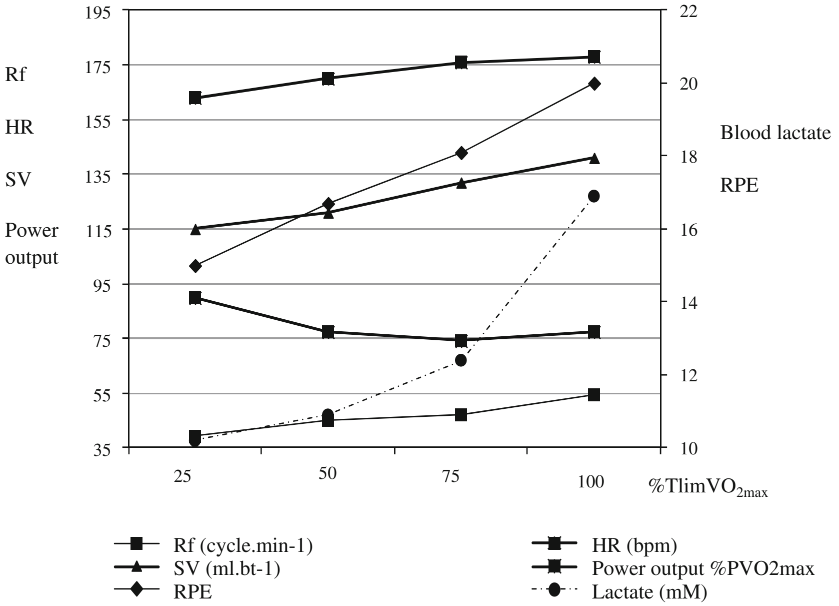


Table 4 Maximal values of variables during incremental test (Inc), constant-power test (CPT) and variable power test (VPT)

Variable	Inc	CPT	VPT	p
VO_{2max} (mL kg^{-1} min^{-1})	53.6 ± 8.9	52.5 ± 8.8	52.4 ± 11.2	0.95 <0.0001
Power output (%PVO_{max})	100	100	77 ± 6	
HR_{max} (bpm)	184 ± 19	171 ± 14	181 ± 12	0.11
SV_{max} (mL bt^{-1})	137 ± 35	152 ± 29	141 ± 34	0.6
CO_{max} (L min^{-1})	25.7 ± 7	26 ± 7	25.1 ± 6	0.1
Da-VO_{2max} (mL)	14.5 ± 2.5	14.5 ± 5.2	14.5 ± 3.5	0.99
Lac_{max} (mmol/L)	11.3 ± 2.4	13.7 ± 3.8	12.9 ± 2.4	0.2
VE_{max} (L min^{-1})	142 ± 40	132 ± 48	123 ± 48	0.6
Rf_{max} (breaths min^{-1})	52 ± 9	46 ± 10	54 ± 12	0.22
RPE_{max}	20 ± 0	20 ± 0	20 ± 0	1
Res SV@VO_{2max} (mL)	–	3,391 ± 3,297	8,708 ± 3,548	0.008*

Values are mean ± SD. See text for abbreviations

* Significant difference between VPT and CPT tests

Table 5 Correlations between Tlim@VO_{2max} and VO_{2max} and physiological variables in both constant-power test (CPT) and variable power test (VPT) ($n = 20$) excepted for the power drop (in VPT only, $n = 10$)

Parameters	VO_{2max}		TlimVO_{2max}	
	r	p	r	p
In CPT + VPT ($n = 10$)				
TlimVO_{2max}	−0.05	0.84	1	1
SVmax	0.53	0.02	0.06	0.82
SV_{mean}	0.48	0.03	−0.17	0.49
HR_{max}	0.27	0.25	0.24	0.31
HR_{mean}	−0.06	0.79	−0.07	0.75
CO_{max}	0.39	0.09	0.18	0.44
$SV_{reserve}$	−0.08	0.74	0.76	<0.01
$HR_{reserve}$	0.22	0.41	0.48	0.05
$CO_{reserve}$	0.07	0.76	0.65	0.01
maxDa-VO_2	0.81	<0.001	0.07	0.78
In VPT ($n = 10$)				
Power drop in the first quarter of TlimVO_{2max} VPT	0.76	0.01	0.39	0.08
Power reserve (average power plateau in % PVO_{max})	0.09	0.71	0.88	0.001

the incremental VO_{2max} test which is in agreement with other studies (Doherty et al. 2003). Indeed, VO_{2max} can be sustained more than six times as long when exercise is controlled by VO_{2max} compared with a classical constant-load test at PVO_{max}. In VPT, the power output is manipulated to keep VO_2 constant at its maximal value (VO_{2max}) between pLT and PVO_{max} with an early drop of the power output applied during the first quarter of the test. This is this early drop of the power output, and not the difference of average power between CPT and VPT, which was correlated with TlimVO_{2max}. This drop of power output was applied once the subject reached VO_{2max} after less than 2 min at PVO_{2max}. This procedure using decremental power output has recently shown to even allow an increase in VO_{2peak} (Mauger and Sculthorpe 2012). Therefore, we can wonder whether VO_{2max} got in an incremental test or even in a constant-load test at PVO_{2max} was really the VO_{2max} and by consequence this could explain the ability for subject to sustaining it for 20 min and more. We can solve this question by responding that VO_{2max} is not by itself a limiting factor of its maintenance but that how it is obtained that is questionable. Indeed, with the same VO_{2max}, but in VPT, subjects were exhausted in 1/6 the time than in CPT.

This preliminary experimental work did not examine the reproducibility of TlimVO_{2max} for the same pattern of power variation. Twenty years ago, we showed the reproducibility of TlimPVO_{2max} but the independency of TlimPVO_{2max} and PVO_{2max} (Billat et al. 1994). Indeed, for the same PVO_{2max} and VO_{2max}, subjects had a great (30 %) variance of TlimPVO_{2max} with a range between 2 and 12 min and an average of 6 min 30 s not far from the TlimPVO_{2max} used in the Péronnet et al.'s mathematical analysis of running performance and world running records (Peronnet and Thibault 1989). The present study shows that the model could be refined with the consideration of TlimVO_{2max} instead of TlimPVO_{2max} which can be extended with submaximal and variable power output.

Despite the individual power variation patterns, we decreased for all subjects, the power output with success in the extension of VO_{2max} plateau duration. This was already suggested 30 years ago by Essén (1978) which showed that a brief recovery period will be of benefit to an athlete involved in activities which demand intermittent exercise as a fall in the level of PCr appears to adversely affect muscle contraction. Therefore, a recovery period with a lower power output in a subsequent bout would maximize the rate of PCr resynthesis (Essén 1978). Here, we decreased power by about 30 W (10 %). This apparently small power decrease allowed a relatively large enhancement of endurance due to the hyperbolic relationship between tolerable duration and power. This was confirmed by a significant relationship between the time to exhaustion at VO_{2max} and the power decrease during the CPT. This variable power controlled by VO_{2max} protocol induced an excess O_2 requirement as previously reported during the decremental phases of ramp exercise (Niizeki et al. 1995; Yano et al. 2000).

Indeed, here we show that the increase of delay of exhaustion at VO_{2max} is directly linked with the decrease of the power but not the average and the early one in the first quarter of VPT. This possibility of getting a long TlimVO_{2max} had already reported in prior works have confirmed that VO_{2max} is reached and sustained for 1–10 min over a wide range of exercise intensities between 80 and 140 % of PVO_{max} (Astrand and Saltin 1961; Poole et al. 2008a; Coats et al. 2003; di Prampero 1999; Hawkins et al. 2007; Howley et al. 1995; Taylor et al. 1955). An interesting point is that exercise controlled by VO_{2max} allows subjects to obtain nearly the same time to exhaustion at VO_{2max} as in the critical power model at VO_{2max} ($CV'_{VO_{2max}}$) we previously proposed (Billat et al. 2000; di Prampero 1985; Morton and Billat 2000). Indeed, $CV'_{VO_{2max}}$ was determined by plotting the work versus time limit as in the critical power concept (Jones et al. 2010), but specifically at VO_{2max} (Billat et al. 2000; di Prampero 1999; Morton and Billat 2000). This is an important finding for the practical applications as it suggests that once subjects reach their VO_{2max} here (in a little more than 1 min at PVO_{2max}), they can decrease the workload down to that at the lactate threshold and still be working at their VO_{2max}. Subjects were able to sustain VO_{2max} at a much lower power, even at that, which is associated with the lactate threshold (~80 % of PVO_{max}). This has been empirically used in the so-called interval training for a century and further experimentally measured in years 2000 when portable gas analysers appeared (for review on interval training, see Billat 2001a, b). Indeed, Billat et al. (2000), reported that in a 30–30– s short interval training run at 100–50 % of the velocity at VO_{2max} (vVO_{2max}), runners stayed at VO_{2max} even during the recovery period from the fifth to the last (18th) repetition of a 30-s run at (vVO_{2max}). This short interval training with active pauses allows individual to sustain VO_{2max} for 10 min (83 % of total run at vVO_{2max} during the high 30 s speed. We also demonstrated that very short interval training (15 s–15 s) around the critical velocity allows middle-aged runners to maintain VO_{2max} for 14 min (Billat et al. 2001a). Furthermore, this very short interval training alternating brief runs at 100 and 70 % of vVO_{2max}, was more easily accepted (more than 70 % of participants completed both test and the training sessions two times a week for 6 weeks) and they increased significantly their VO_{2max} and their maximal lactate steady state velocity by 20 % (Billat et al. 2001a). Interval training which calibrates the duration of hard work considering TlimPVO_{2max} has been, with success for improving performance and VO_{2max} (Smith et al. 2003; Denadai et al. 2006).

However, we have yet never taken into account the TlimVO_{2max}. At first, the value experimentally measured in the present study is in accordance with the one predicted as 10 min and the power at 88 % of PVO_{max} (Morton and Billat 2000). In this present study, subjects achieved a longer average time to exhaustion at VO_{2max} (>14 min) for a lower average power (77 % PVO_{max}). However, the controlling variable was VO_{2max} and not power as in those prior studies proposing the $CV'_{VO_{2max}}$ model. The $CV'_{VO_{2max}}$ model was still based on constant-power exercise that is not the best conditioning for performance (Garcin et al. 2007).

Here we showed that exercise controlled by VO_{2max} induced power variation (VPT). Therefore, in this novel study we propose a method for approaching, if not determining, the maximal work at VO_{2max} we could called "the maximal accumulated oxygen at VO_{2max}" ("MAOVO_{2max}") which could be complementary the maximal accumulated oxygen deficit (MAOD) for characterizing the whole metabolic scope (aerobic/anaerobic) of one subject. Future researches are required now for defining a method for determining the individual MAOVO_{2max} and examine the best procedure according this one.

Indeed, MAOVO_{2max} takes into account the fact that the ability to sustain VO_{2max} is independent of the VO_{2max} value and has probably not the same limiting factor (Billat et al. 2000, 2009). Tlim VO_{2max} and VO_{2max} are both correlated to stroke volume. However, the former is independent of the latter, suggesting that there are different limiting factors between VO_{2max} and the ability to sustain it. di Prampero (1999) showed that VO_{2max} is more centrally (cardiovascular) limited, especially in trained individuals. The ability to sustain VO_{2max} is associated with the sustainability of a submaximal stroke volume that allows a cardiac reserve throughout the VPT. The early power decrease allowed subjects to remain at a submaximal stroke volume and, consequently, there was a positive correlation between the stroke volume reserve and the time to exhaustion at VO_{2max}. Prior work using an exercise model controlled by VO_{2max}, but with submaximal power reported that exercise at the power between the lactate threshold and VO_2peak (Ozyener et al. 2003) elicited VO_{2max} without eliciting the maximal cardiac output and stroke volume (Lepretre et al. 2008). The positive correlation between stroke volume reserve and time to exhaustion at VO_{2max} might be a consequence of the power decrease that may be the primary factor limiting the ability to sustain VO_{2max}.

Thus, the ability to sustain VO_{2max} may be due to a muscle power limitation rather than the inability to maintain Fick equation factors (cardiac output and arterial-venous oxygen content difference) at their maximal values (Bergh et al. 2000; Ekblom 2009; Wagner 2000).

It is now well established that during self-paced exercise, the exercise work rate is regulated by the brain based on the integrates of numerous signals from various physiological systems (Noakes 2012). It has been proposed that the brain regulates the degree of muscle activation and thus exercise intensity specifically to prevent harmful physiological disturbances. In a recent review, Tucker (2009) proposed how RPE is generated as a result of the numerous afferent signals during exercise and serves as a mediator of any subsequent alterations in skeletal muscle activation levels and exercise intensity. He proposed a conceptual model for how the RPE mediates feed forward, anticipatory regulation of exercise performance in various conditions, including heat, hypoxia and reduced energy substrate availability, utilizing an RPE clamp design, central nervous system drugs and the provision of inaccurate duration or distance feedback to exercising athletes. The present protocol was not a free pace protocol but a variable pace controlled for staying at the maximal VO_{2max}. While VO_{2max} was sustained, RPE continuously increased during VPT, and the difference of RPE at TlimPVO_{2max} between VPT and CPT was correlated with the extension of TlimVO_{2max} between CPT and VPT and the cardiac parameters (SV, HR and CO) reserves are the sole factors associated of TlimVO_{2max}.

One interesting point is that the difference of RPE at the same absolute time (TlimPVO_{2max}: 2 min 16 s) allowed to predict 56 % of the extension of the individual TlimVO_{2max} in VPT versus CPT. It, therefore, may be suggested that the RPE is directly related to the power output at any instant of the protocol and could be directly linked to the estimated time limit (ETL scale of Garcin et al. 2007), which could conditioning the test duration and, therefore, TlimVO_{2max} in VPT. Therefore, the future of monitoring exercise testing is probably not the power or the speed, but the perceptual cues in the regulation of exercise performance (Mauger and Sculthorpe 2012; Swart et al. 2011; Pires et al. 2011; Stoudemire et al. 1996).

This new protocol, which sets VO_{2max} as the controlling variable, demonstrated that the ability to sustain VO_{2max} can exceed 15 min independent of the VO_{2max} value and that the limiting factors are different than those of VO_{2max} itself. Specifically, the variation of power is the limiting factor of sustaining VO_{2max} and a VO_{2max}-controlled biofeedback exercise permits a significant delay in precipitating exhaustion at VO_{2max}. Given that we found a strong relationship between the difference in RPE at the same absolute time (i.e., the time limit at PVO_{max}) and the difference in time to exhaustion at VO_{2max}, further studies are required to understand the effect of biofeedback on exercise performance. Prior studies have indicated that endurance is improved for a given task when neuromuscular activity is used as feedback rather than muscle force (Place et al. 2007). However, this new exercise model controlled by VO_{2max} may be a new approach for further investigation of the limits of aerobic power in humans. In the present study, we stopped the test because the subject was not able to sustain VO_{2max} despite in the submaximal power. Further studies are required for elucidating the possibility for optimizing the power variation by plotting the RPE versus the variation of the work at VO_{2max} in a differential equation (Billat et al. 2009) and maybe still extend VO_{2max} by the appropriate power variation.

Acknowledgments This work was funded by the National Institutes of Health U902, INSERM, Paris, France and by the University Genopole, Evry, France.

References

Astrand P-O, Saltin B (1961) Oxygen uptake during the first minutes of heavy muscular exercise. J Appl Physiol 16:971–976

Aunola S, Rusko H (1984) Reproducibility of aerobic and anaerobic thresholds in 20–50 year old men. Eur J Appl Physiol Occup Physiol 53:260–266

Bergh U, Ekblom B, Astrand P-O (2000) Maximal oxygen uptake "classical" versus "contemporary" viewpoints. Med Sci Sports Exerc 32:85–88

Bernstein DP (1986) A new stroke volume equation for thoracic electrical bioimpedance: theory and rationale. Crit Care Med 14:904–909

Billat V, Dalmay F, Antonini MT, Chassain AP (1994) A method for determining the maximal steady state of blood lactate concentration from two levels of submaximal exercise. Eur J Appl Physiol Occup Physiol 69:196–202

Billat VL, Morton RH, Blondel N, Berthoin S, Bocquet V, Koralsztein JP, Barstow TJ (2000) Oxygen kinetics and modelling of time to exhaustion whilst running at various velocities at maximal oxygen uptake. Eur J Appl Physiol 82:178–187

Billat LV (2001a) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. Sports Med 31:13–31

Billat LV (2001b) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part II: anaerobic interval training. Sports Med 31:75–90

Billat V, Hamard L, Koralsztein JP, Morton RH (2009) Differential modeling of anaerobic and aerobic metabolism in the 800-m and 1,500-m run. J Appl Physiol 107:478–487

Borg GA (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14:377–381

Charloux A, Lonsdorfer-Wolf E, Richard R, Lampert E, Oswald-Mammosser M, Mettauer B, Geny B, Lonsdorfer J (2000) A new impedance cardiograph device for the non-invasive evaluation of cardiac output at rest and during exercise: comparison with the "direct" Fick method. Eur J Appl Physiol 82:313–320

Coats EM, Rossiter HB, Day JR, Miura A, Fukuba Y, Whipp BJ (2003) Intensity-dependent tolerance to exercise after attaining VO_{2max} in humans. J Appl Physiol 95:483–490

Day JR, Rossiter HB, Coats EM, Skasick A, Whipp BJ (2003) The maximally attainable VO_2 during exercise in humans: the peak vs. maximum issue. J Appl Physiol 95:1901–1907

Denadai BS, Ortiz MJ, Greco CC, de Mello MT (2006) Interval training at 95% and 100% of the velocity at VO_2 max: effects on aerobic physiological indexes and running performance. Appl Physiol Nutr Metab 31:737–743

Dempsey JA, Hanson PG, Henderson KS (1984) Exercise-induced arterial hypoxaemia in healthy human subjects at sea level. J Physiol 355:161–175

di Prampero PE (1985) Metabolic and circulatory limitations to VO_{2max} at the whole animal level. J Exp Biol 115:319–331

di Prampero PE (1999) The concept of critical velocity: a brief analysis. Eur J Appl Physiol Occup Physiol 80:162–164

di Prampero PE, Atchou G, Brückner JC, Moia C (1986) The energetics of endurance running. Eur J Appl Physiol Occup Physiol 55:259–266

Doherty M, Nobbs L, Noakes TD (2003) Low frequency of the "plateau phenomenon" during maximal exercise in elite British athletes. Eur J Appl Physiol 89:619–623

Ekblom B (2009) Counterpoint: maximal oxygen uptake is not limited by a central nervous system governor. J Appl Physiol 106:339–341

Essén B (1978) Studies on the regulation of metabolism in human skeletal muscle using intermittent exercise as an experimental model. Acta Physiol Scand Suppl 454:1–32

Garcin M, Danel M, Billat V (2007) Perceptual responses in free vs. constant pace exercise. Int J Sports Med 29:453–459

Hawkins MN, Raven PB, Snell PG, Stray-Gundersen J, Levine BD (2007) Maximal oxygen uptake as a parametric measure of cardiorespiratory capacity. Med Sci Sports Exerc 39:103–107

Hill AV, Lupton H (1923) Muscular exercise, lactic acid, and the supply and utilization of oxygen. Q J Med 16:135–171

Howley ET (2007) VO_{2max} and the plateau—needed or not? Med Sci Sports Exerc 39:101–102

Howley ET, Bassett DR Jr, Welch HG (1995) Criteria for maximal oxygen uptake: review and commentary. Med Sci Sports Exerc 27:1292–1301

Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC (2010) Critical power: implications for determination of VO_{2max} and exercise tolerance. Med Sci Sports Exerc 42:1876–1890

Katch VL, Sady SS, Freedson P (1982) Biological variability in maximum aerobic power. Med Sci Sports Exerc 14:21–25

Lepretre PM, Koralsztein JP, Billat VL (2004) Effect of exercise intensity on relationship between VO_{2max} and cardiac output. Med Sci Sports Exerc 36:1357–1363

Lepretre PM, Lopes P, Koralsztein JP, Billat V (2008) Fatigue responses in exercise under control of VO_2. Int J Sports Med 29:199–205

Mauger AR, Sculthorpe N (2012) A new VO_2 max protocol allowing self-pacing in maximal incremental exercise. Br J Sports Med 46:59–63

McKenna MJ, Hargreaves M (2008) Resolving fatigue mechanisms determining exercise performance: integrative physiology at its finest! J Appl Physiol 104:286–287

Morton RH, Billat VL (2000) Maximal endurance time at VO_{2max} (2000). Med Sci Sports Exerc 32:1496–1504

Niizeki K, Takahashi T, Miyamoto Y (1995) A model analysis of asymmetrical response of pulmonary VO_2 during incremental and decremental ramp exercise. J Appl Physiol 79:1816–1827

Noakes TD (2012) The Central Governor Model in 2012: eight new papers deepen our understanding of the regulation of human exercise performance. Br J Sports Med 46:1–3

Ozyener F, Rossiter HB, Ward SA, Whipp BJ (2003) Negative accumulated oxygen deficit during heavy and very heavy intensity cycle ergometry in humans. Eur J Appl Physiol 90:185–190

Peronnet F, Thibault G (1989) Mathematical analysis of running performance and world running records. J Appl Physiol 67:453–465

Place N, Martin A, Ballay Y, Lepers R (2007) Neuromuscular fatigue differs with biofeedback type when performing a submaximal contraction. J Electro Kinesio 17:253–263

Poole DC (2008) Oxygen's double-edged sword: balancing muscle O_2 supply and use during exercise. Med Sci Sports Exerc 40:462–474

Poole DC, Barstow TJ, McDonough P, Jones AM (2008a) Control of oxygen uptake during exercise. Med Sci Sports Exerc 40:462–474

Poole DC, Wilkerson DP, Jones AM (2008b) Validity of criteria for establishing maximal O_2 uptake during ramp exercise tests. Eur J Appl Physiol.102:403–410

Richard R, Lonsdorfer-Wolf E, Charloux A, Doutreleau S, Buchheit M, Oswald-Mammosser M, Lampert E, Mettauer B, Geny B, Lonsdorfer J (2001) Non-invasive cardiac output evaluation during a maximal progressive exercise test, using a new impedance cardiograph device. Eur J Appl Physiol 85:202–207

Richard R, Lonsdorfer-Wolf E, Dufour S, Doutreleau S, Oswald-Mammosser M, Billat VL, Lonsdorfer J (2004) Cardiac output and oxygen release during very high-intensity exercise performed until exhaustion. Eur J Appl Physiol 93:9–18

Rossiter HB, Kowalchuk JM, Whipp BJ (2006) A test to establish maximum O_2 uptake despite no plateau in the O_2 uptake response to ramp incremental exercise. J Appl Physiol 100:764–770

Smith TP, Coombes JS, Geraghty DP (2003) Optimising high-intensity treadmill training using the running speed at maximal O(2) uptake and the time for which this can be maintained. Eur J Appl Physiol 89:337–343

Stoudemire NM, Wideman L, Pass KA, McGinnes CL, Gaesser GA, Weltman A (1996) The validity of regulating blood lactate concentration during running by ratings of perceived exertion. Med Sci Sports Exerc 28:490–495

Taylor HL, Buskirk E, Henschel A (1955) Maximal oxygen intake as an objective measure of cardio-respiratory performance. J Appl Physiol 8:73–80

Teo KK, Hetherington MD, Haennel RG, Greenwood PV, Rossall RE, Kappagoda T (1985) Cardiac output measured by impedance cardiography during maximal exercise tests. Cardiovasc Res 19:737–743

Tordi N, Mourot L, Matusheski B, Hughson RL (2004) Measurements of cardiac output during constant exercises: comparison of two non-invasive techniques. Int J Sports Med 25:145–149

Tucker R (2009) The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. Br J Sports Med 43:392–400

Wagner PD (2000) New ideas on limitations to VO_{2max}. Exerc Sport Sci Rev 28:10–14

Yano T, Yunoki T, Horiuchi M (2000) Kinetics of oxygen uptake during decremental ramp exercise. J Sports Med Phys Fitness 40:11–16