CRITICAL SPEED, THRESHOLDS FOR VO_{2MAX} AND BOUNDARIES OF THE SEVERE EXERCISE INTENSITY DOMAIN

VELOCIDADE CRÍTICA, $VO_{2MÁX}$ E LIMITES DE O DOMÍNIO DE INTENSIDADE DE EXERCÍCIO SEVERO

VELOCIDAD CRÍTICA, $VO_{2MÁX}$ Y LÍMITES DE EL DOMINIO DE LA INTENSIDAD DEL EJERCICIO SEVERO

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ABSTRACT

Introduction: The severe exercise intensity domain can be defined as the range of work rates or speeds over which VO_{2max} can be elicited. Objectives: Our purpose was to determine if critical speed (running analog of critical power) identifies the lower boundary of the severe domain and to identify the upper boundary of the domain. Methods: Twenty-five individuals performed five running tests to exhaustion, each lasting > 2.5 min and < 16 min. The two-parameter speed vs time-to-exhaustion relationship generated values for critical speed and the three-parameter speed vs time-to-reach-VO_{2max} relationship generated values for the threshold speed above which VO_{2max} can be elicited. The relationships were solved to calculate the minimum time needed to elicit VO_{2max}. Results: Critical speed (3.00 ± 0.38 $m{\cdot}s^{-1}$) and the threshold speed above which VO_{2max} can be elicited (2.99 ± 0.37 $m{\cdot}s^{-1}$) were correlated ($r = 0.83$, $p < 0.01$) and did not differ ($p = 0.70$), confirming critical speed as the lower boundary of the severe domain. The minimum time needed to elicit VO_{2max} (103 ± 7 s) and the associated highest speed at which VO_{2max} can be elicited (4.98 ± 0.52 $m{\cdot}s^{-1}$) identified the upper boundary of the severe domain for these participants. Conclusion: The critical power concept, which requires no metabolic measurements, can be used to identify the lowest speed at which VO_{2max} can be elicited. With addition of metabolic measurements, mathematical modeling can also identify the highest speed and shortest exercise duration at which VO_{2max} can be elicited. **Evidence Level I; Validating cohort study with good reference standards.**

Keywords: Exercise; Running; Maximal Voluntary Ventilation; Energy Metabolism.

RESUMO

Introdução: O domínio de intensidade de exercício severo pode ser definido como a faixa de taxas de trabalho ou velocidades sobre as quais o VO_{2max} pode ser obtido. Objetivos: Nosso propósito foi determinar se a velocidade crítica (execução analógica da potência crítica) identifica o limite inferior do domínio severo e identificar o limite superior do domínio. Métodos: Vinte e cinco indivíduos realizaram cinco testes de corrida até a exaustão, cada um com duração > 2,5 min e < 16 min. A relação velocidade de dois parâmetros contra tempo até a exaustão gerou valores para a velocidade crítica e a relação velocidade de três parâmetros contra tempo para alcançar o VO_{2max} valores gerados para a velocidade limite acima da qual o VO_{2max} pode ser obtido. As relações foram resolvidas para calcular o tempo mínimo necessário para eliciar o VO_{2max}. Resultados: A velocidade crítica (3,00 ± 0,38 $m{\cdot}s^{-1}$) e a velocidade limite acima da qual o VO_{2max} pode ser eliciado (2,99 ± 0,37 $m{\cdot}s^{-1}$) foram correlacionadas ($r = 0,83$, $p < 0,01$) e não diferiram ($p = 0,70$), confirmando a velocidade crítica como o limite inferior do domínio grave. O tempo mínimo necessário para eliciar o VO_{2max} (103 ± 7 s) e a maior velocidade associada na qual o VO_{2max} pode ser eliciado (4,98 ± 0,52 $m{\cdot}s^{-1}$) identificou o limite superior do domínio severo para esses participantes. Conclusão: O conceito de potência crítica, que não requer medidas metabólicas, pode ser usado para identificar a velocidade mais baixa em que o VO_{2max} pode ser eliciado. Com a adição de medidas metabólicas, a modelagem matemática também pode identificar a velocidade mais alta e a duração mais curta do exercício em que o VO_{2max} pode ser obtido. ***Nível de Evidência I; Estudo de coorte com alto padrão de referência.***

Descritores: *Exercício Físico; Corrida; Capacidade Respiratória Máxima; Metabolismo Energético.*

RESUMEN

Introducción: El dominio de la intensidad del ejercicio severo se puede definir como el rango de ritmos o velocidades de trabajo sobre las que se puede obtener el VO_{2max}. Objetivos: Nuestro propósito fue determinar si la velocidad crítica (funcionamiento analógico de potencia crítica) identifica el límite inferior del dominio severo e identificar el límite superior del dominio. Métodos: Veinticinco personas realizaron cinco pruebas de carrera hasta el agotamiento, cada una con una duración de > 2,5 min y <16 min. La relación de dos parámetros de velocidad frente a tiempo de agotamiento generó valores para la velocidad crítica y la relación de tres parámetros de velocidad frente a tiempo de alcance de VO_{2max} generó valores para la velocidad umbral por encima del cual se puede obtener el VO_{2max}. Las relaciones se resolvieron para calcular el tiempo mínimo necesario para obtener el VO_{2max}. Resultados: La velocidad crítica (3,00 ± 0,38 $m{\cdot}s^{-1}$) y la velocidad umbral por encima de la cual se puede obtener el VO_{2max} (2,99 ± 0,37 $m{\cdot}s^{-1}$) se

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correlacionaron ($r = 0{,}83$, $p < 0{,}01$) y no difirieron ($p = 0{,}70$), lo que confirma la velocidad crítica como el límite inferior del dominio severo. El tiempo mínimo necesario para obtener el VO_{2max} (103 ± 7 s) y la velocidad más alta asociada a la que se puede obtener el VO_{2max} ($4{,}98 \pm 0{,}52$ $m \cdot s^{-1}$) identificaron el límite superior del dominio severo para estos participantes. Conclusión: El concepto de potencia crítica, que no requiere mediciones metabólicas, se puede utilizar para identificar la velocidad más baja a la que se puede obtener el VO_{2max}. Con la adición de mediciones metabólicas, el modelado matemático también puede identificar la velocidad más alta y la duración más corta del ejercicio a la que se puede obtener VO_{2max}. ***Nivel de Evidencia I; Estudio de cohortes con alto estándar de referencia.***

Descriptores: *Ejercicio Físico; Carrera; Ventilación Voluntaria Máxima; Metabolismo Energético.*

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INTRODUCTION

The asymptote of the exponential power vs time-to-exhaustion relationship is critical power (CP).[1,2] In running, its analogue is critical speed (CS).[3] It is widely accepted that CP is the threshold intensity above which VO_{2max} can be attained,[4-7] with some studies confirming this belief [8-14] and others challenging it.[15-22] As this threshold speed, CS identifies the boundary between the heavy and severe exercise intensity domains, if the latter is defined by the ability to reach VO_{2max}.[5] Since there must be some minimum time needed to reach VO_{2max}, there must be an upper boundary to the severe domain, it being the highest intensity (shortest duration) at which VO_{2max} can be attained.[10,11,23,24]

It is important to achieve VO_{2max} in many exercise research, training, and testing situations. Therefore, it is of practical importance for sport practitioners and researchers to be able to identify the intensities that will elicit VO_{2max}.[25,26] Yet, it remains equivocal that CP or CS is the threshold for VO_{2max},[8-22] and there is little in the literature about an upper boundary of the severe domain.[10,11,23,24] The purpose of the present study was to determine if CS is the threshold speed for attaining VO_{2max} (i.e., lower boundary of the severe domain) and to identify the highest speed and shortest exercise duration at which VO_{2max} can be elicited (i.e., upper bound of the domain).

METHODS

Study design and ethical aspects

The study was approved by the university's Institutional Review Board for Protection of Human Subjects (#16452) and was conducted in accord with the Declaration of Helsinki. Participants provided written informed consent prior to any data collection.Using a within-subjects design, we had 25 participants perform five exercise tests and modeled relationships of speed vs time-to-exhaustion, speed vs time-to-reach-VO_{2max}, and speed vs time-spent-at-VO_{2max}. The validity of CS as the lower boundary of the severe domain was determined by comparison with two parameters derived using metabolic data. The upper boundary of the domain was also identified two ways.

Subjects

Seven women (age, 23 ± 2 y, height, 164 ± 6 cm, mass, 61 ± 6 kg) and 18 men (24 ± 2 y, 182 ± 7 cm, 90 ± 21 kg) participated. All were Kinesiology Majors and were involved in recreational sport or fitness activities, four or more times each week. They did not alter their exercise, diet, or sleep habits over the course of the study.

Exhaustive constant-speed running tests

Participants performed five 0%-grade treadmill tests at different speeds, each on a different day and all within a three-week period. Speeds were individually selected by the senior investigator to elicit exhaustion in ~3 to 12 min (actual time-to-exhaustion were between 2½ and 16 min). Expired gases were analyzed on a breath-by-breath basis using a MedGraphics (St. Paul, MN, USA) metabolic cart, which was calibrated before each test. Tests were scheduled at the same time of day to avoid the confounding effects of circadian rhythms on responses.[27]

Speed vs time-to-exhaustion and determination of critical speed (CS)

For each participant, speed and time-to-exhaustion data were fit to three mathematically equivalent models[2] using SPSSv22 (Armonk, NY, USA) to determine CS and D':

time-to-exhaustion = D' / (speed – CS) (Equation 1a)
distance = (time-to-exhaustion × CS) + D' (Equation 1b) and
speed = CS + (D' / time-to-exhaustion) (Equation 1c)

The value for CS derived using Equation 1a, which correctly (in the physiological sense) sets time-to-exhaustion as the dependent variable,[2] was used as the criterion measure. See Figure 1.

Speed vs time-to-reach-VO_{2max} and the lower boundary of the severe intensity domain

Breath-by-breath VO_2 data were reduced to rolling 8-breath and 30-breath averages. VO_{2max} was the highest 30-breath average in each test, and time-to-reach-VO_{2max} was the time from the onset of exercise to the midpoint of the time frame in which an 8-breath VO_2 first equaled or exceeded the VO_{2max} for that test.[10,14,24,28] This method addresses day-to-day variability in VO_{2max} by calculating the time to reach the highest VO_2 achieved *in that test*. Speed and time-to-reach-VO_{2max} data were fit to Equation 2:

time-to-reach-VO_{2max} =
D" / (speed – maximum-steady-state-speed) + α (Equation 2)

Maximum-steady-state-speed (the vertical asymptote) is the highest speed associated with a steady state VO_2 response and, by definition, the threshold speed above which VO_{2max} can be achieved. The α parameter is the horizontal asymptote. See Figure 1.

Speed vs time-spent at-VO_{2max} and the lower and upper boundaries of the severe intensity domain

There is a hyperbolic relationship between speed and time-spent-at-VO_{2max}[10,14,19,20,24] (time-to-exhaustion minus time-to-reach-VO_{2max}). Speed and time-spent-at-VO_{2max} data were fit to Equation 3:

time-spent-at-VO_{2max} =
D''' / (speed – minimum-VO_{2max}-speed) +
D''' / (upper-bound-speed – minimum-VO_{2max}-speed) (Equation 3)

Minimum-VO_{2max}-speed (the vertical asymptote) defines the lowest speed at which VO_{2max} can be achieved. The upper-bound-speed (x-intercept) is the highest speed associated with attainment of VO_{2max}. The time associated with this speed (minimum time-to-reach-VO_{2max}) was determined using this speed and equation 1a. See Figure 1.

Equation 1a and Equation 2 and the upper boundary of the severe intensity domain

The intersection of the curves described by Equations 1a and 2 identifies the minimum time-to-reach-VO_{2max} (i.e., time-to-exhaustion = time-to-reach-VO_{2max}) and the highest speed associated with attainment of VO_{2max}. This speed was calculated by equating the righthand sides of these two equations, using individual's values for the parameters and solving for speed:

$$D' / (\text{speed} - CS) = D'' / (\text{speed} - \text{maximum-steady-state-speed}) + \alpha \quad \text{(Equation 4)}$$

The time associated with this speed (minimum time-to-reach-VO_{2max}) was determined using this speed and equation 1a.

Statistical analyses

To evaluate the accuracy of the CS measure, values for CS and D' from Equations 1a, 1b, and 1c were compared using a repeated-measures analysis of variance (rANOVA). Estimates of the speed that demarcates the heavy and severe domains (CS from Equation 1a, maximum-steady-state-speed from Equation 2, and minimum-VO_{2max}-speed from Equation 3) were compared using rANOVA. The estimates of the upper boundary of the severe intensity domain (upper-bound-speed from Equation 3 and the speed calculated from the intersection of Equations 1a and 2, using Equation 4) were compared using a paired-means *t*-test. Significance was set at $p < 0.05$. All analyses were performed using SPSSv22. Data are presented as mean ± SD.

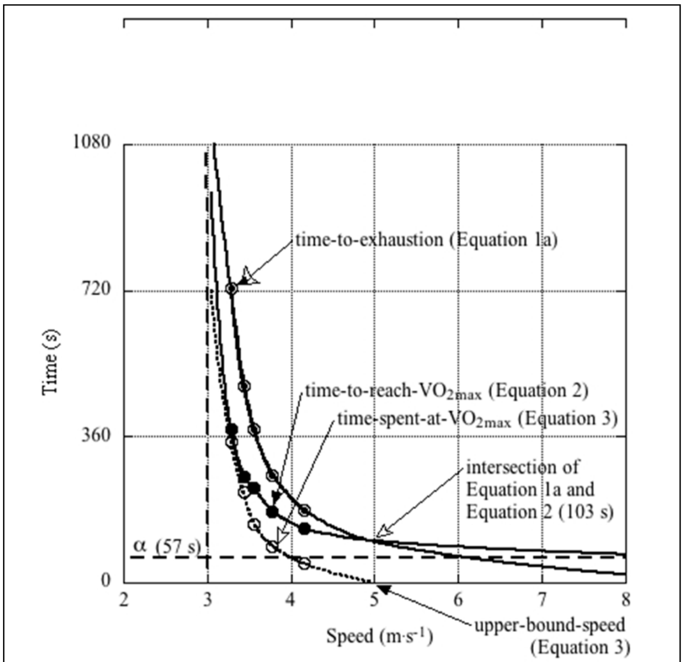

Figure 1. Mean data fit to Equation 1a, Equation 2, and Equation 3. Equation 1a (small closed circles within open circles, solid line) is speed vs time-to-exhaustion; Equation 2 (closed circles, solid line) is speed vs time-to-reach-VO_{2max}; and Equation 3 (open circles, dotted line) is speed vs time-spent-at-VO_{2max}. Data points are the mean values for the 25 participants. The vertical asymptotes (superimposed dashed lines) represent the CS (3.00 ± 0.38 m·s–1 from Equation 1a), maximum-steady-state-speed (2.99 ± 0.37 m·s–1 from Equation 2), and minimum-VO_{2max}-speed (2.98 ± 0.34 m·s–1 from Equation 3). Also identified on the graph are the horizontal asymptote, **α** (57 ± 6 s from Equation 2), the intersection point of Equation 1a and Equation 2 (calculated using Equation 4) (5.01 ± 0.49 m·s–1, 102 ± 7 s), and upper-bound-speed (4.98 ± 0.52 m·s–1) from Equation 3.

RESULTS

Responses in treadmill tests are in Table 1. Values for CS and D' from Equations 1a, 1b, and 1c are in Table 2. Values for the parameters from Equations 2 and 3 are in Table 3. There was no difference ($p = 0.49$) between upper-bound-speed (4.98 ± 0.52 $m \cdot s^{-1}$ from Equation 3) and the highest speed able to elicit VO_{2max} (5.01 ± 0.49 $m \cdot s^{-1}$, obtained using Equation 4; $r = 0.94$, $p < 0.001$). Bland-Altman plot [29] is in Figure 2. Substituting these speeds into Equation 1a showed that the minimum time-to-reach-VO_{2max} was 102 ± 7 s (based on Equation 4) or 103 ± 7 s (based on Equation 3).

Table 2. Mean (± SD) values for CS and D' generated using Equation 1a (which relates time-to-exhaustion and speed), Equation 1b (which relates distance and time-to-exhaustion), and Equation 1c (which relates speed and the inverse of time-to-exhaustion). The SEE of the estimates are also provided, both in the units of measure (in italics square brackets]) and as a percentage of the parameter estimate (in italics). The coefficient of variation (CV) describes the variability among the values from the three equations.

	Equation 1a	Equation 1b	Equation 1c	ANOVA	CV
CS ($m \cdot s^{-1}$)	3.00 ± 0.38	3.00 ± 0.40	3.01 ± 0.43	p = 0.89	0.6 ± 0.5%
	[0.08 ± 0.08]	[2 ± 3]	[5 ± 5]		
	3 ± 1%	1 ± 0%	3 ± 0%		
D' (m)	205 ± 63	205 ± 63	205 ± 59	p = 0.93	0.7 ± 0.6%
	[12 ± 6]	[11 ± 7]	[14 ± 8]		
	6 ± 1%	5 ± 1%	7 ± 2%		
Adjusted R^2	0.997 ± 0.001	0.999 ± 0.001	0.992 ± 0.007		

Table 3. Mean (± SD) values for parameters of Equation 2 (which relates speed and time-to-reach-VO_{2max}) and Equation 3 (which relates speed and time-spent-at-VO_{2max}). The SEE of the estimates are also provided, both in the units of measure (in italics square brackets) and as a percentage of the parameter estimate (in italics). The † symbol identifies variables that are unique to Equation 2 and the ‡ symbol identifies variables that are unique to Equation 3.

	†maximum-steady-state-speed	†D″	†a		
	‡minimum-VO_{2max}-speed	‡D‴		‡upper-bound-speed	R^2
	($m \cdot s^{-1}$)	(m)	(s)	($m \cdot s^{-1}$)	
†Equation 2	2.99 ± 0.37	90 ± 25	57 ± 6		
	[0.11 ± 0.10]	[7 ± 7]	[5 ± 7]		0.979 ± 0.012
	4 ± 1%	8 ± 2%	9 ± 2%		
‡Equation 3	2.98 ± 0.34	125 ± 23		4.98 ± 0.52	
	[0.12 ± 0.11]	[10 ± 8]		[0.17 ± 0.11]	0.983 ± 0.010
	4 ± 1%	8 ± 2%		3 ± 2%	

Note that the maximum-steady-state-speed from Equation 2 identifies the speed above which VO_{2max} can be elicited whereas the minimum-VO_{2max}-speed from Equation 3 is the lowest speed at which VO_{2max} can be elicited.

Table 1. Mean (± SD) responses during the five exhaustive treadmill tests. When ANOVA revealed a significant effect, different superscripts are used to identify means that differed.

	Exhaustive Tests (shortest to longest, from left to right)					ANOVA
speed ($m \cdot s^{-1}$)	4.15 ± 0.43[a]	3.78 ± 0.50[b]	3.55 ± 0.52[c]	3.43 ± 0.56[d]	3.28 ± 0.57[e]	p < 0.01
time-to-exhaustion (s)	180 ± 21[a]	265 ± 38[b]	378 ± 45[c]	485 ± 69[d]	726 ± 102[e]	p < 0.01
time-to-reach-VO_{2max} (s)	133 ± 24[a]	175 ± 31[b]	233 ± 45[c]	262 ± 77[d]	380 ± 104[e]	p < 0.01
time-spent-at-VO_{2max} (s)	47 ± 22[a]	90 ± 35[b]	145 ± 46[c]	223 ± 73[d]	346 ± 102[e]	p < 0.01
VO_{2max} ($L \cdot min^{-1}$)	3.60 ± 0.73	3.59 ± 0.74	3.60 ± 0.70	3.61 ± 0.71	3.60 ± 0.79	p = 0.68

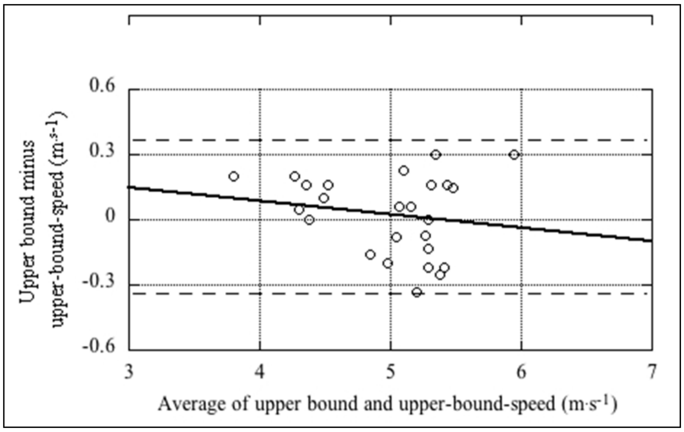

Figure 2. Bland-Altman plot[29] demonstrating the similarity of the two directly determined measures of the upper bound of the severe exercise intensity domain (i.e., the highest speed associated with the attainment of VO_{2max}). The first measure was the intersection of Equation 1a and Equation 2 using Equation 4 and the second measure was upper-bound-speed (from Equation 3). The regression equation describing the relationship (solid line) was Y = 0.338 – 0.062 x X (R2 = 003). The limits of tolerance (mean ± 1.96 x SD) are presented as dashed lines.

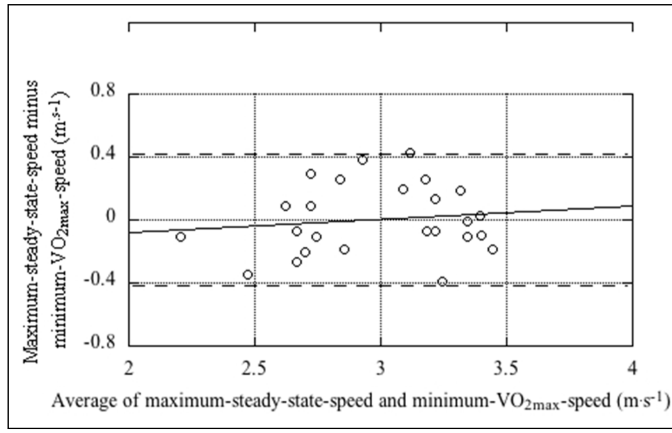

Figure 3. Bland-Altman plot[29] demonstrating the similarity of the two directly determined identifiers of the lower boundary of the severe exercise intensity domain. The first measure was maximum-steady-state-speed (from Equation 2) and the second measure was minimum-VO_{2max}-speed (from Equation 3). The regression equation describing the relationship (solid line) was Y = 0.238 + 0.081 x X (R2 = 002). The limits of tolerance (mean ± 1.96 x SD) are presented as dashed lines. This result verified the suitability of Equation 2 and Equation 3 to describe the relationships between VO_2 kinetics (i.e., time-to-reach-VO_{2max} and time-spent-at-VO_{2max}) and running speed and, therefore, to directly calculate the lower bound of the severe domain.

The results of rANOVA revealed no differences ($p = 0.89$) among the three estimates of the speed that demarcates heavy and severe domains (CS from Equation 1a, maximum-steady-state-speed from Equation 2, and minimum-VO_{2max}-speed from Equation 3). The intraclass correlation was 0.96 ($p < 0.001$). Bland-Altman plots [29] are in Figures 3, 4, and 5.

DISCUSSION

The first important finding in the present study is that CS, the running analog of CP, identifies the threshold speed above which VO_{2max} can be elicited. So, the lower boundary of the severe exercise intensity domain can be identified using Equation 1a, which requires no metabolic measurements. The second important outcome was that the upper boundary of the severe intensity domain (i.e., the highest running speed associated with attainment of VO_{2max}) could be identified by calculating the intersection of the curves described by Equations 1a and 2, or, alternatively, by using Equation 3.

The most widely cited evidence supporting the assertion that VO_{2max} can be achieved only during exercise above CP or CS is from a seminal study in which eight men were tested at CP and at CP + 8% and end-exercise VO_2 at CP + 8% (97 ± 6% VO_{2max}) was not different from VO_{2max} from an incremental test.[12] After training, the same men were tested at their new CP and at CP + 11% and end-exercise VO_2 (95 ± 5% VO_{2max}) was again not different VO_{2max}.[13] Widespread acceptance of this postulate (by reference directly to these studies[12,13] or indirectly to reviews[4-7]) speaks to the potency of the authors but obscures the dearth of direct and undisputed verification. Our results support the contention that CP or CS is the threshold intensity above which VO_{2max} can be achieved and are consistent with the results of studies that used mathematical modeling[10,11,14] or direct measurement of VO_2 at or above CP or CS,[8,9,12,13] but must be weighed against equivocal results[24] and against the contradictory results obtained in well-executed studies by Billat et al.[18-21] and others.[15-17,22]

The second important outcome of the present study was that the upper boundary of the severe intensity domain could be identified. Although there must be some minimum time necessary to reach VO_{2max} in exercise,[8,10,11,14,18,19,23,24,30] few studies have sought to calculate that time.[10,11,23,24] Hill and Ferguson[10] suggested that the intersection of the curvilinear power vs time-to-exhaustion and power vs time-to-reach-VO_{2max} relationships would identify the shortest time-to-reach-VO_{2max}. The present study is the first to do so, using a three-parameter model of

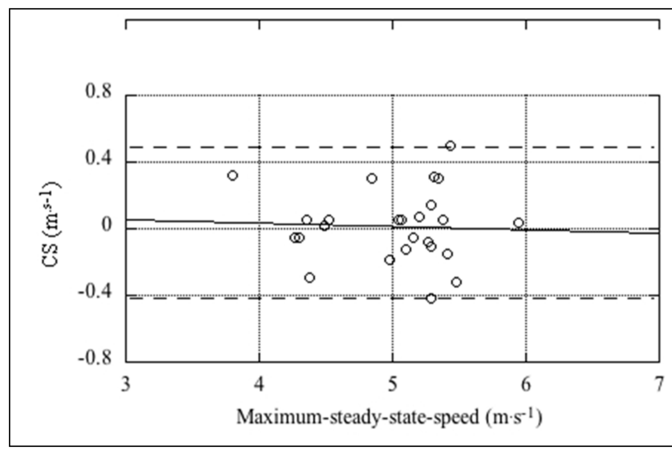

Figure 4. Bland-Altman plot[29] demonstrating the similarity of CS (from Equation 1a) and one of the directly determined identifiers of the lower bound of the severe exercise intensity domain, namely maximum-steady-state-speed (from Equation 2). As proposed by Krouwer,[32] the criterion measure ('gold standard') is used as the X-axis (rather than the average of the two measures). The regression equation describing the relationship (solid line) was Y = 0.428 – 0.138 x X (R2 = 055). The limits of tolerance (mean ± 1.96 x SD) are presented as dashed lines. This result verified the postulate that CS is the threshold intensity above which VO_{2max} can be elicited and that it identifies the lower boundary of the severe exercise intensity domain.

the speed vs time-to-reach-VO_{2max} relationship (Equation2). Equation 2 is theoretically-sound and it fit the data well, generating parameter estimates with small SEE and high R^2 (see Table 3). We also used a three-parameter hyperbolic model of the relationship between speed and time-spent-at-VO_{2max} (Equation 3). Equation 3 also is theoretically-sound and it fit the data well (see Table 3). Thus, the results validated that these models directly identify the lower boundary of the severe intensity domain.

Results from Equation 3 showed that VO_{2max} could be achieved in running at a speed ≤ 4.98 ± 0.52 $m{\cdot}s^{-1}$, a speed associated with a tolerable duration of 103 ± 7 s; and results from Equation 4 yielded 5.01 ± 0.49 $m{\cdot}s^{-1}$ and 102 ± 7 s. Previous estimates of the minimum time-to-reach-VO_{2max} in cycling were 136 ± 17 s,[11] ~151 s,[24] ~152 s,[24] or 159 ± 38 s for kinesiology students,[23] 103 ± 51 s for endurance-trained cyclists,[23] and 153 ± 50 s for trained runners.[23] Together, these results suggest that the upper boundary of the severe domain is associated with tolerable durations of ~1½ to ~2½ min and is affected by exercise mode and

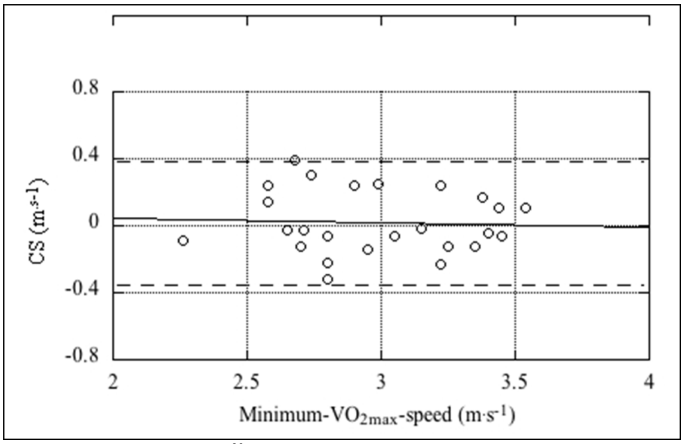

Figure 5. Bland-Altman plot[29] demonstrating the similarity of CS (from Equation 1a) and one of the directly determined identifiers of the lower bound of the severe exercise intensity domain, namely minimum-VO_{2max}-speed (from Equation 3). As proposed by Krouwer,[32] the criterion measure ('gold standard') is used as the X-axis (rather than the average of the two measures). The regression equation describing the relationship (solid line) was Y = 0.104 – 0.028 x X (R2 = 003). The limits of tolerance (mean ± 1.96 x SD) are presented as dashed lines. This result verified the postulate that CS is the threshold intensity above which VO_{2max} can be elicited and that it identifies the lower boundary of the severe exercise intensity domain.

perhaps fitness level. The upper boundary can be estimated using the (a) linear relationships between time-to-exhaustion and time-to-reach-VO_{2max},[11,23,24] (b) hyperbolic relationship between time-to-exhaustion and the amplitude of the slow component,[23] (c) intersection point of Equation 1a and Equation 2 (present study), or (d) asymptotic relationship between time-spent-at-VO_{2max} and speed (Equation 3, present study).

An important consideration in studies like this one is the accuracy of the calculation of CP or CS. Values are accurate if the estimates from Equations 1a, 1b, and 1c are similar[31] and, in the present study, they were: the average coefficient of variation among the three CS estimates, as well as among the three D' estimates, was less than 1%. In addition, the SEE associated with CS and D' were 3 ± 1% and 6 ± 1% of the respective parameter estimates, well within validated guidelines for accuracy.[31]

A new parameter, α, was introduced. Just as minimum-VO_{2max}-speed (vertical asymptote) in Equation 2 is the *speed* above which VO_{2max} can be achieved, so *α* (horizontal asymptote) is the *time* above which VO_{2max} can be achieved. In Figure 1, the Equation 2 curve suggests that, as speed increases, time-to-reach-VO_{2max} decreases and approaches 57 s: this *should* be the minimum time-to-reach-VO_{2max} for our participants. However, when the Equation 1a curve is superimposed on the Equation 2 curve, it is clear that VO_{2max} will not be elicited in exercise at speeds above ~5.00 $m{\cdot}s^{-1}$ (for our participants) because exhaustion occurs while VO_2 is still increasing, projecting towards its maximum.[24,30] For our participants, the actual minimum time-to-reach-VO_{2max} was 102 ± 7 s or 103 ± 7 s, not 57 ± 6 s. We hypothesize that *α* provides a measure of the potentially (or, at least, theoretically) fastest possible kinetics, in the form of a theoretical minimum time-to-reach-VO_{2max}. It is a virtual parameter, because VO_{2max} cannot actually be attained because exercise in the extreme intensity domain is terminated by fatigue prior to achievement of VO_{2max}. Nevertheless, the *α* parameter is an important descriptor of the overall VO_2 response that dictates the reliance on anaerobic reserves, and thereby influences tolerance in both severe and extreme intensity exercise, and whose calculation does not involve the complications associated with modeling VO_2 kinetics.

Knowledge of the boundaries of the severe domain is of practical importance for sport scientists and practitioners designing protocols for testing and training of VO_{2max}. Obviously, many coaches and athletes will not have access to equipment needed for measuring metabolic responses. However, most of them do know what VO_{2max} is, why it is important, and that training at VO_{2max} is important for advanced athletes. To train at VO_{2max} requires knowing what speeds or work rates will elicit VO_{2max}. Even without access to VO_2 testing, coaches can determine individually for their athletes the minimum work rate or speed to achieve VO_{2max} by calculating their CP or CS using time trial or competition data. Coaches who do not have access to VO_2 testing and cannot determine their athletes' maximum speed to achieve VO_{2max} on an individual basis, can benefit from our finding that a minimum tolerable duration of ~1½ min is needed for eliciting VO_{2max} in running, probably slightly less in higher fit athletes. This means that training speeds must be sustainable, *and sustained*, for at least ~1½ min if VO_{2max} is to be achieved.

CONCLUSIONS

It is concluded that two three-parameter hyperbolic models (Equation 2 and Equation 3) provide valid descriptions of the relationships between speed and time-to-reach-VO_{2max} and between speed and time-spent-at-VO_{2max}, respectively. We confirm that CS is the threshold for attaining VO_{2max} can be identified without the need to actually measure VO_2. In addition, we report that the upper boundary of the severe domain for running can be identified, first by using the relationship between speed and time-spent-at-VO_{2max} (Equation 3) or second by using our Equation 4 to calculate the intersection of the speed vs time-to-exhaustion curve (Equation 1a) and the speed vs time-to-reach-VO_{2max} curve (Equation 2). The upper boundary was associated with a time-to-exhaustion of ~103 s in our participants, the shortest time in which VO_{2max} can be attained. Finally, the speed vs time-to-reach-VO_{2max} model (Equation 2) generates a parameter (*α*) that may describe an important characteristic of the aerobic system.

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