Time Limit at $\dot{V}O_{2max}$ Velocity in Elite Crawl Swimmers

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Key words
- time limit
- velocity at $\dot{V}O_{2max}$
- elite swimmers

accepted after revision
January 1, 2007

Bibliography
DOI 10.1055/s-2007-965113
Published online Sept. 13, 2007
Int J Sports Med 2008; 29: 145 – 150 © Georg Thieme Verlag KG Stuttgart · New York · ISSN 0172-4622

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Abstract

The purpose of this study is to assess, with elite crawl swimmers, the time limit at the minimum velocity corresponding to maximal oxygen consumption (TLim-v$\dot{V}O_{2max}$), and to characterize its main determinants. Eight subjects performed an incremental test for v$\dot{V}O_{2max}$ assessment and, forty-eight hours later, an all-out swim at v$\dot{V}O_{2max}$ until exhaustion. $\dot{V}O_2$ was directly measured using a telemetric portable gas analyzer and a visual pacer was used to help the swimmers keeping the predetermined velocities. Blood lactate concentrations, heart rate and stroke parameter values were also measured. TLim-v$\dot{V}O_{2max}$ and v$\dot{V}O_{2max}$, averaged, respectively, 243.2 ± 30.5 s and 1.45 ± 0.08 $m \cdot s^{-1}$. TLim-v$\dot{V}O_{2max}$ correlated positively with $\dot{V}O_2$ slow component ($r = 0.76$, $p < 0.05$). Negative correlations were found between TLim-v$\dot{V}O_{2max}$ and body surface area ($r = -0.80$) and delta lactate ($r = -0.69$) ($p < 0.05$), and with v$\dot{V}O_{2max}$ ($r = -0.63$), v corresponding to anaerobic threshold ($r = -0.78$) and the energy cost corresponding to v$\dot{V}O_{2max}$ ($r = -0.62$) ($p < 0.10$). No correlations were observed between TLim-v$\dot{V}O_{2max}$ and stroking parameters. This study confirmed the tendency to TLim-v$\dot{V}O_{2max}$ be lower in the swimmers who presented higher v$\dot{V}O_{2max}$ and vAnT, possibly explained by their higher surface area, energy cost and anaerobic rate. Additionally, O_2SC seems to be a determinant of TLim-v$\dot{V}O_{2max}$.

Introduction

In swimming, maximal oxygen consumption ($\dot{V}O_{2max}$) is considered to be an important performance-influencing factor. Although the concept of $\dot{V}O_{2max}$ is well known for over 80 years and its assessment in swimming was accomplished since the 1960s [1], the capacity to sustain it in time has been neglected and very little explored. To our knowledge, the number of studies on the capacity to maintain a swimming effort at the velocity corresponding to $\dot{V}O_{2max}$ – the time limit at v$\dot{V}O_{2max}$ (TLim-v$\dot{V}O_{2max}$) – is very much scarce. Complementarily, the few available studies were mainly conducted in a swimming flume, not in normal swimming pool conditions [6,9,10], or did not assess the swimmers main respiratory parameters [22].

Nonetheless, with the small amount of TLim-v$\dot{V}O_{2max}$ -related studies found in the literature, TLim-v$\dot{V}O_{2max}$ is becoming a new criterion for evaluation of maximal aerobic capacity (aerobic power) of swimmers. Billat [3] refers that TLim-v$\dot{V}O_{2max}$ can bring new references for the selection of the duration of the $\dot{V}O_{2max}$ training sets, and could be a new criterion of aerobic power assessment, more sensible and complementary to $\dot{V}O_{2max}$.

The principal current understandings about TLim-v$\dot{V}O_{2max}$ are the following: (i) TLim-v$\dot{V}O_{2max}$ test is reproducible, namely in running [5]; (ii) there is not large interindividual variability in the swimming TLim-v$\dot{V}O_{2max}$ values, ranging between 4 min [13] and 6.15 min [9], when comparing to the data obtained in running and cycling from 4 until 11 min [3,5]; (iii) there is a negative relationship between TLim-v$\dot{V}O_{2max}$ and v$\dot{V}O_{2max}$, i.e., swimmers with slower aerobic power velocities can perform longer at that precise intensities [6,10,13,22]; (iv) the variability of TLim-v$\dot{V}O_{2max}$ and its negative relationship with v$\dot{V}O_{2max}$ is so far mainly explained by differences in the anaerobic capacity of swimmers [3,10,13]; (v) TLim-v$\dot{V}O_{2max}$ seems to be positively influenced by some precise bioenergetical parameters, mainly by accumulated oxygen deficit [10] and $\dot{V}O_2$ slow component (O_2SC) [11]; (vi) TLim-v$\dot{V}O_{2max}$ seems to be negatively related with some specific bio-

Table 1 Individual and mean (± SD) values for some physical characteristics of the subjects

Swimmer	Age (years)	Height (cm)	Body mass (kg)	Body mass index	Fat (kg)	Lean body mass (kg)	Surface area (m^2)	$v\dot{V}O_{2max}$ (LENpoints)
#1 (f)	18.8	164.0	60.4	22.5	14.6	45.8	1.63	531
#2 (f)	17.2	170.0	63.2	21.9	12.6	50.6	1.71	532
#3 (f)	16.7	165.0	58.4	21.5	12.2	46.2	1.61	536
#4 (f)	14.7	168.0	58.2	20.6	10.2	48.0	1.63	533
#5 (f)	17.2	162.0	54.8	20.8	11.0	43.6	1.56	513
Mean (± SD)	16.9 (1.5)	165.8 (3.2)	59.0 (3.1)	21.5 (0.8)	12.1 (1.7)	46.8 (2.6)	1.63 (0.05)	529.2 (9.07)
#6 (m)	18.9	184.0	80.6	23.8	6.2	74.4	2.01	534
#7 (m)	18.0	168.0	68.6	21.9	5.0	63.6	1.76	512
#8 (m)	20.3	192.0	83.0	22.5	5.2	77.8	2.09	573
Mean (± SD)	19.1 (1.1)	181.3 (12.2)	77.4 (7.7)	22.7 (1.0)	5.5 (0.6)	71.9 (7.4)	1.95 (0.17)	539.6 (30.8)

$v\dot{V}O_{2max}$ (LENpoints), minimum velocity corresponding to $\dot{V}O_{2max}$ converted in Ligue Européenne de Natation Point Score System

energetical parameters, namely by 3.5 mmol/l blood lactate anaerobic threshold [11] and energy cost of exercise (C) [13]; and (vii) TLim-$v\dot{V}O_{2max}$ does not seem to be related to $\dot{V}O_{2max}$ [6,10,11].

Almost all the above-referred studies were conducted with non-elite athletes. This fact seems to point out a lack in the specialized studies since elite athletes, as “top of the pyramid” sportsmen, should be used as a reference for normative parameters. Complementarily, once top level swimmers are expected to be characterized by high developed capacities, very close to human genetic limits, significant differences are expected to occur in some important swimming determinant bioenergetical and biomechanical factors [3,8,17,26,28].

The purpose of this study is to assess TLim-$v\dot{V}O_{2max}$ in elite front crawl swimmers, performing in normal swimming pool conditions, and to analyze its main bioenergetical and biomechanical determinants. Knowing that top-level swimmers are expected to have their specificities that could distinguish them from regular practitioners [17] and that TLim-$v\dot{V}O_{2max}$ was never assessed in elite swimmers performing in a swimming pool, the originality and pertinence of this study are clearly stated. So, as it is well accepted that exercising against the water flow in a flume implies some mechanical constraints that make it different than performing in normal swimming pool conditions [25], we tried to evaluate the swimmer in a more specific training and competition situation.

Material and Methods

Subjects

Eight front crawl middle-distance elite swimmers (3 males and 5 females) of the Portuguese National Swimming Team volunteered to participate in this study and signed an informed consent form. Individual and mean (± SD) values for physical characteristics of the subjects are described in **Table 1**. Body mass, fat and lean body mass were assessed through bioelectric impedance analysis method (Tanita TBF 305, Tokyo, Japan). Body mass index was calculated with the traditionally used formula: body mass·height^{-2}. The surface area (SA) was estimated using the equation of Du Bois and Du Bois [23]:

$$SA = height^{0.655} \cdot body\ mass^{0.441} \cdot 94.9 \quad (1)$$

For greater group homogeneity, swimmers were matched for performance by converting the individual $v\dot{V}O_{2max}$ values into the Ligue Européenne de Natation Point Score System (LENpoints). No difference was observed between genders ($p = 0.49$). The weekly training frequencies of the swimmers were higher than 9 training units per week. The tests were carried out in a microcycle of recuperation in the end of the general preparatory period of the third (and last) macrocycle of the season.

Test protocol

Briefly, each subject performed an individualized intermittent incremental protocol for front crawl $v\dot{V}O_{2max}$ assessment, with increments of 0.05 $m \cdot s^{-1}$ each 200-m stage and 30-s intervals until exhaustion [11]. $\dot{V}O_2$ was directly measured using a telemetric portable gas analyzer (K4 b^2, Cosmed, Rome, Italy) connected to the swimmer by a respiratory snorkel and valve system [15]. The K4 b^2 apparatus was calibrated following the procedures described in the specialized studies [15]. Expired gas concentrations were measured breath-by-breath (B × B). A visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal), with flashing lights on the bottom of the pool, was used to help the swimmers keep the predetermined swimming velocities. All equipment was calibrated prior to each experiment.

$\dot{V}O_{2max}$ was considered to be reached according to primary and secondary traditional physiological criteria [14], namely the occurrence of a plateau in $\dot{V}O_2$ despite an increase in swimming velocity, high levels of blood lactate concentrations (≥ 8 $mmol \cdot l^{-1}$), elevated respiratory exchange ratio ($r \geq 1.0$), elevated heart rate (HR > 90% of [220 – age]), and exhaustive perceived exertion (controlled visually and case-by-case). $v\dot{V}O_{2max}$ was considered to be the swimming velocity correspondent to the first stage that elicits $\dot{V}O_{2max}$. If a plateau less than 2.1 $ml \cdot min^{-1} \cdot kg^{-1}$ could not be observed, the $v\dot{V}O_{2max}$ was calculated as proposed by Kuipers et al. [16]:

$$v\dot{V}O_{2max} = v + \Delta v \cdot (n \cdot N^{-1}) \quad (2)$$

where v is the velocity corresponding to the last stage accomplished, Δv is the velocity increment, n indicates the number of seconds that the subjects were able to swim during the last stage and N the preset protocol time (in seconds) for this step.

Capillary blood samples (25 µl) for lactate concentrations ([La^-]) analysis were collected from the earlobe at rest (after previous local hyperemia with Finalgon®), in the 30-s rest interval, at the end of exercise and during the recovery period (YSI1500LSport

Table 2 Mean (± SD) values for $\dot{V}O_{2max}$ (absolute and relative), $[La^-]_{max}$, HR_{max}, vAnT, $v\dot{V}O_{2max}$, $Cv\dot{V}O_{2max}$ and C_{slope} (incremental test), and TLim-$v\dot{V}O_{2max}$, $[La^-]_{max}$, $\Delta[La^-]$, HR_{max}, O_2SC, SR, SL and SI (time limit test) for the total group of subjects and for male and female swimmers. Significant differences between genders are shown by * ($p \leq 0.05$)

Parameters	Total group (n = 8)	Male swimmers (n = 3)	Female swimmers (n = 5)
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	64.28 ± 10.27	71.74 ± 6.09	59.80 ± 9.97
$\dot{V}O_{2max}$ (l·min^{-1})*	4.34 ± 1.32	5.68 ± 0.79	3.53 ± 0.77
$[La^-]_{max}$ (mmol·l^{-1})	8.34 ± 3.02	7.77 ± 3.36	8.69 ± 3.15
HR_{max} (b·min^{-1})	182.50 ± 5.73	180.33 ± 4.04	183.80 ± 6.61
AnT (mmol·l^{-1})	2.59 ± 0.97	3.36 ± 1.19	2.13 ± 0.47
vAnT (m·s^{-1})*	1.34 ± 0.10	1.45 ± 0.05	1.27 ± 0.03
$v\dot{V}O_{2max}$ (m·s^{-1})*	1.45 ± 0.08	1.55 ± 0.02	1.39 ± 0.02
$Cv\dot{V}O_{2max}$ (J·kg^{-1}·m^{-1})*	14.20 ± 2.02	16.23 ± 0.57	12.98 ± 1.42
C_{slope} (J·kg^{-1}·m^{-1})	32.54 ± 11.59	37.74 ± 9.95	30.47 ± 12.56
TLim-$v\dot{V}O_{2max}$ (s)	243.17 ± 30.49	217.67 ± 20.84	258.46 ± 25.10
$[La^-]_{max}$ TLim (mmol·l^{-1})	6.92 ± 2.53	8.60 ± 1.97	5.92 ± 2.43
$\Delta[La^-]$ (mmol·l^{-1})	6.23 ± 2.30	7.97 ± 1.67	5.19 ± 2.06
HR_{max} TLim (b·min^{-1})	180.00 ± 6.44	177.67 ± 3.22	181.40 ± 7.80
O_2SC (ml·min^{-1})	356.27 ± 168.16	283.54 ± 62.74	385.36 ± 194.25
SR (cycle·min^{-1})	44.27 ± 6.92	41.45 ± 7.31	45.96 ± 6.89
SL (meter·cycle^{-1})	2.02 ± 0.38	2.30 ± 0.40	1.86 ± 0.30
SI (meter^2·[cycle·s]$^{-1}$)*	2.95 ± 0.68	3.55 ± 0.64	2.59 ± 0.42

$\dot{V}O_{2max}$: maximal oxygen consumption; $[La^-]_{max}$: maximal blood lactic acid concentrations; HR_{max}: maximal heart rate; AnT: anaerobic threshold; vAnT: velocity corresponding to anaerobic threshold; $v\dot{V}O_{2max}$: minimum velocity corresponding to $\dot{V}O_{2max}$; $Cv\dot{V}O_{2max}$: energy cost corresponding to $v\dot{V}O_{2max}$; C_{slope}: slope of the regression line obtained from the relationship between $\dot{E}$ and corresponding velocities in the incremental test; TLim-$v\dot{V}O_{2max}$: time limit at $v\dot{V}O_{2max}$; $\Delta[La^-]$: lactate production; O_2SC: oxygen slow component; SR: stroke rate; SL: stroke length; SI: stroke index; n: number of subjects

auto-analyzer – Yellow Springs Incorporated, Yellow Springs, OH, USA). Those data allowed us to assess individual anaerobic threshold (AnT), that was determined by the $[La^-]$/velocity curve modelling method (least square method) [12]. With this referred mathematical method for the AnT assessment, it was possible to determine the exact point for the beginning of an $[La^-]$ exponential rise. HR was monitored and registered continuously each 5 s through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland).

The energy expenditure ($\dot{E}$) values for each exercise step were obtained through the addition of the net $\dot{V}O_2$ values and the values resultant from the transformation of the net $[La^-]$ into O_2 equivalents, using the proportionality constant of 2.7 mlO_2·kg^{-1}·mM^{-1} [13,21].

Energy cost (C) was assessed using two swimming economy related parameters: (i) the C corresponding to $v\dot{V}O_{2max}$ ($Cv\dot{V}O_{2max}$), determined as the ratio of $\dot{E}$ and the corresponding swimming minimum velocity that elicits $\dot{V}O_{2max}$ [19], and (ii) the slope of the regression line obtained from the relationship between $\dot{E}$ and corresponding velocities in the incremental test (C_{slope}) [28].

The second test session occurred 48 hours later. All subjects swam at their previously determined $v\dot{V}O_{2max}$ to assess TLim-$v\dot{V}O_{2max}$. This protocol consisted of two different phases, all paced: (i) a 10-min warm-up at an intensity correspondent to 60% $v\dot{V}O_{2max}$, followed by a short rest (20 s) for earlobe blood collection, and (ii) the maintenance of that swimming at $v\dot{V}O_{2max}$ until volitional exhaustion or until the moment that the swimmers were unable to swim at the selected pace. TLim-$v\dot{V}O_{2max}$ was considered to be the total swimming duration at the predetermined velocity.

$[La^-]$ were assessed at rest, during the 20-s intervals, immediately after exercise and at the third and fifth min of the recovery period. The delta lactate ($\Delta[La^-]$) was determined as the difference between the maximal values measured after the test and those measured after the warm-up. HR was registered continuously using the same procedure previously described. O_2SC was assessed through mathematical modelling, using three exponential terms, with the three terms describing the cardiodynamic phase, the fast component and the O_2SC, respectively [2,18].

Stroke rate (SR) was determined as the number of cycles per min (registered by the number of strokes in each 25 m), stroke length (SL) was calculated by dividing velocity by SR, and the product of SL to the velocity allowed the assessment of stroke index (SI) [8].

Both testing sessions took place in a 25-m indoor swimming pool. In-water starts and open turns, without underwater gliding, were used.

Statistical analyses

Mean (± SD) computations for descriptive analysis were obtained for all variables (all data were checked for distribution normality with the Shapiro-Wilk test). Pearson's correlation coefficient and unpaired samples Student's *t*-test were also used. A significance level of 5% was accepted.

Results

▼

Data concerning the variables obtained in the incremental test: $\dot{V}O_{2max}$, $[La^-]_{max}$, HR_{max}, AnT (velocity and $[La^-]$ values), $v\dot{V}O_{2max}$, $Cv\dot{V}O_{2max}$, C_{slope} and the parameters assessed in the time limit test: TLim-$v\dot{V}O_{2max}$, $[La^-]_{max}$, $\Delta[La^-]$, HR_{max}, O_2SC, SR, SL and SI, are reported in **Table 2** (for the total group of subjects and for each gender group). Considering all subjects of the sample, TLim-$v\dot{V}O_{2max}$ ranged from 195 to 293 s and O_2SC from 202 to 649 ml·l^{-1}.

In **Fig. 1**, it is possible to observe a positive relationship between TLim-$v\dot{V}O_{2max}$ and O_2SC. In addition, negative relationships were found between TLim-$v\dot{V}O_{2max}$ and SA (**Fig. 2**), $\Delta[La^-]$ (**Fig. 3**) and LENpoints ($r = -0.80$), all for a $p \leq 0.05$. TLim-$v\dot{V}O_{2max}$ was also negatively related to absolute $\dot{V}O_{2max}$

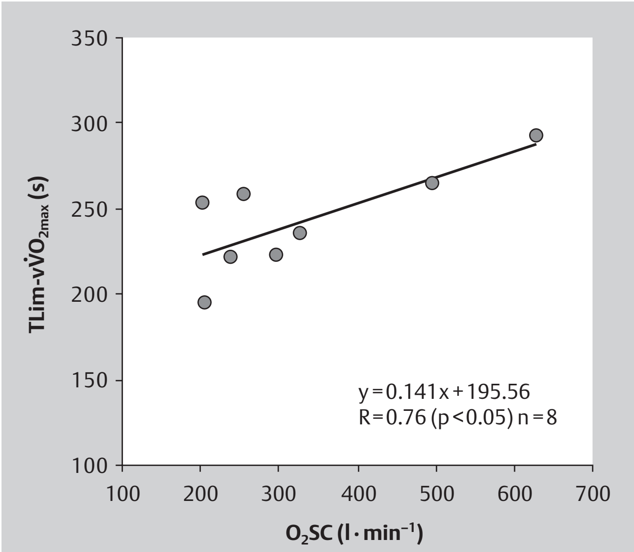

Fig. 1 Relationship between TLim-v$\dot{V}O_{2max}$ and O_2SC. Linear regression equation and correlation values are indicated.

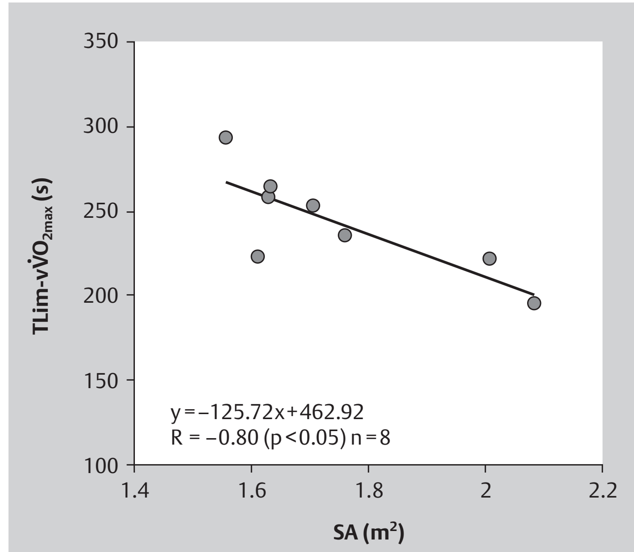

Fig. 2 Negative relationship between TLim-v$\dot{V}O_{2max}$ and SA. Linear regression equation and correlation values are indicated.

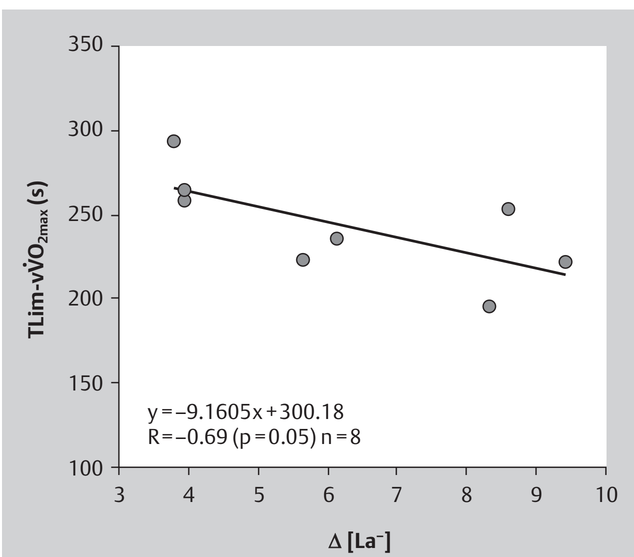

Fig. 3 Negative relationship between TLim-v$\dot{V}O_{2max}$ and $\Delta[La^-]$. Linear regression equation and correlation values are indicated.

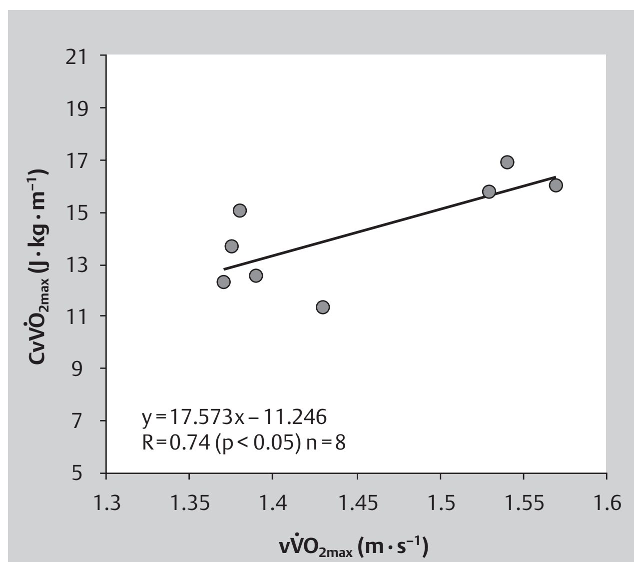

Fig. 4 Positive relationship between v$\dot{V}O_{2max}$ and Cv$\dot{V}O_{2max}$. Linear regression equation and correlation values are indicated.

($r = -0.69$), v$\dot{V}O_{2max}$ ($r = -0.63$), vAnT ($r = -0.62$), Cv$\dot{V}O_{2max}$ (-0.67) and $[La^-]_{max}$ TLim ($r = -0.63$), but only for a $p < 0.10$.

No significant correlations were found neither between TLim-v$\dot{V}O_{2max}$ and relative $\dot{V}O_{2max}$ ($r = -0.47$), HR_{max} ($r = 0.60$), C_{slope} ($r = -0.50$) and $[La^-]_{max}$ ($r = 0.33$), parameters obtained in the incremental test nor between TLim-v$\dot{V}O_{2max}$ and HR_{max} ($r = 0.58$), C_{slope} ($r = -0.50$), SF ($r = 0.29$), SL ($r = -0.46$) and SI ($r = -0.54$), factors attained in the time limit test ($p > 0.10$).

A positive relationship was observed between Cv$\dot{V}O_{2max}$ and SA ($r = 0.86$, $p < 0.01$). However, SA was not related with C_{slope} ($r = 0.38$, $p > 0.05$).

v$\dot{V}O_{2max}$ was significantly positively related to vAnT ($r = 0.93$, $p < 0.01$), SI ($r = 0.79$, $p < 0.05$) and Cv$\dot{V}O_{2max}$ ($r = 0.74$, $p < 0.05$) (**Fig. 4**).

Discussion

The aim of this study was to assess TLim-v$\dot{V}O_{2max}$ in elite front crawl swimmers and to identify its main determinants. The experimentations were conducted in normal swimming pool conditions, using modern procedures for collecting and measuring B × B expired gas, which allowed the characterization of $\dot{V}O_2$ kinetics during swimming exercise. The modified snorkel and valve system, specific for B × B analysis, was earlier considered suitable for measurements during swimming [15]. The utilization of an intermittent incremental protocol for swimming v$\dot{V}O_{2max}$ assessment has been noticed to be a valid method [7, 11].

The TLim-v$\dot{V}O_{2max}$ values obtained in the present study confirm the low interindividual variability of this parameter in swimming when comparing to running [5]. However, elite male swimmers maintain $v\dot{V}O_{2max}$ for a shorter time than the lower value reported in the swimming related literature [13]. This fact seems to be explained by elite male swimmers' higher $v\dot{V}O_{2max}$ and $Cv\dot{V}O_{2max}$, when comparing to elite female swimmer participants in this study, high-trained [6,11,13,22] and low-level swimmers [13], and pentathletes [9].

Closely related to the above described finding, the negative relationship observed between TLim-$v\dot{V}O_{2max}$ and $v\dot{V}O_{2max}$ seems to indicate that the swimmers with higher aerobic power velocities perform less at those precise intensities. This fact was already described [6,10,13,22], and appears to be explained by two factors: (i) higher swimming velocities implies superior $\dot{E}$ and, consequently, higher C [26], confirmed in this study by the high correlation value between $v\dot{V}O_{2max}$ and $Cv\dot{V}O_{2max}$, and (ii) higher swimming velocities indicates more strenuous efforts, with more pronounced recruitment of anaerobic energy pathways, leading to earlier fatigue stages and, consequently, to lower TLim-$v\dot{V}O_{2max}$. In the present study, TLim-$v\dot{V}O_{2max}$ correlated negatively with $\Delta[La^-]$ and with $[La^-]_{max}$, confirming the above referred idea, and corroborating the literature data [3,10,13].

In the perspective discussed above, one of the main determinants of TLim-$v\dot{V}O_{2max}$ seems to be C, since TLim-$v\dot{V}O_{2max}$ is negatively related to $Cv\dot{V}O_{2max}$. The higher level of maximal metabolic rate of the more proficient swimmers may be associated with a smaller capacity to sustain that precise exercise intensity. Complementarily, and accordingly, knowing that C is affected by some physical characteristics, namely by SA [19], a strong relationship between $Cv\dot{V}O_{2max}$ and SA was searched and observed. This last relationship indicates that body characteristics also have an important role in TLim-$v\dot{V}O_{2max}$ efforts, probably also the cross-sectional area, a parameter well related with SA [29], implying that higher body sizes impose greater drag to be overcome by muscular work, increasing C [27].

In addition, TLim-$v\dot{V}O_{2max}$ was also negatively related to vAnT. This negative correlation was already described before, but only for the averaged value of 3.5 mmol/l of $[La^-]$ [11]. Knowing that $[La^-]$ corresponding to AnT has been reported to have great variability between swimmers, the methodology for vAnT assessment used in this study was considered more appropriated than the commonly used averaged values of 3.5 and 4 mmol/l of $[La^-]$, because it allowed to find more specific and individualized values for aerobic/anaerobic transition intensities [12]. As expected, vAnT was highly correlated to $v\dot{V}O_{2max}$ ($r = 0.93$, $p < 0.01$), in accordance to previous available results [6,10,13,22].

Other main bioenergetical influencing factors of TLim-$v\dot{V}O_{2max}$ seems to be O_2SC. In the present study, O_2SC was assessed through mathematical modelling [2,18], a more precise and accurate method, since its magnitude has been commonly determined rather simplistically by calculating the increase in $\dot{V}O_2$ between the second or the third min of exercise, and the time at which exhaustion occurs. The mean value obtained in this study for O_2SC seems to have physiological meaning once it was higher than 200 $ml \cdot min^{-1}$ [4] and is in agreement with the report of Demarie et al. [9] conducted in pentathletes performing in a flume. Its significant relationship with TLim-$v\dot{V}O_{2max}$ appears to indicate that higher TLim-$v\dot{V}O_{2max}$ probably corresponds to higher expected O_2SC amplitude. These data are in accordance with a previous study conducted in high-level swimmers [11]. The hypothesis that the appearance of the O_2SC phenomenon is related to a major recruitment of fast twitch muscle fibers, with high glycolytic capacity, associated with the fatigue of the previously recruited fibers [2], wasn't confirmed either by us or Demarie et al. [9] for swimming: no relationship was obtained between O_2SC and $[La^-]_{max}$ or $\Delta[La^-]$. Nevertheless, it is unlikely that blood lactate per se can be responsible for the O_2SC phenomenon, but rather by associated metabolic acidosis. This fact allows for keeping the suggestion that one of the O_2SC major contributors is probably related to the superior rates of recruitment of type II fibers.

From the present results, in accordance with the literature data [6,10,11], it was shown once again that TLim-$v\dot{V}O_{2max}$ seems not to depend directly on swimmers relative $\dot{V}O_{2max}$. However, a relationship between TLim-$v\dot{V}O_{2max}$ and absolute $\dot{V}O_{2max}$ was observed although only for a $p < 0.10$. This last parameter, as it is not related to body mass, is not sufficient to corroborate that $\dot{V}O_{2max}$ plays a central role among the energy-yielding mechanisms in swimming [20] and that aerobic power is important in swimming performance. The low and not significant correlation values obtained between TLim-$v\dot{V}O_{2max}$ and relative $\dot{V}O_{2max}$ could be explained by the influence of other factors that may obscure the importance of aerobic energy production during swimming, namely in specific TLim-$v\dot{V}O_{2max}$ efforts. As it is well accepted that $\dot{V}O_{2max}$, in elite athletes, is very close to its genetic limit, this parameter could be a poor predictor of performance due to its relatively insensitivity to detect variations in homogeneous samples of swimmers.

Understanding that the ability to achieve and maintain a specific swimming velocity in an event is related to metabolic but also to biomechanical factors [24,26], the relationship between TLim-$v\dot{V}O_{2max}$ and the stroking parameters was also analysed. Nonetheless, considering the absence of studies relating to the above referred parameters, it was expected that TLim-$v\dot{V}O_{2max}$ would be negatively related with SR and positively related with SL and SI. However, no significant correlation values were obtained. Nevertheless, SI was strongly related to $v\dot{V}O_{2max}$, meaning that faster swimmers were also the most technically proficient [8].

In conclusion, TLim-$v\dot{V}O_{2max}$ values obtained by elite swimmers are situated in the lower extreme of the interval defined in the literature data. TLim-$v\dot{V}O_{2max}$ seems to be lower in the swimmers who presented higher $v\dot{V}O_{2max}$ and vAnT, which seems to be explained by the higher anaerobic rate in that specific effort. Complementarily, the faster swimmers also have higher energy cost, namely due to their greater SA. Additionally, O_2SC was observed in elite swimmers and seems to be a determinant of TLim-$v\dot{V}O_{2max}$. The faster swimmers were also the more technically proficient, but no evidence of a possible influence of biomechanical factors on TLim-$v\dot{V}O_{2max}$ was found in a sample of elite swimmers. The findings of this paper seems to emphasize the importance of the individualization of the training process in elite swimmers, namely in what concerns TLim-$v\dot{V}O_{2max}$ typical efforts, that are very well related to middle-distance swimming events.

Acknowledgements

We acknowledge the Portuguese Swimming Federation and the swimmers, and their coaches, for their participation in this study.

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