

Bioenergetics Applied to Swimming: An Ecological Method to Monitor and Prescribe Training

Rodrigo Zacca and Flávio Antônio de Souza Castro
Universidade Federal do Rio Grande do Sul
Brazil

1. Introduction

Systematic assessments of athletes' physiological conditions are central to monitor and prescribe swimming training according to the needs and goals. Thus, it is possible to understand the current physiological state and follow its development in order to assess the effects of training, to identify the swimmer's skills profile and to predict athletic performance (Vilas-Boas & Lamares 1997). Specifically regarding swimmers and their skills, aerobic capacity is a major determinant of these athletes performance, and it is defined as the ability to maintain a high percentage of maximal oxygen uptake (VO_{2max}) for a long period of time (DI PRAMPERO et al., 2011). Furthermore, the endurance is influenced by VO_{2max} , swimming economy (or energy cost, defined as the total energy expenditure required to move the body to a certain distance in a determined velocity) and anaerobic capacity (Dekerle & Pelayo 2011). In a group of swimmers with similar values of swimming economy and anaerobic capacity, those with greater aerobic potential (VO_{2max} and aerobic capacity) will be faster at distances of 400 m and longer. Four hundred meters, when swimming in front *crawl*, is usually suggested as a trial in which VO_{2max} is reached (Dekerle & Pelayo 2011). Thus, the longer events (800 m, 1500 m and open water marathon), which are covered primarily with energy from aerobic metabolism, are covered in a fraction of the VO_{2max} . The intensity will be lower the longer is the distance, reaching 60-65% of VO_{2max} on the 25 km open water marathon (Zamparo et al. 2005). In this sense, one of the objectives of the swimming training is to increase the aerobic capacity. Thus, a valid and reliable measure of the swimmer aerobic profile is essential to verify the benefits that the training program is or is not providing, and, also, to set training intensities according to the physiological profile of the athlete. Dekerle & Pelayo (2011) emphasize that the methodology used for this purpose cannot be considered valid unless it is reliable. Whenever possible, the degree of reliability should be assessed. The origin of the variability measurement (human error, equipment error, biological variation, or motivational factors when performing the test) needs to be taken into account. Thus, the aim of this chapter is to present a careful review of the bioenergetics contribution on the physiological assessment of the swimmer, especially related to aerobic profile.

2. Critical velocity (CV)

The performance achieved in competitions is an important setting information from training sessions in swimmers (Sweetenham & Atkinson, 2003). However, constant evaluations are necessary during the cycles and training sessions in order to verify the effectiveness of training and ensure the best performance in the competition (Sweetenham & Atkinson, 2003). Physiological and biomechanical swimmers conditions' knowledge is crucial to implement and/or to control the training processes that surround them (Pyne et al. 2001). These assessments can be applied in the field of competitive and / or recreational swimming. Tests used to evaluate and determine swimming speeds (SS) for the development of aerobic endurance training can be divided into invasive and noninvasive (Pyne et al. 2001), based on the relationship between oxygen consumption (VO_2), blood lactate concentration ([La]), heart rate (HR) and SS (Vilas-Boas & Lamares 1997). Although the precision provided by some of these tests, which require invasive sampling, such as those using the [La], ethical conflicts may arise (Heck et al. 1985), especially when applied to children. Moreover, it is common a high number of athletes to be evaluated in a training session by only one coach, so that they may require a longer period for implementation. Another limiting factor is the high cost for each testing session (Heck et al. 1985).

Considering these difficulties, the tests that verify the SS in durations of 30 (T_{30}) and 60 (T_{60}) minutes (Olbrecht et al. 1985; Madsen 1982) or even over distances of 2000 m (T_{2000}) (Touretski 1993) and 3000 m (T_{3000}) (Madsen 1982), the perceived exertion (PE) (Lima et al. 2006), the critical velocity (CV) (Ettema 1966) and 400 m testing (T_{400}) (Wakayoshi et al. 1993a; Dekerle et al. 2006; Alberty et al. 2006; Pelayo et al. 2007) have been widely disseminated in swimming. However, T_{30} , T_{60} , T_{2000} and T_{3000} can provide very subjective information to determine training intensities in young and/or low level of experience swimmers. These protocols require the maintenance of a given SS for a long time require psychological and physiological capacity compatible with the demands of the test (Zacca & Castro 2008, 2009). Regarding the PE, the athlete needs good training base to swim extensive sets with minimal adjustments in intensity between each repetition (Zacca & Castro 2008, 2009). In this sense, determination of SS for swimming training through the CV (Dekerle et al. 2006; Greco et al. 2008; Leclair et al. 2008; Vandewalle et al. 2008) seems to correspond to these swimmers profiles. CV's use is also justified due to the low cost and facility to apply in various populations. Another advantage is that CV is able to be gotten even during competitions (Vilas-Boas & Lamares 1997).

Since Hill (1927), it is accepted that the relationship between power output and time to exhaustion is a hyperbole. The asymptote of this relationship of power (critical power or PC) is equivalent to the slope of the regression line related to the work and time to exhaustion (time limit or *tlim*) (Monod & Scherrer 1965). Since then, CP represents, at least theoretically, the largest power that could be sustained, whose energy would be derived preferably by the aerobic metabolism without fatigue, and is suggested as a good performance index in events of long duration (Vandewalle et al. 1997).

Ettema (1966) applied the CP concept in cyclists, swimmers, speed skaters and runners. Instead of power and work, the author used speed (S) and distance limit (*dlim*), respectively. The hyperbolic relationship between S and *tlim* (Hill 1927) and the linear relationship between *dlim* and *tlim* (Equation 1), usually called critical velocity (CV), have the same physiological meaning of CP (Pepper et al. 1992; Housh et al. 2001).

In Equation 1, the slope of the regression line corresponds to CV (obtained through a two-parameter model, CV_{2par}), the y-intercept (second parameter) is mathematically defined as a finite stock of reserve power available pre-exercise (Ettema 1966; Wakayoshi et al. 1992), usually referred as "anaerobic distance capacity" (ADC_{2par}).

$$dlim = CV_{2par} \cdot tlim + ADC_{2par} \tag{1}$$

The non-linear SS-time limit to exhaustion ("SS-*tlim*"), the linear relationship between distance limit and time limit (*dlim-tlim*) and the linear relationship between SS and the inverse of *tlim* (Equation 2) are two-parameter models commonly used to estimate the VC (Billat et al. 1999; Housh et al. 2001; Whipp et al. 1982).

$$SS = \frac{ADC_{2par}}{tlim} + CV_{2par} \tag{2}$$

Equation 2 shows that the CV can be obtained by expressing SS as a function of *tlim* (Ettema 1966). In order to revise the statement that in the hyperbolic model SS is infinite when time approaches zero, Morton (1996) proposed a mathematical model including an additional parameter representing the maximum instantaneous velocity (V_{max} obtained from a three-parameter model, $V_{max3par}$).

$V_{max3par}$ allows a time asymptote (*tlim*) which is below the x-axis where *tlim* is zero, thus providing a V_{max} in the y-intercept (Morton 1996). Equation 3 expresses SS as a function of *tlim* (Zacca et al. 2010; adapted from Morton 1996).

$$SS = \frac{ADC_{3par}}{tlim + \frac{ADC_{3par}}{V_{max3par} - CV_{3par}}} + CV_{3par} \tag{3}$$

Where SS is the swimming speed, *tlim* is the time limit and ADC_{3par} , $V_{max3par}$ and CV_{3par} are the parameters. The fact that two-parameter model assumes that there is no upper limit for power output or SS (Morton et al. 1996; Dekerle et al. 2006) leads some authors choose three-parameter models (Gaesser et al. 1995; Bull et al. 2000; Hill et al. 2003).

However, both (two and three parameters) models have an important limitation: they do not take into account the "aerobic inertia" (τ) (Wilkie 1980; Vandewalle et al. 1989), regarding to the cardio respiratory adjustments for the VO_2 reaches the steady state or maximum value. Thus, a four-parameter model (CV_{4par} , CDA_{4par} , $V_{max4par}$ and τ) as proposed by Zacca et al. (2010) could provide more information on bioenergetics in sports (Equation 4).

$$SS = \frac{ADC_{4par}}{tlim + \frac{ADC_{4par}}{V_{max4par} - CV_{4par} \left(1 - e^{-\frac{tlim}{\tau}}\right)}} + CV_{4par} \left(1 - e^{-\frac{tlim}{\tau}}\right) \tag{4}$$

Zacca et al. (2010) proposed to plot *tlim* and SS values using a four-parameter model (Equation 4). The CV was corrected on this model by an exponential factor, proposed by Wilkie (1980). This exponential factor represents the time constant of the increased aerobic

involvement, called "aerobic inertia" (τ), understood as a temporary delay in the response of VO_2 , caused by dissociation of O_2 absorbed in lungs and used especially by skeletal muscle. The use of CV in swimming training is suggested since 1966 (Ettema 1966). Studies by researchers about its use continue to be published (Dekerle & Pelayo 2011).

3. Intensity domains (training zones)

Some authors (Gaesser et al. 1996; Greco et al. 2008) suggest a range of intensities of three domains (sometimes referred as training zones) and others (Dekerle & Pelayo 2011) a scale of five domains and their physiological effects. According to Table 1, exercise can be conducted in three different intensity domains, resulting in very distinctive physiological effects in each of these domains (Gaesser et al. 1996; Greco et al. 2008).

Intensity domains	Effects
SEVERE	<ul style="list-style-type: none"> • There is no variable metabolic stabilization; • Accumulation and increase of lactate / pyruvate relationship and increase of protons concentration $[H^+]$; • VO_2 increases toward the maximum.
HEAVY	<ul style="list-style-type: none"> • $[La]$ stabilizes at high values of concentration • The efficiency appears to be lower; • High VO_2 values (development of a slow component); • It is still possible to maintain a stable physiological state and perform the exercise for a longer period.
MODERATE	<ul style="list-style-type: none"> • $[La]$ stabilizes quickly; • VO_2 has a quick adjustment; • The individual can maintain this intensity for hours without exhaustion.

Table 1. Intensity domains and their physiological effects (Gaesser et al. 1996; Greco et al. 2008)

3.1 Moderate intensity domain

$[La]$ stabilizes quickly and can be maintained almost similar to resting levels. Similarly, VO_2 shows a quick set (1-3 min) before stabilization, and the individual can maintain the intensity for hours without exhaustion. The main explanation for the "end" of the exercise refers to substrate depletion (muscle and liver glycogen), changes related to hydration and electrolytes or problems related to the process of thermoregulation (Greco et al. 2008).

3.2 Heavy intensity domain

Production and removal rates of lactate levels are high due to a high metabolic demand. Consequently, $[La]$ tends to stabilize at higher concentrations when compared to exercise at moderate intensity. Moreover, the efficiency of the specific motor gesture seems to be smaller, generating higher VO_2 values than the linear relationship between VO_2 and exercise intensity that characterizes the Moderate intensity domain (development of a slow

component of VO_2). Although the metabolic stress is high, it is possible to maintain a state of physiological balance and to perform the exercise for a long period (Greco et al. 2008). However, Baron et al. (2008) found exercise performed at maximum intensity possible to maintain the stabilization of the $[La]$, i.e., in the maximal lactate steady state (MLSS), depletion occurred while physiological reserve capacity still existed, but in association with an increase in PE assessments, as predicted by the central regulator model (Noakes & St Clair Gibson 2004; Noakes et al. 2005). The end of the exercise could then be induced by an integrative homeostatic control of peripheral physiological system to ensure specifically the maintenance of homeostasis.

3.3 Severe intensity domain

There is no stabilization in metabolic variables. Specifically, the rate of lactate production is greater than the rate of removal, with a consequent increase in the accumulation and the relationship between lactate and pyruvate and the concentration of protons ($[H^+]$) (Greco et al. 2008). At the same time, VO_2 increases towards to its maximum (VO_{2max}) and the amplitude of the slow component is much higher than those that characterize the heavy intensity exercise (Xu & Rhodes 1999). This reduces exercise tolerance, with *tlim* related to the cellular level of disturbance (metabolites production and removal rates), caused by high demand of muscle adenosine 3-phosphate (ATP) (Greco et al. 2008).

3.4 Scale of five intensity domains proposed by Dekerle & Pelayo (2011)

Dekerle & Pelayo (2011) propose a scale of five domains and their physiological effects. On this scale, lactate threshold (LT), MLSS and CV_{2par} can be understood as boundaries that demarcate some intensity domains. Figure 1 shows the five intensity domains proposed by Dekerle & Pelayo (2011), in which the behavior of $[La]$ and VO_2 is illustrated in each domain.

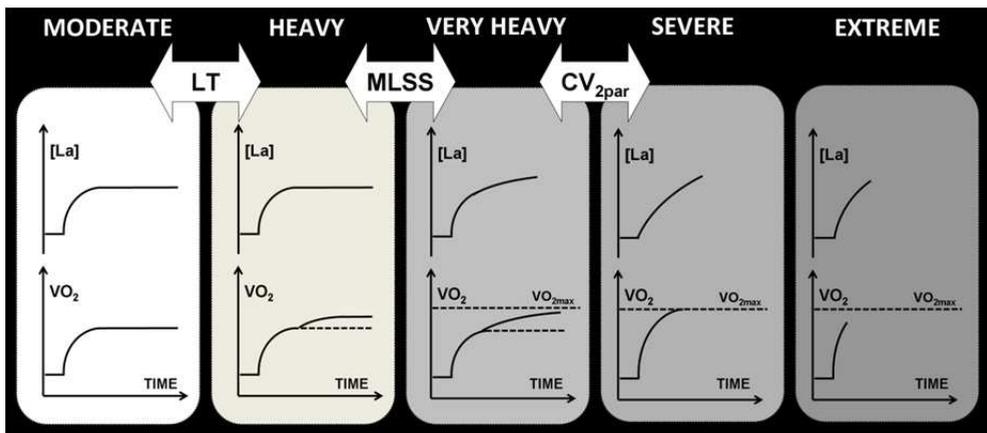


Fig. 1. Intensity domains (adapted from Dekerle & Pelayo 2011) and the response of each to $[La]$ and VO_2 kinetics during exercise in different SS.

Each of the five intensity domains (Dekerle & Pelayo, 2011) is characterized by acute specific physiological responses. Dekerle & Pelayo (2011) establish the lactate threshold (LT) as the boundary between moderate and heavy domain. The LT is defined as the first increase in lactate response to an incremental test (Wasserman et al. 1990).

3.4.1 Heavy intensity domain

The exercise is performed in intensity very close to the LT, but a little higher, which causes a small increase in [La] (no more than 1 mmol l⁻¹) in the first minutes, with subsequent stabilization close to resting levels (≈ 2.1 mmol l⁻¹). The maximum exercise intensity at which [La] stabilization occurs is defined as maximal lactate steady state (MLSS, ≈ 3 -5 mmol l⁻¹) (Beneke, 1995). The MLSS is the heavy intensity domain upper limit (Barstow 1994). The intensity corresponding to LT can be maintained for a very long period (e.g. aquatic marathons) and occurs at a slower speed when compared to MLSS ($t_{lim} \approx 60$ min). MLSS is located in the smaller SS than CV_{2par} ($t_{lim} \approx 14.3$ to 39.4 min). Importantly, for being difficult to detect the MLSS through the curve obtained in [La] and SS, and also to avoid any misinterpretation, the term "anaerobic threshold" should not be associated to the MLSS. Swimming in a very low SS is a difficult task (<0.4 to 0.5 m·s⁻¹ or 50-60% of V₄₀₀ -average speed of 400 m front *crawl* in maximal effort). Thus, the lowest speed that can be adopted by swimmers using a good technique, it is almost equal to LT (Dekerle & Pelayo 2011).

3.4.2 Severe intensity domain

In SS above the MLSS (heavy intensity domain upper limit) there is an increase in [La], HR and VO₂ (occurrence of the slow component). Initially, it was suggested that the increase in VO₂ in these intensities reach the maximum (VO_{2max}) before exhaustion, which characterizes the severe intensity domain). This statement is controversial and difficult to investigate because of the low reliability of time to exhaustion obtained in constant intensity tests (variability of t_{lim}) (Hinckson & Hopkins, 2005). The SS equivalent to the Severe intensity domain includes performances of approximately 2 to 60 minutes (VO_{2max} reaching the end of the exercise) with the performance of 400 m in front *crawl*, the maximum aerobic speed (MAS) and CV_{2par} lying within that domain (Lavoie & Montpetit et al 1981; Lavoie et al. 1983; Lavoie & Leone 1988; Rodrigues 2000; Pelayo et al. 2007; Billat et al. 2000; Dekerle et al. 2010).

3.4.3 Extreme intensity domain

This domain includes performances of very short duration (< 2 min). Due to the limited response of VO₂, VO_{2max} is not reached during exercise, although the task is performed to exhaustion.

3.4.4 Very heavy intensity domain

Dekerle & Pelayo (2011) suggest the subdivision of Heavy intensity domain. According to these authors, the range of effort associated to this area is wide (performances of ≈ 2 to 60 min) and associated with many chronic responses to training, i.e., the physiological adaptations of a training period in SS near the MLSS are different from the training adaptations induced by a training period in MAS or above.

In addition, the physiological responses to swimming at intensities equal to or above the MLSS are still unclear, since it is not certain that VO_{2max} is reached. Thus, it is justifiable to establish at least one domain between the MLSS and CV_{2par} : the “very heavy intensity domain”. Thus, exercise performed in this domain (very heavy) suggests an increase in [La] and the occurrence of the VO_2 slow component, but without reaching VO_{2max} in the end of the exercise (Dekerle et al. 2010). VO_{2max} would only be achieved if the exercise was conducted in intensity above CV_{2par} and continued until exhaustion (featuring the severe domain). Thus, CV_{2par} represents the boundary between very heavy and severe intensity domain. However, Dekerle & Pelayo (2011) suggest that more experiments are needed in these models of training zones. As a result, coaches and swimmers will be able to use them with a greater degree of reliability.

Based on the information presented, it is believed that the model of five intensity domains proposed by Dekerle & Pelayo (2011) best describes the physiological responses to exercise in different intensities.

4. Physiological meaning of each parameter

4.1 Two-parameter model

4.1.1 Critical Speed (CV_{2par})

PC was used initially to determine exercise intensity that could be theoretically maintained for a long period of time without exhaustion (Monod & Scherrer 1965). CP (or CV in running or swimming) proved to be valid for aerobic capacity prediction (Dekerle et al. 2005a) and sensitive to physiological changes from aerobic training programs (Jenkins & Quigley, 1991). CP or CV determined by two-parameter model (CP_{2par} or CV_{2par}) represents the lower boundary of the severe intensity domain (Poole et al. 1990; Hill & Ferguson 1999). Poole et al. (1990) found that when subjects performed exercise intensity on CP_{2par} , VO_2 stabilized around 75% VO_{2max} . In addition, studies have investigated the hyperbolic relationship between power and time to achieve VO_{2max} . The results also suggest that this relationship is the lower boundary of the severe intensity domain, or CP_{2par} (or CV_{2par}) (Hill & Smith 1999; Hill & Ferguson 1999). Thus, CV_{2par} can determine the exercise intensity equivalent to the lower boundary of the severe intensity domain.

4.1.2 Anaerobic distance capacity (ADC_{2par})

The physiological meaning of ADC_{2par} is still subject of many studies (Moritani et al. 1981; Green et al. 1994; Miura et al. 2000; Heubert et al. 2005). Evidence trying to suggest the ADC_{2par} anaerobic nature was observed in cyclists (Green et al. 1994). Also in cyclists, Heubert et al. (2005) found a decrease of 60 to 70% in ADC_{2par} values as a result of a 7 s maximal effort performed before a protocol of four exercises at constant intensity (95, 100, 110 and 115% VO_{2max}) and to determine the ADC_{2par} and CP_{2par} . CP_{2par} values did not change. Moritani et al. (1981) also found no differences in ADC_{2par} values in response to ischemia, hypoxia and hyperoxia. In relation to prior depletion of glycogen, Miura et al. (2000) found a decrease in ADC_{2par} values (in cycle ergometer). Jenkins & Quigley (1993) found an increase in ADC_{2par} values in response to high-intensity training in untrained individuals, but the CP_{2par} values did not change. ADC_{2par} values also showed increases in response to creatine supplementation (Miura et al. 1999) and demonstrated good correlation with predominantly anaerobic exercises (Vandewalle et al. 1989; Jenkins & Quigley 1991; Hill 1993; Dekerle et al. 2005b).

4.2 Three-parameter model

4.2.1 Critical Velocity (VC_{3par})

The oxygen supply spends a period of time to reach a steady state or maximum. This has led some researchers (Vandewalle et al. 1989; Morton 1996) questioned the "immediate" availability of CV in two-parameter models (CV_{2par}). As a result of this lapse of time, probably CV_{2par} was being overestimated. In addition, studies found that CV_{2par} could be sustained only by 14.3 to 39.4 min by swimmers (Dekerle et al. 2010). These results suggest that the concept of CV_{2par} as a speed that could be sustained infinitely would not be appropriate.

There is little information on CV and the type of mathematical model used to obtain it in sports. Morton (1996) suggests that CV_{2par} values may be overestimated. Gaesser et al. (1996) also found that three-parameter model generated CP values (CP_{3par}) significantly lower, and the subjects were able to resist in a continuous work for a long period. Thus, CV_{3par} seems not to be at the lower boundary of the severe intensity domain, requiring further investigation. Probably CV_{3par} is below the lower boundary of the severe intensity domain.

4.2.2 Anaerobic distance capacity (ADC_{3par})

Vandewalle et al. (1989) question the assumption that at exhaustion all ADC_{2par} is used, as theoretically is suggested by two-parameter models. Thus, ADC_{2par} may be underestimated (Vandewalle et al. 1989; Morton 1996).

4.2.3 Maximum instantaneous velocity ($V_{max3par}$)

As a result of the lapse of time ("immediate" availability of CV_{2par}), Morton (1996) proposed a three-parameter model (Equation 3) which the "maximum instantaneous speed" ($V_{max3par}$) was included (third parameter). With the addition of the parameter $V_{max3par}$, the three-parameter model is more accurate in estimating the CV (and therefore ADC) surpassing the initial concept of the relationship velocity-*tlim*, that when *tlim* approaches zero, velocity is infinite (Morton 1996). $V_{max3par}$ allows a time asymptote below the x-axis, where time = zero, and provides a $V_{max3par}$ value in the intercept-x (MORTON 1996).

4.3 Three-parameter model

4.3.1 Critical velocity (CV_{4par})

Both models (two and three-parameter models) have an important limitation: do not predict the "aerobic inertia" (τ) (Wilkie 1980; Vandewalle et al. 1989), related to cardio respiratory adjustments so that the VO_2 reach steady state or maximum. Thus, a four-parameter model (CV_{4par} , ADC_{4par} , $V_{max4par}$ and τ) proposed by Zacca et al. (2010) could provide more information on bioenergetics in cyclic sports. The four-parameter model proposed by Zacca et al. (2010) was based on the three-parameter model, and CV_{4par} was corrected by an exponential factor, first proposed by Wilkie (1980). This exponential factor is theoretically defined as the time constant that describes the increased aerobic involvement, the "aerobic inertia" (τ). Zacca et al. (2010) suggest that CV is sensitive to additional parameters in young swimmers (93% of the variation was explained by the mathematical model used). The effect of the models showed that CV_{2par} was higher than CV_{3par} and CV_{4par} . CV_{3par} and CV_{4par} were similar (and therefore the physiological meanings of both models are also similar). Thus, future studies are necessary to understand the physiological meaning of CV_{3par} and CV_{4par} in young swimmers and probably in other sports. Figure 2 shows the plot of the data using two, three and four-parameter models with speed and *tlim* data of 50, 100, 200, 300, 400, 800

and 1500 m from swimmers (adapted from Zacca et al. 2010). It is easy to see that the data fits more appropriately in three and four-parameter models. Thus, CV_{2par} was higher than CV_{3par} and CV_{4par} , as previously described.

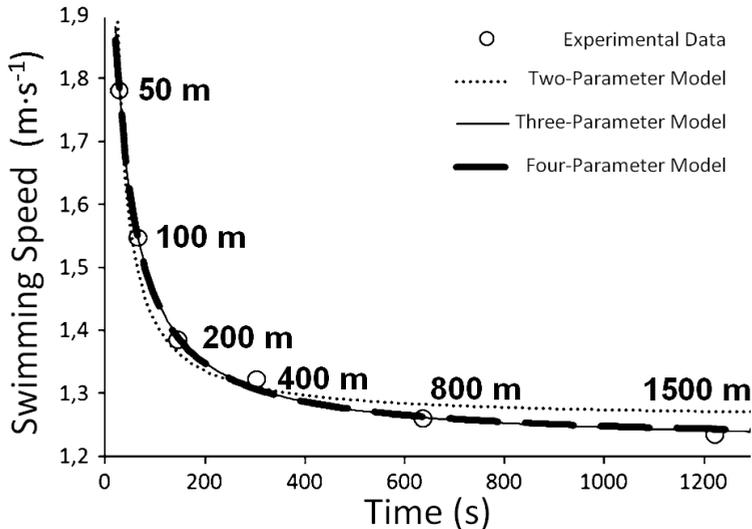


Fig. 2. Swimming speed and time of 50, 100, 200, 300, 400, 800 and 1500 m from sprint swimmers and fitted curves through two, three and four-parameter models (adapted from Zacca et al. 2010).

4.3.2 Anaerobic distance capacity (ADC_{4par})

ADC_{2par} was originally defined as the maximum distance (m) that could be covered anaerobically (Ettema 1966). However, Costill (1994) conceptualized ADC_{2par} as the total work that can be performed by a set of limited power of the human body (phosphagen, anaerobic glycolysis and oxygen reserves) suggesting that the anaerobic energy system is predominant but not exclusive (Gastin 2001). Zacca et al. (2010) compared ADC_{2par} , ADC_{3par} and ADC_{4par} values. The results showed that ADC_{2par} (13.77 ± 2.34 m) was lower than ADC_{3par} and ADC_{4par} (30.89 ± 1.70 and 27.64 ± 0.03 m respectively). Moreover, ADC_{3par} and ADC_{4par} values were similar. These results are consistent with others that also observed an overestimation of the parameter ADC in two-parameter model (Billat et al. 2000). Dekerle et al. (2002) evaluated ten well-trained swimmers, when the objective was to verify the possibility of determining ADC_{2par} . They concluded that ADC_{2par} is not perfectly linear and is very sensitive to variations in performance. Thus, according to the authors, it is impossible to estimate the anaerobic capacity by two-parameter models. Toussaint et al. (1998) also suggest that the anaerobic capacity in swimming obtained by two-parameter model does not provide an accurate estimate of the real anaerobic capacity. It seems clear that three and four-parameter models seem more suitable to predict ADC.

4.3.3 Maximum instantaneous velocity

There are gaps in the literature regarding the prediction of V_{\max} by mathematical models. Billat et al. (2000) found that $V_{\max3\text{par}}$ was not different from the maximum speed obtained in 20 m at maximal effort. However, Bosquet et al. (2006) suggest that $V_{\max3\text{par}}$ is smaller than the real V_{\max} (obtained by the average speed of the last 10 m of a maximal 40 m effort). Zacca et al. (2010) found that V_{\max} was higher in sprint than endurance swimmers ($2.53 \pm 0.15 \text{ m s}^{-1}$ and $2.07 \pm 0.19 \text{ m s}^{-1}$ respectively) independent of the mathematical model used (three or four parameters). In addition, $V_{\max4\text{par}}$ was greater than $V_{\max3\text{par}}$ ($2.42 \pm 0.29 \text{ m s}^{-1}$ and $2.18 \pm 0.34 \text{ m s}^{-1}$ respectively), suggesting future studies to compare V_{\max} and real V_{\max} .

4.3.4 Aerobic inertia

The two-parameter model given by the relation "SS-*tlim*" (or "D*lim-tlim*") and three-parameter model given by the relation "SS-*tlim*" have an important limitation: they do not take into account the "aerobic inertia" (τ) (Wilkie 1980; Vandewalle et al. 1989). The " τ " is a temporary delay in VO_2 response because of dissociation between O_2 absorbed in the lungs and the mainly used by skeletal muscle, lasting approximately 15 to 20 s. " τ " is associated to vasodilatation, i.e., the time it takes for the body to increase heart rate and redirect blood flow. Studies regarding oxygen kinetics during exercise with children and adolescents is limited to few articles and until recently was based on data collected with adults (FAWKNER & ARMSTRONG 2003). Invernizzi et al. (2008) suggest that the time to reach steady state in VO_2 after the beginning of the exercise depends on the characteristics of the subject: endurance swimmers reach this balance sooner than sprint swimmers, and children reach earlier than adults. Thus, " τ " could be a good tool for evaluating cardiovascular and pulmonary performance in athletes (Kilding et al. 2006; Duffield et al. 2007).

5. Swimming speeds prescription through a 400 m front *crawl* maximum effort (T_{400})

Although many distances used in swimming competition does not exceed 2 min (50, 100 and 200 m), the zone related to VO_2 , commonly referred as aerobic power, is relevant in swimming (Di Prampero 2003), perhaps because T_{400} is performed in similar SS reach $\text{VO}_{2\max}$ (Rodrigues 2000). The concept of aerobic power refers to the rate of oxidative energy synthesis (i.e., the maximum power at which the oxidative system can operate, also known as maximum aerobic speed, MAS), available to the muscle work, which can be measured by $\text{VO}_{2\max}$. Measuring $\text{VO}_{2\max}$ in swimming is always a great challenge (PELAYO et al. 2007). This is due to the fact that conventional techniques interfere in swimming biomechanics (Keskinen et al. 2003; Barbosa et al. 2010), which performs the side breathing impossible, changes can occur in hydrodynamics, and most of the times the turns are not performed (Montpetit et al. 1981). Training programs, in order to develop aerobic power in swimmers, are related to the increase in $\text{VO}_{2\max}$ and the ability to use a high percentage of $\text{VO}_{2\max}$ for a long time. Maximal aerobic power is widely used to assess aerobic fitness and training intensities prescription (Lavoie & Montpetit 1986).

In an attempt to find alternatives and make the evaluation of athletes swimming closer to reality applied in swimming pools, several studies have been conducted in order to verify the possibility to prescribe training intensities through a single test, but not so extensive such as T_{30} (Lavoie et al. 1981; Lavoie et al. 1983; Lavoie & Montpetit 1986; Rodrigues 2000; Takahashi et al. 2002; Takahashi et al. 2003, 2009). The attainment of $\text{VO}_{2\max}$ values from the

recovery curve of VO₂ (the back extrapolation method proposed by Di Prampero et al. 1976) was first tested on swimmers by Lavoie et al. back in 1983. Lavoie et al. (1983) found a high correlation between VO_{2max} and *tlim* of T₄₀₀. The possibility to prescribe training intensities using a single test has renewed expectations of swimming coaches and researchers. The attainment of VO_{2max} values trough the back extrapolation involves obtaining VO₂ after swimming and applying a simple regression curve between the time and the values of consumption in order to predict the value of VO₂ in time zero (Lavoie & Montpetit 1986).

It is believed that the high correlation between VO_{2max} and *tlim* T₄₀₀ m found by Lavoie et al. (1983) is probably the first indication of the T₄₀₀ as a non-invasive alternative. Since then, T₄₀₀ is a reference to verify the MAS and prescribe swimming training intensities (Montpetit et al. 1981; Lavoie et al. 1983; Rodrigues 2000; Pelayo et al. 2007). However, despite many studies reporting the use of T₄₀₀ by swimming coaches (Wakayoshi et al. 1993b; Dekerle et al. 2005a; Alberty et al. 2006; Dekerle et al. 2006; Pelayo et al. 2007), we did not find a reliable protocol for prescribe more than one swimming training zone through the T₄₀₀, i.e., a protocol not only able to predict aerobic power, but also another training zone.

By questioning some brazilian coaches, we find that some of them use a protocol (of unknown origin) based on the T₄₀₀ to monitor and to prescribe three different SS for swimmers and triathletes. Table 2 presents a summary of the equations used to calculate the SS for "aerobic threshold", "anaerobic threshold" and "VO_{2max}".

OBJECTIVE	DISTANCE	EQUATION
VO _{2max} (I _{VO2})	400 m (t400I _{VO2})	= 400 / (400 / <i>tlim</i> 400 m) · k
	800 m (t800I _{VO2})	= t400I _{VO2} · 2 + 3 s
	200 m (t200I _{VO2})	= t400I _{VO2} / 2 - 3 s
	100 m (t100I _{VO2})	= t200I _{VO2} / 2 - 2 s
	50 m (t50I _{VO2})	= t100I _{VO2} / 2 - 1,5 s
ANAEROBIC THRESHOLD (I _{LA})	400 m (t400I _{LA})	= 400 / ((400 / <i>tlim</i> 400 m) · k) · 0,95
	800 m (t800I _{LA})	= t400I _{LA} · 2 + 3 s
	200 m (t200I _{LA})	= t400I _{LA} / 2 - 3 s
	100 m (t100I _{LA})	= t200I _{LA} / 2 - 2 s
	50 m (t50I _{LA})	= t100I _{LA} / 2 - 1,5 s
AEROBIC THRESHOLD (I _{LAe})	400 m (t400I _{LAe})	= 400 / (((400 / <i>tlim</i> 400 m) · k) · 0,95) · 0,93
	800 m (t800I _{LAe})	= t400I _{LAe} · 2 + 3 s
	200 m (t200I _{LAe})	= t400I _{LAe} / 2 - 3 s
	100 m (t100I _{LAe})	= t200I _{LAe} / 2 - 2 s
	50 m (t50I _{LAe})	= t100I _{LAe} / 2 - 1,5 s

Table 2. Equations used to calculate the SS for "aerobic threshold", "anaerobic threshold" and "VO_{2max}". K is a constant: K = 0.94 if *tlim* is between 3 min 50 s to 4 min 40 s, K = 0.95 if *tlim* is between 4 min 41 s to 5 min 40 s, K = 0.96 the *tlim* is between 5 min 41 s to 6 min 40 s, K = 0.97 if *tlim* is above 6 min 41 s, t = time prescribed for a given distance; I_{VO2} = intensity prescribed to increase VO_{2max}, I_{LA} = intensity for anaerobic threshold and I_{LAe} = intensity prescribed for aerobic threshold.

In this protocol, the coach just needs that your athletes swim 400 m in front *crawl* under maximum intensity (in training situation, but preferably in competitive situation).

According to the protocol, the T_{400} is able to prescribe SS in three different intensities for training in swimming called (1) "aerobic threshold" (I_{LAe}) (2) "anaerobic threshold" (I_{LA}) and (3) "increased VO_{2max} " (I_{VO2}) (Olbrecht 2000; Maglischo 1999). For each intensity, the protocol suggests the time prescription for distances of 50, 100, 200, 400 and 800 m. SS prescribed by T_{400} for I_{VO2} is between 94 and 97% from the SS of 400 m (V_{400}). SS prescribed for I_{LA} is proposed as approximately 90% of the V_{400} . SS prescribed for I_{LAe} stands at approximately 84% of the V_{400} .

It can be seen throughout this review that the literature presents a wide naming to explain the [La] response to exercise. However, despite being related to the same phenomenon, the physiological responses are often different, such as LT and MLSS mentioned above, and I_{LAe} and I_{LA} used in this protocol. This means that it cannot be used interchangeably.

As Maglischo (1999) and Olbrecht (2000) suggest, sets on I_{LAe} are swum in SS ranging from an intensity which is observed in the first rise in [La] above the resting level to the SS that sits comfortably below the I_{LA} of the swimmer. The total distance can vary between 2,000 and 10,000 m for adult swimmers or 20 to 120 min for young swimmers. Any distance can be used in the interval sets. Regarding the rest intervals between each repetition, it is suggested 5 to 30 s (Olbrecht 2000). Still, in I_{LA} sets, the total distance of the set can range from 2,000 to 4,000 m for adults, or approximately 30 min for younger athletes (Maglischo 1999; Olbrecht 2000). Distances between 25 and 4,000 m can be used in the interval sets (Maglischo 1999; Olbrecht 2000), with rest intervals between 10 to 30 s (Olbrecht 2000). Series aimed to increase VO_{2max} , Maglischo (1999) suggests SS slightly above the I_{LA} until 95% of best performance (Maglischo 1999) (Severe intensity domain). It is suggested distances between 25 to 2,000 m, with intervals of rest of 30 s to 120 s between each repetition (Maglischo 1999). However, the SS percentage suggested for training zones prescription have not been observed in constant speed tests until exhaustion. However, similarities were observed in *tlim* and percentage of training zones prescription between the T_{400} and the 1 mile running applied by Daniels (2005). Daniels's concepts (Daniels 2005) were based on "velocity at VO_{2max} " (vVO_{2max}).

6. Velocity at VO_{2max} (vVO_{2max})

Although VO_{2max} is accepted as the physiological variable that best describes cardiovascular and respiratory capacities (Hill & Lupton 1923; Billat & Koralsztein 1996), vVO_{2max} was measured only five decades later in order to provide a practical method to measure aerobic fitness in runners (Billat & Koralsztein 1996). In the 80's there was a growth interest in the physiological assessments in order to monitor athletic training (Billat & Koralsztein 1996). However, it is known that protocols for VO_{2max} measurement, for example, require trained professionals, special equipment and need to be conducted in a controlled environment.

The first field test used to measure vVO_{2max} was intended to replace the 12 min test Cooper (Cooper 1968) as an alternative to predict VO_{2max} in a unique effort to simplify procedures and reduce costs. Cooper (1968) reported a correlation of 0.9 between VO_{2max} and the distance covered in a 12 min test running or walking. However, the motivation and rhythm was mentioned as critical to achieve good reliability in a 12 min test (Cooper 1968). Importantly, when prescribing training intensities based on the performance test, is also considered the psychological characteristic of the race, because instead of applying laboratory tests to monitor training status of the athlete, we use the performance obtained in competitive events, which is directly affected by the willingness to deal as discomfort. Tests

based on test performances reflect everything that an athlete recruited to travel any distance in a competitive situation (Daniels, 2005).

The Cooper test (1968) was based on the linear relationship between running speed and VO_2 when, while driving the subject until exhaustion, it was possible to determine $\text{VO}_{2\text{max}}$. Billat & Koralsztein (1996) suggest that the accuracy of prediction of $\text{VO}_{2\text{max}}$, or also its inaccuracy, depends on the energy cost inter-individual variation, i.e., the total energy expenditure required to move the body to a certain distance.

Daniels et al. (1984) introduced the term "velocity at $\text{VO}_{2\text{max}}$ " ($v\text{VO}_{2\text{max}}$) suggesting that it is a useful variable that combines $\text{VO}_{2\text{max}}$ and movement economy (Conley & Krähenbühl 1980) on a single factor that identifies aerobic differences among various runners or group of runners. According to Daniels (2005), $v\text{VO}_{2\text{max}}$ explains individual differences in performance that $\text{VO}_{2\text{max}}$ or running economy alone could not identify, i.e. individuals with the same $\text{VO}_{2\text{max}}$ for example, may have different performance times.

Daniels et al. (1984) found in female runners who had various combinations of $\text{VO}_{2\text{max}}$ and running economy (submaximal VO_2), that $v\text{VO}_{2\text{max}}$ was similar to the average speed required to run 3,000 m (maintained approximately for 9 min). In a study with sub-elite distance runners, Billat et al. (1994a) measured a *dlim* at $v\text{VO}_{2\text{max}}$ of $2,008.7 \pm 496$ m. However the authors suggest that there is a need to distinguish total run at $v\text{VO}_{2\text{max}}$ and time run at $\text{VO}_{2\text{max}}$ race only. Daniels et al. (1984) calculated $v\text{VO}_{2\text{max}}$ extrapolating through a regression curve relating running speed and VO_2 . When $\text{VO}_{2\text{max}}$ was reached, the running speed corresponding to $\text{VO}_{2\text{max}}$ was identified. Sub-maximal VO_2 was calculated from efforts of 6 min at speeds of 230, 248 and 268 $\text{m}\cdot\text{min}^{-1}$ at intervals of 4 to 7 min between each effort. $\text{VO}_{2\text{max}}$ was measured separately in a test based on the incremental pace of 5,000 m, adding 1% for the treadmill speed every minute until the test is terminated, where subjects reported that they would not be able to run more than 30 s. The highest VO_2 achieved during the maximal test was considered as $\text{VO}_{2\text{max}}$.

7. *tlim* that swimmers are able to keep at $v\text{VO}_{2\text{max}}$ ($t\text{lim}-v\text{VO}_{2\text{max}}$)

For several years, many studies have remained focusing on measuring $v\text{VO}_{2\text{max}}$ during swimming. However, few investigations in order to determine the $t\text{lim}-v\text{VO}_{2\text{max}}$ were carried out. This training tool which requires the swimmer to keep the exercise intensity corresponding to its $v\text{VO}_{2\text{max}}$ has been studied mainly by the Billat et al research group. Based on the pioneering work of Hill and Lupton (1923), Billat & Koralsztein (1996) defined this parameter as the maximum time that the $v\text{VO}_{2\text{max}}$ is maintained until exhaustion ($t\text{lim}-v\text{VO}_{2\text{max}}$).

The difficulties of measuring VO_2 in the aquatic environment hindered the swimming research and related modalities. The first studies were conducted in "swimming flume" (Faina et al. 1997; Demarie et al. 2001). To our knowledge, the first study in the pool, i.e., under normal swimming conditions, was performed by Renoux (2001). However, Renoux (2001) did not present results for cardio respiratory parameters such as VO_2 and ventilation. The main results obtained in studies with "swimming flume" suggested that: a) the $t\text{lim}-v\text{VO}_{2\text{max}}$ has low inter-individual variability in swimming, unlike other sports such as running (Billat et al. 1994b), and the values are between 4 min 45 s and 6 min 15 s; b) There is an inverse relationship between $t\text{lim}-v\text{VO}_{2\text{max}}$ and $v\text{VO}_{2\text{max}}$, similar to running (Billat et al. 1994c); c) There was an inverse relationship between $t\text{lim}-v\text{VO}_{2\text{max}}$ and anaerobic threshold.

Studies carried out in swimming pool with both genders and different levels of performance showed some results that agreed with "swimming flume" studies. Fernandes et al. (2003a, 2003b) suggest little variability in $\text{tlim-vVO}_{2\text{max}}$ between subjects at the same level of performance (Fernandes et al. 2006c), genders (Fernandes et al. 2005), or swimming techniques (Fernandes et al. 2006a). Still, there was an inverse relationship between $\text{tlim-vVO}_{2\text{max}}$ and $\text{vVO}_{2\text{max}}$ (Fernandes et al. 2003b, 2005, 2006a), and between $\text{tlim-vVO}_{2\text{max}}$ and anaerobic threshold corresponding blood concentrations of 3,5 mmol l⁻¹ (Fernandes et al. 2003b).

The method for obtaining $\text{vVO}_{2\text{max}}$ of swimmers in swimming pool proved to be valid by Fernandes et al. (2003a). First, each subject performed an intermittent and individualized protocol, with increments of 0.05 m.s⁻¹ at each stage of 200 m and with 30 s intervals between each stage, until exhaustion. The VO_2 was measured directly with a ergospirometer (K4b2, Cosmed, Rome, Italy) connected to the swimmer through a snorkel and a valve system (Keskinen et al. 2003). The concentrations of expired gases were measured *breath-by-breath*. A speed controller (*visual pacer*, TAR. 1.1, GBK-electronics, Aveiro, Portugal) with lights in the pool, was used to help the swimmers to keep their pre-determined SS. $\text{VO}_{2\text{max}}$ was considered to be reached according to primary and secondary physiological criteria: (HOWLEY et al. 1995):

- a. Occurrence of a VO_2 plateau independent of the increase in SS;
- b. [La] level ($\geq 8\text{mmol l}^{-1}$);
- c. High respiratory exchange ratio ($r \geq 1,0$);
- d. High HR ($\geq 90\%$ of $[220-\text{age}]$);
- e. High value of PE (visually controlled).

Thus, $\text{vVO}_{2\text{max}}$ is equal to the SS corresponding to the first stage at which $\text{VO}_{2\text{max}}$ is reached. If a plateau lower than 2.1ml min⁻¹ kg⁻¹ could not be observed, the $\text{vVO}_{2\text{max}}$ was then calculated by the equation proposed by Kuipers et al. (1985):

$$v\dot{\text{VO}}_{2\text{max}} = SS + \Delta S \cdot (n \cdot N^{-1}) \quad (5)$$

where SS is the speed corresponding to the last completed stage, ΔS is the increment of speed, n indicates the number of seconds that the subjects were able to swim during the last stage, and N is the preset time (in seconds) to that stage. After determining the $\text{vVO}_{2\text{max}}$ of each swimmer, followed by an adequate recovery period, applies the test of $\text{tlim-vVO}_{2\text{max}}$ when each swimmer trying to stay in your swimming $\text{vVO}_{2\text{max}}$ (speed control) to exhaustion.

The main studies in swimming suggest that $\text{tlim-vVO}_{2\text{max}}$:

- a. Correlates inversely with the energy cost, ie, it has a direct relationship with swimming economy (Fernandes et al. 2005);
- b. Correlates inversely with the speed of the individual anaerobic threshold (Fernandes et al. 2006a);
- c. Presents negative correlation values with the delta lactate ($\Delta[\text{La}]$), ie, the difference found between [La] at the end and [La] at the beginning of exercise ($\Delta[\text{La}]$) (Fernandes et al. 2008);
- d. Presents negative correlation with maximum values of [La]. (Fernandes et al. 2008);
- e. Shows no significant correlation with $\text{VO}_{2\text{max}}$ (Fernandes et al. 2003a; 2003b; 2005; 2006a; 2006b; 2006c);

- f. Depends on the biomechanical parameters, correlating inversely with the strokes frequency and directly with the distance traveled per stroke cycle and the swimming index (product of the average SS and average distance traveled per stroke cycle) (Fernandes et al. 2006b);
 - g. During the protocol to obtaining $t_{lim-vVO_{2max}}$ there is a significant increase in stroke frequency and a great decline in the distance per stroke cycle (Marinho et al. 2004, 2006).
- Studies in runners and cyclists (Billat & Koralsztein 1996) found that the $t_{lim-vVO_{2max}}$ is less than 12 minutes, and the average is about 6 minutes.

Study	n	t_{lim} (s)	vVO_{2max} ($m \cdot s^{-1}$)	d_{lim} (m)
FERNANDES et al. (2003a)	10 Males (students)	325±76.5 (4min8s to 6min41s)	1.19±0.08	295.7 to 477.79
FERNANDES et al. (2003b)	15 Males (athletes)	260.2±60.73 (3min19s to 5min21s)	1.46±0.06	279.26 to 487.8
FERNANDES et al. (2006a)	8 (athletes)	243.17±30.49 (3min33s to 4min34s)	1.45±0.08	308.38 to 396.80
FERNANDES et al. (2006b)	13 Males	234.49±57.19 (4min17s to 4min51s)	1.45±0.04	257.08 to 422.93
	10 Females	231.90±52.37 (3min to 4min44s)	1.35±0.03	242.36 to 383.76
	Total = 23 (athletes)	233.37± 53.92 (3min to 4min47s)	1.40±0.06	240.44 to 419.42
FERNANDES et al. (2008)	3 Males	217.67±20.84 (3min17s to 3min58)	1.55±0.02	301.15 to 374.47
	5 Females	258.46 ± 25.10 (3min53s to 4min44s)	1.39±0.02	319.70 to 399.82
	Total = 8 (athletes)	243.20 ± 30.50 (3min32s to 4min34s)	1.45±0.08	291.54 to 418.76

Table 3. Studies that measured $t_{lim-vVO_{2max}}$ in swimmers.

Despite these results, is not only the complexity of measuring vVO_{2max} that affect the application of this concept by coaches. Because it is an abstract goal, the use of vVO_{2max} and $t_{lim-vVO_{2max}}$ in swimming training would be more attractive if a " d_{lim} " was associated with $t_{lim-vVO_{2max}}$. The studies presented in Table 3 suggest that efforts related to aerobic power (vVO_{2max}) have very similar d_{lim} of 400 m front crawl, ranging from 4min01s (3min17s to 5min21s, elite swimmers) and 5min25s (4min8s to 6min41s, recreational swimmers). Fastest swimmers endure less time vVO_{2max} likely for two reasons:

- a. Higher SS imply higher energy cost (Fernandes et al. 2008);
- b. Higher vVO_{2max} in best swimmers require more strenuous levels of exercise, more anaerobic system request (Fernandes et al. 2008).

8. Conclusion

Is well justified that CV_{2par} seems to be higher than CV_{3par} and CV_{4par} . CV_{3par} and CV_{4par} better represent the relationship between “*SS-tlim*” due to its better fit. CV_{3par} and CV_{4par} are similar and probably are located below the lower intensity domain. However, its applicability to swimming training is questioned because of the need to conduct many maximum efforts to obtain the CV.

In this sense, obtaining vVO_{2max} through the T_{400} seems to be an interesting ecological non-invasive protocol. *tlim-vVO_{2max}* relationship should be considered during swimming training, specifically in the evaluation sessions of the training status. This parameter, together with other indicators, such as LT, MLSS, PE and general biomechanical parameters allow improving the assessment and intensity prescription of training programs. In this sense, assuming some limitations that bring non-invasive tests, vVO_{2max} can be obtained through a single effort of 400 m front *crawl* at maximum intensity (T_{400}), with the advantage of being easy to use, low cost, and have great ecological validity (i.e., reflect the real swimming condition, as it is applied in the training environment. Thus, evaluations and prescriptions for training swimmers would be more practical and accessible, not only for the shortest time spent (i.e, collected even in a competitive situation) but also because do not impact cost. The ability to prescribe more than one training zone through T_{400} still deserves further studies.

9. Acknowledgment

Thanks to Universidade Federal do Rio Grande do Sul - Programa de Pós Graduação em Ciências do Movimento Humano (<http://www.esef.ufrgs.br/pos/>), Grupo de Pesquisa em Esportes Aquáticos (<http://www.geeaufrgs.wordpress.com>), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (<http://www.capes.gov.br>), Grêmio Náutico União Swim Team (www.gnu.com.br), Caixeiros Viajantes Swim Team (www.caixeirosviajantes.com.br/), Grêmio Náutico Gaúcho Swim Team (www.gngaicho.com.br/gng/home.php) and Biomechanics and Kinesiology Research Group - UFRGS (www.esef.ufrgs.br/pos/gruposdepesquisa/gpbic.php). Also thanks to the Graduate Student Rodrigo Carlet. We would like to leave here a special thanks to Coach Marcelo Diniz da Costa for his great contribution to this topic.

10. References

- Alberty M, Sidney M, Hout-Marchand F, Dekerle J, Gorce P, Lensel G, Pelayo P. *Effects of stroking parameters changes on time to exhaustion*. In: Vilas-Boas JP, Alves F, Marques A. (Eds). *Biomechanics and medicine in swimming X: proceedings of the Xth Internacional Symposium on Biomechanics and medicine in swimming*; Port J Sports Sci. 2006;6:287-289.

- Barbosa T, Silva AJ, Reis AM, Costa M, Garrido N, Policarpo F, Reis VM. (2010) *Kinematical changes in swimming front Crawl and Breaststroke with the AquaTrainer® snorkel*. Eur J Appl Physiol 2010 Aug;109(6):1155-62, DOI: 10.1007/s00421-010-1459-x.
- Baron B, Noakes TD, Deckerle J, et al. *Why does exercise terminate at the maximal lactate steady state intensity?* Br J Sports Med 2008;42:828-833. doi:10.1136/bjism.2007.040444
- Barstow TJ. (1994) *Characterization of VO₂ kinetics during heavy exercise*. Med Sci Sports Exerc, 26(11), 1327-34.
- Beneke R. (1995). *Anaerobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing*. Med Sci Sports Exerc, 27(6), 863-7.
- Billat V, Pinoteau J, Petit B, et al. (1994a) *Times to exhaustion at 90, 100 and 105% of speed at VO_{2max} and critical speed in elite long distance runners*. Med Sci Sports Exerc; 26 (5 Suppl.) 106S.
- Billat V, Renoux JC, Pinoteau J, Petit B, Koralsztein JP. (1994b) *Reproducibility of running time to exhaustion at VO_{2max} in subelite runners*. Med. Sci. Sports Exerc. 2:254-257.
- Billat V, Pinoteau J, Petit B, Renoux JC, Koralsztein JP. (1994c) *Time to exhaustion at 100% of velocity at VO_{2max} and modelling of the relation time-limit/velocity in elite long distance runners*. Eur J App Physiol. 69:271-273.
- Billat V, Koralsztein JP. *Significance of the velocity at VO_{2max} and time to exhaustion at this velocity*. Sports Med. 1996 Aug;22(2):90-108.
- Billat VL, Blondel N, Berthoin S. *Determination of the velocity associated with the longest time to exhaustion at maximal oxygen uptake*. Eur J Appl Physiol Occup Physiol. 1999; 80:159-161.
- Billat VL, Morton RH, Blondel N, Berthoin S, Bocquet V, Koralsztein, Barstow TJ. (2000) *Oxygen kinetics and modeling of time to exhaustion whilst running at various velocities at maximal oxygen uptake*. Eur J Appl Physiol 82 (3) 178-187.
- Bosquet L, Duchene A, Lecot F, Dupont G, Leger L. (2006) *Vmax estimate from three-parameter critical velocity models: validity and impact on 800m running performance prediction*. Eur J Appl Physiol 97: 34-42.
- Bull AJ, Housh TJ, Johnson GO, Perry SR (2000) *Electromyographic and mechanomyographic responses at critical power*. Can J Appl Physiol 25(4):262-270.
- Conley DL, Krahenbuhl GS. (1980) *Running economy and distance running performance of highly trained athletes*. Med Sci Sports Exerc; 12: 357-60.
- Cooper KH. *A mean of assessing maximal oxygen intake*. JAMA 1968; 203: 201-4.
- Costill DL, Maglischo BW, Richardson AB. (1994) *La natation*. Paris: Vigot 215.
- Daniels J, Scardina N, Hayes J, et al. *Elite and subelite female middle- and long-distance runners*. In: Landers DM, editor. Sport and Elite Performers, Vol. 3. Proceedings of the 1984 Olympic Scientific Congress: 1984 Jul 19-23: Oregon. Champaign (IL): Human Kinetics, 1984: 57-72.
- Daniels JT. (2005) *Daniels' Running Formula: Proven programs 800 m to the marathon*. Human Kinetic. 2nd edition ISBN 0-7360-5492-8.
- Deckerle J, Sidney M, Hespel JM, Pelayo P. *Validity and Reliability of Critical Speed, Critical Stroke Rate and Anaerobic Capacity in Relation to Front Crawl Swimming Performances*. Int J Sports Med. 2002;23:93-98.
- Deckerle J, Nesi X, Lefevre T, Depretz S, Sidney M, Huot-Marchand F, Pelayo P. *Striking parameters in front crawl swimming and maximal lactate steady state speed*. Int J Sports Med. 2005a; 26: 53-58.

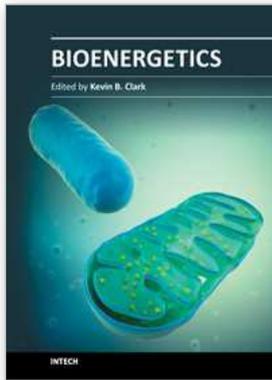
- Dekerle J, Pelayo P, Clipet B, Depretz S, Lefevre T, Sidney M. *Critical swimming speed does not represent the speed at maximal lactate steady state*. Int J Sports Med 2005b; 26:524-530.
- Dekerle J, Pelayo P, Sidney M, Brickley G. *Challenges of using critical swimming velocity. From scientists to coaches*. In: Vilas-Boas JP, Alves F, Marques A. (Eds). Biomechanics and medicine in swimming X: proceedings of the Xth Internacional Symposium on Biomechanics and medicine in swimming; Port J Sports Sci. 2006;6:296-299.
- Dekerle J, Brickley G, Alberty M, Pelayo P. (2010) *Characterising the slope of the distance-time relationship in swimming*. J Sci Med Sport, May,13(3):365-70.
- Dekerle J, Pelayo P. (2011) *Assessing aerobic endurance in swimming*. World book of swimming: from science to performance. Editors, Ludovic Seifert and Didier Chollet. 276-93 ISBN 978-161668-202-6.
- Demarie S; Sardella F; Billat V; Magini W; Faina M. (2001) *The VO₂ slow component in swimming*. Eur J Appl Physiol. 84:95-99.
- DI Prampero PE, Cortili G, Magnani P, Saibene F. *Energy cost of speed skating and efficiency of work against air resistance*. Journal of Applied Physiology. 1976. 40:548-591.
- Di Prampero PE. (2003) *Factors limiting maximal performance in humans*. Eur. J. Appl. Physiol. 90:420-429.
- Di Prampero PE, Pendergast D, Zamparo P. (2011) *Swimming Economy (Energy Cost) And Efficiency*. World book of swimming: from science to performance / editors, Ludovic Seifert and Didier Chollet. 297-312 ISBN 978-161668-202-6.
- Duffield R, Edge J, Bishop D, Goodman C. (2007) *The relationship between VO₂ slow component, muscle metabolites and performance during very-heavy exhaustive exercise*. J Sci and Med Sport 10;127-134.
- Ettema JH. (1966) *Limits of human performance and energy production*. Int Z Ang Physiol Einschl Arbeitphysiol. 22:45-54.
- Faina M, Billat V, Squadrone R, De Angelis M, Koralsztein JP, Dal Monte A. (1997) *Anaerobic contribution to the time to exhaustion at the minimal exercise intensity at which maximal oxygen uptake occurs in elite cyclists, kayakists and swimmers*. Eur. J. Appl. Physiol. 76:13-20.
- Fawkner SG, Armstrong N. (2003) *Oxygen Uptake Kinetic Response to Exercise in Children*. Sports Med 2003; 33 (9): 651-669
- Fernandes RJ, Cardoso CS, Soares SM, Ascensão AA, Colaço PJ; Vilas-Boas JP (2003a) *Time limit and VO₂ slow component at intensities corresponding to VO_{2max} in swimmers*. Int J. Sports Med. 24 :576-81.
- Fernandes RJ, Billat V, Vilas-Boas JP. (2003b) *Time limit at vVO_{2max} and VO_{2max} slow component in swimming. A pilot study in university students*. In J.-C. Chatard (ed.), Biomechanics and Medicine in Swimming IX (pp. 331-336) Publications de l'Université de Saint-Étienne, Saint Étienne: France.
- Fernandes RJ, Billat VL, Cruz AC, Colaço PJ, Cardoso CS, Vilas-Boas JP. (2005) *Has gender any effect on the relationship between time limit at VO_{2max} velocity and swimming economy?* J. Hum. Movement Stud. 49:127-148.
- Fernandes R, Cardoso C, Silva JA, Vilar S, Colaço P, Barbosa T, Keskinen KL, Vilas-Boas JP. *Assessment of time limit at lowest speed corresponding to maximal oxigen consumption in the four competitive swimming strokes*. In: Vilas-Boas JP, Alves F, Marques A. (Eds). Biomechanics and medicine in swimming X: proceedings of the Xth Internacional

- Symposium on Biomechanics and medicine in swimming; Port J Sports Sci. 2006a;6:128-130.
- Fernandes RJ, Marinho D, Barbosa TM, Vilas-Boas JP. *Is time limit at the minimum swimming velocity of VO_{2max} influenced by stroking parameters?* Perceptual and Motor Skills, 2006b, 103, 67-75.
- Fernandes RJ, Billat VL, Cruz AC, Colaço PJ, Cardoso CS, Vilas-Boas JP. (2006c) *Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity?* J Sports Med Phys Fitness; 46: 373-380.
- Fernandes R, Keskinen K, Colaço P, Querido A, Machado L, Morais P, Novais D, Marinho D and Vilas Boas JP. (2008) *Time limit at VO_{2max} velocity in elite crawl swimmers.* International Journal of Sports Medicine 29, 145-150
- Gaesser GA, Carnevale TJ, Garfinkel A, Walter DO, Womack CJ (1995) *Estimation of critical power with nonlinear and linear models.* Med Sci Sports Exerc 27(10):1430-1438
- Gaesser GA, Poole DC. (1996) *The slow component of oxygen uptake kinetics in humans.* Exerc Sport Sci Rev 24:35-71.
- Gastin PB. (2001) *Energy System Interaction and Relative Contribution During Maximal Exercise.* Sport Med 31 (10): 725 - 741.
- Greco CC, Caputo F, Denadai BS. *Puissance critique et consommation maximale d'oxygène: estimation de la limite haute du domaine d'intensité severe, un nouveau challenge?* Science & Sports 23 (2008) 216-222.
- Green S, Dawson BT, Goodman C, Carey MF. (1994) *Y-intercept of the maximal work-duration relationship and anaerobic capacity in cyclists.* Eur J Appl Physiol Occup Physiol. 69(6):550.
- Heck H, Mader A, Hess G, Mucke S, Muller R, Hollmann W. *Justification of the 4 mmol/l lactate threshold.* Int J Sports Med. 1985;6:117-30.
- Heubert RA, Billat VL, Chassaing P, Morton RH, Koralsztein JP, Di Prampero PE. (2005) *Effect of a previous sprint on the parameters of the work-time to exhaustion relationship in high intensity cycling.* Int J Sports Med. 26(7):583.
- Hill AV, Lupton L. *Muscular exercise, lactic acid and the supply and utilization of oxygen.* QJ Med 1923; 16:135-71.
- Hill AV (1927) *Muscular movement in man: the factors governing speed and recovery from fatigue.* McGraw-Hill, New York, pp 41-44.
- Hill DW. *The critical power concept. A review.* Sports Med 1993;16:237-54.
- Hill DW, Ferguson CS. *A physiological description of critical velocity.* Eur J Appl Physiol 1999; 79:290-3.
- Hill DW, Smith JC. *Determination of critical power by pulmonary gas exchange.* Can J Appl Physiol 1999;24:74-86.
- Hill DW, Alain C, Kennedy MD (2003) *Modeling the relationship between velocity and time to fatigue in rowing.* Med Sci Sports Exerc 35(12):2098-2105
- Hincson EA, Hopkins WG. (2005) *Reliability of time to exhaustion analyzed with critical-power and log-log modeling.* Med Sci Sports Exerc, 37(4), 696-701.
- Housh TJ, Cramer JT, Bull AJ, Johnson GO, Housh DJ (2001) *The effect of mathematical modeling on critical velocity.* Eur J Appl Physiol 84:469-475.
- Howley ET, Basseet T, Welch HG. *Criteria for maximal oxygen uptake: review and commentary.* Med Sci Sports Exerc 1995; 27: 1292-1301

- Invernizzi PL, Caporaso G, Longo S, Scurati R, Alberti G. (2008) *Correlations between upper limb oxygen kinetics and performance in elite swimmers*. Sport Sci Health 3;19-25.
- Jenkins DG, Quigley BM. (1991) *The y-intercept of the critical power function as a measure of anaerobic work capacity*. Ergonomics. Jan;34(1):13-22.
- Jenkins DG, Quigley BM. (1993). *The influence of high intensity exercise on the Wlim-Tlim relationship*. Medicine and Science in Sports and Exercise 25: 275 - 282.
- Keskinen K, Rodriguez F, Keskinen O (2003) *Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming*. Scand J Med Sci Sports 13:322-329.
- Kilding AE, Winter EM, Fysh M. (2006) *A comparison of pulmonary oxygen uptake kinetics in middle and long distance runners*. Int J Sports Med 27;419-426.
- Kuipers H, Verstappen FT, Keize HA, Guerten P, van Kranenburg G. *Variability of aerobic performance in the laboratory and its physiologic correlates*. Int J Sports Med 1985; 6: 197-201.
- Lavoie JM, Léger LA, Montpetit RR, Chabot S. *Backward extrapolation of VO_2 from the O_2 recovery curve after a voluntary maximal 400m swim*. In: Hollander, Huijing, de Groot (Eds) Biomechanics and medicine in swimming. International series on sport science. 1983 Vol 14, pp 222-227, Human Kinetics Publishers, Champaign, Illinois, USA.
- Lavoie JM, Montpetit RR. *Applied Physiology of Swimming*. Sports Med. 1986. 3:165-189.
- Lavoie JM, Taylor AW, Montpetit RR. *Physiological effects of training in elite swimmers as measured by a free swimming test*. J Sports Med Phys Fitness. 1981;21:38-42.
- Lavoie JM, Leone M. (1988). *Functional maximal aerobic power and prediction of swimming performances*. J. Swimming Research; 4 (4), 17-19.
- Leclair E, Mucci P, McGawley K, Berthoin S. *Application du concept de puissance critique à différentes populations*. Science & Sports 23 (2008) 206-215.
- Lima MCS, et al. *Proposta de teste incremental baseado na percepção subjetiva de esforço para determinação de limiares metabólicos e parâmetros mecânicos do nado livre*. Revista Brasileira de Medicina do Esporte, v.12(5), p.268-274, 2006.
- Madsen O. *Anaerobic training not so fast, there*. Swim Tech. 1982;19(3):13-18.
- Maglisho, E. W. *Nadando ainda mais rápido*. 1ª ed. Brasileira. São Paulo. Manole, 1999.
- Marinho D, Vilas-Boas J, Cardoso C, Barbosa T, Soares S, Fernandes R. (2004). *Stroke rate and stroke length in a typical swimming time limit at VO_{2max}* . In E. Van Praagh; J. Coudert; N. Fellmann; P. Duché (Eds.), Abstracts of 9th Annual Congress of the European College of Sport Science (pp. 338). Clermont-Ferrant: University of Clermont-Ferrant.
- Marinho D, Ramos L, Carmo C, Vilar S, Oliveira R, Rodriguez F, Keskinen KL, Fernandes RJ, Vilas-Boas JP. (2006). *Stroke performance during front crawl swimming at the lowest speed corresponding to maximal oxygen consumption*. In: J.P. Vilas-Boas, F. Alves e A. Marques (eds), Book of Abstracts of the Xth International Symposium on Biomechanics and Medicine in Swimming. Portuguese J Sport Scienc. 6(1):45.
- Miura A, Kino F, Kajitani S, Sato H, Sato H, Fukuba Y. (1999) *The effect of oral creatine supplementation on the curvature constant parameter of the power-duration curve for cycle ergometry in humans*. Jap J Physiol. 49:169-174.

- Miura A, Sato H, Sato H, Whipp BJ, Fukuba Y. (2000) *The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry.* Ergonomics. 43:133-141.
- Monod H, Scherrer J. (1965) *The work capacity of synergic muscle groups.* Ergonomics. 8:329-338.
- Montpetit R, Léger L, Lavoie, JM, Cazorla G. *VO₂ Peak During Free Swimming Using the Backward Extrapolation of the O₂ Recovery Curve.* European Journal of Applied Physiology. 47, 385-391, 1981.
- Moritani T, Nagata A, De Vries HA, Muro M. (1981) *Critical power as a measure of physical work capacity and anaerobic threshold.* Ergonomics. 24:339-350.
- Morton RH. (1996) *A 3-parameter critical power model.* Ergonomics 39: 611-619.
- Noakes TD, St Clair Gibson A. *Logical limitations to the "catastrophe" models of fatigue during exercise in humans.* Br J Sports Med 2004;38:648-9.
- Noakes TD, St Clair Gibson A, Lambert EV. *From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions.* Br J Sports Med 2005;39:120-4.
- Olbrecht J, Madsen O, Mader A, Liesen H, Hollmann W. *Relationship between swimming velocity and lactic concentration during continuous and intermittent training exercises.* Int J Sports Med. 1985; 6(2):74-7.
- Olbrecht, J. *The Science of Winning. Planning, periodization and optimizing swim training.* Luton: Swimshop. 2000.
- Pelayo P, Alberty M, Sidney M, Potdevin F, Dekerle J. *Aerobic potential, stroke parameters, and coordination in swimming Front-crawl performance.* International Journal of Sports Physiology and Performance. 2007 2, 347-359.
- Pepper ML, Housh TJ, Johnson GO. (1992) *The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running.* Int j of Sports Medicine, 13, 121-124.
- Poole DC, Ward SA, Whipp BJ. *The effects of training on the metabolic and respiratory profile of high-intensity cycle ergometer exercise.* Eur J Appl Physiol 1990;59:421-9.
- Pyne BD, Lee HE, Swanwick KM. *Monitoring the lactate threshold in world-ranked swimmers.* Med Sci Sports Exerc. 2001;33:291-297.
- Renoux J-C. (2001). *Evaluating the time limit at maximum aerobic speed in elite swimmers. Training implications.* Arch. Physiol. Biochem. 109(5):424-9.
- Rodrigues FA. *Maximal oxygen uptake and cardiorespiratory response to maximal 400-m free swimming, running tests in competitive swimmers.* J. Sports Med. Phys. 2000. 40: 87-95.
- Sweetenham B, Atkinson J. *Championship swim training.* Champaign: Human Kinetics, 2003.
- Takahashi S, Wakayoshi K, Hayashi A, Sakaguchi Y, Kitagawa K. *A Method for Determining Critical Swimming Velocity.* Int J Sports Med 2009; 30: 119-123.
- Takahashi S, Wakayoshi K, Nagasawa S, Kitagawa K. *A simplified method for determination of critical swimming velocity as a swimming fatigue threshold for sprinters and distance swimmers.* (in Japanese with English abstract). Jap J Biom Sports Exer 2002; 6: 110-115.
- Takahashi S, Wakayoshi K, Nagasawa S, Sakaguchi Y, Kitagawa K. *A simplified method for determination of critical swimming velocity as a swimming fatigue index for freestyle sprinters and distance swimmers.* In: Chatard JC. (Ed) Biomechanics and medicine in swimming IX: proceedings of the IX Internacional Syposium on Biomechanics and medicine in swimming, Université de Saint-Etienne 2003 421-427.
- Touretski G. 1993 *Japan official swimming coach clinic.* Jap Amateur swim federation. 1994:93-139.

- Toussaint HM, Wakayoshi K, Hollander AP, Ogita F. (1998) *Simulated front crawl swimming performance related to critical speed and critical power*. Med Sci Sports Exerc. Jan;30(1):144-51.
- Vandewalle H, Kapitaniak B, Grun S, Raveneau S, Monod H. (1989) *Comparison between a 30-s all-out test and a time-work test on a cycle ergometer*. Eur J Appl Physiol Occup Physiol. 58(4):375.
- Vandewalle H, Vautier JF, Kachouri M, Lechevalier JM, Monod H. (1997) *Work-exhaustion time relationships and the critical power concept*. J Sports Med Phys Fitness 37: 89-102.
- Vandewalle H. *Puissance critique: passé, présent et futur d'un concept*. Science & Sports 23 (2008) 223-230.
- Vilas-Boas J, Lamares JP. *Velocidade Crítica: Critério para a Avaliação do Nadador e para a Definição de Objetivos*. In: XX Congresso Técnico Científico da Associação Portuguesa dos Técnicos de Natação, 1997.
- Wakayoshi K, Ilkuta K, Yoshida T, Udo M, Moritani T, Mutoh Y. *Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer*. Eur J Appl Physiol. 1992;64:153-7.
- Wakayoshi K, Yoshida T, Ikuta Y, Mutoh Y, Miyashita M. *Adaptations to six months of aerobic swim training: changes in velocity, stroke rate, stroke length and blood lactate*. Int J Sports Med. 1993a; 14:368-72.
- Wakayoshi K, Yoshida T, Udo M, Harada T, Moritani T, Mutoh Y, Miyashita M. *Does critical swimming velocity represent exercise intensity at maximal lactate steady state?* Eur J Appl Physiol. 1993b;66:90-95.
- Wasserman K, Beaver WL, Whipp BJ. (1990) *Gas exchange theory and the lactic acidosis (anaerobic) threshold*. Circulation, 81 (1 Suppl), II14-30.
- Whipp BJ, Huntsman DJ, Stoner N, Lamma N, and Wasserman K. (1982) *A constant which determines the duration of tolerance to high-intensity work*. Federation Proceedings 41:1591
- Wilkie DR (1980) *Equations describing power input by humans as a function of duration of exercise*. In: Cerretelli P, Whipp B (eds) *Exercise bioenergetics and gas exchange*. Elsevier North Hollands, Amsterdam, pp 75-80.
- Xu F, Rhodes EC. *Oxygen uptake kinetics during exercise*. Sports Med 1999; 27:313-27.
- Zacca R, Castro FAS (2009) *Comparison between different models to determine the critical speed in young swimmers*. Brazilian J Exerc Physiol 8(2):52-60.
- Zacca R, Castro FAS. *Velocidade Crítica em nadadores juvenis: determinação por meio de diferentes combinações de distância de prova*. In: XII Congresso de Ciências do Esporte e Educação Física dos Países de Língua Portuguesa, Porto Alegre, 2008.
- Zacca R, Wenzel BM, Piccin JS, Marcilio NR, Lopes AL, Castro FAS. (2010) *Critical velocity, anaerobic distance capacity, maximal instantaneous velocity and aerobic inertia in sprint and endurance young swimmers*. Eur J Appl Physiol (2010) 110:121-131 Doi 10.1007/s00421-010-1479-6.
- Zamparo P, Bonifazi M, Faina M, Milan A, Sardella F, Shena F, Capelli C. (2005) *Energy cost of swimming of elite distance swimmers*. Eur J Appl Physiol, 94, 697-704.



Bioenergetics

Edited by Dr Kevin Clark

ISBN 978-953-51-0090-4

Hard cover, 272 pages

Publisher InTech

Published online 02, March, 2012

Published in print edition March, 2012

Cellular life depends upon energy storage, transformation, utilization, and exchange in order to optimally function and to stay-off death. The over 200-year-old study of how cells transform biological fuels into usable energy, a process broadly known as bioenergetics, has produced celebrated traditions in explaining origins of life, metabolism, ecological adaptation, homeostasis, biosynthesis, aging, disease, and numerous other life processes. InTech's edited volume, Bioenergetics, brings together some of these traditions for readers through a collection of chapters written by international authorities. Novice and expert will find this book bridges scientific revolutions in organismic biology, membrane physiology, and molecular biology to advance the discipline of bioenergetics toward solving contemporary and future problems in metabolic diseases, life transitions and longevity, and performance optimization.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Rodrigo Zacca and Flávio Antônio de Souza Castro (2012). Bioenergetics Applied to Swimming: An Ecological Method to Monitor and Prescribe Training, Bioenergetics, Dr Kevin Clark (Ed.), ISBN: 978-953-51-0090-4, InTech, Available from: <http://www.intechopen.com/books/bioenergetics/bioenergetics-applied-to-swimming-an-ecological-method-to-monitor-and-prescribe-training>

INTECH

open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2012 The Author(s). Licensee IntechOpen. This is an open access article distributed under the terms of the [Creative Commons Attribution 3.0 License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.