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SWIMMING BIOENERGETICS: INTEGRATING BIOMECHANICAL AND PHYSIOLOGICAL DATA INTO A COHERENT BIOPHYSICAL MODEL FOR PERFORMANCE AND TRAINING

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ABSTRACT

The purpose of the present paper is to synthesise a number of scientific contributions of our research group, into a coherent corpus of knowledge related to swimming biophysics, specially centred on the availability and use of energy in swimming. After an introductory part that intends to underline the relevance of this approach base on the conceptualization of the swimmer, and swimming action itself, as a thermodynamic system and its mechanical output, we will survey a number of studies and respective contributions for a more advanced understanding of swimming performance, that can be transferred into training and enhancement of swimmers' working capacity.

Most of the studies referred were conducted over samples of swimmers of both genders and of different types, from university/participative swimmers to Portuguese elite swimmers, crossing the large population of trained national level swimmers. Those swimmers were studied in the four different competitive swimming strokes, accomplishing progressive protocols based over distances of 200 m. Physiologic parameters like VO_2 (and associated ventilatory and respiratory parameters), post exercise capillary blood $[La-]$ peaks, and heart rate, were directly measured. Kinematical parameters were also measured in the different studies, ranging from simple semi-quantitative parameters, like stroke length (SL), and stroke frequency (SF), to more elaborated biomechanical data, like intracyclic speed fluctuations and propulsive segments kinematics.

The focus of interest ranged from swimming economy of different strokes and genders (and of different technical alternatives of the same stroke), to the effects over energy cost of intracyclic speed fluctuations. Energetic input determinant factors, like swimming VO_2 kinetics, including VO_2 slow component, and VO_2 time limit, and its determinants, will also be analysed.

Key words: Swimming bioenergetics, energy cost, VO_2 time limit, VO_2 slow component.

1. INTRODUCTION

Swimming, as most of the cyclic modes of human motion, can be interpreted as a simple thermodynamical process, where an energy input (E) is processed in each instant of time (t) until a mechanical work (W) is performed with of a given energetic efficiency (e):

$$E \rightarrow W; e = W * E^{-1} * 100 \quad (1)$$

Swimming performance capacity is measurable by the maximum velocity (v) that a swimmer can attain in a certain context (technique, distance, practice conditions, etc.). This context is

a determinant for the understanding of the difference between efficiency (e), and energy cost (EC). In fact a swimmer can perform two tasks with a same e value, and the same energy input (E), but ending up to rather different mean maximum velocity for a given competitive distance. In this case the swimmer will produce the same mechanical power output (P) but, for instance, in one case, if submitted to larger drag forces (D) – due to poor technique, morphology, or fatigue -, he will swim slowly, once P can be described as:

$$P = D * v \quad (2)$$

Equation (2) do not describe the total mechanical work performed per unit of time (power) by a swimmer. We take it as a simple example, considering only the work done to overcome D , and excluding the work performed to accelerate water mass (W_{H2O}), the work done to accelerate the swimmers mass plus the added mass of water (W_{ma}), and the internal work (W_i).

From equations (1) and (2) it is now possible to extract a very old biophysical expression that models the factors determining swimming performance (di Prampero et al., 1974):

$$V = E * e * D^{-1} \quad (3)$$

where e is the efficiency of the biomechanical system (the swimmer) that produce propulsive force (p) to overcome D .

Rearranging equation (3) offers some insight over the concept of “energy cost” (Schmidt-Nielsen, 1972) - EC -, also an old concept, but still determinant for the understanding of the relevance of the particular biomechanical structure of locomotion movements:

$$EC = E * V^{-1} = D * e^{-1} \quad (4)$$

Vilas-Boas & Santos (1994) and Vilas-Boas (1996) showed empirically for the first time that energy cost of swimming grows with intracyclic speed fluctuations in breaststroke. As a consequence, this paper also reports about the recent attempts of our group to address this issue, but taking the other swimming competitive strokes as object of study.

Once obtained r values were not as high as possibly expected, suggesting a relevant influence of other factors in EC , the analysis of more and increasingly detailed biomechanical influencing factors was also conducted and reported here.

Finally, once it is obviously critical to swimming performance to understand the energy input to the system, this paper will address also to the recent contributions of our group in what VO_2 kinetics is concerned, specially trying to figure out the influencing factors and their relevant characteristics for training (VO_2 time limit, and VO_2 slow component).

2. METHODS

Sampling: The subjects were Portuguese competitive swimmers of both genders representing a large scale of performances from regular national to international top level.

Protocol: The experiments were conducted in an indoor 25 x 12 x 2 m swimming pool. Each swimmer was submitted to an incremental protocol of “n” (<8) x 200 m, either in front crawl or in one’s first stroke. The velocities and increments were chosen in agreement with swimmers, so that they would attain their best performance on the 7th trial. The starting velocity was set at a speed corresponding to a low training pace, approximately 0.3 m·s⁻¹ less than the swimmer’s best performance. After every 200 m, the swimmers rested passively for a period of 30 s, to allow the collection of ear-lobe capillary blood samples for the assessment of lactate concentration, and for feedback (some preliminary work was conducted with continuous protocols, and the adequacy of the intermittent one was previously shown – Cardoso et al., 2003). From stage to stage, a 0.05 m·s⁻¹ increase in swimming intensity was scheduled. The testing session terminated upon exhaustion and/or when the swimmer could not keep the predefined pace. The velocity was controlled by a

visual feedback system (GBK-Pacer from GBK Electronics, Portugal). Prior to exercise, resting values for the physiologic variables were obtained.

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

In some particular situations, swimmers were asked to perform sets of 3x25 m repetitions, at specified velocities, particularly in Butterfly stroke, for biomechanical analysis. Those sets included complete resting periods between repetitions.

Physiologic measurements: Heart rate was continuously monitored using *Polar Vantage* monitors, recording at 5 s intervals. Oxygen consumption (VO_2) was directly measured through a K4b² (Breath by Breath) Pulmonary Gas Exchange System, from *Cosmed* (Italy). A low hydrodynamic resistance respiratory valve was used to collect expired air samples (Toussaint et al., 1987) and connected to a breath-by-breath gas analyser (Keskinen et al., 2003; Rodriguez et al., 2003). VO_{2max} was considered to be reached according to primary and secondary traditional physiological criteria (Howley et al., 1995). The swimming velocity corresponding to VO_{2max} (vVO_{2max}) was considered to be the swimming velocity that elicits VO_{2max} . If a plateau, less than $2.1 \text{ mlO}_2 \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ could not be observed, the vVO_{2max} was calculated as proposed by Kuipers et al. (1985):

$$vVO_{2max} = v + \Delta v \cdot (n \cdot N^{-1}), \quad (5)$$

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 pre-set protocol time (in seconds) for this step.

Blood samples (25 μl) were collected from the ear-lobe before the evaluation, in each rest period and at the end of the protocol, immediately after, and at 1, 3, 5 and 7 minutes of recovery, if the lactate concentrations didn't decrease between collections. For the analysis of the blood lactate concentrations an automatic analyser *YSI 1500L* (*Yellow Springs, Ohio, USA*), was used.

The energetic input (E) was calculated using the VO_{2net} ($VO_{2net} = VO_{2exercise} - VO_{2rest}$) and the net blood lactate ($[La-]_{net} = [La-]_{exercise} - [La-]_{rest}$), transformed into VO_2 equivalents using a $2.7 \text{ mlO}_2 \cdot \text{Kg}^{-1} \cdot \text{mmol}^{-1}$ constant (di Prampero et al., 1978). The energy cost (EC) was computed dividing E by v .

Biomechanical measurements: Stroke parameters (SL , SF , stroke index - SI -, and v) were measured in each of the 25 m laps swam during the progressive protocol. Mean value was calculated for each 200 m swim. The v value was obtained from the distance covered and the split time - t . SF was measured through a base-3 chronofrequencymeter. SL was calculated by the ratio between v and SF (Craig & Pendergast, 1979), and SI was obtained from the product of SL times v (Costill et al., 1985).

Two pairs of video cameras (*JVC GR-SX1 SVHS* and *JVC GR-SXM 25 SVHS*) were used for dual media videotape recording in non-coplanar planes. Both pairs of cameras were synchronised on real time and edited on a mixing table (*Panasonic Digital Mixer WJ-AVE55 VHS* and *Panasonic Digital AV Mixer WJ-AVE5*) creating one single "dual media" image, as it was previously described by Vilas-Boas et al. (1997). One of the two supports was set in one forehead wall, 8.10 m away from the trajectory of the swimmer. The second structure was set in one of the lateral walls at 9.30 m from the forehead wall where the first structure was installed and at 10.20 m from the trajectory of the swimmer. Another camera (*Panasonic DP 200 SVHS*) was set in an underwater window in the forehead wall, at 0.90 m deep. One last camera (*Panasonic DP 200 SVHS*) was set 4.50 m above the water surface. In these two

last cameras, the optical axis was oriented in the direction of the displacement of the swimmers. Each camera, or pair of cameras, recorded images of the swimmer in non-coplanar planes. Synchronisation of the images was obtained using LED's placed on the recording field of every camera or pair of cameras, which were turned-on regularly and simultaneously to initiate the synchronisation every time the swimmer entered the performance volume. This was assumed to be delimited by the calibration volume, which was defined by a 27 m³ cube volume. The calibration cube was marked with 32 calibration points. The study comprised the 3D kinematical analysis of the different stroke cycles using the "Ariel Performance Analysis System" from Ariel Dynamics Inc. and a VCR (Panasonic AG 7355) at a frequency of 50 Hz. Zatsiorsky's model was used as adapted by de Leva (1996) with 22 anatomical points of reference. The 3D reconstruction of the digitised images was performed using DLT. Coefficients of variation (*CV*) for the horizontal velocity of the centre of mass along the stroke cycle were calculated – intra-cyclic velocity variation (*dv*).

Statistical procedures: Common descriptive statistics was used. Differences between mean values were studied using ANOVA. Individual regression equations (linear and polynomial) describing the relation between the bioenergetic and biomechanical variables were computed, as well as, its coefficients of determination and correlation. Partial correlations were also used when necessary. Statistical confidence was set to $p \leq 0.05$.

3. RESULTS & DISCUSSION

3.1. Swimming economy profiles of different swimming techniques

Figure 1 presents the economy profiles obtained for the four swimming strokes (Barbosa et al., 2006a).

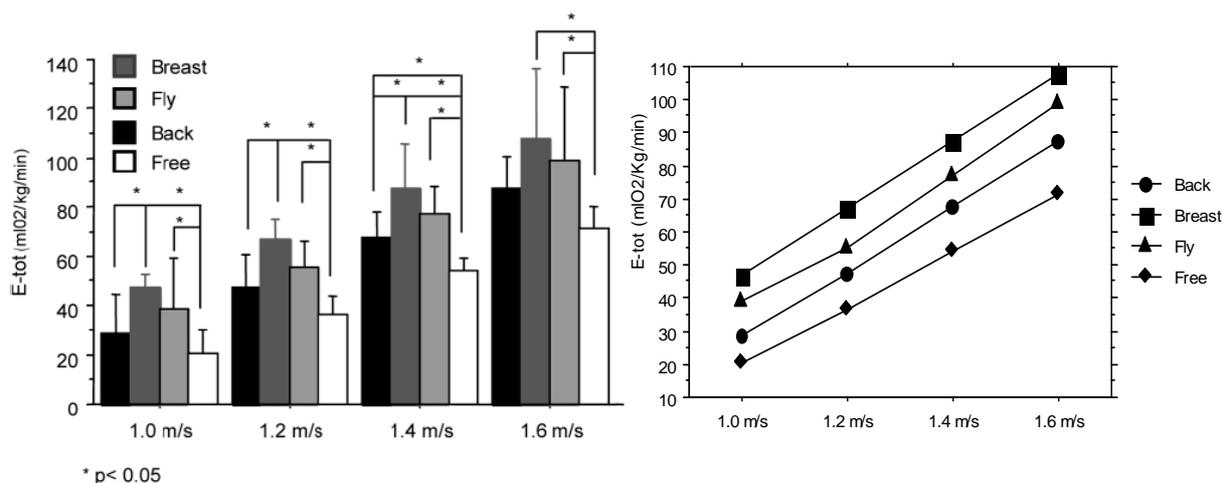


Figure 1. Total energy expenditure (E_{tot}) at standardized swimming velocities for the four competitive swimming strokes (some data were inter or extrapolated from $E(v)$ individual curves) (Barbosa et al., 2006a).

Comparing the results presented in figure 1 with the previously available, specially those from Holmér (1974), it is possible to understand that butterfly stroke significantly improved its economy over time, especially compared with breaststroke and backstroke. This allows to partially bridge the energy cost gap between continuous and discontinuous swimming techniques, reducing the spectrum of performance variability among competitive swimming techniques. It is also interesting to note that the tendency of the economy lines of breaststroke and butterfly to cross at lower swimming speeds was confirmed in a posterior approach (Barbosa et al., 2006b) – Figure 4B – where also a perceived tendency for butterfly stroke to cross the backstroke line at very high velocities was observed. This may be expected if a dramatic reduction in speed fluctuation is observed in v of the butterfly stroke.

In figure 2 economy profiles of different variants of the breaststroke are presented. Figure 2 shows that along with increased speed fluctuations (the inverse of the Strukhal number), also energy cost increased, supporting the significance of correlations obtained in the referred study.

This relationship was used to investigate also the other three swimming strokes. In figure 3, this relationship is reported for butterfly stroke (Barbosa et al., 2005a) based on a sample of 5 elite butterflyers, swimming 3 x 200 m (75, 85, 100%), with a 30 min rest.

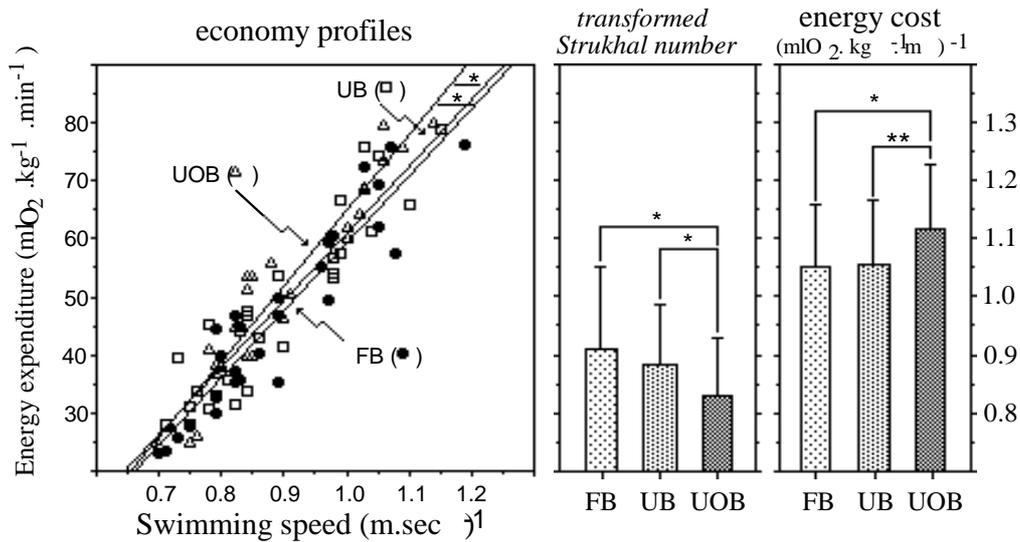


Figure 2. Swimming economy profiles for flat (FB), undulated (UB) and undulated over-water arm recovery breaststrokers (UOB) (Vilas-Boas & Santos, 1994).

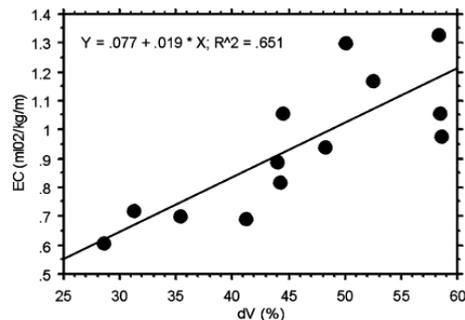


Figure 3. Relationship between energy cost (EC) and intracyclic speed fluctuations (dv) in butterfly (Barbosa et al., 2005b).

In another study, we tried to explore this relationship in the four competitive swimming strokes (figure 4) in elite swimmers. Significant positive correlation coefficients ($p < 0.05$) were observed for freestyle, butterfly and backstroke, but a negative relationship was found for the breaststroke.

The finding in figure 4B can possibly be explained by the fact that higher dv values were observed at lower mean speeds for breaststroke, associated with the possibility that v (and D) plays a more determinant role on EC than dv . When v was partialled out, the r value for the breaststroke between energy cost and dv was 0.60 ($p < 0.05$), which was of the same magnitude as the one observed for the other swimming techniques (0.55 for backstroke and butterfly stroke, and 0.62 for freestyle).

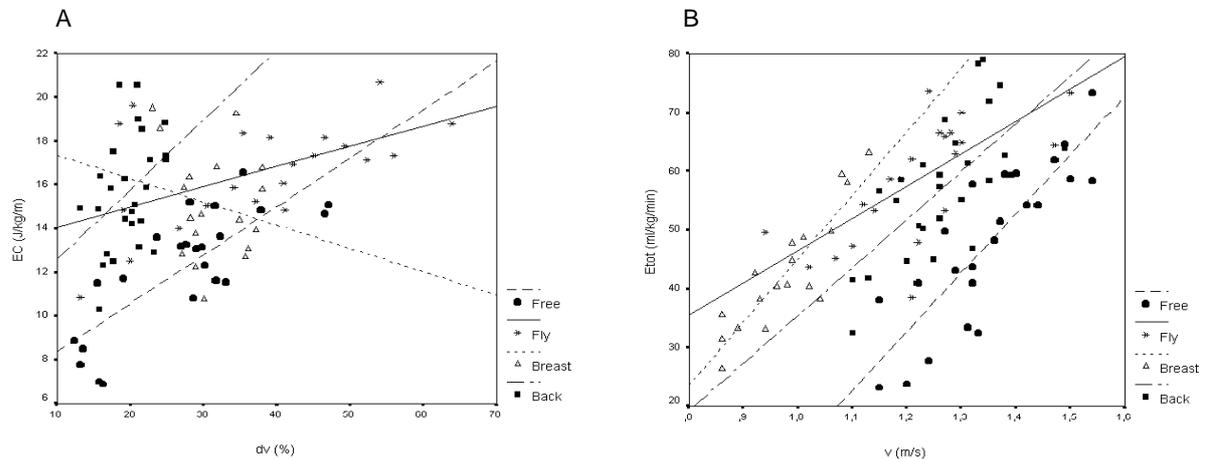


Figure 4. A - Relationship between energy cost (EC) and intracyclic speed fluctuations (dv), and B – relationship between energy expenditure (E_{tot}) and swimming velocity (v) for the four competitive swimming strokes (Barbosa et al., 2006b).

A similar effect was observed in the relationship between EC, and SI (figure 5 c) for butterfly stroke, showing a high influence of v if it is taken into consideration that the relationship between EC and SL was negative, when individual analysis is performed (figure 5 b).

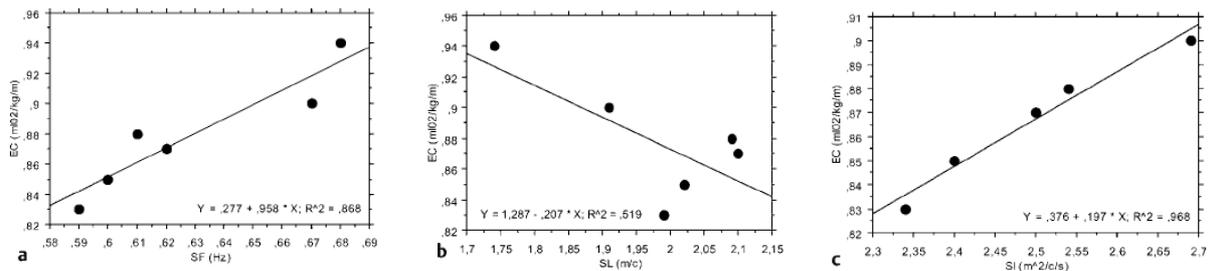


Figure 5. Relationship between energy cost (EC) and stroke frequency (SF) stroke length (SL), and stroke index (SI), measured as the product between v and SL on individual basis (Barbosa et al. 2005a).

3.2. VO_2 kinetics and time-limit at vVO_{2max}

A typical VO_2 kinetics profile of a rectangular maximal test after warm-up can be observed in figure 6. This was obtained from a university or a regular level swimmer. It is possible to observe that during easy warm-up period, VO_2 values grow until more than 50% VO_{2max} . Afterwards, during the maximal test, two phases can be clearly identified: a fast component, and a slow component. The latter has been one of the main interests of our research in the last few years, specially its relationship with $TLim-vVO_{2max}$.

It is very interesting to note in figure 6 that, approximately, only 90 s are needed to reach VO_{2max} , and that around 5 min is the maximal time that the swimmer can sustain vVO_{2max} , half of it with a clear slow component kinetics. This $TLim-vVO_{2max}$ was significantly correlated with O_2SC ($r = 0.74$, $p < 0.05$), and was slightly higher than the previously reported by other research groups, both in swimming and other sports (Billat et al, 1996; Faina et al., 1997; Demarie et al., 2001). The general characteristics of the O_2 kinetics presented in the previous example were that the higher the competitive level of the swimmer, and its VO_{2max} , (i) the lower the $TLim-vVO_{2max}$, and (ii) the lower the time to reach VO_{2max} . These findings are relevant for training purposes: repetitions per set for aerobic power training don't need to exes distances longer than 100 / 150 m, nor longer than 400 m.

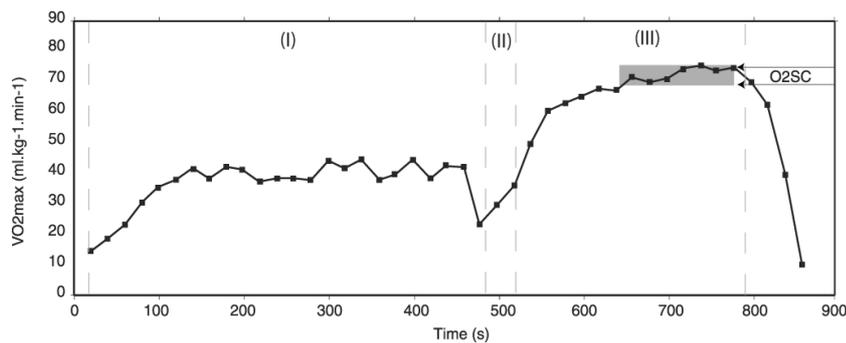


Figure 6. Typical VO_2 kinetics profile of a rectangular maximal test of a university to regular level swimmer. (I) 500 m easy warm-up period; (II) 50 m progressive to vVO_{2max} after a 30 s rest for blood collection; (III) maximal test to exhaustion at vVO_{2max} ($TLim-vVO_{2max}$ test). The VO_2 slow component region (O_2SC) is shown (Fernandes et al., 2003).

Figure 7 demonstrates that the $TLim-vVO_{2max}$ is inversely related to vVO_{2max} , and with the velocity corresponding to the anaerobic threshold ($vAnT$).

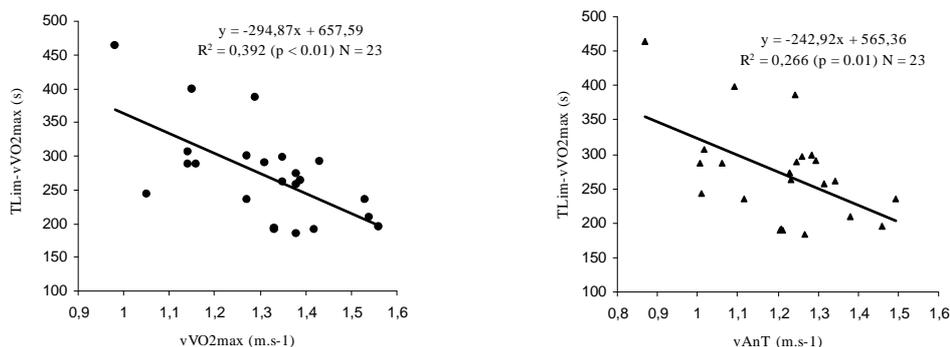


Figure 7. Relationships between $TLim-vVO_{2max}$, vVO_{2max} , and the velocity correspondent to the anaerobic threshold ($vAnT$) (Fernandes et al., 2006b).

These findings, even though surprising, show that top performers have high vVO_{2max} , and $vAnT$, with a short $T_{Lim-vVO_{2max}}$, as compared to their inferior counterparts. This is probably because vVO_{2max} of elite swimmers is more anaerobic (more participation of glycolytic energy pathways) than that of lower competitive level swimmers, imposing higher $\Delta[La-]$ between the beginning and the end of the T_{Lim} test - 6.8 ± 2.2 vs. 8.2 ± 1.6 mmol.l^{-1} , $p < 0.05$ (Fernandes et al., 2006a). Mean $T_{Lim-vVO_{2max}}$ for elite front crawl swimmers was found to be 237.3 ± 54.6 s, significantly different ($p < 0.05$) than the 313.8 ± 63.0 s observed for lower level swimmers (Fernandes et al., 2006a), similar with the 310 s of the example of figure 6. It is important to stress out that there are no significant differences in $T_{Lim-vVO_{2max}}$ attributable to the swimming stroke performed (Fernandes et al., 2006b). We did find out mean values for freestyle of about 238.75 ± 39.03 s, for backstrokers of 246.08 ± 51.93 s, for butterflyers of 277.63 ± 85.64 s, and for breaststrokers of 331.43 ± 82.73 s.

Interestingly to note, especially to relate the first and second parts of this paper, is that, exploring the relationships between $T_{Lim-vVO_{2max}}$ and swimming economy, we correlated it with energy expenditure at vVO_{2max} , with EC at vVO_{2max} , with EC at 1.2 and 1.3 m.s^{-1} (velocities commonly used both by low and higher level swimmers, males and females), with EC of the incremental protocol test, and with the C_{slope} of the $E(v)$ function. The only significant correlation that we found was a negative one, obtained between $T_{Lim-vVO_{2max}}$ and C_{slope} of the $E(v)$ function (Figure 8).

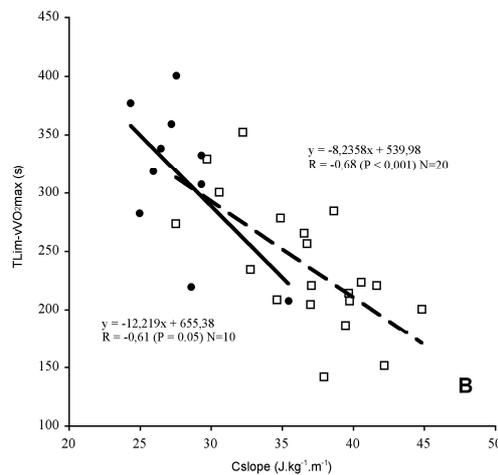


Figure 8. Relationship between $T_{Lim-vVO_{2max}}$ and C_{slope} of the $E(v)$ function, computed for 10 low level, and 20 highly trained swimmers (Fernandes et al., 2006a).

The inverse relationships suggests that, the less economic the swimmer is, the lower the $T_{Lim-vVO_{2max}}$ value, conflicting with the major findings that support the idea that the best swimmers attain lower $T_{Lim-vVO_{2max}}$. The explanation for this may be found in the differences between the vVO_{2max} values. Due to the expected cubic relationship between mechanical power and swimming velocity:

$$P = D * v = K * v^2 * v = K * v^3 \quad (6)$$

the much higher vVO_{2max} of the elite swimmers impose also much higher EC , in proportion rather higher than the difference observed in velocity, determining lower economy values (C_{slopes}) for the high level swimmers.

Supporting this idea, and contradicting the possible easy lecture that the less economic (higher $Cslope$) are the most proficient (the lower $TLim-vVO_{2max}$), we obtained significantly higher EC values for low level ($13.6 \pm 2.2 \text{ j.kg}^{-1}.\text{m}^{-1}$) than highly trained ($11.7 \pm 2.3 \text{ j.kg}^{-1}.\text{m}^{-1}$) swimmers. In figure 9 a global overview of the economy plots of a large sample of swimmers can be observed, both from the groups of low (LLS), and high level (HTS). It is possible to understand that LLS tend to spend more energy for the same v , or swim slower with the same E , but is also possible to perceive that there is important overlapping between the two groups. Moreover, it is rather important to note that from 0.9 to 1.4 m.s^{-1} (55% increase), energy expenditure rises 5 times, even if extreme values are measured in swimmers of different proficiency.

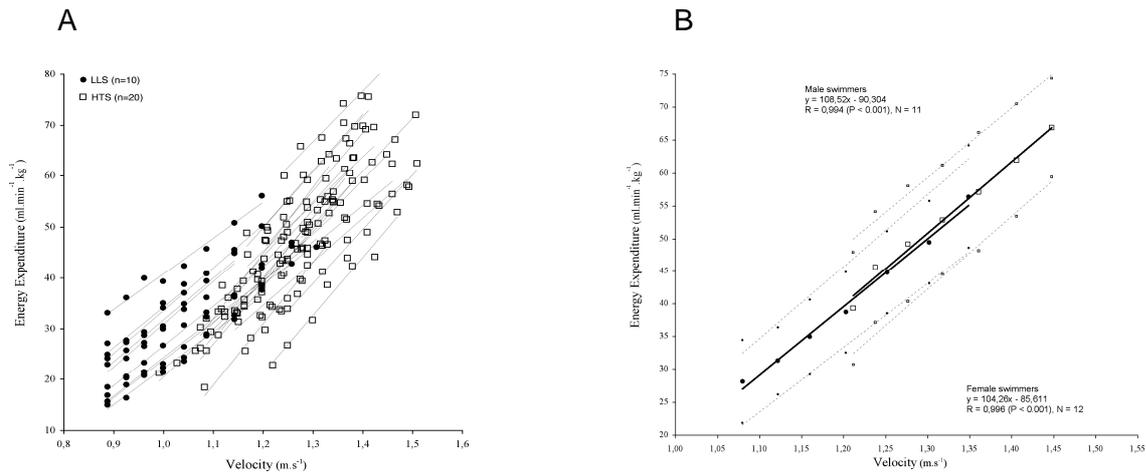


Figure 9. A - Economy scattergram (E vs. v) of a large sample of swimmers ($n = 30$), both from the groups of low (LLS), and high level (HTS); B – Male and female mean (and 95% confidence intervals) economy profiles (Fernandes et al., 2006a).

Similar effect as the one observed for the $Cslope$ was noticed for SL and SI (Fernandes et al., 2006c) – figure 10.

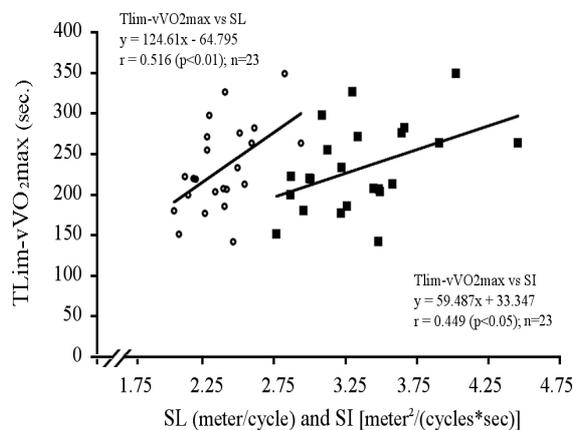


Figure 10. Relationships between $TLim-vVO_{2max}$ and SL and SI , computed for 23 highly trained swimmers (Fernandes et al., 2006c).

High *SL* and *SI* values correspond to rather different velocities, being the ones of the elite swimmers (lower $T_{Lim-vVO_2max}$) which were much higher and, supposedly, determinant of less gliding techniques and, consequently, with lower *SL* and *SI* values.

4. CONCLUSION

Swimming energetic is needed to understand performance, and the complexity of its determinant factors;

With years of training, relative economy of different swimming techniques seem to be changing, despite continuous swimming techniques (front crawl and backstroke) are still considered most economic even though butterfly stroke seem to be have changed most over the recent years;

Swimming economy is dependent on intra-cyclic speed fluctuations in all four competitive strokes, despite absolute mean velocity can influence more to the energy cost than its fluctuation;

Stroke parameters, such as *SL*, *SF*, and *SI*, are also related to swimming economy;

- Swimming economy seem to be similar between genders;
- Aerobic energy expenditure determine the contribution of the swimmers' overall energy expenditure. To train the maximal aerobic power of a swimmer, it is important to note that 90 s is sufficient to attain VO_{2max} , and that it can be sustained from almost 4 min to more than 5 min. Distances between 100 and 400 m can be used to plan training sets;
- The higher the competitive level of a swimmer, the lower the $T_{Lim-vVO_2max}$, probably because vVO_{2max} seem to be more anaerobic;
- The slow component of VO_2 kinetics is always perceptible, and seem to play an important role in swimming energy expenditure, specially in swimmers of lower competitive level.

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