Journal of Sports Sciences

ISSN: 0264-0414 (Print) 1466-447X (Online) Journal homepage: http://www.tandfonline.com/loi/rjsp20

Biomechanics, energetics and coordination during extreme swimming intensity: effect of performance level

João Ribeiro, Pedro Figueiredo, Sara Morais, Francisco Alves, Huub Toussaint, João Paulo Vilas-Boas & Ricardo Jorge Fernandes

To cite this article: João Ribeiro, Pedro Figueiredo, Sara Morais, Francisco Alves, Huub Toussaint, João Paulo Vilas-Boas & Ricardo Jorge Fernandes (2017) Biomechanics, energetics and coordination during extreme swimming intensity: effect of performance level, Journal of Sports Sciences, 35:16, 1614-1621, DOI: 10.1080/02640414.2016.1227079

To link to this article: https://doi.org/10.1080/02640414.2016.1227079

JOURNAL OF SPORTS SCIENCES, 2017
VOL. 35, NO. 16, 1614–1621
https://doi.org/10.1080/02640414.2016.1227079

Routledge
Taylor & Francis Group

Biomechanics, energetics and coordination during extreme swimming intensity: effect of performance level

João Ribeiro[a,b], Pedro Figueiredo[c,d], Sara Morais[b], Francisco Alves[e], Huub Toussaint[f], João Paulo Vilas-Boas[a,b] and Ricardo Jorge Fernandes[a,b]

[a]Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Porto, Portugal; [b]Porto Biomechanics Laboratory, University of Porto, Porto, Portugal; [c]School of Physical Education, Federal University of Rio Grande do Sul, Porto Alegre, Brazil; [d]Department of Kinesiology, University of Maryland, College Park, MD, USA; [e]Faculty of Human Movement Technical, University of Lisbon, Lisbon, Portugal; [f]School of Sports and Nutrition, Amsterdam University of Applied Sciences, Amsterdam, Netherlands

ABSTRACT

The present study aimed to examine how high- and low-speed swimmers organise biomechanical, energetic and coordinative factors throughout extreme intensity swim. Sixteen swimmers (eight high- and eight low-speed) performed, in free condition, 100-m front crawl at maximal intensity and 25, 50 and 75-m bouts (at same pace as the previous 100-m), and 100-m maximal front crawl on the measuring active drag system (MAD-system). A 3D dual-media optoelectronic system was used to assess speed, stroke frequency, stroke length, propelling efficiency and index of coordination (IdC), with power assessed by MAD-system and energy cost by quantifying oxygen consumption plus blood lactate. Both groups presented a similar profile in speed, power output, stroke frequency, stroke length, propelling efficiency and energy cost along the effort, while a distinct coordination profile was observed ($\boldsymbol{F}_{(3,\ 42)} = 3.59$, $P = 0.04$). Speed, power, stroke frequency and propelling efficiency (not significant, only a tendency) were higher in high-speed swimmers, while stroke length and energy cost were similar between groups. Performing at extreme intensity led better level swimmers to achieve superior speed due to higher power and propelling efficiency, with consequent ability to swim at higher stroke frequencies. This imposes specific constraints, resulting in a distinct IdC magnitude and profile between groups.

ARTICLE HISTORY
Accepted 10 August 2016

KEYWORDS
Kinematics; power; propelling efficiency; coordination; energy cost; front crawl

Introduction

Competitive swimmers' goal is to perform as fast as possible in a specific event. To accomplish that it is required a certain mechanical power output (P_O) that depends on metabolic power input ($\dot{E}$) and on overall efficiency of locomotion (η_o): $P_O = \dot{E} * \eta_o$ (Toussaint & Hollander, 1994; Zamparo & Swaine, 2012). $\dot{E}$ depends on aerobic, anaerobic lactic and alactic energy pathways, while η_o results from the ratio between the total mechanical work per unit of distance (W_{tot}) and the energy cost of exercise (i.e., the economy of swimming; C): $\eta_o = W_{tot}/C$. For a given η_o, C can be compromised since not all the total mechanical work is used for propulsion, with the portion of W_{tot} that is transformed into useful work to overcome drag (W_D) being given by propelling efficiency (η_p): $\eta_p = W_D/W_{tot}$ (Toussaint & Hollander, 1994; Zamparo, 2006; Zamparo et al., 2008). But, other than that, swimming speed and, consequently, C are not only dependent on η_p, but also on the timing between the swimmers' propulsive actions and its frequency (stroke frequency, SF) (Chollet, Chalies, & Chatard, 2000; Seifert et al., 2015). SF results from the ratio of swimming speed and the distance the swimmer's body moves through the water in each swimming cycle (SL) (Craig, Skehan, Pawelczyk, & Boomer, 1985): SF = speed/SL.

The aforementioned theoretical background reveals that swimming performance depends on several factors, varying significantly with swimmers competitive level. In fact, the best performance of higher-level swimmers can result from an optimal SF and SL combination, enabling an inter-limb coordination mode that minimises the time gap between propulsive phases (Chollet et al., 2000; Lerda & Cardelli, 2003; Seifert, Chollet, & Chatard, 2007). This seems to be a fine solution to produce sufficient propulsion to overcome the consequent superior drag, but not necessarily warranting a higher η_p (Seifert et al., 2015). Indeed, for higher swimming speeds, superior P_O and $\dot{E}$ are required, while η_p is expected to decline, compromising swimming economy and leading to C increase (Fernandes et al., 2006; Seifert, Komar et al., 2010; Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010).

In this context, despite some studies having already provided valuable information on the relationship among the aforementioned factors in distinct swimmers' levels (e g., (Cappaert, Bone, & Troup, 1992; Lerda & Cardelli, 2003; Seifert, Komar et al., 2010), their methodological approach focused mainly on non-competitive swimming scenarios. Research is thus lacking the analysis of the referred performance determinants throughout swimming competitive

CONTACT João Ribeiro jamribeiro@icloud.com Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Rua Dr. Plácido Costa, Porto 91 4200-450, Portugal

distances. Moreover, it has not been assessed swimming performance at different levels using a comprehensive biophysical approach, existing a shortage of quantitative data particularly at extreme intensities. As the 100-m freestyle is the swimming event that better represents performance at this intensity domain (effort ~1-min duration), we aimed to examine the behaviour of selected biomechanical, energetic and coordinative factors of high-and low-speed swimmers throughout an extreme intensity swim. It was hypothesised that a distinct profile of the analysed variables along the effort would be presented according to the performance level, as well as superior SF, SL, η_p and IdC in high-speed swimmers, and a higher C in the low-speed counterparts.

Methods

Participants

Sixteen voluntary male swimmers were divided in two performance level groups. Their main characteristics were: 21.1 ± 3.3 *vs.* 18.6 ± 1.6 years of age, 1.79 ± 0.03 m *vs.* 1.77 ± 0.03 m of height, 73.9 ± 6.4 *vs.* 69.1 ± 2.5 kg of body mass, 115 ± 4% *vs.* 124 ± 3% of 100-m freestyle world record time for high- ($n = 8$; national level) and low-speed ($n = 8$; regional level) groups, respectively. Participants (or parent/guardian when participants were under 18 years old) provided informed written consent before data collection and avoided strenuous exercise, and abstained from smoking and consuming alcohol or caffeine 48 h prior to testing. Swimmers were previously familiarised with the experimental equipment and procedures that were approved by the local ethics committee and performed according to the Declaration of Helsinki.

Experimental design

The test sessions took place in a 25-m indoor pool (1.90-m deep) with a water temperature of 27.5°C and 60% relative humidity. Each participant performed, in free-swimming condition, 100-m front crawl at maximal intensity. Secondarily, to determine the parameters that could not be assessed during 100-m bout test, swimmers accomplished: (i) 25, 50 and 75-m front crawl bouts (with 90-min active rest interval) at the same swimming speed (controlled by a visual light pacing system placed in the bottom of the pool with a flash every 5 m; Pacer2Swim OEM Kulzer TEC, Aveiro, Portugal) as in the previous 100-m test, to enable the [La^-] increments along each 25-m split of the total exercise (blood lactate increase speed method; Laffite et al., 2004); and (ii) after 24-h rest, 100-m front crawl at maximal intensity on the measuring active drag system (MAD-system) using only the upper limbs (the lower limbs were supported by a standard pull buoy). All test sessions were preceded by an individual warm-up consisting on 15 min of low to moderate intensity and 10-min passive rest was taken between warm-up and exercise bouts to ensure that previous workout did not influence exercise tolerance (Bailey, Vanhatalo, Wilkerson, Dimenna, & Jones, 2009). In-water starts and open turns (without gliding) were always used eliminating the influence of the dive and gliding in the analysis of swimming cycle.

Data collection and analysis

Biomechanics

Kinematics parameters were assessed using seven land plus eight underwater cameras (Oqus 3+ and Oqus Underwater, Qualisys AB, Gothenburg, Sweden) operating at 60 Hz. The calibrated volume (approximately: 5.50 m × 2.00 m × 1.80 m) was defined using under water, above the water and twin to merge the first and the latter (according to the manufacturer's guidelines) dynamic calibrations performed using a wand calibration procedure. This enabled the creation of 3D dual media working volume, where the orthogonal axes were defined as x for horizontal (swimming direction), y for the mediolateral and z for vertical ($z = 0$ defines the water surface) movements, respectively. Data acquisition was performed with Qualisys Track Manager version 2.7 (Qualisys AB, Gothenburg, Sweden).

Each swimmer was equipped with upper body retroreflective markers, with the acromion, lateral and medial humerus epicondyle, radius- and ulna-styloid processes, third distal phalanx, iliac crest and anterior and posterior iliac spine (for both right and left body sides) selected as anatomical landmarks. Data post-processing employed Visual3D (C-Motion, Germantown, MD, USA) using a low-pass digital filter of 6 Hz. For each 25-m lap, SF was assessed by the inverse of the time needed to complete one non-breathing front crawl cycle (defined as two consecutive water entries of the same hand) at the middle of the pool (representing the clean velocity) and SL was obtained by the horizontal displacement of the pelvis centre of mass (CM). Swimming speed was computed by dividing the horizontal displacement of the pelvis CM by the time required to complete one front crawl cycle. For the pooled sample (combining high- and low-speed swimmers), the mean speed along the event was calculated, and delta mean speed (Δv) was assessed by the difference in mean speed between the last and first laps. Hand speed was computed as the sum of the instantaneous 3D speed of the right and left hands during the underwater phase and η_p was estimated from the pelvis CM speed to 3D mean hand CM speed (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011). The computed efficiency represents the Froude/theoretical efficiency (internal work is not considered) of the upper limb cycle only (cf. Zamparo & Swaine, 2012 for a more detailed discussion).

In the MAD-system condition, swimmers pushed-off from fixed pads (1.35 m apart) attached to a 23-m rod at 0.8 m below water surface, which was instrumented with a force transducer allowing measuring the push-off force from each pad. The force signals were acquired by an A/D converter (BIOPAC Systems, Inc.) at a sample rate of 1000 Hz and filtered with a low-pass digital filter with a cut-off frequency of 10 Hz (Ribeiro et al., 2013). For each performance level group, the ₽$_O$ of each lap was calculated as the product of the mean speed and the mean force of the lap. Moreover, to analyse the relationship between this parameter and speed, the mean P_O along the event was calculated, and delta mean P_O (ΔP_O) was assessed by the difference in P_O between the last and first laps (computed for the pooled sample).

Energetics

Oxygen uptake ($\dot{V}O_2$) was directly and continuously measured using a telemetric portable gas analyser (K4b^2, Cosmed, Rome, Italy) connected to a specific respiratory snorkel and valve system (Aquatrainer, Cosmed, Rome, Italy). This snorkel is a breath-by-breath low hydrodynamic resistance device (Baldari et al., 2013; Ribeiro, Figueiredo, Guidetti et al., 2016) that allows swimming front crawl without restrictions. Capillary blood samples for lactate concentration ([La$^-$]) analysis were collected before and after all bouts (at 1, 3, 5 and 7 min) using a portable lactate analyser (Lactate Pro, Arkray, Inc., Kyoto, Japan).

Energy systems contribution were determined, for each 25-m lap, as follows: (i) the aerobic participation was assessed from the time integral of the net $\dot{V}O_2$versus time relationship; (ii) the anaerobic contribution was estimated using a methodology (recognised to be valuable to have an approximation of the anaerobic energy demands during supra-maximal exercise in several forms of locomotion, as reviewed by Zamparo, Capelli, & Pendergast, 2011) that considers the sum of the energy derived from lactic acid production with the one derived from phosphocreatine splitting in the contracting muscles (Figueiredo et al., 2011; Ribeiro, Figueiredo, Sousa et al., 2015; Sousa, Vilas, & Fernandes, 2014):

$$\mathrm{AnL} = \beta * [\mathrm{La}]_{\mathrm{net}} * M,$$

where $[\mathrm{La}]_{\mathrm{net}}$ is the difference between the blood lactate accumulation after and before exercise, β is the energy equivalent for blood lactate accumulation (2.7 ml O_2 mM^{-1} kg^{-1})(Di Prampero, Pendergast, Wilson, & Rennie, 1978; di Prampero et al., 1978) and M is the mass of the participant. $[\mathrm{La}]_{\mathrm{net}}$ was calculated as the difference in [La] before and after each lap: $[\mathrm{La}]_{\mathrm{net}}$ 25 = $[\mathrm{La}]_{\mathrm{post}}$ 25–[La] rest, $[\mathrm{La}]_{\mathrm{net}}$ 50 = $[\mathrm{La}]_{\mathrm{post}}$ 50–$[\mathrm{La}]_{\mathrm{post}}$ 25, $[\mathrm{La}]_{\mathrm{net}}$ 75 = $[\mathrm{La}]_{\mathrm{post}}$75–$[\mathrm{La}]_{\mathrm{post}}$ 50 and $[\mathrm{La}]_{\mathrm{net}}$ 100 = $[\mathrm{La}]_{\mathrm{post}}$100–$[\mathrm{La}]_{\mathrm{post}}$75 for the first, second, third and fourth laps (respectively); and (iii) The anaerobic alactic contribution (AnAl) was obtained using the following equation (Capelli, Pendergast, & Termin, 1998; Figueiredo et al., 2011; Ribeiro, Figueiredo, Sousa et al., 2015):

$$\mathrm{AnAl} = \mathrm{PCr}\left(1 - e^{(-t/\tau)}\right) * M,$$

where t is the time duration, τ is the time constant of phosphocreatine splitting at work onset (23.4 s) (Binzoni, Ferretti, Schenker, & Cerretelli, 1992), M is the mass of the participant and PCr is the phosphocreatine concentration at rest assumed to be 18.5 mmol · kg^{-1} (Capelli et al., 1998; Ribeiro, Figueiredo, Sousa et al., 2015; Zamparo et al., 2011). The energy derived from the utilisation of the phosphocreatine stores was estimated assuming that, in the transition from rest to exhaustion, its concentration decreases by 18.5 mmol · kg^{-1} (wet weight) in maximally active muscle assumed to correspond to 30% of body mass.

Anaerobic alactic contribution for each lap was calculated as the difference in AnAl before and after each 25 m: AnAl 25 = AnAl 25–AnAl rest, AnAl 50 = AnAl 50–AnAl 25, AnAl 75 = AnAl 75–AnAl 50 and AnAl 100 = AnAl 100–AnAl 75 for the first, second, third and fourth laps (respectively). To express different energy sources in the same units (kJ), the anaerobic alactic contribution was converted to kJ assuming a phosphorus/oxygen ratio of 6:25 and a energy equivalent of 0.468 kJ · mmol · kg^1 (Capelli et al., 1998), while for the aerobic energy contributions the energy equivalent was 20.9 kJ · lO_2^{-1} (Figueiredo et al., 2011; Ribeiro, Figueiredo, Sousa et al., 2015; Sousa et al., 2014). Based on these overall data, energy expenditure was assessed and C was obtained as the ratio between energy expenditure rate and mean speed (Fernandes et al., 2006).

Coordination

For coordination data analysis, front crawl upper limbs movements were split into four phases, determined from the swimmer's x and z positions of the hand CM and acromion (Chollet et al., 2000): (i) entry and catch, between the first z negative coordinate and the beginning of the backward movement of the hand CM; (ii) pull, from the end of the entry and catch phase until the mid-underwater position, determined by coincident x positions of hand CM and acromion; (iii) push, from the end of the pull until the hand release from the water, determined by the z positive coordinate of hand CM after the underwater trajectory; and (iv) recovery, from the end of the push until re-entry of the hand CM. Upper limbs coordination was quantified using the index of coordination (IdC), measuring the lag time between the propulsive phases of the limbs actions, expressed as the percentage of the overall duration of the front crawl cycle that can shift from catch-up (IdC < 0%) to opposition (IdC = 0%) and superposition (IdC > 0%) modes (Chollet et al., 2000).

Statistical analysis

Standard statistical methods were used to calculate mean and standard deviation (SD) and normal Gaussian data distribution was verified using the Shapiro–Wilks test. A two-way ANOVA [lap × performance level] was used to compare changes in the studied variables along the 100-m effort, with sphericity (homogeneity of variance and covariance) verified by means of the Mauchley test. If the assumption of sphericity was not met, the significance of the *F*-ratios was adjusted according to the Greenhouse–Geisser procedure. When a significant *F*-value was achieved, Bonferroni *post hoc* procedures were performed to locate the pairwise differences between the means. Cohen's *f* was used to compute the effect size considering that 0.1 are small, 0.3 moderate and 0.5 large, 0.7 very large and 0.9 extremely large (Hopkins, Marshall, Batterham, & Hanin, 2009). The relationships between mean speed and mean P_O and Δv and ΔP_O were analysed through Pearson correlation test, and to compare the 25, 50, and 75-m tests between the 100-m bout and the different simulated swims, a one-way repeated measures ANOVA was used. No SF differences were detected for the first (P = 0.11, f = 0.29), second (P = 0.61, f = 0.18) and third laps (P = 0.09, f = 0.30), as well as for rest [La$^-$], (P = 0.80, f = 0.13). For all tests, the level of significance was set at 5%.

Results

High-speed swimmers completed the front crawl maximal 100-m effort at a faster mean speed than the low-speed counterparts ($P = 0.001$, $f = 1.33$) both when swimming freely (1.48 ± 0.05 *vs* $1.33 \pm 0.07\ \text{m} \cdot \text{s}^{-1}$) and on the MAD-system (1.64 ± 0.06 *vs* $1.49 \pm 0.10\ \text{m} \cdot \text{s}^{-1}$). However, both groups presented the same speed ($P = 0.73$, $f = 0.62$; Figure 1 left panel) and $\dot{P}_O$ data distribution (same shape curve) ($P = 0.33$, $f = 0.29$; Figure 1 right panel), decreasing from the first to the last lap of the 100-m effort ($P < 0.001$, $f = 0.62$ and $P < 0.001$, $f = 1.36$, respectively). Furthermore, in every 25 m, high-speed swimmers presented superior speed ($P = 0.002$, $f = 1.00$) and $\dot{P}_O$ ($P = 0.05$, $f = 0.56$). Considering the pooled sample, mean speed was positively related with mean P_O ($r = 0.78$, $P < 0.001$) and Δv (first and last lap: 1.66 ± 0.10–$1.37 \pm 0.10\ \text{m} \cdot \text{s}^{-1}$) presented a high positive relationship with ΔP_O (first and last lap: 116.12 ± 33.35–84.71 ± 24.01 W) ($r = 0.84$, $P < 0.001$), corresponding to approximately 21% and 23% decrease (respectively).

The general stroking parameters evolution along the four 25-m laps (Figure 2, left panel) evidenced no interaction effect (same profile) for SF ($P = 0.55$, $f = 0.20$) and SL ($P = 0.45$, $f = 0.25$). High-speed swimmers presented superior SF ($P = 0.002$, $f = 1.02$) and similar SL ($P = 0.35$, $f = 0.26$) values compared with low-speed swimmers in the four laps. In both groups, SF decreased from the first to the third lap and increased in the fourth ($P < 0.001$, $f = 1.04$), whereas SL was stable in the first three partials and decreased on the fourth lap ($P < 0.001$, $f = 0.78$). The pooled sample pattern for SF between free swimming and MAD-system conditions were similar since no [lap × swimming condition] interaction effect was observed ($P = 0.60$, $f = 0.14$) and no normalised SF differences ($P = 0.07$, $f = 0.33$) were evidenced (Figure 2, right panel).

Both groups of swimmers remained in catch-up coordination mode, but presented distinct IdC profiles throughout the effort, as a [lap × group] interaction effect was observed ($P = 0.04$, $f = 0.59$). High-speed swimmers presented higher IdC ($P = 0.04$, $f = 0.60$) than the low-speed ones (with exception of first lap), maintaining it in the second partial and increasing the values in the last two laps. On the other hand, low-speed swimmers decreased the IdC from the first to second lap, and increased it from this partial to the fourth lap ($P < 0.001$, $f = 0.79$; Figure 3).

High- and low-speed swimmers presented the same η_p ($P = 0.83$, $f = 0.14$) and C profiles ($P = 0.33$, $f = 0.29$) along the 100-m front crawl effort, remaining stable ($P = 0.06$, $f = 0.52$; Figure 4, left panel), while C was maintained until the third lap followed by an increase in the fourth 25 m ($P = 0.007$, $f = 0.58$; Figure 4, right panel). High-speed swimmers presented a tendency for superior η_p ($P = 0.09$, $f = 0.48$, not significant but with a large effect size), while C was similar between groups ($P = 0.90$, $f = 0.03$).

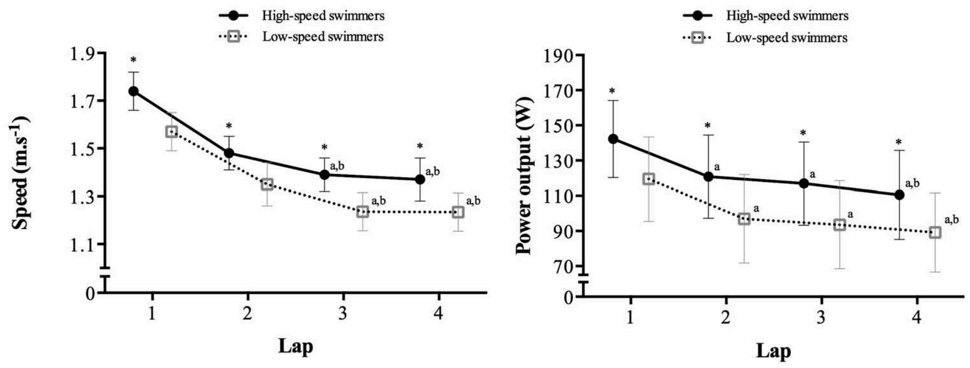

Figure 1. Speed and power output (left and right panels, respectively) for high- and low-speed swimmers in each 25-m lap of the 100-m maximal effort – mean (± SD). ^{a,b} Different from the first and second lap, respectively. *Different from low-speed swimmers ($P < 0.05$).

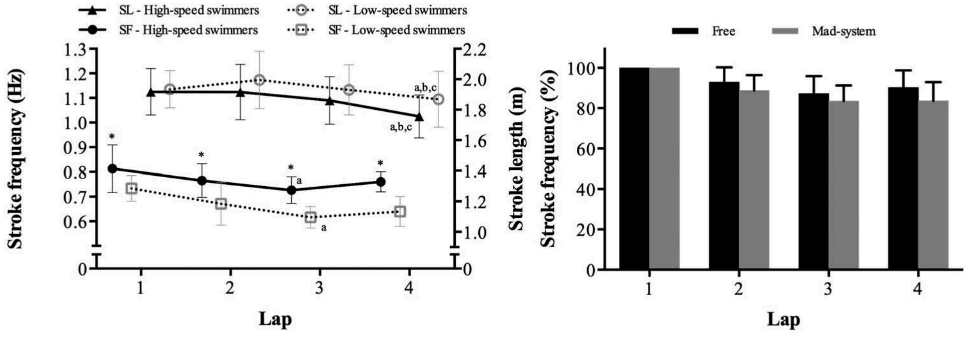

Figure 2. Stroke frequency (SF) and stroke length (SL) values for high- and low-speed swimmers in each 25-m lap of the free 100-m maximal effort (left panel). The normalised SF of the pool sample is also presented during unimpeded and MAD-system (black and grey bars, respectively) conditions (right panel) – mean (± SD). ^{a,b,c} Different from the first, second and third lap, respectively. *Different from low-speed swimmers ($P < 0.05$).

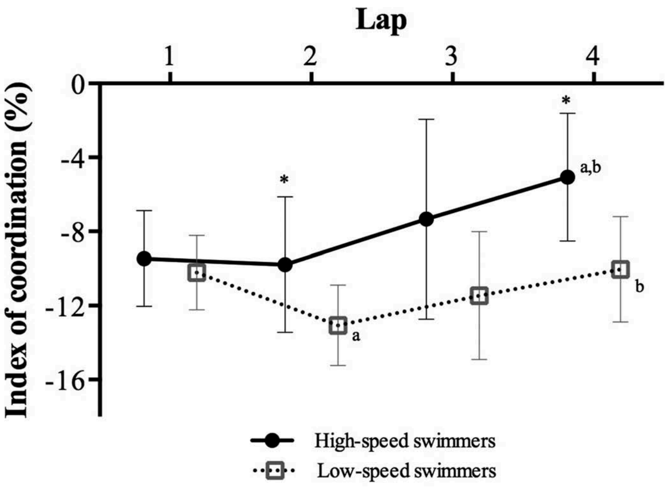

Figure 3. Index of coordination values for high- and low-speed swimmers in each 25-m lap of the free 100-m maximal effort – mean (± SD). ^{a,b} Different from the first and second lap, respectively. *Different from low-speed swimmers ($P < 0.05$).

Discussion

The main findings of the present study were that the front crawl speed, P_O, SF, SL, η_p and C profiles in the 100-m maximal effort seemed not to discriminate the distinct performance of high- and low-speed swimmers. Nevertheless, a higher magnitude in P_O and η_p, as well as the consequent ability to swim at a superior SF (leading to a higher IdC by diminishing the lag time between propulsive phases), can partially explain the better performance achieved by the faster swimmers.

Swimming speed declined along the extreme intensity effort in accordance with the literature (Chollet, Pelayo, Delaplace, Tourny, & Sidney, 1997; Toussaint, Carol, Kranenborg, & Truijens, 2006; Vorontsov & Binevsky, 2003), but it was not influenced by swimmers' level, as both groups presented the same profile and percentage decrease. This could be explained by the fact that all-out efforts presuppose a faster speed starting that necessarily decreases throughout the exertion time. Consequently, shorter duration efforts imply less margin for the adoption of a pacing strategy compared to longer competitive swimming distances (Craig et al., 1985; Maglischo, 2003). In spite of the same speed profile, high-speed swimmers were faster along the four 25-m laps, due to their greater capacity to generate power (Sharp, Troup, & Costill, 1982; Toussaint et al., 2006), as observed by the high positive relationship between Δv and ΔP_O.

Both high- and low-speed swimmers exhibited a reduction in SF until the third lap, followed by an increase in the fourth to compensate the decrease in SL. This is a common finding in the last moments of swimming events, when the swimmers strive to maintain speed (Chollet et al., 1997; Seifert, Boulesteix, Carter, & Chollet, 2005; Seifert et al., 2007; Toussaint et al., 2006; Vorontsov & Binevsky, 2003). Notwithstanding both groups presented the same profile, high-speed swimmers were able to achieve superior SF along the effort imposed by the higher P_O (dependent on work per stroke times SF) and, consequently, higher swimming speed (Chollet et al., 1997; Seifert et al., 2007). This highlights the importance of performing with high SF, underling the consequence of this parameter in force generation (Ribeiro et al., 2013) and, necessarily, power production (Toussaint et al., 2006; Vorontsov & Binevsky, 2003) at extreme swimming intensities. In this sense, implementing assisted and resisted sprint training could be a solution to increase the swimmers ability to achieve higher SF and, respectively, superior power output.

While swimming speed and SF reduced along the effort, SL was maintained stable (with the exception of the decline in the last stage) in both groups. This supports the assumption that the decay in swimming speed affects less SL and mainly SF, confirming the role of SF as an indicator of power production loss (Toussaint et al., 2006; Vorontsov & Binevsky, 2003). In the current study, both groups presented the same SL profile. This parameter is linked to swimming speed and SF, and since the pattern of these variables was similar in high- and low-speed swimmers, the same SL profile was also expected. In addition, the inverse relationship between SL and speed explains why high-speed swimmers, performing at superior speeds, presented the same SL magnitude as the low-speed ones.

During swimming P_O is hard to assess and so, in the present study, it was assumed to be similar to that obtained using the MAD-system, i.e., swimmers performed in situations of equal relative effort when swimming 100 m at maximal intensity in MAD and free conditions. To support this assumption some considerations can be put forward: (i) the equivalent relative SF decrease in each 25-m lap when comparing the

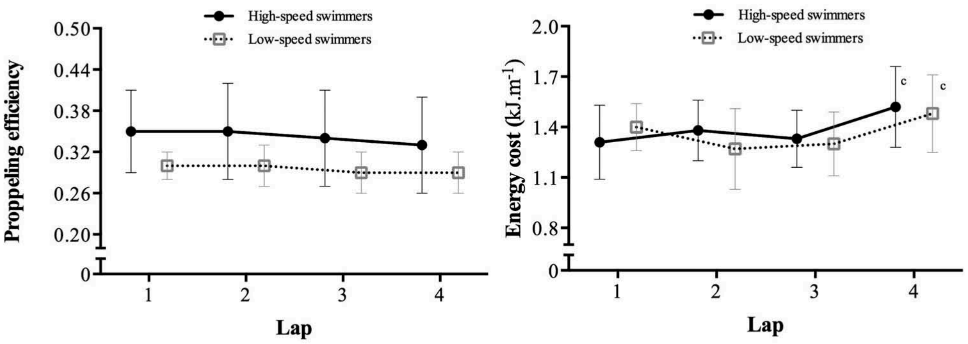

Figure 4. Propelling efficiency and energy cost values (left and right panels, respectively) for high- and low-speed swimmers (circles and squares, respectively) in each 25-m lap of the free 100-m maximal effort – mean (± SD). ^{c} Different from the third lap. *Different from low-speed swimmers ($P < 0.05$).

free swimming *vs* MAD-system condition; (ii) the same relative speed and P_O declines; and (iii) the observed association between these two variables (Δv and ΔP_O). Moreover, previous electromyographic measurements during unimpeded and MAD-system swimming conditions revealed that muscular activation patterns are similar (Clarys et al., 1988). The higher speed on the MAD-system compared with free swimming is due to the power expended giving the water a change in kinetic energy during free condition (Seifert, Toussaint et al., 2010; Toussaint et al., 2006).

Along the 100-m effort, high- and low-speed swimmers presented the same P_O profile, mirroring the swimming speed pattern. In fact, these two parameters were highly related and so the superior speed presented by the high-speed swimmers might be due to their greater capacity to generate P_O. This fact corroborates previous studies in which a high relationship between P_O and sprint swimming performance was observed (Hawley & Williams, 1991; Hawley, Williams, Vickovic, & Handcock, 1992; Sharp et al., 1982; Shionoya et al., 1999). Despite the superior P_O achieved by high-speed swimmers, both groups presented the same relative reduction of this parameter along the exercise, in accordance with previous findings in experienced swimmers (~24%), for the same distance (Toussaint et al., 2006). This decline led to a decrease in swimming speed as, consequence of SF decline, suggesting that P_O and SF seem to be the best discriminative factors of an extreme intensity swim (Lätt et al., 2010; Toussaint et al., 2006), corroborating the importance of carrying out long term training strategies to promote the greatest muscular strength and force time relationship, within the required context of extreme intensity.

High-speed swimmers presented higher coordination pattern variability than the low-speed counterparts, substantially increasing IdC along the effort. This fact could be interpreted as an effective way to deal with fatigue, compensating the reduction in P_O generating ability (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005). In fact, P_O decline along the laps affects SF, leading high-speed swimmers to gradually adapt the motor organisation (by minimising the time gap between propulsive phases) to maintain their superior speed (Chollet et al., 2000). As it is known that swimming technique must be sufficiently flexible and adaptable to enable emerging patterns of coordination to be modified according to constraints (Glazier, Wheat, Pease, & Bartlett, 2006), high-speed swimmers' coordination pattern variability can be interpreted as a functional property that helps them to adapt the movement behaviours according to performance constraints (Davids, Button, & Bennett, 2008; Glazier et al., 2006; Seifert et al., 2014). This justifies the importance of inciting swimmers to adapt their technique to the emerging constraints that exist in non-homeostatic race conditions.

Complementarily, high-speed swimmers were capable to achieve higher IdC values along the swim (with exception of first moment), in accordance with the literature that reveals that faster swimmers present a less negative IdC than the slower ones (Chollet et al., 2000; Lerda & Cardelli, 2003; Seifert et al., 2007). This is justified by the fact that faster swimmers present higher P_O and, consequently, higher maximal speed, more drag resistance and superior SF and, since low-speed swimmers present a lower SF, their glide could be favoured and IdC maintained in a more negative value (Bideault, Herault, & Seifert, 2013).

Despite the differences in IdC values, both groups remained in catch-up coordination mode throughout the 100-m effort, in line with the values found for a longer but still extreme swimming intensity (200-m front crawl; Figueiredo et al., 2011), but is at odds with studies where a superposition coordination model was reported (Seifert et al., 2005, 2007). These differences may warrant some caution in its interpretation since: (i) swimmers of distinct levels can present dissimilar IdC values and (ii) different methodological procedures in IdC determination (kinematical data *vs* visual inspection) may influence the outputs.

Concerning $\eta_{p,}$ its pattern on both groups remained approximately constant (with non-significant 3–5% decrease) throughout the effort, corroborating the literature (Toussaint et al., 2006). Considering the theoretical basis, it was expected that η_p mirrored SL, decreasing also in the last stages. The absence of this occurrence could be explained by the fatigability experienced along the effort, leading to a reduction in hand speed (4.94 ± 0.37, 4.68 ± 0.37, 4.39 ± 0.38, 4.35 ± 0.39 $m \cdot s^{-1}$ for first, second, third and fourth lap, respectively) concomitant with speed decrease, which allows η_p maintenance. Comparing current data to a 200-m front crawl maximal effort (Figueiredo et al., 2011), elite swimmers were able to maintain η_p until the third part (i.e., 150 m), but a reduction in the last lap was observed, suggesting that, despite the superior pace of the 100-m effort, its short duration could enable η_p conservation. In fact, due to the high speeds achieved in the 100-m effort, η_p was lower from the very beginning and so, it was also easier to sustain throughout the exercise.

The η_p is commonly considered a discriminative skill factor (Zamparo, 2006; Zamparo et al., 2008), but in the current study, no differences in η_p patterns of the two groups were observed. Nonetheless, high-speed swimmers presented a tendency for superior η_p along the effort, which might indicate that swimmers could benefit from training drill strategies (e.g., based on hand velocity/orientation) to promote η_p maintenance in fatigued conditions (extreme efforts). It should be taken into account, though, that the methodology to assess η_p is limited to a ratio swimming/hand speed, neither considering technical aspects responsible for propulsion (like hand and forearm orientation essential to pointing lift and drag forces in a favourable direction) nor thrust-producing vortices (Triantafyllou & Triantafyllou, 1995). Moreover, the calculation of this parameter is based on the analysis of one single-stroke cycle that could also influence the results. Notwithstanding, it can be conjectured that high-speed swimmers performing with superior hand velocities (mean 100-m effort: 4.74 ± 0.42 vs 4.43 ± 0.41 $m \cdot s^{-1}$ for high- and low-speed swimmers, respectively) were able to create higher propulsion-enhancing outcome as a result of a strong axial flow component along the rotating upper limb: the "pumping effect" (Toussaint, Van Den Berg, & Beek, 2002).

The C values reported in this study are compatible with values found in the literature for the same effort (Ribeiro, Figueiredo, Sousa et al., 2015; Zamparo, Capelli, Cautero, &

Di Nino, 2000). However, it was expected that high-speed swimmers presented superior C due to their higher speed, explained by the non-linear relationship between C and swimming speed, which presupposes that minor increases in speed leads to a substantial intensification of C (Wakayoshi, D'Acquisto, Cappaert, & Troup, 1995). However, considering that the superior speed achieved by faster swimmers also imply greater available energy (Fernandes et al., 2006), specially in short swimming events where the task goal is to swim as fast as possible, the ratio energy expenditure/speed was probably maintained along the four laps, being similar to the low-speed swimmers (but with higher absolute value of energy expenditure and speed). This is consistent with the influence of energy expenditure and drag on C, with high-speed swimmers showing higher energy expenditure and expected higher drag, leading to similar C values as their slower counterparts. This indicates that despite the short duration of the extreme effort, strengthen swimmers metabolic power could promote a better 100-m performance.

In both groups, C was maintained during the event, with the exception of last stage where an increase was observed. Some assumptions can be put forward to support this raise in the last moment, considering that C main determinants are η_p and hydrodynamic resistance (Zamparo et al., 2008). In one hand, a slight diminishment of η_p could occur considering that SL also decreased and, on the other hand, drag could have increased, despite the decay on speed. This is justified considering that as the speed decreases, swimmers' bodies tend to adopt a less streamline position and trunk inclination becomes critical, particularly at speeds lower than $1.4 \text{ m} \cdot \text{s}^{-1}$ (Zamparo, Gatta, Pendergast, & Capelli, 2009), and also because some deterioration on swimming technique could appear at the end of effort, as swimmers become fatigued and higher lactate accumulation occurs (Toussaint et al., 2006; Wakayoshi et al., 1995).

Conclusion

During an extreme intensity swim, the mode that high- and low-speed swimmers organise the general biomechanical parameters, P_O, η_p and C seems not to discriminate their differences in final performance. However, high-speed swimmers are characterised by greater values of P_O and a tendency for superior η_p (with consequent higher SF), leading to a distinct coordination profile along the effort. In this sense, it could be stated that to enhance 100-m front crawl performance, preference should be given to the direct development of the biophysical performance determinants rather than establishing strategies for their organisation during the event. In this sense, swimmers should increase their mechanical power (through specific strength and higher SF) as well as optimise the capacity to avoid power decline during fatigue conditions. A consequent adaption in coordination should be emphasised focusing on the diminishment of lag time between propulsive phases, without compromise too much the technical features that ensure stroke length and propelling efficiency. Moreover, due to short duration of the effort, metabolic power should be enhanced preferentially to satisfy the high-energy requirements of extreme intensity rather than promoting swimming economy.

Acknowledgments

This work was supported by Portuguese Science and Technology Foundation under Grant PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577) and SFRH/BD/81337/2011.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Portuguese Science and Technology Foundation under: [Grant Numbers PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577) and SFRH/BD/81337/2011].

ORCID

João Paulo Vilas-Boas http://orcid.org/0000-0002-4109-2939

References

Alberty, M., Sidney, M., Huot-Marchand, F., Hespel, J. M., & Pelayo, P. (2005). Intracyclic velocity variations and arm coordination during exhaustive exercise in front crawl stroke. *International Journal of Sports Medicine*, *26*(6), 471–475. doi:10.1055/s-2004-821110

Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., Dimenna, F. J., & Jones, A. M. (2009). Optimizing the "priming" effect: Influence of prior exercise intensity and recovery duration on O2 uptake kinetics and severe-intensity exercise tolerance. *Journal of Applied Physiology*, *107*(6), 1743–1756. doi:10.1152/japplphysiol.00810.2009

Baldari, C., Fernandes, R. J., Meucci, M., Ribeiro, J., Vilas-Boas, J. P., & Guidetti, L. (2013). Is the new AquaTrainer® snorkel valid for VO2 assessment in swimming? *International Journal of Sports Medicine*, *34*(4), 336–344. doi:10.1055/s-0032-1321804

Bideault, G., Herault, R., & Seifert, L. (2013). Data modelling reveals inter-individual variability of front crawl swimming. *Journal of Science and Medicine in Sport*, *16*(3), 281–285. doi:10.1016/j.jsams.2012.08.001

Binzoni, T., Ferretti, G., Schenker, K., & Cerretelli, P. (1992). Phosphocreatine hydrolysis by 31P-NMR at the onset of constant-load exercise in humans. *Journal of Applied Physiology*, *73*(4), 1644–1649.

Capelli, C., Pendergast, D. R., & Termin, B. (1998). Energetics of swimming at maximal speeds in humans. *European Journal of Applied Physiology and Occupational Physiology*, *78*(5), 385–393. doi:10.1007/s004210050435

Cappaert, J. M., Bone, M., & Troup, J. P. (1992). Intensity and performance related differences in propelling and mechanical efficiencies. In D. Maclaren, T. Reilly, & A. Lees (Eds.), *Biomechanics and medicine in swimming, swimming science VI* (pp. 49–52). London: E & FN Spon.

Chollet, C., Chalies, C., & Chatard, J. C. (2000). A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine*, *21*(1), 54–59. doi:10.1055/s-2000-8855

Chollet, D., Pelayo, P., Delaplace, C., Tourny, C., & Sidney, M. (1997). Stroking characteristic variations in the 100-M freestyle for male swimmers of differing skill. *Perceptual and Motor Skills*, *85*(1), 167–177. doi:10.2466/pms.1997.85.1.167

Clarys, J. P., Toussaint, H. M., Bollens, E., Vaes, W., Huijing, P. A., De Groot, G., … Cabri, J. (1988). Muscular specificity and intensity in swimming against a mechanical resistance - surface EMG in MAD and free swimming. In B. E. Ungerechts, K. Wilkie, & K. Reischle (Eds.), *Swimming science V* (pp. 191–199). Champaign, IL: Human Kinetics Publishers.

Craig, A. B., Skehan, P. L., Pawelczyk, J. A., & Boomer, W. L. (1985). Velocity, stroke rate,and distance per stroke during elite swimming competition.

Medicine & Science in Sports & Exercise, *17*(6), 625–634. doi:10.1249/00005768-198512000-00001

Davids, K., Button, C., & Bennett, S. J. (2008). *Dynamics of skill acquisition: A constraints-led approach*. Champaign, IL: Human Kinetics Publishers.

di Prampero, P. E., Pendergast, D., Wilson, D., & Rennie, D. W. (1978). Blood lactic acid concentrations in high velocity swimming. In B. Eriksson & B. Furberg (Eds.), *Swimming medicine IV* (pp. 249–261). Baltimore, MD: University Park Press.

Fernandes, R. J., Billat, V. L., Cruz, A. C., Colaço, P. J., Cardoso, C. S., & Vilas-Boas, J. P. (2006). Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *Journal of Sports Medicine and Physical Fitness*, *46*(3), 373–380.

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J. P., & Fernandes, R. J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology*, *111*(5), 767–777. doi:10.1007/s00421-010-1696-z

Glazier, P. S., Wheat, J. S., Pease, D., & Bartlett, R. M. (2006). Dynamic systems theory and the functional role of movement variability. In K. Davids, S. J. Bennett, & K. Newell (Eds.), *Movement system variability*. Champaign, IL: Human Kinetics Publishers.

Hawley, J. A., & Williams, M. M. (1991). Relationship between upper body anaerobic power and freestyle swimming performance. *International Journal of Sports Medicine*, *12*(1), 1–5. doi:10.1055/s-2007-1024645

Hawley, J. A., Williams, M. M., Vickovic, M. M., & Handcock, P. J. (1992). Muscle power predicts freestyle swimming performance. *British Journal of Sports Medicine*, *26*(3), 151–155. doi:10.1136/bjsm.26.3.151

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–13. doi:10.1249/MSS.0b013e31818cb278

Laffite, L. P., Vilas-Boas, J. P., Demarle, A., Silva, J., Fernandes, R., & Billat, V. L. (2004). Changes in physiological and stroke parameters during a maximal 400-m free swimming test in elite swimmers. *Canadian Journal of Applied Physiology*, *29*(S1), S17–S31. doi:10.1139/h2004-055

Lätt, E., Jürimäe, J., Mäestu, J., Purge, P., Rämson, R., Haljaste, K., … Jürimäe, T. (2010). Physiological, biomechanical and anthropometrical predictors of sprint swimming performance in adolescent swimmers. *Journal of Sports Science and Medicine*, *9*(3), 398–404.

Lerda, R., & Cardelli, C. (2003). Breathing and propelling in crawl as a function of skill and swim velocity. *International Journal of Sports Medicine*, *24*(1), 75–80. doi:10.1055/s-2003-37195

Maglischo, E. W. (2003). *Swimming fastest: The essential reference on technique, training, and program design*. Champaign, IL: Human Kinetics Publisher.

Ribeiro, J., De Jesus, K., Figueiredo, P., Toussaint, H., Guidetti, L., Alves, F., … Fernandes, R. (2013). Biomechanical determinants of force production in front crawl swimming. *Journal of Sports Medicine and Physical Fitness*, *53*(3 suppl 1), 30–37.

Ribeiro, J., Figueiredo, P., Guidetti, L., Alves, F., Toussaint, H., Vilas-Boas, J. P., … Fernandes, R. J. (2016). AquaTrainer® snorkel does not increase hydrodynamic drag but influences turning time. *International Journal of Sports Medicine, 37,* 324–328.

Ribeiro, J., Figueiredo, P., Sousa, A., Monteiro, J., Pelarigo, J., Vilas-Boas, J. P., … Fernandes, R. F. (2015). VO2 kinetics and metabolic contributions during full and upper body extreme swimming intensity. *European Journal of Applied Physiology*, *115*, 1117–1124. doi:10.1007/s00421-014-3093-5

Seifert, L., Boulesteix, L., Carter, M., & Chollet, D. (2005). The spatial-temporal and coordinative structures in elite male 100-m front crawl swimmers. *International Journal of Sports Medicine*, *26*(4), 286–293. doi:10.1055/s-2004-821010

Seifert, L., Chollet, D., & Chatard, J. C. (2007). Kinematic changes during a 100-m front crawl: Effects of performance level and gender. *Medicine & Science in Sports & Exercise*, *39*(10), 1784–1793. doi:10.1249/mss.0b013e3180f62f38

Seifert, L., Komar, J., Barbosa, T., Toussaint, H., Millet, G., & Davids, K. (2014). Coordination pattern variability provides functional adaptations to constraints in swimming performance. *Sports Medicine*, *44*, 1333–1345. doi:10.1007/s40279-014-0210-x

Seifert, L., Komar, J., Leprêtre, P. M., Lemaitre, F., Chavallard, F., Alberty, M., … Hellard, P. (2010). Swim specialty affects energy cost and motor organization. *International Journal of Sports Medicine*, *31*(9), 624–630. doi:10.1055/s-0030-1255066

Seifert, L., Schnitzler, C., Bideault, G., Alberty, M., Chollet, D., & Toussaint, H. M. (2015). Relationships between coordination, active drag and propelling efficiency in crawl. *Human Movement Science*, *39*, 55–64. doi:10.1016/j.humov.2014.10.009

Seifert, L., Toussaint, H. M., Alberty, M., Schnitzler, C., & Chollet, D. (2010). Arm coordination, power, and swim efficiency in national and regional front crawl swimmers. *Human Movement Science*, *29*(3), 426–439. doi:10.1016/j.humov.2009.11.003

Sharp, R. L., Troup, J. P., & Costill, D. L. (1982). Relationship between power and sprint freestyle swimming. *Medicine & Science in Sports & Exercise*, *14*(1), 53–56. doi:10.1249/00005768-198201000-00010

Shionoya, A., Shibukura, T., Koizumi, M., Shimizu, T., Tachikawa, K., Hasegawa, M., & Miyake, H. (1999). Development of ergometer attachment for power and maximum anaerobic power measurement in swimming. *Applied Human Science*, *18*(1), 13–21. doi:10.2114/jpa.18.13

Sousa, A., Vilas, B. J. P., & Fernandes, R. J. (2014). VO2 kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at VO2max. *BioMed Research International*, *2014*, 1–9. doi:10.1155/2014/675363

Toussaint, H. M., Carol, A., Kranenborg, H., & Truijens, M. J. (2006). Effect of fatigue on stroking characteristics in an arms-only 100-m front-crawl race. *Medicine & Science in Sports & Exercise*, *38*(9), 1635–1642. doi:10.1249/01.mss.0000230209.53333.31

Toussaint, H. M., & Hollander, A. P. (1994). Energetics of competitive swimming: Implications for training programmes. *Sports Medicine*, *18*(6), 384–405. doi:10.2165/00007256-199418060-00004

Toussaint, H. M., Van Den Berg, C., & Beek, W. J. (2002). "Pumped-up propulsion" during front crawl swimming. *Medicine and Science in Sports and Exercise*, *34*(2), 314–319. doi:10.1097/00005768-200202000-00020

Triantafyllou, M. S., & Triantafyllou, G. S. (1995). An efficient swimming machine. *Scientific American*, *272*(3), 64–70. doi:10.1038/scientificamerican0395-64

Vorontsov, A. R., & Binevsky, D. A. (2003). Swimming speed, stroke rate and stroke length during maximal 100 m freestyle ofBoys 11-16 years of age. In J. C. Chatard (Ed.), *Biomechanics and medicine in swimming IX* (pp. 195–201). Saint-Étienne: Publications de l'Universií de Saint-Étienne.

Wakayoshi, K., D'Acquisto, L. J., Cappaert, J. M., & Troup, J. P. (1995). Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *International Journal of Sports Medicine*, *16*(1), 19–23. doi:10.1055/s-2007-972957

Zamparo, P. (2006). Effects of age and gender on the propelling efficiency of the arm stroke. *European Journal of Applied Physiology*, *97*(1), 52–58. doi:10.1007/s00421-006-0133-9

Zamparo, P., Capelli, C., Cautero, M., & Di Nino, A. (2000). Energy cost of front-crawl swimming at supra-maximal speeds and underwater torque in young swimmers. *European Journal of Applied Physiology*, *83*(6), 487–491. doi:10.1007/s004210000318

Zamparo, P., Capelli, C., & Pendergast, D. (2011). Energetics of swimming: A historical perspective. *European Journal of Applied Physiology*, *111*(3), 367–378. doi:10.1007/s00421-010-1433-7

Zamparo, P., Gatta, G., Pendergast, D., & Capelli, C. (2009). Active and passive drag: The role of trunk incline. *European Journal of Applied Physiology*, *106*(2), 195–205. doi:10.1007/s00421-009-1007-8

Zamparo, P., Lazzer, S., Antoniazzi, C., Cedolin, S., Avon, R., & Lesa, C. (2008). The interplay between propelling efficiency, hydrodynamic position and energy cost of front crawl in 8 to 19-year-old swimmers. *European Journal of Applied Physiology*, *104*(4), 689–699. doi:10.1007/s00421-008-0822-7

Zamparo, P., & Swaine, I. L. (2012). Mechanical and propelling efficiency in swimming derived from exercise using a laboratory-based whole-body swimming ergometer. *Journal of Applied Physiology*, *113*(4), 584–594. doi:10.1152/japplphysiol.00324.2012