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THE ARM STROKE EFFICIENCY IN FRONT CRAWL SWIMMING: UPDATING THE STATE OF THE ART

IN *CO-TUTELLE DE THÉSE* WITH THE FEDERAL UNIVERSITY OF RIO GRANDE DO SUL

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Department of Neurological, Biomedical and Movement Sciences

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Ricardo Peterson Silveira

Porto Alegre, December, 2016

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Academic thesis submitted with the purpose of obtaining the doctoral degrees in Science of Physical Exercise and Human Movement (UNIVR, Italy) and Human Movement Sciences (UFRGS, Brazil).

Supervisors: Prof. Dr. Paola Zamparo (UNIVR) and Flávio Antônio de Souza Castro (UFRGS)

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“Our chief want is someone who will inspire us to be what we know we could be”

Ralph Waldo Emerson

General abstract

The Arm Stroke Efficiency in Front Crawl Swimming:

Updating the State of the Art

The main topic of this thesis was the arm stroke efficiency in front crawl swimming. Hence, it was developed in three original articles aiming to: (1) investigate the interplay between propelling efficiency and arm's power output in determining the maximal speed in front crawl swimming, (2) estimate the effects of leg kick on the swimming speed and on arm stroke efficiency in front crawl, and (3) to compare different methods to assess the arm stroke efficiency and to identify the main biophysical predictors of maximal speed in 200 m swimming with the arms only. Different approaches were used to quantify the arm stroke efficiency. For instance, the paddle-wheel model (studies 1, 2, and 3), the ratio forward speed/hand speed (study 3), and the MAD System approach (study 3). The leg kick contribution was estimated individually, considering the differences in speed at paired stroke frequencies, in a range of speeds. Useful and non-useful components of the total mechanical power exerted by the arm stroke were obtained from dry land (using a customized arm-crank ergometer; study 1) and swimming protocols (using the MAD System; study 3), combined to the assessment of physiological and biomechanical parameters, including the arm stroke efficiency. The maximal speed in 200 m was determined by the balance between biomechanical (75% of the variances explained by the external mechanical power and the arm stroke efficiency; 98% of the variances explained by the external mechanical power, the arm stroke efficiency and the speed-specific drag) and physiological parameters (98% of the variances explained by the total metabolic power and the energy cost of swimming). Moreover, leg kick contribution to forward speed increased from low to maximal stroke frequencies (and speeds) and individual adjustments to the leg kick contribution should be considered when assessing the arm stroke efficiency in "full front crawl stroke" front crawl. Furthermore, the different methods provided significantly different values of arm stroke efficiency, although they agreed with each other. Therefore, arm stroke efficiency data should be interpreted carefully, considering the method used.

Key-words: Froude efficiency, Propelling efficiency, Economy, Performance prediction.

Resumo geral

Eficiência da Braçada no Nado Crawl:

Atualização do Estado da Arte

O tópico principal desta tese de doutorado foi a efficiência da braçada no nado *crawl*. A tese foi composta e dividida em três artigos originais, com o objetivo de: (1) investigar as relações existentes entre a eficiência da braçada e a potência de membros superiores na determinação da velocidade máxima do nado crawl, (2) estimar os efeitos da pernada na velocidade de nado e no cálculo da eficiência da braçada no nado *crawl*, e (3) comparar os diferentes métodos utilizados para estimativa da eficiência da braçada e identificar os principais preditores biofísicos da velocidade máxima em 200 m *crawl* utilizando apenas os braços. Diferentes métodos foram utilizados para quantificar a eficiência da braçada, como o modelo da "roda de pás" (estudos 1, 2, e 3), a razão entre a velocidade de nado e a velocidade deslocamento da mão (estudo 3), e o método utilizando o *MAD System* (estudo 3). A contribuição da pernada foi estimada individualmente, considerando as diferenças de velocidade de nado para uma determinada frequência gestual, em diferentes intensidades. Os componentes úteis e não-úteis para a potência mecânica total exercida pela braçada foram obtidos por meio de protocolos fora d'água (utilizando um ergômetro de brações específico; estudo 1) e dentro d'água (utilizando o *MAD System*; estudo 3), combinados com medidas fisiológicas e biomecânicas, incluindo a eficiência da braçada. A velocidade máxima em 200 m teve como determinantes o equilíbrio entre variáveis biomecânicas (75% das variâncias pôde ser explicado pela potência mecânica externa e a eficiência da braçada; 98% das variâncias pôde ser explicado pela potência mecânica externa, eficiência propulsiva e o coeficiente de arrasto) e variáveis fisiológicas (98% das variâncias pôde ser explicado pela potência metabólica total e o custo energético). Ainda, a contribuição da pernada para a velocidade de nado aumentou com o aumento da frequência de braçadas (e da velocidade). Assim, ajustes individuais relativamente à contribuição da pernada devem ser considerados no cálculo da eficiência da braçada ao se nadar o nado *crawl* "completo" (usando braços e pernas). Por fim, os diferentes métodos fornecem valores de eficiência significativamente diferentes, embora haja concordância entre os mesmos. Portanto, valores de eficiência da braçada devem ser interpretados com cautela, considerando o método utilizado.

Palavras-chave: Eficiência de Froude, Eficiência propulsiva, Economia, Predição de desempenho.

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Presentation

This Ph.D. thesis, which main subject is the arm stroke efficiency in front crawl swimming, is the final document resulting from the doctoral studies conducted under a *co-tutela* agreement between the University of Verona and the Federal University of Rio Grande do Sul (Appendix 1). It has started in January 2012, in Verona, followed by a period in Porto Alegre, Brazil, and Porto, Portugal. The Ph.D. thesis defense is expected to take place at the Federal University of Rio Grande do Sul, in December 2016.

The data was obtained during the doctoral thesis period in three countries (Italy, Brazil and Portugal, in the latter, specifically at the University of Porto) and discussed in three original articles. Therefore, as described in the agreement, this document is in English and is organized in chapters in accordance to the papers, all of them related to the general topic of the Ph.D thesis.

Hence, after the introduction, with the general theme, the research problems and the main aims, three papers are presented:

Original article 1 - **The interplay between arms-only propelling efficiency, power output and speed in master swimmers**, published in 2014, in the European Journal of Applied Physiology; this paper was developed before the *co-tutela* agreement, only under the University of Verona's Doctoral Program subscription.

Original article 2 **- The effects of leg kick on the swimming speed and on arm stroke efficiency in front crawl**, published in 2016, in the Journal of Sports Performance and Physiology.

Original article 3 - **A biophysical analysis on the arm stroke efficiency in front crawl swimming: comparing methods and determining the main performance predictors,** to be submitted after the thesis defence.

In the end, a general conclusion is presented, with applications, limitations and suggestions regarding swimming efficiency, which is the main topic of the thesis.

This thesis was evaluated and approved by the UFRGS' Research Ethics Committee (Appendix 2).

General Introduction

Determining the efficiency (and the economy) of a movement is a primary goal for those interested in understanding, and possibly improving, human locomotion and/or athletic performance. This goal is particularly difficult to achieve in swimming where different "efficiencies" could be computed based on the partitioning of mechanical power output into its useful and non-useful components as well as because of the difficulties in measuring the forces that a swimmer can exert in the water.

The arm stroke (Froude) efficiency (η_F), for instance, represents the fraction of the external mechanical power ($\dot{W}_{ext}$) that is converted into useful propulsive power (power to overcome drag, $\dot{W}_d$) and has been reported as one of the main determinants of swimming performance.

Besides, there is quite a debate in the literature on which are the key determinants of maximal speed in swimming. Technique is one of them since it defines the capability of a swimmer to exert useful forces in water. However, also the "absolute" value of the power that a swimmer can exert (on land or in water) should play an important role in swimming performance. The relationship between the arm stroke efficiency, the power output and maximal swimming speed should thus depend on the population of swimmers observed (male and female swimmers, children and master athletes).

The total mechanical power of human locomotion ($\dot{W}_{tot}$) can be described as the sum of two terms: the internal power (the power needed to accelerate and decelerate the limbs with respect to the centre of mass, ($\dot{W}_{int}$) and the external power (the power needed to overcome external forces, ($\dot{W}_{ext}$):

$$\dot{W}_{tot} = \dot{W}_{ext} + \dot{W}_{int} \qquad (1)$$

Moreover, in aquatic locomotion, $\dot{W}_{ext}$ can be further partitioned into $\dot{W}_d$ and the power wasted to the water ($\dot{W}_k$). Both $\dot{W}_d$ and $\dot{W}_k$ give water kinetic energy but only $\dot{W}_d$ effectively contribute to propulsion (Alexander, 1983; Daniel, 1991).

$$\dot{W}_{ext} = \dot{W}_d + \dot{W}_k \qquad (2)$$

In this regard, Figure 1 shows the partitioning of total metabolic power into useful and non-useful mechanical components and the different efficiencies that can be calculated in swimming.

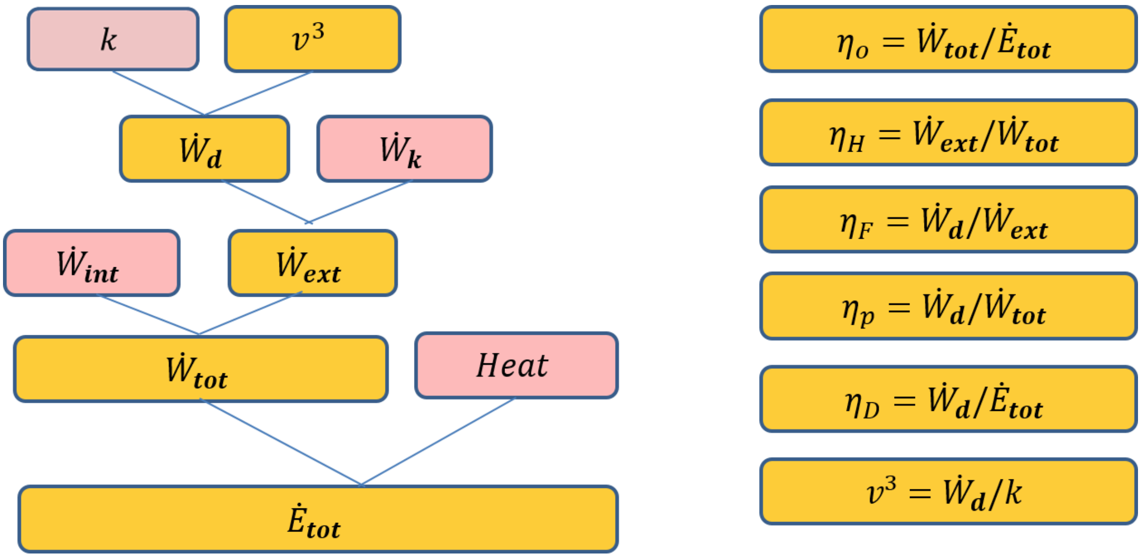

Figure 1. Cascade of fractionating energy expenditure rate into useful mechanical components (yellow) and not helpful (pink) in aquatic locomotion. $\dot{E}_{tot}$ is the total metabolic power, $\dot{W}_{tot}$ is the total mechanical power, $\dot{W}_{int}$ is the internal mechanical power, $\dot{W}_{ext}$ is the external mechanical power, $\dot{W}_d$ is the power needed to overcome drag, $\dot{W}_k$ is the power wasted to the water, k is the speed-specific drag, v is the average swimming speed, η_O is the overall efficiency, η_H is the hydraulic efficiency, η_F is the Froude efficiency, η_P is the propelling efficiency, and η_D is the drag efficiency.

As indicated in Figure 1, the arm stroke efficiency is the fraction of the $\dot{W}_{ext}$ that can be converted into $\dot{W}_d$; as such η_F is a parameter of pivotal importance in swimming. However, the assessment of $\dot{W}_{ext}$ and $\dot{W}_d$ is quite a challenge in the aquatic environment, the more so in a practical perspective (to be of any use for the swimmer and his/her coach). Indeed, kinetic measurements are scarce in swimming studies due to the difficulty of measuring forces in real swimming conditions; on the other hand, kinematic measurements are more largely utilized since they allow the evaluation of swimming actions with a more "ecological" approach.

Propulsion (Froude) efficiency can indeed be measured also from the ratio of the forward speed of the centre of mass to the average speed of the "trailing edge of the moving segments" (e. g. the hands and feet, for human swimming); this ratio represents the theoretical efficiency in all fluid machines (Fox and McDonald, 1992) as well as the theoretical (Froude) efficiency in those animals who swim using "rowing-like actions" (Alexander, 1983). This method could then be applied, and has been applied, to investigate the arm stroke efficiency in front crawl. As first reported by Martin et al. (1981), in a model describing the arm stroke propulsion in front crawl, assuming the forward speed of the centre of mass and the angular speed of the moving limbs around the shoulder are constant. This kinematical model of the arm stroke considers that drag and propulsive forces are equal for a given constant speed, hence η_F could be calculated based on the ratio of the forward speed and the tangential hand speed.

Another approach to the assessment of η_F in front crawl swimming has been reported by Toussaint et al. (1988), based on direct measures of metabolic power input ($\dot{E}_{tot}$) and $\dot{W}_d$ for a given constant speed. In this method, swimmers are first submitted to a condition in which no power is wasted in transferring kinetic energy to the water ($\dot{W}_k = 0$) by pushing-off underwater fixed pads distributed along the swimming pool using the Measure of Active Drag (MAD) System. In this condition, $\dot{W}_d$ and $\dot{W}_{ext}$ are assumed to be equal for a given constant speed. Then, considering the relationship between $\dot{E}_{tot}$ and $\dot{W}_{ext}$ obtained from the MAD System protocol, the $\dot{W}_{ext}$ could be estimated in free-swimming based on the $\dot{E}_{tot}$ for this condition. Hence, assuming $\dot{W}_d$ is the same in both conditions, for a given constant speed, the η_F could be calculated based on the ratio of the $\dot{W}_d$ and $\dot{W}_{ext}$.

Given the complexity of the methods previously reported in the literature, a third approach to the assessment of the η_F in front crawl was proposed by Zamparo et al. (2005) based on a simplified “paddle-wheel” paradigm, which is in fact an adaptation to the kinematical model proposed by Martin et al. (1981), considering only the underwater phases of the arm stroke. Moreover, the tangential hand speed is based on a theoretical moving limb represented by the shoulder-to-hand distance, considering the elbow angle at the end of the in-sweep phase of the arm stroke, instead of summing the lengths of the arm and forearm segments.

Despite the variety of methods described, only the kinematical models could be used in actual “full stroke” swimming condition, by considering the arm stroke and leg kick contributions to swimming speed. In fact, Zamparo et al. (2005) reported the arm stroke and leg kick η_F considering that the arm stroke contribution to swimming speed was 90%, and hence the contribution of the leg kick to swimming speed was 10%. However, it is not clear whether the contribution of the arm stroke and the leg kick are constant in a range of speeds.

Therefore, we hope to find answers to the following problems:

1. Which are the main determinants of maximal swimming speed in front crawl?
2. Does the contribution of arms and legs to the swimming speed change according to the swimming speed? Is it better to use individual values to adjust the calculation of arm stroke propelling efficiency in front crawl swimming?
3. How acurate are the methods described for assessing the arm stroke efficiency in front crawl? Do they agree with each other?
4. Which are the biophysical adaptations to swimming front crawl pushing-off fixed pads relatively to a free-swimming condition?

The specific aims of each study are:

Original article 1:

To investigate the interplay between the arm stroke efficiency and arm's power output in determining maximal speed in front crawl swimming.

Original article 2:

To individually estimate the leg kick contribution in front crawl at different self-selected speeds and compare: (a) the arm stroke efficiency calculated using individual adjustments to the leg kick contribution, (b) The arm stroke efficiency when swimming with the arms only, and (c) the arm stroke efficiency calculated assuming a contribution of 90% from the arms to the swimming speed.

Original article 3:

(a) to compare the power-based, speed-based and paddle-wheel methods to assess the arm stroke efficiency, when swimming front crawl using the arms only, on the MAD System and in a free-swimming condition;

(b) to compare the biophysical responses to free-swimming and MAD System conditions, in a range of paired speeds;

(c) to identify the main biophysical predictors of maximal swimming speed in 200 m front crawl using the arms only.

Original article 1 – The interplay between arms-only propelling efficiency, power output and speed in master swimmers

Running title: Efficiency, power, and maximal swimming speed

Abstract

Purpose: to explore the interplay between arms-only propelling efficiency (η_P), mechanical power output ($\dot{W}_{tot}$) and swimming speed (v); these three parameters are indeed related through the following equation $v^3 = 1/k \cdot \eta_P \cdot \dot{W}_{tot}$ (where k is the speed-specific drag; $k = F/v^2$); thus, the larger are η_P and $\dot{W}_{tot}$the larger is v. We furthermore wanted to test the hypothesis that a multiple linear regression between $\dot{W}_{tot}$, η_P and v would have a stronger correlation coefficient than a linear regression between $\dot{W}_{tot}$ and v alone. **Methods:** to this aim we recruited 29 master swimmers (21 M/8 F) who were asked to perform (1) an incremental protocol at the arm-ergometer (dry-land test) to determine $\dot{W}_{tot}$ at $\dot{V}O_{2max}$ (e.g. v_{max}); (2) a maximal 200 m swim trial (with a pull buoy: arms only) during which v and η_P were determined. **Results:** no relationship was found between W ˙ max and η_P (not necessarily the swimmers with the largest W ˙ max are those with the largest η_P and vice versa) whereas significant correlations were found between $\dot{W}_{max}$ and v (R = 0.419, P = 0.024) and η_P and v (R = 0.741, P = 0.001); a multiple linear regression indicates that about 75% of the variability of v can be explained by the variability of $\dot{W}_{max}$ and η_P (R = 0.865, P < 0.001). **Conclusions:** these findings indicate that η_P should be taken into consideration when the relationship between $\dot{W}_{max}$ and v is investigated and that this allows to better explain the inter-subject variability in performance (swimming speed).

Keywords

Front crawl, Swimming velocity, Swimming efficiency, Swimming power

The interplay between arms-only propelling efficiency, power output and speed in master swimmers

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Introduction

The mechanical power output ($\dot{W}_{tot}$) that can be produced to sustain locomotion (on land and in water) depends on the metabolic power input ($\dot{E}$ derived from aerobic or anaerobic energy sources) and on the overall efficiency of locomotion (η_O):

$$\eta_O = \dot{W}_{tot}/\dot{E} \qquad (1)$$

However, in water only a fraction of $\dot{W}_{tot}$ can be utilized to overcome resistive forces (hydrodynamic resistance, $\dot{W}_d$) since the swimmer has to produce additional power to give water kinetic energy not useful for propulsion (e.g. Alexander 1977; Daniel 1991). The fraction of $\dot{W}_{tot}$ that can be utilized, in water, to overcome hydrodynamic resistance is termed propelling efficiency (η_P):

$$\eta_P = \dot{W}_d / \dot{W}_{tot} \qquad (2)$$

$\dot{W}_d$ can be assessed based on values of drag force (F_d) and swimming speed ($\dot{W}_d = F_d \cdot v$); since, as a first approximation, F_d is proportional to the square of swimming speed:

$$F_d \approx k \cdot v^2 \qquad (3)$$

and:

$$\dot{W}_d \approx k \cdot v^3 \qquad (4)$$

By combining Eqs. 2 and 4 one obtains:

$$v^3 = 1/k \cdot \eta_p \cdot \dot{W}_{tot} \qquad (5)$$

Equation 5 defines the relationship among η_P, $\dot{W}_{tot}$ and k (speed-specific drag) at any given speed (v): it shows that the speed of locomotion, in the aquatic environment, will be larger when $\dot{W}_{tot}$ and η_P are higher and constant k is lower.

This theoretical background is useful to understand why swimming performance bears a closer relationship to the power developed during tethered and semi-tethered swimming than to the power measured using dry-land tests (e.g. Voronstov 2011). Indeed, in the former case (in water) the mechanical power output corresponds to the product $\eta_P \cdot \dot{W}_{tot}$. It represents the useful power that can be applied in water for propulsion (see Eq. 2) whereas, in the latter case (on land), the power corresponds to $\dot{W}_{tot}$: hence, in theory, η_P should also be measured and taken into account when considering the effects of mechanical power output on swimming speed.

Indeed, when dry-land tests are utilized to determine $\dot{W}_{tot}$ in a group of swimmers of similar anthropometric and technical characteristics, the variability of η_P (and k) can be expected to be low and hence a good (and significant) relationship between v and $\dot{W}_{tot}$ can be expected, otherwise the relationship between these two parameters can be expected to be weak or insignificant. As an example, Costill et al. (1986) reported a significant relationship between sprint speed (over a distance of 25 yards) and the mechanical power exerted in the water (R = 0.84, N = 76) but not with the mechanical power exerted during a dry-land test (R = 0.24, N = 76), both assessed during all out efforts lasting 12 s (e.g. the same duration of the swim test).

A further consideration that derives from this theoretical background is that the relationship between mechanical power and swimming performance has to be evaluated during tests of comparable duration (as in the study of Costill et al. 1986). Mechanical power output indeed decreases as a function of the duration of exercise (e.g. Wilkie 1980) and the time of exhaustion (during maximal all out efforts) determines the relative contribution of the aerobic and anaerobic energy sources to total energy expenditure (e.g. di Prampero 2003; di Prampero et al. 2011). This consideration can explain why a gradual reduction in the correlation between mechanical power output (assessed by means of dry-land test or semi-tethered swim test of few seconds duration) and v is observed over increasing swimming distances: the longer the distance (and thus the exercise time); the lower the correlation between these two parameters (e.g. Voronstov 2011; Sharp et al. 1982).

Moreover, whereas $\dot{W}_{tot}$ increases with the swimming speed, propelling efficiency decreases with it. Indeed, as indicated by Zamparo (2006), propelling efficiency is proportional to the distance covered per stroke and both tend to decrease at the high speeds attained in short course events; see, as an example, the curves relating speed and stroke frequency reported by Craig and Pendergast (1979). The slope of these curves represents the distance covered per stroke which is roughly constant at low to medium speeds but decreases sharply at maximal speeds. This means that the decrease in propelling efficiency counteracts the increase in $\dot{W}_{tot}$ when the speed increases (and vice-versa): thus, η_P acts as a confounding factor (when not taken into account) when the relationship between $\dot{W}_{tot}$ and v is investigated.

In the literature the relationship between upper body dry-land power (or semi-tethered swimming power) and swim velocity is mainly focused on sprint swimming (25–50 m, anaerobic energy sources) (e.g. Costill et al. 1986; Dominguez-Castelles et al. 2013; Swaine and Doyle 2000); however, the correlation between these two parameters ($\dot{W}_{tot}$ and v) should be significant also at slower speeds (e.g. over the 200–400 m distances where the aerobic energy sources are more relevant in determining mechanical power output) provided that all parameters of Eq. 5 are properly determined.

On the basis of these considerations, the main purpose of this study was to explore the interplay between arms only propelling efficiency (η_P), mechanical power output ($\dot{W}_{tot}$) and swimming speed (v) in a heterogeneous group of swimmers during a 200 m event. A further purpose of this study was to test the hypothesis that a multiple correlation between power output, η_P and v would have a stronger correlation coefficient than the simple correlation between power output and swimming speed.

To this aim we recruited male and female master swimmers with different technical and anthropometric characteristics, whom we asked to perform two tests:

Dry-land test: an incremental protocol at the arm-ergometer (arms only) to determine the mechanical power output at $\dot{V}O_{2max}$.

Swim test: a 200 m maximal test (with a pull buoy: arms only, as during the dry-land test) during which v and η_P were determined.

Material and methods

Participants

Twenty-nine master swimmers (21 male, 8 female) were recruited for this study; their principal anthropometric characteristics are reported in Table 1. Their technical level was quite heterogeneous as indicated by the large SD values in their years of swimming experience (see Table 1) but all subjects learned to swim at a young age (5–7 years), trained regularly and competed at local or national level. The purpose and objectives of the study were carefully explained to each individual and written informed consent was obtained. The study conformed to the standards set by the Declaration of Helsinki, and the local Institutional Review Board approved the procedures.

Table 1. Anthropometric characteristics of the swimmers and years of practice.

	Age (years)	Body mass (kg)	Stature (m)	BMI ($kg \cdot m^{-2}$)	Years of practice
M (21)	33.5±9.1	75.2±8.8	1.80±0.06	23.2±2.5	7.8±6.5
F (18)	28.5±8.6	57.8±4.2*	1.63±0.03*	21.6±1.3*	8.1±9.1
Range	20-50	52-99	157-197	18.4-29.5	1-30

Data are means ± 1SD

*Significant differences between M and F swimmers

Experimental procedures

Dry-land protocol (arms only)

Swimmers were requested to complete a maximal incremental test on a modified arm-crank-ergometer (Ergoline, Cosmed, I) (see Fischer et al. 2013). The protocol consisted of a 3-min warm up (unloaded) followed by incremental steps of 10 W/min (Male) or 5 W/min (Female) at a cadence of 60 rpm, until voluntary exhaustion. With this test, the maximal oxygen uptake ($\dot{V}O_{2max}$) and the corresponding mechanical power output were determined.

Before the beginning of the test the subjects were familiarised with the equipment and the procedures and their position on the ergometer was adjusted: the distance between the saddle and the crank was arranged to allow for full arm extension; the crank axis was positioned at the same height as the shoulders; the swimmers had to keep the back straight (un-supported) and to position their feet on the ground.

During these experiments, heart rate (HR), oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($V\dot{C}O_2$), minute ventilation ($\dot{V}E$) and respiratory exchange ratio (RER) were determined on a breath by breath basis by means of a previously calibrated metabolimeter (Quark b2, Cosmed, Italy). The values recorded during the last 30 s of the highest completed load were then computed (see Table 1). The highest completed mechanical load was then defined as $\dot{W}_{max}$.

Overall efficiency of arm-cranking (η_O) was calculated based on data of mechanical power ($\dot{W}$, W) and oxygen consumption ($\dot{V}O_2$, l·s^{-1}). The latter was expressed in W ($\dot{E}$, W) according to a formula which takes into account the respiratory exchange ratio:

$$\dot{E} = (4.94 \cdot RER + 16.04) \cdot \dot{V}O_2 \cdot 1{,}000.$$

Overall efficiency of arm-cranking was calculated from the slope of the individual $\dot{E}$ vs. $\dot{W}$ relationship based on the values assessed during the last 30 s of each load:

$$\dot{E} = a + b \cdot \dot{W}$$

where b (the slope) is the reciprocal of η_O. These calculations were performed by taking into account metabolic data for which RER ≤1 (for further details see Zamparo and Swaine 2012).

Swimming protocol (arms only)

The experiments were performed in a 25 m swimming pool. The subjects were asked to swim the 200 m at maximal speed while using a pull buoy (i e. propulsion was obtained by means of the upper limbs only); they were asked to start with a push off from the wall and were allowed to perform regular turning motions at the end of each length. The average speed was then calculated from the time taken to cover the 200 m distance and termed v_{200m}.

The actual speed maintained by the subjects during each length (v, m·s^{-1}) was measured from the time taken to cover the middle 10 m of each length, during which the average stroke frequency (SF, Hz) was also computed from the time taken to complete a given number of strokes. The distance covered per stroke (the stroke length, SL, m) was calculated by dividing the average speed by the corresponding stroke frequency. For all these parameters (v, SF and SL), the average value over the eight lengths of the pool was computed and used in further analysis.

The arm stroke efficiency (η_P) was calculated according to the simple model proposed by Zamparo et al. (2005). The model is based on the assumption that the arm is a rigid segment of length l, rotating at constant angular speed ($\omega = 2\,\pi \cdot SF$) about the shoulder and yields the average "Froude" efficiency for the underwater phase only, as follows:

$$\eta P = (v/(2\pi \cdot SF \cdot l))(2\,/\pi) \qquad (6)$$

where v is the swimmer's speed (in the central 10 m of each lane), SF is the stroke frequency and l is the average shoulder to hand distance (calculated as described below). Since, in this study, the swim test was conducted with the use of a pull buoy, the contribution of the legs to forward propulsion is assumed to be nil and thus no correction to the speed of progression is needed to take into account for this factor (see "Discussion" and Zamparo et al. 2005 for further details on this topic).

Video records were taken by means of an underwater camera (Sea-viewer, USA) positioned in a waterproof cylinder about 0.5 m below the water surface, frontally to the swimmer's direction. After the experiments, the data were downloaded to a PC and digitized using a commercial software package (Twin Pro, SIMI, g). The elbow angle (EA) was measured at the end of the in-sweep (when the plane of the arm and forearm is perpendicular to the camera) for both sides (right and left arm) and for different arm cycles. Three to eight values of elbow angle were recorded for each subject every other lane; no differences were observed in EA as measured on the left and right side nor as a function of the distance covered: the average subject's elbow angle was then computed, on the basis of which the shoulder to hand distance (l, m) was calculated (see Zamparo et al. 2005).

Statistical analysis

Mean ± 1 SD values are reported. Linear regression analyses were applied to investigate the relationship among the investigated parameters. A multiple linear regression analysis was applied to investigate the relationship between $\dot{W}_{max}$, η_P and v_{200m}. Statistical analysis was carried out by using a statistical package (SigmaPlot 11.0, US). The level of significance was set at P ≤ 0.05. A simple t test was applied to test for differences between male and female swimmers in the investigated parameters.

Results

Data collected during the dry-land protocol are reported in Table 2. Maximal oxygen uptake was larger in male than in female swimmers ($\dot{V}O_{2max}$ = 33 and 27 ml·min^{-1}·kg^{-1} in male and female swimmers, respectively) and the corresponding maximal mechanical power ($\dot{W}_{max}$) was of 136 and 78 W (in male and female, respectively). The overall efficiency of arm-cranking was similar in the two groups of swimmers (about 0.20).

Table 2. The parameters collected during the “dry-land” protocol.

	$\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1})	HR_{max} (bpm)	$\dot{V}E_{max}$ (l·min^{-1})	$\dot{W}_{max}$ (W)	RER_{max}	η_O
Male	33.1 ± 4.6	172 ± 10	112.7 ± 21.6	135.8 ± 24.8	1.16 ± 0.07	0.21 ± 0.02
Female	27.2 ± 4.2[a]	165 ± 14[a]	69.6 ± 15.2[a]	78.7 ± 14.3[a]	1.10 ± 0.05	0.20 ± 0.02
Range	19.6 – 39.9	145 – 187	35.8 – 157.5	55 – 180	1.0 – 1.3	0.16 ± 0.25

Data are means ± SD

$\dot{V}O_{2max}$: maximal oxygen uptake; HR_{max}: heart rate at $\dot{V}O_{2max}$; $\dot{V}E_{max}$: expired ventilation at $\dot{V}O_{2max}$; $\dot{W}_{max}$: mechanical power output at $\dot{V}O_{2max}$; RER_{max}: respiratory exchange ratio at $\dot{V}O_{2max}$; η_O: overall mechanical efficiency.

[a] Significant differences between male and female swimmers.

Data collected during the swimming protocol are reported in Table 3. The duration of this test was of about 3–3.5 min, thus the exercise was sustained based mainly on aerobic energy sources (see “Discussion”). Stroke frequency (SF = 0.60 Hz in male and

0.58 Hz in female swimmers) and propelling efficiency (0.30 in male and 0.31 in female swimmers) were similar in the two groups and no significant differences were observed in the other parameters (with the exception of the shoulder to hand distance, l, that was found to be larger in male than in female swimmers).

Table 3. The parameters collected during the "swimming" protocol (a 200 m simulated race, with pull buoy, in a 25 m swimming pool).

	Male (n=21)	Female (n=8)	Range
$\boldsymbol{T_{200m}}$ (s)	187.8 ± 32.7	204 ± 24.9	134.5 – 252.2
$\boldsymbol{v_{200m}}$ (m·s^{-1})	1.10 ± 0.19	0.99 ± 0.14	0.79 – 1.49
$\boldsymbol{v}$ (m·s^{-1})	1.03 ± 0.17	0.94 ± 0.14	0.73 – 1.37
$\boldsymbol{SF}$ (Hz)	0.60 ± 0.07	0.58 ± 0.05	0.48 – 0.70
$\boldsymbol{SL}$ (m)	1.72 ± 0.29	1.62 ± 0.17	1.26 – 2.38
$\boldsymbol{EA}$ (deg)	125 ± 11	130 ± 13	101 – 152
$\boldsymbol{l}$ (m)	0.59 ± 0.04	0.53 ± 0.03	0.48 – 0.65
$\boldsymbol{\eta_P}$	0.30 ± 0.05	0.31 ± 0.03	0.24 – 0.42

Data are mean ± SD.

Time needed to cover the 200 m distance (T_{200m}), and corresponding speed (v_{200m}). Average values of speed (v), stroke frequency (SF), stroke length (SL), elbow angle (EA), shoulder to hand distance (l) and propelling efficiency (η_P) in the 8 lengths.

[a] Significant differences between male and female swimmers.

In Figure 2 the average values of speed (v, a), stroke frequency (SF, b) and stroke length (SL, c) are reported for each of the eight lengths of the pool during the simulated 200 m race (data refer to both male and female swimmers). These figures show that average speed was larger in the first length (due to the push off from the wall), that SF was maintained constant during the race while SL tended to decrease, due to fatigue, in the last lengths. The changes in SL mirror the changes in propelling efficiency (not shown in figure). The relationship between SL and η_P is indeed rather good: $\eta_P = 0.151 \cdot SL + 0.045$, n= 232, R = 0.899, P < 0.001 (e.g. about 80 % of the variability of η_P could be explained by the variability of SL).

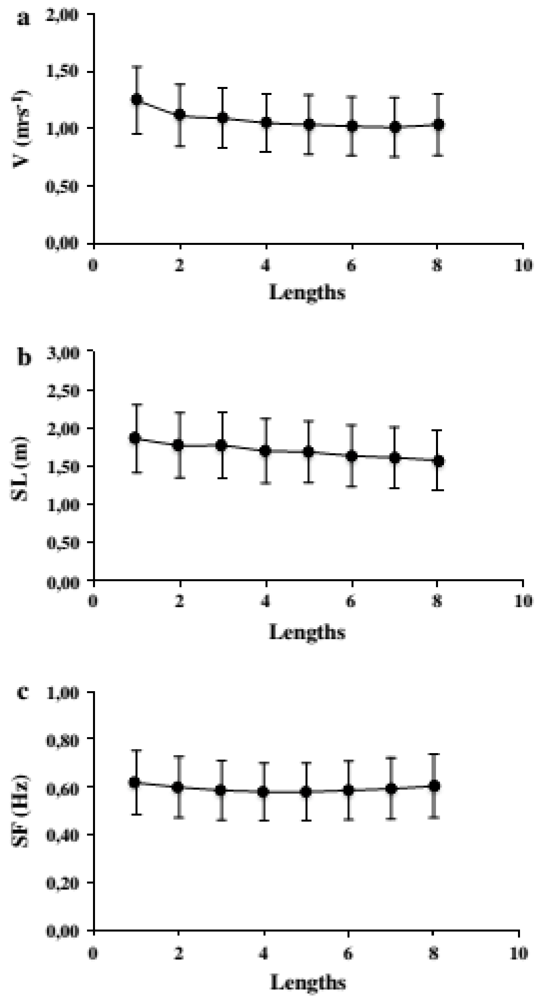

Figure 2. Average values of speed (a), stroke frequency (b) and stroke length (c) as measured in the 8 lengths during the simulated 200 m race (arms only) in a 25 m pool. Data are mean ± 1SD and refer to both male and female swimmers.

To analyse the relationships between $\dot{W}_{max}$, η_P and v_{200m} the data of male and female swimmers were pooled together (N = 29). Figure 3 reports the relationship between maximal power output (dry-land arms only, W) and the swimming speed (arms only) during the 200 m maximal trial (v_{200m}, m·s^{-1}); this relationship is well described by the following equation: $v_{200m} = 0.802 + 0.002 \cdot \dot{W}_{max}$, N = 29, R = 0.419, P = 0.024. This indicates that the higher the maximal power output the faster is the swimming speed.

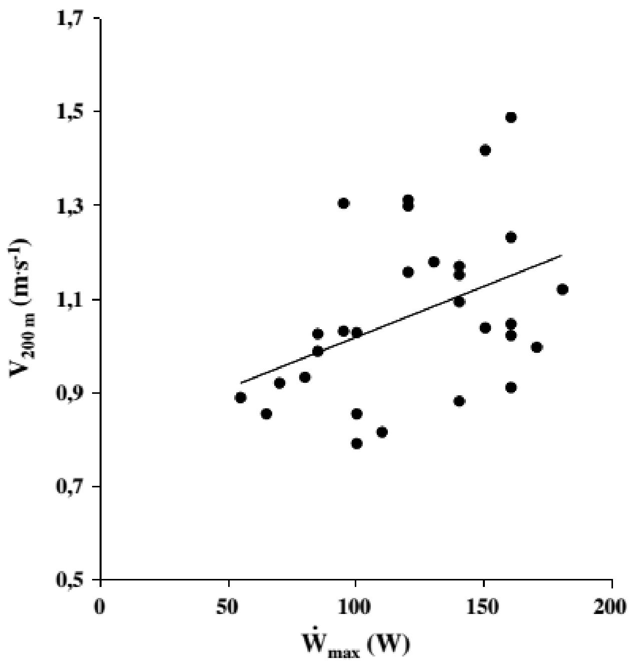

Figure 3. the relationship between maximal power output ($\dot{W}_{max}$, dry-land test, W) and swimming speed during the 200 m maximal trial (v_{200m}, $m \cdot s^{-1}$): about 17 % of the variability of v_{200m} can be explained by the variability of $\dot{W}_{max}$ (R = 0.419, P = 0.024).

Figure 4 reports the relationship between propelling efficiency and swimming speed during the 200 m maximal trial; this relationship is well described by the following equation: $v_{200m} = 0.162 + 3.00 \cdot \eta_P$, N = 29, R = 0.741, P < 0.001. This indicates that the higher the propelling efficiency the fastest is the swimming speed.

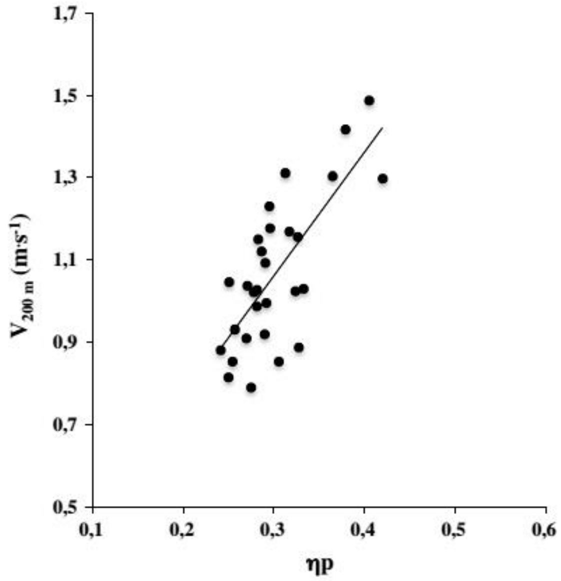

Figure 4. The relationship between propelling efficiency (η_P) and swimming speed during the 200 m maximal trial (v_{200m}, m·s^{-1}) about 55 % of the variability of v_{200m} can be explained by the variability of η_P (R = 0.741, P<0.001).

No relationship was found between maximal power output and propelling efficiency during the swimming test (N = 29, R = 0.035, nS): not necessarily the swimmers with the highest power output are those with the higher propelling efficiency and vice-versa.

A multiple linear regression, taking into account all three parameters, indicates that about 75 % of the variability of v_{200m} can be explained by the variability of $\dot{W}_{max}$ and η_P: $v_{200m} = -0.140 + 3.066 \cdot \eta_P + 0.002 \cdot \dot{W}_{max}$, N = 29, R = 0.865, P < 0.001. This indicates that, as expected, both η_P and $\dot{W}_{max}$ are important factors in determining maximal speed in swimming events (P < 0.001 in both cases). This relationship is reported in Figure 5.

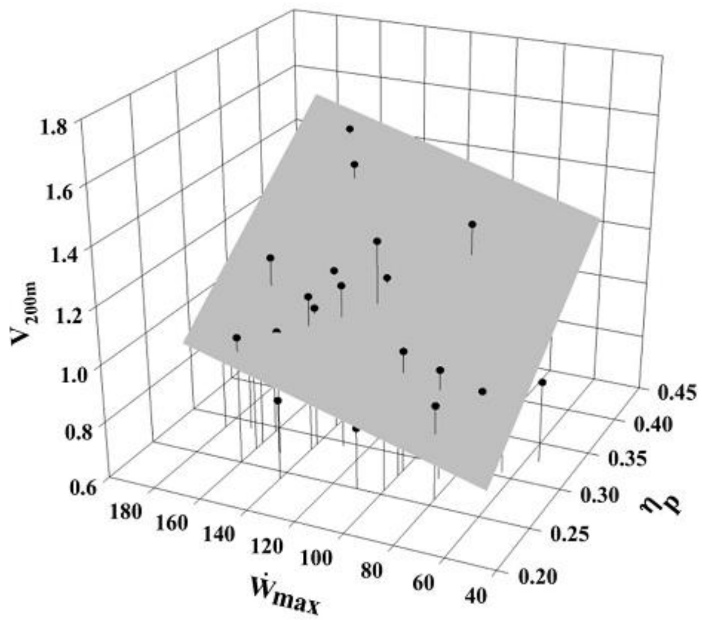

Figure 5. The multiple linear regression between maximal power output ($\dot{W}_{max}$, dry-land test, W), propelling efficiency (η_P) and swimming speed during the 200 m maximal trial (v_{200m}, m·s^{-1}): about 75 % of the variability of v_{200m} can be explained by the variability of $\dot{W}_{max}$ and η_P (R = 0.865, P < 0.001).

When this analysis is applied to the data of male and female swimmers separately, the relationship between $\dot{W}_{max}$, η_P and $\mathrm{v}_{200\mathrm{m}}$ is essentially the same (male swimmers: $\mathrm{v}_{200\mathrm{m}} = -0.120 + 3.175 \cdot \eta_P + 0.002 \cdot \dot{W}_{max}$, N = 21, R = 0.866, P<0.001; female swimmers: $\mathrm{v}_{200\mathrm{m}} = -0.123 + 2.039 \cdot \eta_P + 0.006 \cdot \dot{W}_{max}$, N = 8, R = 0.896, P = 0.017).

By applying Equation 5, the coefficients of the multiple regression change but the R value and the level of significance remain about the same: $v^3{}_{200m} = -3.411 + 12.328 \cdot \eta_P + 0.008 \cdot \dot{W}_{max}$, N = 29, R = 0.877, P<0.001. When the mechanical power is normalized per kg of body mass, the correlation coefficient of the multiple regression is even larger (R = 0.893: about 80% of the variability of $v^3{}_{200m}$ can be explained by the variability of $\dot{W}_{max}$).

Discussion

Data reported in this study indicate that maximal speed in swimming is dependent not only on maximal power output (assessed in dry-land conditions) but also on propelling efficiency, as it can be hypothesized on theoretical grounds. We thus confirmed our hypothesis that a multiple correlation between $\dot{W}_{tot}$, η_P and v^3 would have a larger correlation coefficient than the simple correlation between $\dot{W}_{tot}$, and v.

Theoretically, the relationship between $\dot{W}_{tot}$, η_P and v, described by Equation 5, should have a correlation coefficient = 1. Why this is not the case can be attributed to sources of variability derived from the methods adopted in this study to determine the parameters of Equation 5, these will be therefore discussed in detail.

Energy sources and swimming speed

The contribution of the aerobic and anaerobic energy sources to total metabolic energy expenditure differs widely according to the distance covered (or more correctly, as a function of the exercise duration): in the front crawl the world records range from about 20 s (50 m, anaerobic energy sources) to about 15 min (1,500 m, aerobic energy sources). The 400 m distance, that is swum in about 4 min (in front crawl elite swimmers), is generally taken as the competition eliciting the $\dot{V}O_{2max}$ of the swimmer. Indeed, competitions over longer distances (longer race times) are swum at a fraction of $\dot{V}O_{2max}$ which is smaller the longer the exercise duration. Competitions over shorter distances (shorter race times) relay also on anaerobic (lactic and alactic) energy sources.

As indicated by di Prampero (2003) and di Prampero et al. (2011), for swim races lasting 200–300 s, about 80% of the energy requirements are derived from aerobic energy sources. The simulated 200 m race in this study lasted, in average, 188 s for male swimmers, and 204 s for female swimmers, and thus was indeed mainly sustained by aerobic metabolism. However, about 20% of the energy requirements in this condition are not aerobic and this could represent a source of variability. We selected the 200 m distance (and not the 400 m one) because the swimmers had to use a pull buoy and therefore we expected that a simulated race over the 400 m distance would have been too demanding especially for those with lower technical capacities and lower swimming experience. If we had to perform these experiments with elite male swimmers (without pull buoy and without the constrains of this study) we would certainly have selected the 400 m distance instead. The values of speed reported in this study (v_{200m}) range from 0.79 to 1.49 m·s^{-1}, and indicate a large variability in our sample. This was not only expected but intentional since we wanted to investigate a heterogeneous group of swimmers to better characterize the relationship between $\dot{W}_{max}$ and v.

Maximal mechanical power in land and in water

The values of $\dot{W}_{max}$ were assessed by means of a simple arm-crank ergometer. As discussed by Zamparo and Swaine (2012) there are obvious limitations to exact simulation of the swimming stroke within the laboratory and this kind of ergometer is open to criticism because it does not allow an exact replication of the swimming actions. In spite of these limitations, laboratory-based swimming ergometry has been widely used to study the physiological responses to swimming exercise and to investigate the role that muscle power has in front-crawl swimming performance (e.g. Johnson et al. 1993; Sharp et al. 1982; Swaine 1994; Takahashi et al. 1992). Points in favour of this choice are that arm-ergometers similar to that utilized in this study are of common use and simple to utilize so that these experiments can be easily replicated.

A source of variability in the determination of $\dot{W}_{max}$ can also be attributed to the fact that, in some cases, the test was terminated because of local fatigue and not because the swimmers reached their actual maximal mechanical output. Indeed, for some swimmers (especially male swimmers with large power output) the duration of the protocol was too long due to the relatively slow rate of the increments in power output (10 W/min in male and 5 W/min in female swimmers). In spite of this limitation we preferred to maintain the same protocol for all subjects. If we had to perform these experiments with a homogeneous group of elite male swimmers we would certainly have selected a different protocol (e.g. with increments of 50 W/min, as proposed by Zamparo and Swaine 2012).

As measured, $\dot{W}_{max}$ represents the external mechanical power output of the upper limbs. As indicated by Cavagna and Kaneko (1977) the total mechanical power of locomotion ($\dot{W}_{tot}$) is the sum of two terms: the power needed to accelerate and decelerate the limbs with respect to the centre of mass (the internal power, $\dot{W}_{int}$) and the power needed to overcome external forces (the external power, $\dot{W}_{ext}$). As reported by Zamparo et al. (2005), $\dot{W}_{int}$ can be estimated based on values of stroke frequency ($\dot{W}_{int} = 38.2 \cdot SF^3$). SF in the 200 m swim test was of about 0.6 Hz, i e. lower than that adopted in the incremental test: 60 rpm = 1 Hz. We can thus expect differences in $\dot{W}_{tot}$ in the two conditions since $\dot{W}_{int}$ amounts to 8 W in the incremental test and to 38 W in the swim test; this could be considered another source of variability: when the maximal power output that can be exerted in water is calculated based on data collected on land the movement frequency should be matched, as much as possible.

The values of $\dot{W}_{max}$ reported in this study range from 55 to 180 W (0.96 – 2.28 $W \cdot kg^{-1}$), and indicate a large variability in our sample. This was not only expected but intentional since we wanted to investigate a heterogeneous group of swimmers to better characterize the relationship between $\dot{W}_{max}$ and v. In their upper range these values are comparable to those reported in the literature for elite male swimmers (175–180 W of external power for the upper limbs) and obtained with a similar protocol (e.g. Zamparo and Swaine 2012). As indicated in “results”, when the values of $\dot{W}_{max}$ are expressed per kg of body mass (to reduce the inter-subject variability) the relationship between $\dot{W}_{max}$, η_P and v^3 reach a correlation coefficient of 0.893.

In this study, we assessed the dry-land power of arms only and, therefore, we had to ask our swimmers to perform the swim test with arms-only (and this is clearly a limitation). A more complete approach would have been to utilize a whole-body swimming ergometer, such as that described by Zamparo and Swaine (2012) to take into account also the contribution of the legs. In spite of this limitation (and in spite of work already involving a whole-body ergometer) we do think that these findings can add to our understanding of the factors that contribute to swimming speed, as indicated in the "general Discussion".

Overall and propelling efficiency

The values of overall efficiency (η_O) reported in this study (range: 0.16–0.25) are comparable with those recently reported by Zamparo and Swaine (2012) by utilizing a whole-body dry-land swimming ergometer (about 0.23) and by taking into consideration the external work component of $\dot{W}_{tot}$ only, as is the case of this study. This finding is rather important since, as discussed in detail by these authors, values of 0.20–0.25 should be expected for simulated swimming in dry-land conditions as well as in actual swimming conditions. This further underlines that the low values of overall (gross) swimming efficiency reported so far in some swimming studies have to be attributed to an incomplete computation of all work components/energy losses (for a discussion on this point see Zamparo and Swaine 2012).

The efficiency calculated by means of Equation 6 is, properly speaking, the Froude (theoretical) efficiency of the arm stroke; however, Froude efficiency and propelling efficiency in the arm stroke (front crawl) are essentially the same since the internal work is negligible (about 8 W in this study, as indicated above). The difference between these two parameters is, indeed, that Froude efficiency does not take into account this component of $\dot{W}_{tot}$ whereas propelling efficiency does (for a discussion on this point see Zamparo et al. 2005).

The model utilized in this study estimates the efficiency of the arm stroke (η_P) from the ratio of forward speed (v) to hand speed ($2\pi \cdot SF \cdot l$), since this ratio represents the theoretical efficiency of all hydraulic machines (Fox and McDonald 1992). In the equation proposed by Zamparo et al. (2005), for the front crawl, a correction for the speed value is proposed to take into account that speed is sustained also by the lower limbs propulsion. In this study, however, the subjects were asked to swim with a pull buoy and thus this correction was not necessary. In this way, we have reduced a possible source of variability deriving from inter-subject differences in leg propulsion/efficiency. In a recent study, by Figueiredo et al. (2011), it was shown that the values calculated by means of this model and those obtained by measuring the body center of mass speed and the 3D hand speed (by means of underwater kinematic analysis) are comparable (not statistically different) thus confirming the validity of this simple model to estimate η_P in front crawl swimming. Finally, the validity of this model in estimating propelling efficiency was demonstrated and discussed in detail by Zamparo and Swaine (2012).

The values of propelling efficiency reported in this study range from 0.24 to 0.42; in their upper range are thus comparable to those reported in the literature for elite male swimmers: 0.40–0.45 (Zamparo et al. 2005; Figueiredo et al. 2011) the large variability in the η_P values was expected (we intentionally recruited for this study a heterogeneous group of swimmers) for similar reasons to those already discussed, since we wanted to demonstrate that the differences in this parameter do indeed allow us to explain why the relationship between $\dot{W}_{max}$ and v can be significant in some cases and not in others. As an example, it could be expected that in a more homogeneous group of swimmers (with similar values of η_P) the relationship between $\dot{W}_{max}$ and v would have a larger correlation coefficient than the relationship between η_P and v (i.e. the contrary of what was found in this study).

The product of overall efficiency and propelling efficiency is the drag efficiency ($\eta_D = \eta_P \cdot \eta_O$), i.e. the efficiency with which the metabolic power input is transformed into useful power output (the power to overcome hydrodynamic resistance: $\eta_D = \dot{W}_d/\dot{E}_{tot}$). Thereby, the calculated values of drag efficiency range from 0.04 to 0.08 and are comparable to those reported in the literature and calculated based on values of active drag (for a discussion on this point see di Prampero et al. 2011; Zamparo et al. 2005; Zamparo and Swaine 2012).

As indicated in "results" the relationship between SL and η_P has a large correlation coefficient (R = 0.899, N = 232, P<0.001). This equation can thus be utilized to estimate propelling efficiency based on simple measures of SL.

Speed-specific drag and the validity of Equation 5

Equation 5 indicates that another parameter influences performance in swimming and this is the speed-specific drag (k). This parameter was not considered in this study and this is the last, but not least, source of variability (see "general discussion" below). However, based on Equation 5, k can be estimated and this calculation could give useful information on the validity of the equation itself: were the values of v_{200m}, $\dot{W}_{max}$ and η_P reported in this study correctly measured/estimated we should expect also "reasonable" values of k (i e. in the range of those reported in the literature). Based on the values of v, $\dot{W}_{max}$ and η_P (independently measured/estimated), k was calculated for each swimmer and found to amount to 25 ± 4 for female swimmers and to 34 ± 12 for male swimmers. The large SD has to be attributed, rather than to inter-individual differences, to the sources of variability discussed above (i e. we do not suggest to apply this method to estimate drag in swimming). The average values of k are indeed in the range of those reported in the literature and support, albeit indirectly, the calculations proposed in this study (e.g.

the validity of Equation 5). As an example, Zamparo et al. (2009) report data of k = 23 and 19 (male and female swimmers, respectively) for passive drag and k = 43 e 34 (male and female, respectively) for active drag. Albeit indirectly, this finding supports also the assumption made in the Introduction that $F \approx k \cdot v^2$.

General discussion

Our findings are relevant since, even if it is generally acknowledged that improving η_P and $\dot{W}_{max}$ is useful to improve performance in swimming, no studies have been conducted so far to investigate the interplay among these three factors. To our knowledge, the only other paper that attempted to investigate this topic is that of Shimonagata et al. (1999). These authors investigated the relationship between "maximum propulsion" (P_O, the maximal force exerted during tethered swimming), "active drag" (D_a, estimated by means of a semi-tethered swimming protocol) and maximal speed (attained during a semi-tethered swimming protocol). They found that v is significantly correlated with P_O and D_a (multiple regression analysis: R = 0.84, P = 0.01) but that no significant relationship can be found between P_O and v or between D_a and v alone. Even if they utilized values of force (and not of power output, as indicated by Equation 5) and even if the methods they utilized for computing P_O and D_a can be matter of discussion, their conclusions are in line with the theoretical analysis proposed in this study (Equation 5): swimming speed is faster as P_O is higher and D_a is lower.

Data reported in this paper allow greater comprehension of swimming performance (as well as of aquatic locomotion, in more general terms) since they show that the parameters entering Equation 5 should be taken into consideration together. Indeed, even if this is theoretically known, no studies have attempted so far to consider propelling efficiency when investigating the relationship between (dry-land) mechanical power output and swimming speed. Further studies should assess the effect of leg kicking on the parameters of Equation 5 (e.g. by using a whole-body swimming ergometer) and these experiments could be replicated in different conditions (with the appropriate combination of $\dot{W}_{max}$, η_P and v values). Finally, even if, in this study, we did not investigate the relationship between $\dot{W}_{max}$, η_P and v in elite swimmers (as already discussed, this was because we decided to investigate this relationship in an heterogeneous group of swimmers), we can draw general conclusions out of this study.

Indeed, Figure 5 can be utilized to identify swimmers in respect to their swimming abilities: the upper corner of the 3D plane identifies male, good level, swimmers with high values of v, $\dot{W}_{max}$ and η_P, while the right corner identifies female, good level, swimmers with high values of η_P but with lower values of $\dot{W}_{max}$ (and hence of v) in respect to their male counterparts; the left corner identifies swimmers with high values of $\dot{W}_{max}$ but with low technical skills (low values of η_P, and hence of v). Hence, coaches should help swimmers to move up in this plane: indeed, v will increase both by increasing $\dot{W}_{max}$ (strength training) and/or by increasing η_P (improving technical skills by means of specific training in water). As a consequence, detraining will imply a move down on this plane since the bottom corner identifies swimmers with the lowest values of $\dot{W}_{max}$, η_P and v. As an example, in this position we can find older master swimmers since both $\dot{W}_{max}$ and η_P tend to decrease with age (e.g. Zamparo et al. 2012) but also pre-pubertal swimmers (characterized by low values of $\dot{W}_{max}$ and η_P) (e.g. Zamparo et al. 2008).

Conclusions

In conclusion, a multiple linear relationship that takes into account dry-land arms-only mechanical power output and propelling efficiency better explains swimming speed than the previously established relationship between power output (dry-land) and speed alone. Furthermore, data reported in this study explain why different results were obtained so far when investigating the relationship between dry-land $\dot{W}_{max}$ and v or between $\dot{W}_{max}$ (assessed in water) and v: in previous studies, when $\dot{W}_{max}$ was assessed by means of dryland protocols, the contribution of η_P was not accounted for. These findings further underline that $\dot{W}_{max}$ and η_P (as well as k, and hence hydrodynamic resistance) should be the focus of any intervention aimed to improve performance in swimming. Unfortunately, Equation 5 can only be applied to the front crawl because no data are reported in the literature about the propelling efficiency in the other strokes. Further studies are needed to understand (besides arms propulsion) the role of leg propulsion and hydrodynamic resistance in determining v in the framework of Equation 5.

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Original article 2 - The effects of leg kick on the swimming speed and on arm stroke efficiency in front crawl

Running title: Leg kick contribution and arm stroke efficiency

Abstract

Purpose: to analyze the effects of swimming pace on the relative contribution of leg kick to swimming speed, and to compare arm stroke efficiency (η_F) assessed when swimming with the arms only (SAO) and while swimming front crawl (FCS) using individual and fixed adjustments to arm stroke and leg kick contribution to forward speed. **Methods:** twenty-nine master swimmers (21 males, 8 females) performed SAO and FCS at six self-selected speeds from very slow to maximal speed. The average swimming speed (v), stroke frequency (SF), stroke length (SL) were assessed in the central 10 m of the swimming pool. Then, a second-order polynomial regression was used to obtain values of v at paired SF. The percentage difference in v between FCS and SAO, for each paired SF, was used to calculate the relative contributions of the arm stroke (AC) and leg kick (LC) to FCS. Then η_F was calculated using the indirect "paddle-wheel" approach in three different ways: using general, individual, and no adjustments to AC. **Results:** the LC increased with SF (and speed) from -1±4% to 11±1% (p<0.05). At the lower FCS speeds, η_F calculated using general adjustments was lower than η_F calculated using individual adjustments (p<0.05) but differences disappear at the fastest speeds. Last but not least, η_F calculated using individual adjustments to the leg kick contribution in the FCS condition did not differ with η_F assessed in the SAO condition at all the investigated speeds. **Conclusions:** the relative contributions of the arm stroke and leg kick should be individually estimated to reduce errors when calculating arm stroke efficiency at different speeds and different swimmers.

Key-words:

Arm stroke efficiency, Froude efficiency, upper limbs contribution, lower limbs contribution

The effects of leg kick on the swimming speed and on arm stroke efficiency in front crawl

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Introduction

The efficiency with which an energetic input is converted into mechanical output has been reported as a measure of performance either in animal (Alexander & Goldspink, 1977) or human locomotion (Cavagna & Kanelo, 1977). In this regard, the fraction of the total metabolic power ($\dot{E}_{tot}$) converted into total mechanical power ($\dot{W}_{tot}$) is defined as overall or mechanical efficiency (η_o). In aquatic locomotion, $\dot{W}_{tot}$ is composed by useful and non-useful components, yielding to a cascade of efficiencies, such as the hydraulic efficiency, the Froude efficiency, the propelling efficiency, the drag or performance efficiency (Zamparo et al., 2002), as described in Figure 6.

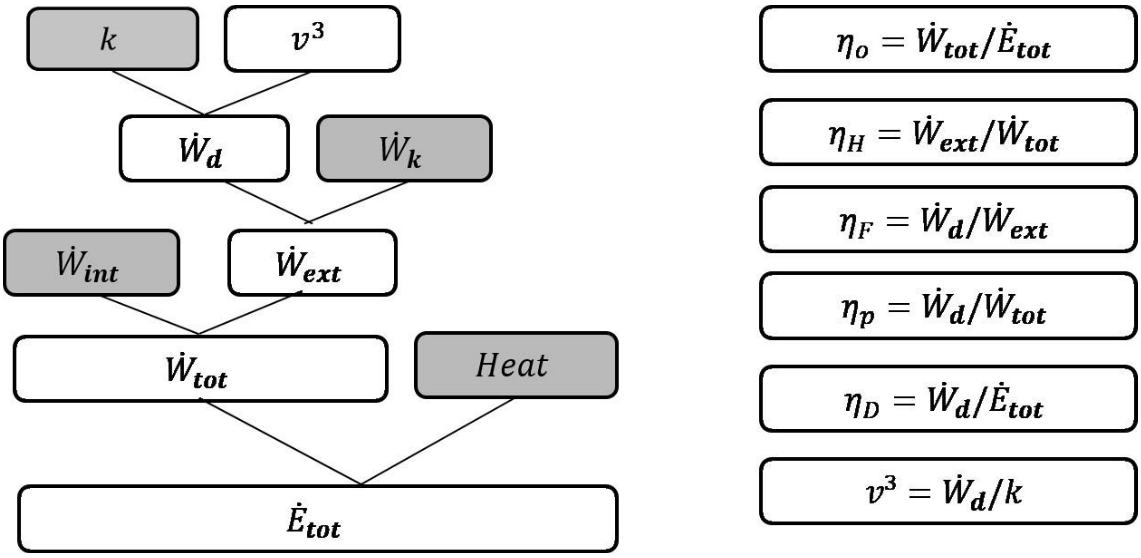

Figure 6. Useful and non-useful components of the cascade of efficiencies. η_o: overall efficiency; η_H: hydraulic efficiency; η_F: Froude efficiency; η_P: propelling efficiency; η_D: drag efficiency; $\dot{E}_{tot}$: total metabolic power input; $\dot{W}_{tot}$: total mechanical power output; $\dot{W}_{int}$: internal mechanical power; $\dot{W}_{ext}$: external mechanical power; $\dot{W}_d$: power needed to overcome drag (useful propulsive power); $\dot{W}_k$: power that does not contribute to generate propulsion; k: speed-specific drag coefficient; v: swimming speed.

While Froude efficiency is defined as the fraction of the external mechanical power ($\dot{W}_{ext}$) converted into useful propulsive power ($\dot{W}_d$, the power needed to overcome drag force), propelling efficiency is defined as the fraction of $\dot{W}_{tot}$ converted into $\dot{W}_d$. The difference between these two parameters is thus that the latter takes into account the internal mechanical power needed to move the limbs with respect to the center of mass ($\dot{W}_{int}$) while the former does not (see Figure 6). Since $\dot{W}_{int}$ is seldom measured/estimated/taken into account in swimming literature, the majority of the data reported on this topic are indeed data of “Froude efficiency”, even if they are often referred to as “propelling efficiency” values. As shown by Zamparo et al.(2005), $\dot{W}_{int}$ is negligible in the arm stroke of front crawl swimming and, therefore, in this specific condition: $\eta_P \approx \eta_F$. In this paper, we will define this parameter, in more general terms, as “arm stroke efficiency”. Based on the literature on this topic, arm stroke efficiency is inversely related to the energy cost of swimming (Pendergast, Zamparo & di Prampero, 2003) and it is one of the main determinants of performance (Zamparo et al., 2005; Zamparo et al., 2014). Although difficult ways to assess this parameter are described in the literature (Toussaint et al., 1988), an indirect and coach-friendly way has been largely used due to its applicability, both in training routine and research (Zamparo et al., 2005; Zamparo et al., 2008; Figueiredo et al., 2011).

To our knowledge, only two approaches considered the relative contribution of arms and legs when calculating arm stroke efficiency in whole-body front crawl swimming: the indirect “paddle-wheel” model (Zamparo et al., 2005) based on values reported in previous studies in which a contribution of 90% from the arms to propulsion (and 10% from legs) is suggested (Hollander et al., 1988; Deschodt, Arsac & Rouard, 1999), and the method described by Gourgoulis et al.(2014), based on indirect assessments of effective and resultant forces, in which the contribution of arms (~87%) and legs (~13%) were individually assessed to avoid an overestimation of efficiency in full stroke swimming. Although these values are supported in the literature for front crawl sprinting (Gourgoulis et al., 2014; Bucher, 1975), higher relative contribution of the leg kick (~31%) in a fully tethered swimming protocol have been reported (Morouço et al., 2015). During 200-m trials at low, moderate and high stroke frequencies, values of ~11% were found (Morris et al., 2016). However, a larger range of speeds should be considered to individually estimate arm stroke and leg kick contributions.

Thus, considering these conflicting results and the lack of information regarding the effects of individual estimation of arm stroke and leg kick contribution on the assessment of arm stroke efficiency, the aims of the present study were to analyze the effects of speed on the relative contribution of leg kick to whole-body front crawl swimming and to compare the arm stroke efficiency assessed when swimming with the arms only and while swimming front crawl using individualized and fixed adjustments to the leg kick contribution to the swimming speed. We hypotezised that relative contribution of leg kick increases with swimming speed and, therefore, the assessment of arm stroke efficiency should consider individual adjustments to leg kick contribution.

Material and Methods

Participants

Twenty-nine master swimmers (21 males, 8 females) were recruited for this study (age: 32.3 ± 9.3 years; body mass: 69.4 ± 9.0 kg; height: 174.9 ± 8.2 cm). To test the hypothesis that leg kick contribution responds individually to swimming speed, men and women were intentionally collapsed into one heterogeneous group. The purpose and the aims of the study were carefully explained to each individual and written informed consent was obtained. The study conformed to the standards set by the Declaration of Helsinki, and the local Institutional Review Board approved the procedures.

Experimental procedure

Swimmers performed 25-m using the front crawl stroke (FCS) and the front crawl stroke while swimming with the arms only (SAO), in a randomized order, at six incremental self-selected speeds, from very slow ($V1$) to maximal speed ($V6$), resting at least 3 minutes between trials. The experiments were conducted in a 25-m indoor swimming pool and all parameters were assessed in the central 10-m to avoid the influence of the push-off start and finish. The average clean swimming speed (v; $m \cdot s^{-1}$) was assessed by the ratio of the 10-m to time taken to cover it, using the head of the swimmer as reference. The stroke frequency (SF; Hz) was calculated from the number of complete strokes performed in the central 10-m and the time taken from the first and last entry of the same hand in the water, recorded by two experienced researchers using stopwatches (SEIKO digital stopwatch S141, Japan). From dividing the average speed by the corresponding stroke frequency, stroke length (SL; m) was calculated.

During the SAO condition, swimmers used a pull buoy and a rubber band around their ankles to avoid propulsion generated from the leg kick action. The arm stroke (Froude) efficiency was calculated according to the indirect "paddle-wheel" model (Zamparo et al., 2005) in which the upper arm is considered a rigid segment of length l rotating at constant angular speed ($\omega = 2\pi \cdot SF$) around the shoulder that yields the theoretical efficiency of the underwater phase only, neglecting the internal mechanical power, as follows:

$$\eta_F = (v/(2\pi \cdot SF \cdot l)) \cdot (2/\pi) \qquad (1)$$

Where v is the average swimming speed, SF is the stroke frequency, l is the shoulder to hand distance (calculated as described at the end of this section) and π is the ratio of the circumference traveled by the hand in the model and its diameter (~3.14).

Arm stroke efficiency in the FCS condition was also calculated according to the "paddle-wheel" model (Zamparo et al., 2005), in three different ways: (i) with no adjustments regarding the contribution of the arms and legs to the swimming speed

(Equation 1); (ii) with a general adjustment to the arm stroke contribution, as previously described (Zamparo et al., 2005):

$$\eta_F = (v \cdot 0.9/(2\pi \cdot SF \cdot l))(2/\pi) \qquad (2)$$

and (iii) with an individual adjustment to the arm stroke contribution to the swimming speed:

$$\eta_F = (v \cdot AC/(2\pi \cdot SF \cdot l))(2/\pi) \qquad (3)$$

Where AC is the individual contribution of the arm stroke to the swimming speed at a given speed (see below).

An underwater video camera (50 Hz; Sea-viewer, USA) positioned in a waterproof cylinder at 0.5-m below the surface was positioned on the frontal wall, to record the swimmer's transverse plane. Videos were digitized using a commercial software package (Twin pro, SIMI, G) and the elbow angle was measured at the end of the in-sweep phase (when the plane of the arm and forearm is perpendicular to the optical axis of the camera) for the right and left sides and for, at least, six different arm strokes (three from each side). As shown in Figure 7 and described in Equation 4, the average elbow angle between both sides was then used to calculate l by trigonometry considering the arm (from the lateral epicondyle of the humerus to the acromion process) and forearm lengths (from the center of the hand to the lateral epicondyle of the humerus) previously measured with a meter tape (0.01 cm resolution):

$$l = \sqrt{{l_{arm}}^2 + {l_{forearm}}^2 - 2 \cdot l_{arm} \cdot l_{forearm} \cdot \cos\alpha} \qquad (4)$$

In which α is the elbow angle in radians, l_{arm} and $l_{forearm}$ are the arm and forearm lengths in m, respectively.

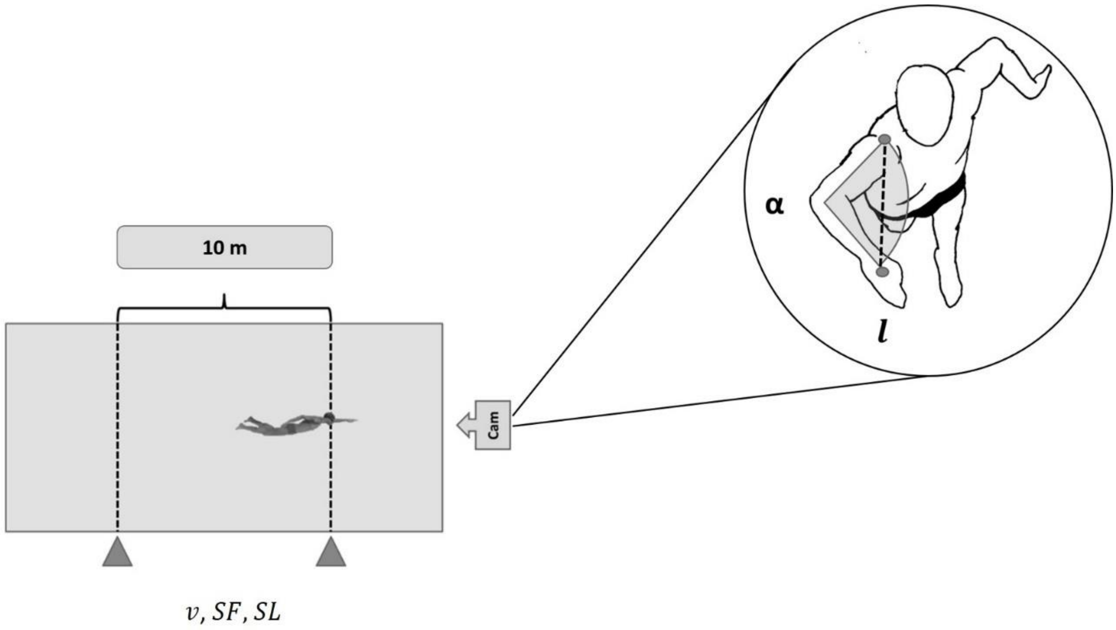

Figure 7. Stroke parameters assessed in the central 10 m of the swimming pool, as well as from a frontal camera recording the frontal plane of the swimmer. v: average swimming speed; SF: average stroke frequency; SL: average stroke length; α: elbow angle at the end of the in-sweep phase; l: shoulder to hand distance.

Arm stroke and leg kick contribution to swimming speed

The SF vs. v relationship was individually determined for each swimmer in both conditions (FCS and SAO), as illustrated in Figure 8, and a second order polynomial regression equation was used (Barbosa et al., 2008), to predict the swimming speed when swimming FCS at specific stroke frequencies corresponding to the values measured in the SAO condition for $V1, V2, V3, V4, V5$ and $V6$. The quality of the fit of these individual regressions was assessed by the coefficient of determination (R^2) and the standard error of the estimate (SEE). The mean ± 1SD values of R^2 and SEE observed were 0.98 ± 0.02 (0.91-1.00) and 0.02 ± 0.01 (0.00-0.05) respectively.

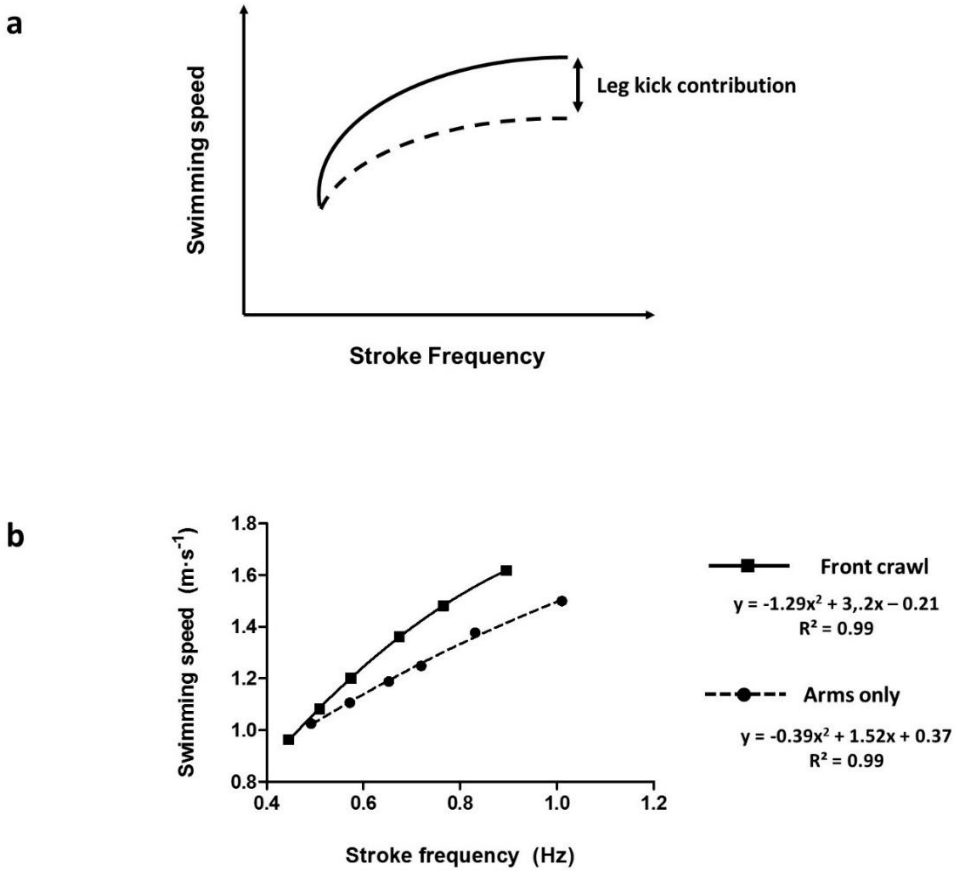

Figure 8. Stroke frequency (SF) vs. speed (v) relationship determined for the whole-body front crawl stroke (FCS) and swimming front crawl with the arms only (SAO) plotted to determine the contribution of the leg kick to forward speed (LC; the percentage difference in *v* between FCS and *SAO* at a given SF).

Then, the AC was calculated for each paired SF (from $V1$ to $V6$) based on Equation 5:

$$AC = (v_{SAO}/v_{FCS}) \cdot 100 \qquad (5)$$

In which v_{SAO} and v_{FCS} are the average swimming speeds in the SAO and FCS conditions, respectively.

Finally, the same polynomial regressions were used to estimate v_{SAO} and v_{FCS} in a range of 21 paired SF to obtain data with an increase of 2.5%, which was considered as a significant increase in swimming speed (Chollet, Chalies & Chatard, 2000; Millet et al., 2002; Seifert, Chollet & Bardy, 2004). The relative contribution of leg kick (LC) to swimming speed was obtained for each paired SF from 50 to 100% of the maximal SF observed in the FCS condition, as follows:

$$LC = ((v_{FCS} - v_{SAO})/v_{FCS}) \cdot 100 \qquad (6)$$

Statistical analysis

Descriptive statistics are reported for all variables (mean ± SD). Normality of data distribution was tested with a Shapiro-Wilk's test and a Levene's test was applied to verify the equality of the variances. The Mauchly's sphericity test was used to validate the subsequent comparison tests. A two-way repeated measures ANOVA was applied for the data comparison regarding (1) the effects of pace and swimming condition on v, SF and SL; (2) the effects of pace on the leg kick contribution; and (3) the effects of self-selected pace and the method used on the arm stroke efficiency calculation. When any significant effect was identified, Fisher's least significant difference *post-hoc* analysis was performed to compare the different paces, conditions or methods. If an interaction between factors occurred, the simple effect of each factor on each level of the other factor was calculated. Effect sizes were estimated using the partial η^2 to describe the proportion of the total variance made up by the variance of the means. The ratio of variance explained of the sample was calculated for each effect and parameter estimate. Interpretation of η^2 indicates small ($\eta^2 \geq 0.02$), medium ($\eta^2 \geq 0.13$) or large effect sizes ($\eta^2 \geq 0.26$) for a two-way ANOVA and small ($\eta^2 \geq 0.01$), medium ($\eta^2 \geq 0.06$) or large effect sizes ($\eta^2 \geq 0.14$) for a one-way ANOVA according to the general rules of thumb on magnitudes of effect sizes (Cohen, 1988). The level of significance adopted was $p \leq 0.05$.

Results

As a response to the increase in the self-selected speed, swimmers increased, as expected, v; SF increased in a similar manner in FCS and SAO while SL was reduced (the values of SL were lower in SAO than in FCS). Since there was an interaction between self-selected speed and swimming condition ($p<0.001$), v was compared between FCS and SAO conditions for each trial separately. All results regarding the effects of self-selected speed and swimming condition on the stroke parameters are presented in Table 4.

Table 4. Stroke parameters (mean ± SD) across the different self-selected paces and conditions.

Trial	$\boldsymbol{v_{FCS}}$ (m·s^{-1})	$\boldsymbol{v_{SAO}}$ (m·s^{-1})	$\boldsymbol{SF_{FCS}}$ (Hz)	$\boldsymbol{SF_{SAO}}$ (Hz)	$\boldsymbol{SL_{FCS}}$ (m)	$\boldsymbol{SL_{SAO}}$ (m)
V1	0.93 ± 0.10 [a]	0.87 ± 0.09	0.45 ± 0.07	0.44 ± 0.05	2.13 ± 0.41	1.98 ± 0.29
V2	1.02 ± 0.11 [a]	0.94 ± 0.10	0.49 ± 0.07	0.48 ± 0.06	2.09 ± 0.34	1.96 ± 0.29
V3	1.09 ± 0.11 [a]	1.03 ± 0.11	0.53 ± 0.06	0.54 ± 0.06	2.08 ± 0.29	1.92 ± 0.30
V4	1.19 ± 0.13 [a]	1.10 ± 0.13	0.59 ± 0.07	0.60 ± 0.07	2.03 ± 0.23	1.85 ± 0.22
V5	1.29 ± 0.14 [a]	1.18 ± 0.15	0.66 ± 0.08	0.67 ± 0.09	1.97 ± 0.22	1.77 ± 0.21
V6	1.43 ± 0.16 [a]	1.28 ± 0.18	0.78 ± 0.10	0.78 ± 0.10	1.84 ± 0.21	1.64 ± 0.18
Effect of speed						
Significance	p<0.001		p<0.001		p<0.001	
Effect size	0.934		0.897		0.538	
Observed power	1.000		1.000		1.000	
Effect of condition						
Significance	p<0.001		p=0.891		p<0.001	
Effect size	0.702		0.001		0.631	
Observed power	1.000		0.052		1.000	
Interaction						
Speed vs. condition						
Significance	p<0.001		p=0.212		p=0.190	
Effect size	0.418		0.051		0.051	
Observed power	1.000		0.436		0.518	

v_{SFC}: average swimming speed when swimming front crawl; v_{SAO}: average swimming speed when swimming front crawl with the arms only; SF_{FCS}: stroke frequency when swimming front crawl; SF_{SAO}: stroke frequency when swimming with the arm stroke only; SL_{FCS}: stroke length when swimming front crawl; SL_{SAO}: stroke length when swimming front crawl with the arms only.

[a]. Individual difference between FCS and SAO conditions (p<0.01).

LC increased with SF (and consequently speed), as shown in Figure 9. At 100% of SF (at maximal swimming speed) it was equal to 11.4 ± 4.4 % and the AC, at this same speed was therefore 88.6 ± 4.4 %.

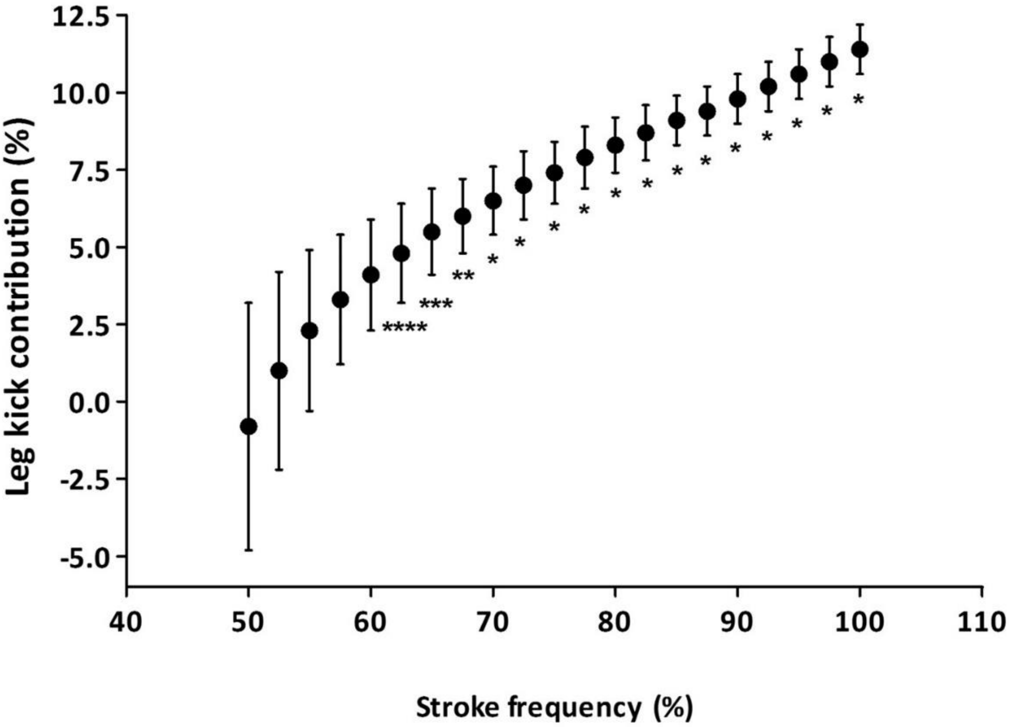

Figure 9. Relative contribution of the leg kick when swimming whole-body front crawl (*FCS*) in a range of 21 paired stroke frequencies (*SF*). Data are presented as Mean ± 1SE.

*Increased speed is different from the values corresponding to the range of 50 to 100% of the maximal SF (p<0.05).

**Increased speed is different from the values corresponding to the range of 52.5 to 100% of the maximal SF (p<0.05).

***Increased speed is different from the values corresponding to the range of 55 to 100% of the maximal SF (p<0.05).

****Increased speed is different from 57.5 to 100% of the maximal SF (p<0.05).

There was a significant effect of swimming pace ($\eta^2 = 0.573$; Observed power = 1.000; $p<0.001$) as well as of the way used to calculate the arm stroke efficiency ($\eta^2 = 0.670$; Observed power = 1.000; $p<0.001$). An interaction between swimming pace and the way used was also observed ($\eta^2 = 0.111$; Observed power = 1.000; $p<0.001$). Thus, the different ways to calculate arm stroke efficiency (η_F) were compared for each pace, separately.

As presented in Figure 10, η_F decreases as a function of speed (as is the case for SL). In the FCS condition, η_F calculated without any adjustment to the LC, is larger than η_F adjusted using individual and general adjustments, as well as larger than η_F in the SAO condition. At the lower speeds ($V1$-$V4$), η_F in the FCS condition, calculated using general adjustments, is lower than η_F calculated using individual adjustments but the difference disappears at the fastest speeds ($V5$-$V6$). Last but not least, η_F calculated using individual adjustments to the LC in the FCS condition did not differ with η_F assessed in the SAO condition at all the investigated speeds, meaning that methods are indeed measuring the same thing.

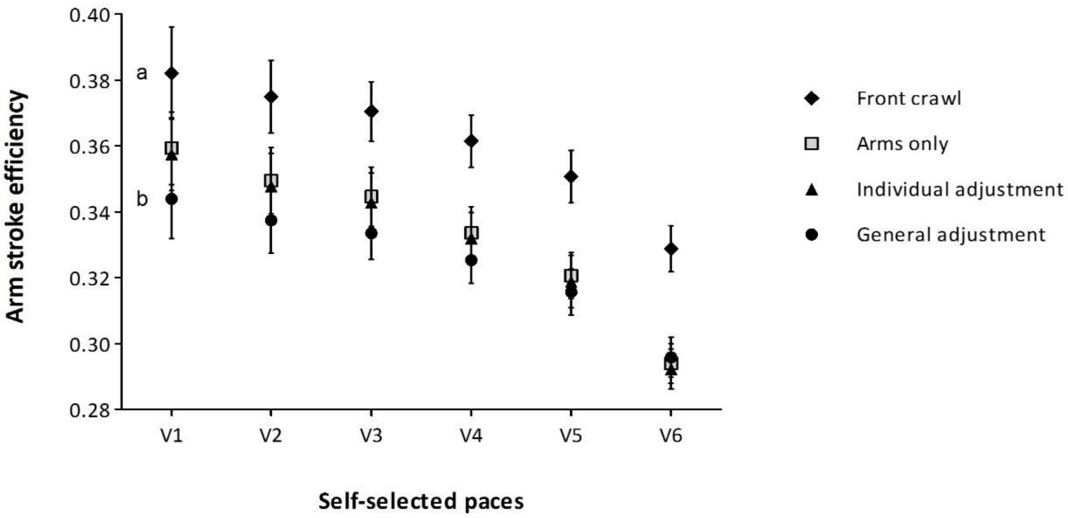

Figure 10. Arm stroke efficiency (η_F) at each self-selected speed. The data regarding front crawl swimming with the arms only (SAO) condition was individually adjusted for stroke frequencies equal to the ones observed in the front crawl stroke (FCS). Data are presented as Mean ± 1 SE, black lozenges are non-adjusted FCS values, black triangles are the SAO values, gray squares are individually-adjusted FCS values and black circles are FCS values adjusted assuming 90% of contribution from the arms to swimming speed.

a. η_F is different from all the other methods in each and every self-selected speed ($p<0.05$);

b. η_F is different from the SAO and the individually-adjusted FCS values at the first, second and third self-selected speed ($p<0.05$).

Discussion

The aims of this study were to test the effects of speed on the LC and to compare arm stroke efficiency assessed in the SAO and FCS conditions. The main results indicate that speed has a significant effect on the LC, as well as on arm stroke efficiency. Moreover, data reported in this study indicate that arm stroke efficiency in the FCS condition is overestimated (compared to SAO) if not adjusted by LC, and that, at slow (but not necessarily at fast) swimming speeds, individual adjustments to the LC should be applied.

The increase in LC with swimming speed and SF, may be hydrodynamically explained. Indeed, at higher speeds associated to higher SF and lower time duration of a swimming cycle, swimmers face a shorter time period to perform the kick. So, assuming an (at least) not proportional reduction in kicking amplitude, foot velocity relative to the water will be higher compared to lower speeds and frequencies, allowing both for higher intensity of quasi-stable hydrodynamic force production during the downbeat and the upbeat. Also, it allows a much more sudden reverse of feet direction of movement, allowing a more intense vortex generation and shedding and higher propulsive effects extracted from unstable flow generated by the kick (Ungerechts & Arellano, 2011). Once with the leg kick swimmers gain an extra propulsive impulse, they can reach higher speeds for the same shoulder angular velocity and efficiency is improved compared to SAO. Results also showed that specifically correcting this effect induced by the kicking action allow similar results. This means that the efficiency markers used in this study are quite sensitive to factors affecting swimming propulsion, as convenient.

To increase speed, from $V1$ to $V6$, swimmers increased their SF with a consequent decrease in SL. This pattern was observed in both conditions (FCS and SAO), as expected (Craig et al., 1985; Seifert et al., 2010). The average swimming speed and SL were larger in FCS than in SAO condition but SF was essentially the same. That reflects a similar strategy adopted by the swimmers to the task constraint of increasing the self-selected speed, controlling the SF in both conditions and indicates a direct effect of the flutter kick on the SL. Increases in SF and SL are expected when comparing sprint front crawl swimming with and without leg kicking (Gourgoulis et al., 2014). Although we have not observed any effect of the swimming condition on the SF, that may have been a response to the different task constraints. In our study, swimmers were asked to perform the front crawl, either with and or without leg kicking, at a range of six self-selected speeds, instead of swimming only at the maximal swimming speed.

Our results show that the LC to FCS significantly increase with speed. At low speeds the AC and LC seem to be individually determined, whereas, at maximal speeds the inter-subject difference is rather low (small SD), as previously reported (Deschodt et al., 1999; Gourgoulis et al., 2014; Bucher, 1975) at maximal swimming effort, in which the LC was ~10%. Data of 200-m trials (Morris et al., 2016) reporting an increase in LC from low to high SF in female swimmers support our findings, although male swimmers did not present the same results, reinforcing our argument that LC is individually determined and may increase with SF and speed. Also, the distance and number of trials chosen in our study allowed us to obtain a larger range of SF, from very slow to maximal speeds (and SF).

Measurements of flutter kick power (Gatta, Cortesi & di Michele, 2012) by towing the swimmers with an electromechanical motor, at six different speeds, showed a decrease in power when increasing the towing speed, suggesting that the capability to produce power by the legs reduces in speeds above the maximal flutter kick speed. The paradoxical results found in our study may be related to other adaptations that occur when swimming the FCS, such as the ones regarding swimming coordination, economy and the efficiency cascade. Furthermore, the already suggested unstable flow propulsive effect of the crawl flutter kick, particularly expected at the higher velocities, may gain with increased translational swimming velocity, allowing exploiting different hydrodynamic mechanisms not accessible at maximal kicking swimming velocity only.

A coordinative adaptation on leg kicking occurs as a response to the increase in front crawl swimming speed, changing from a two-beat to a six-beat pattern (Millet et al., 2002). It is not clear, however, whether the adaptations in the leg kick pattern is related to its contribution to swimming speed, but our findings showing the increasing LC suggests so. Also, at low swimming speeds, the role of the leg kick is mostly related to the maintenance of a horizontal body position, reducing the frontal projected area and drag forces whereas its propulsive role seems to increase following the changes on arm to leg coordination from two to four or six beats per stroke (Zamparo, 2006).

Higher net energy expenditure, as well as higher energy cost to cover a given distance, is observed when comparing leg kicking at surface and the front crawl stroke (Pendergast et al., 2003). Thus, economy seems to be one of the main reasons that lead swimmers to adopt a given leg kicking pattern, as well as a given AC and LC, according to the pace they are supposed to swim. Efficiency, in its different forms, may also be a determinant factor when it comes to adopting the optimal leg kick pattern and contribution to swimming speed. Previous findings (Swaine, 2000) showed that legs produced higher power output than arms during an all-out 30-s simulated swimming test, what is in line with the higher energy expenditure observed in human swimming (Pendergast et al., 2003). However, they found that leg kick has lower propelling, overall and performance efficiencies than swimming front crawl. Thus, a lower fraction of the metabolic power is converted into mechanical power, what may be related to a higher internal mechanical power (Zamparo et al., 2005) as well as to a lower fraction of the total mechanical power and metabolic power output that are actually transformed into useful power to overcome drag (Swaine & Doyle, 1999).

Considering the relative contribution of arms and legs to the average tethered force when swimming FCS, AC and LC of 70.3% vs. 29.7%, for males, and 66.6% vs. 33.4%, for females, were previously reported (Morouço et al., 2015) during a 30-s all-out tethered swimming protocol. However, the relative contribution of arms and legs to the average tethered force when swimming FCS not necessarily represents the relative contribution to the swimming speed. Also, besides assessing the contribution of arms and legs only at maximal effort, considering the sum of the arms only and leg kicking conditions as a reference, the authors probably overestimated the average force of the actual front crawl swimming, since there was a force deficit when comparing swimming with the whole body and the sum of the other two conditions.

Therefore, changing the AC and LC seems to be an intrinsic strategy adopted by swimmers to optimize the economy and efficiency at a given speed, and to cope with velocity generation requirements, reducing the LC at lower speeds and increasing it at higher speeds. Adaptive movement patterns emerge as a function of the organism's propensity to minimize metabolic energy expenditure with respect to task, environment and organism constraints to action (Sparrow & Newell, 1998). Indeed, motor organization in swimming will occur in response to one of those three constraints: organismic (e.g. gender, expertise, anthropometry, physiological requirements, swimmer's discipline), environmental (e.g. active and wave drag, propelling efficiency) and task constraints (e.g. task goal, instructions given to the swimmer, imposed pace and distance) (Seifert, Chollet & Rouard, 2007; Newell, 1986).

The large standard deviations in LC observed in the present study at low swimming speeds may thus: (1) reflect the heterogeneity of the subjects and (2) confirm the necessity of an individualized estimation of AC and LC, considering the pace and inter-individual effects on it, instead of assuming a given fixed value; on the other hand, at maximal swimming speeds, also suggested by the few studies that assessed the differences in maximal swimming speed between FCS and SAO conditions (Deschodt et al., 1999; Bucher, 1975), the LC seems to be rather constant and on the range of 10-12%.

One of the main issues on assessing propelling (or Froude) efficiency in swimming is the fact that the most used approach reported in the literature refer to the arm stroke only. These values of arm stroke efficiency should thus be compared to our SAO values since the legs are supported by a pull buoy and do not contribute to propulsion. Other approaches for assessing the arm stroke efficiency in front crawl swimming have been used, based on the concepts previously described for the front crawl stroke[31] and for the analysis of locomotion in "rowing animals" (Alexander, 1983). These indirect approaches consider the ratio of the average swimming speed to the hand speed ($\eta_F = v_{swim}/v_{hand}$) and may be assessed by a 2D simplified model (Zamparo et al., 2005), as the one used in the present study, or a 3D model (Figueiredo et al., 2011), in which arm stroke efficiency is considered as the ratio of the horizontal speed of the center of mass to the 3D resultant hand speed ($\eta_F = v_{CM}/v_{3Dhand}$). Indirect assessments of effective and resultant forces generated by the hands have also been used to assess the arm stroke efficiency in a previous study (Gourgoulis et al., 2014) in which individual adjustments to the arm stroke contributions to swimming speed were considered to avoid overestimation of the arm stroke efficiency during full stroke swimming.

Although the assessment of arm stroke efficiency with the "paddle-wheel" model (Zamparo et al., 2005) relies on the assumption that the upper-limbs are a rigid segment of length l moving at constant speed, it is a coach-friendly approach that may be applied to assess the arm stroke efficiency not only in the SAO but also in the FCS conditions by considering the AC. Furthermore, a previous study (Figueiredo et al., 2011) reported similar average values of arm stroke efficiency between the method used in the present study and a 3D model. Moreover, despite AC has been often assumed (Deschodt et al., 1999) as 90%, independently of the pace or the level of the swimmers, our results suggest that the AC and LC should be individually estimated, at least at lower swimming speeds, since both depend on the swimming pace. In fact, when individual adjustments to the AC were used, arm stroke efficiency did not differ between FCS and SAO conditions, at paired SF. Furthermore, our data show that, when assuming a AC of 90%, arm stroke efficiency is underestimated only at the lower speeds, from $V1$ to $V3$, since no differences were observed at the highest speeds.

Using polynomial regressions to predict swimming speed at a given SF can be a limitation of the method used to estimate AC and LC in the present study, since swimmers did not necessarily perform at those specific speeds or SF. However, we attempted to reduce this limitation by predicting speeds nearly within the range of SF (and speeds) that they actually performed in both conditions. Regarding the use of a pull-buoy in the SAO and the use of the leg kick in the FCS, a leg-raising effect has been reported for both conditions (Gourgoulis et al., 2014; Zamparo et al., 2009), although a slightly larger trunk incline (11.46 ± 1.51° vs. 10.01 ± 2.56°) has been observed at maximal swimming speed in SAO than in FCS (Gourgoulis et al., 2014). Thus, the contribution of leg kick to swimming speed may not be related only to the propulsion generated by the lower limbs, but also to a reduction in resistive drag (Kjendlie, Stallman & Stray-Gundersen, 2004).

Practical applications

Data reported in this study, using coach-friendly methods, may help coaches and scientific community to better understand and evaluate arm stroke efficiency in front crawl swimming, with no constraints regarding the lower limbs. Our results show that the contribution of the leg kick action in front crawl stroke increases with speed and should be considered in the calculation of arm stroke efficiency. In addition, the methods used in this study could be considered by coaches and practitioners to assess changes in front crawl performance related to the arm stroke or leg kick actions. Our findings could also be considered when prescribing training according to the arm stroke and leg kick contributions to swimming speed.

Conclusion

As a general effect, leg kicking action leads to an increase in stroke length (and consequently speed) at comparable stroke frequencies. Moreover, the percentage contribution of the flutter kick to forward speed increases with the swimming pace. Thus, regarding the assessment of arm stroke efficiency, the contribution of arms and legs should be individually estimated in order to reduce the errors when analyzing different speeds and different swimmers.

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Original article 3 - A biophysical analysis on the arm stroke efficiency in front crawl swimming: comparing methods and determining the main performance predictors

Running title: Swimming efficiency and performance prediction

Abstract

The purpose of the study was to compare different methods to assess the arm stroke efficiency (η_F), when swimming front crawl using the arms only, on the MAD System and in a free-swimming condition and to identify biophysical adaptations to swimming on the MAD System and the main biophysical predictors of maximal swimming speed in 200 m front crawl using the arms only v_{200m}. Fourteen swimmers performed 5 x 200 m incremental trials using the front crawl stroke using the arms only, once swimming freely and once swimming on the MAD System. The aerobic and anaerobic components of the total metabolic power were assessed in both conditions. Biomechanical parameters were obtained from video analysis and force data recorded on the MAD System. The η_F was calculated using the direct measures of mechanical and metabolic power (power-based method), the forward speed/ hand speed ratio (speed-based method), and the simplified paddle-wheel model. Both methods to assess the arm stroke efficiency on the MAD System differed (p<0.001) from the expected values for this condition (η_F=1), the speed-based method provided the closest values (η_F~0.96). In the free-swimming condition, the power-based ($\eta_F \sim 0.75$), speed-based ($\eta_F \sim 0.62$) and paddle-wheel ($\eta_F \sim 0.39$) efficiencies were significantly different (p<0.001). In both conditions the methods provided values that agreed with each other, thus indicating that they could be used for this purpose. In addition, the main biophysical predictors of v_{200m} were included in two models: biomechanical (external mechanical power, η_F, and speed-specific drag; R^2=0.98) and physiological (total metabolic power and energy cost; R^2=0.98).

Keywords

Propelling efficiency, Froude efficiency, MAD System, Principal Components Analysis

A biophysical analysis on the arm stroke efficiency in front crawl swimming: comparing methods and determining the main performance predictors

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Introduction

The arm stroke efficiency in swimming has been usually represented by the fraction of the external mechanical power that is converted into useful propulsive power (i.e. Froude efficiency; η_F) and reported as one of the main determinants of swimming performance (Toussaint, 1989; Zamparo et al. 2014). Thus, understanding and developing methods that are both feasible and coach-friendly is a major concern in swimming research. Although several methods have been used to assess η_F (Toussaint et al., 1988; Martin et al., 1981; Zamparo et al., 2005; Toussaint et al., 2006; Figueiredo et al., 2011), it is unclear whether these methods provide accurate values and agree with each other.

For instance, Toussaint et al. (1988) suggested that η_F could be obtained from a power-based method, in which direct assessments of the external mechanical power ($\dot{W}_{ext}$) for a given metabolic power input, as well as the useful propulsive power (i.e. power to overcome drag; $\dot{W}_d$) for a given swimming speed, are extrapolated from a condition in which η_F is forced to maximal to a normal free swimming condition. Considering the limitations imposed by the aquatic environment, Martin et al. (1981) have described a theoretical model of the arm stroke propulsion, from which η_F could be obtained from a speed-based method that estimates the ratio of the average forward speed and the tangential hand speed (v), assuming propulsive and drag forces are the same for a given constant speed. This theoretical model was later adapted by Zamparo et al. (2005) as a simplified paddle-wheel model to estimate η_F during the underwater phase only, over half a cycle.

Considering that these methods might provide different values of η_F for a given v, as indicated by the data reported in the literature, comparing them in a controlled condition in which no power is wasted to transfer kinetic energy to the water ($\dot{W}_k = 0$), and hence η_F is maximal, is the first step in identifying the potential differences and main limitations of each method. One way to impose a minimal $\dot{W}_k$, and a maximal η_F, has been the use of the Measure of Active Drag (MAD) System, in which swimmers must push-off fixed pads to generate propulsion with no major changes in swimming technique (Hollander, 1985; Toussaint, 1988; Seifert et al., 2015). Identifying the biophysical adaptations to swimming on the MAD System, relatively to free swimming, could also reinforce theoretical assumptions on the interplay between swimming efficiency and economy, since experimental data are scarce and the anaerobic contribution is usually neglected (Toussaint et al., 1988; Toussaint, 1990; Toussaint et al., 1990; Toussaint and Vervoorn, 1990).

Thus, the aims of this study were (1) to compare the power-based, speed-based and paddle-wheel methods to assess η_F, when swimming front crawl using the arms only, on the MAD System and in a free-swimming condition, (2) to compare the biophysical responses to free-swimming and MAD System conditions, in a range of paired speeds, and (3) to identify the main biophysical predictors of maximal swimming speed in 200 m front crawl using the arms only (v_{200m}).

Material and methods

Participants

Fourteen national level competitive swimmers (8 males, 6 females) volunteered to this study (age: 17.3 ± 2.2 years; body mass: 65.3 ± 10.6 kg; height: 171.7 ± 9.9 cm). The purpose and the aims of the study were carefully explained to each individual and written informed consent was obtained. The study conformed to the standards set by the Declaration of Helsinki, and the local Institutional Review Board approved the procedures.

Experimental procedures

The experimental protocol consisted of two testing sessions separated by 8 hours. During each session, swimmers completed a standardised warm up followed by 5 x 200 m trials at pre-determined speeds. Testing took place in a 25 m indoor swimming pool with a water temperature of 27.5ºC and relative air humidity of 60%. All swimmers were familiarized and experienced with the apparatus used in the data collection.

The 5 x 200 m incremental trials were performed using the front crawl stroke using the arms only, once swimming freely and once swimming on the MAD System. During each trial, v was controlled by a visual pacer with flashing lights at the bottom of the swimming pool (Pacer2Swim, KulzerTEC, Aveiro, Portugal). In both conditions swimmers used a pull buoy and a rubber band around their ankles to avoid propulsion generated from the leg kick action and in-water starts and open turns were used. Passive recovery periods of at least 5 min were given to the participants after each step.

Physiological assessments

Respiratory and pulmonary gas-exchange data were directly and continuously assessed breath-by-breath using a telemetric portable gas analyser (K4b2, Cosmed, Rome, Italy) connected to a low hydrodynamic resistance respiratory snorkel and valve system (AquaTrainer, Cosmed, Rome, Italy) as reported by Ribeiro et al. (2016). The apparatus was suspended at 2 m above the water surface following the swimmer along the pool using a steel cable system designed to minimize disturbance of the normal swimming movements. The telemetric portable gas analyser was calibrated before each test with gases of known concentration (16% oxygen and 5% carbon dioxide) and the turbine volume transducer calibrated with a 3 L syringe. Anomalous $\dot{V}O_2$ values greater than ±4 SD from the mean of the final 60 s of each step were manually removed before data were averaged. The average of the final 60 s of $\dot{V}O_2$ data ($mlO_2 \cdot kg \cdot min^{-1}$) were used for analysis and calculations.

Capillary blood samples (5 µL) for lactate concentration [La^-] analysis were collected from the earlobe at rest, at the end of each step and in the recovery periods (after 1, 3, and 5 min) and analysed using a portable lactate analyser (Lactate Pro 2, Arkay, Inc, Kyoto, Japan). The net [La^-], in $mmol \cdot l^{-1}$, was then transformed into $\dot{V}O_2$ equivalents using a 2.7 $mlO_2 \cdot kg^{-1}$ constant (di Prampero et al., 1978; Thevelein et al., 1984):

$\dot{V}O_2(An) = 2.7 \cdot [La^-]_{net}/t_{step}$ (1)

Where $VO_2(An)$ represents the volume of oxygen ($mlO_2 \cdot kg \cdot min^{-1}$) consumed over the duration of each step if the anaerobically produced energy had instead been produced via aerobic pathways and t_{step} is the step duration (min).

Estimations of metabolic power produced by aerobic ($\dot{E}_{aer}$) and anaerobic lactic pathways ($\dot{E}_{aner}$) were converted to watts, considering the body mass of the swimmers and the energy equivalent of O_2 (α), as previously described (Capelli et al., 1998; di Prampero, 1986):

$\alpha = 15.87 + 5.26 \cdot RER$ (2)

$\dot{E}_{aer} = \dot{V}O_2 \cdot \alpha \cdot BM/60$ (3)

$\dot{E}_{aner} = \dot{V}O_2(An) \cdot \alpha \cdot BM/60$ (4)

The overall metabolic power input ($\dot{E}_{tot}$) resulted from the sum of $\dot{E}_{aer}$ and $\dot{E}_{aner}$:

$\dot{E}_{tot} = \dot{E}_{aer} + \dot{E}_{anaer}$ (5)

Finally, to obtain the energy cost of swimming (C, expressed in $kj \cdot m^{-1}$), $\dot{E}_{tot}$ was converted to $kJ \cdot s^{-1}$ and divided by the swimming speed, as follows:

$C = (\dot{E}_{tot}/1000)/v$ (6)

Biomechanical assessments in free swimming

Swimmers were recorded in the sagittal plane with a stationary video camera (50 Hz; HDR CX160E, Sony Electronics Inc., USA) positioned on the opposite side of the swimming pool. The space recorded was calibrated using lane marks measuring the central 10 m of the swimming pool (7.5 m to 17.5 m). Video images were analysed using a motion analysis software (Kinovea v. 0.8.15) and the number of complete strokes recorded within the calibration marks and the time taken from the first and last entry of the same hand in the water were computed, yielding the average stroke frequency:

$SF_{free} = n_{strokes}/t_{strokes}$ (7)

where SF_{free} is the stroke frequency in the free-swimming condition, $n_{strokes}$ is the number of complete arm strokes and $t_{strokes}$ is the time taken to complete them. The vertex was digitized in the same frames of the first and last hand entry in the water, allowing the calculation of the average swimming speed:

$$v_{free} = d_{strokes}/t_{strokes} \qquad (8)$$

In which v_{free} is the actual swimming speed in the free-swimming condition and $d_{strokes}$ is the distance covered by the vertex of the swimmer from the first and last hand entry of the same hand in the water registered. No differences higher than 0.01 m/s were observed between v_{free} and the imposed swimming speed.

The average stroke length (SL_{free}) was calculated by combining equations 7 and 8, as follows:

$$SL_{free} = v_{free}/SF_{free} \qquad (9)$$

An underwater video camera (50 Hz; Sea-viewer, USA) positioned in a waterproof cylinder at 0.5-m below the surface was positioned on the frontal wall, to record the swimmer's transverse plane. The elbow angle was measured at the end of the in-sweep phase (when the plane of the arm and forearm is perpendicular to the optical axis of the camera) for the right and left sides and for, at least, six different arm strokes (three from each side). As shown in Figure 11, and described in Equation 10, the average elbow angle between both sides was then used to calculate l by trigonometry considering the arm (from the lateral epicondyle of the humerus to the acromion process) and forearm lengths (from the center of the hand to the lateral epicondyle of the humerus) previously measured with a meter tape (0.01 cm resolution):

$$l = \sqrt{{l_{arm}}^2 + {l_{forearm}}^2 - 2 \cdot l_{arm} \cdot l_{forearm} \cdot \cos\theta} \qquad (10)$$

In which θ is the elbow angle in radians, l_{arm} and $l_{forearm}$ are the arm and forearm lengths in m, respectively.

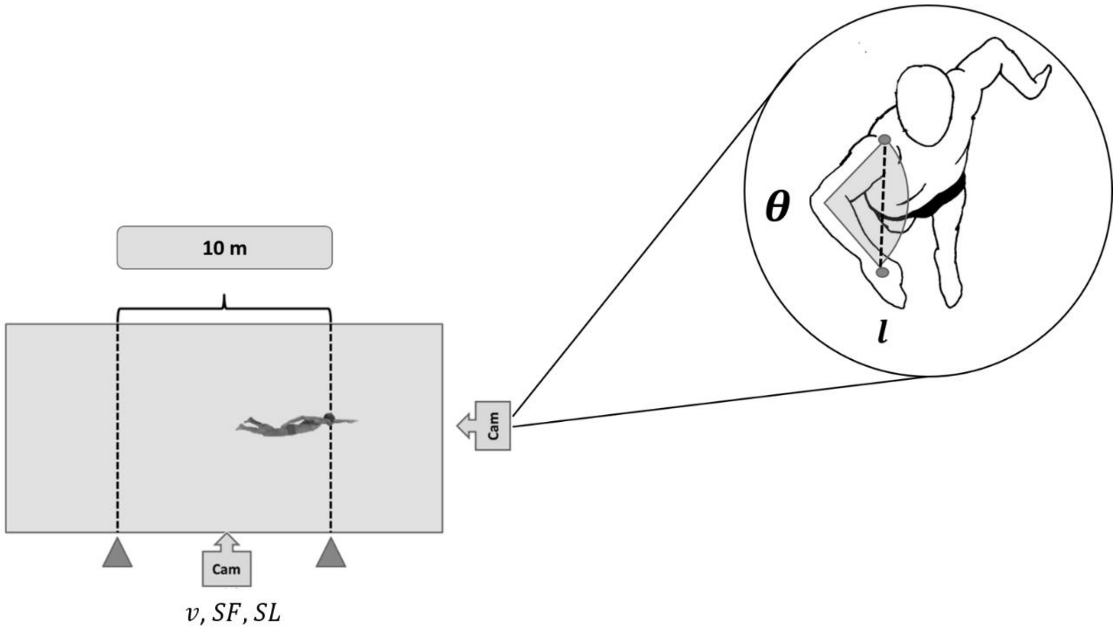

Figure 11. Stroke parameters assessed in the central 10 m of the swimming pool, as well as from a frontal camera recording the frontal plane of the swimmer. v: average swimming speed; SF: average stroke frequency; SL: average stroke length; θ: elbow angle at the end of the in-sweep phase; l: shoulder to hand distance.

Biomechanical assessments on the MAD system

When swimming on the MAD System, propulsion was generated without wasting kinetic energy to the water ($\dot{W}_k = 0$) and therefore $\eta_F = 1$ (Toussaint et al., 1988). Swimmers pushed-off from fixed pads attached to a 23-m rod placed 0.8 m below the water surface, with l fixed at 0.45 m and with a standard inter-pad distance of 1.35 m (16 pads in total). The rod is instrumented with a force transducer, allowing the measurement of direct push-force at each pad and the calculation of the mean force at each lap, as presented in Figure 12.

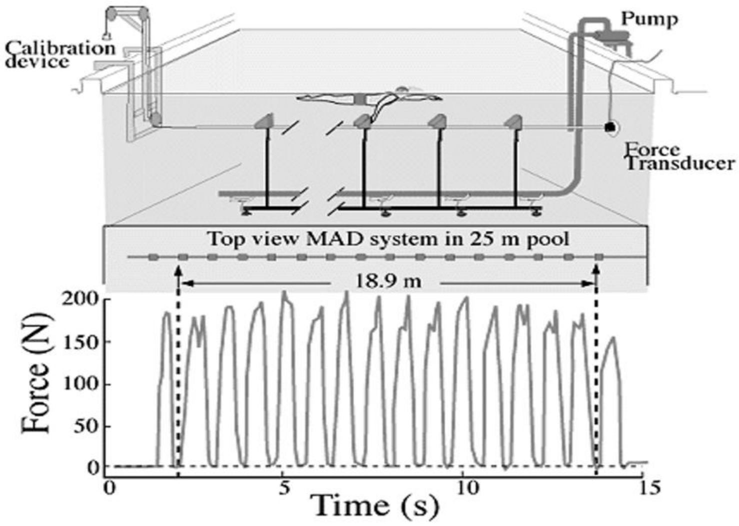

Figure 12. The structure of the MAD System. Forces were applied the push-off pads and assessed for each arm stroke by a force transducer (adapted from Toussaint et al., 1988).

The force signal was acquired using 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., 2016). The first and last push-off were neglected to eliminate the influence of the push-off from the wall (first pad) and the deceleration of the swimmer at the end of the lane (last pad). The remaining force signal was time integrated, yielding the average force at each lap.

Actual swimming speed was computed from the force signal, considering the time needed to cover the distance between the second and the last pad (18.9 m), and no differences larger than 0.01 m/s from the imposed swimming speed were observed. Average stroke frequency in this condition (SF_{MAD}) was calculated from the imposed swimming speed and the inter-pad distance ($d_{inter-pad}$), as follows:

$$SF_{MAD} = v/2 \cdot d_{inter-pad} \qquad (11)$$

Assuming each swimmer performed at a constant swimming speed, their mean force was equal to the mean drag force, with the five velocity/drag ratio data being least square fitted in a power function, as follows:

$$D = k \cdot v^n \qquad (12)$$

in which D is the total active drag, v is the average swimming speed and k (speed-specific drag) and n are parameters of the power function. The power to overcome drag ($\dot{W}_d$) was calculated as the product of v and the correspondent D:

$$\dot{W}_d = D \cdot v \qquad (13)$$

The power needed to overcome external forces ($\dot{W}_{ext}$) is determined by:

$$\dot{W}_{ext} = F_{hand} \cdot v_{hand} \qquad (14)$$

In which F_{hand} is the resultant propulsive force exerted by the hand and v_{hand} is the average effective hand speed.

The $\dot{W}_{ext}$ can be partitioned in the power needed to overcome drag forces ($\dot{W}_d$) and the power needed to give water kinetic energy ($\dot{W}_k$):

$$\dot{W}_{ext} = \dot{W}_d + \dot{W}_k \qquad (15)$$

Since no power is wasted to the water when swimming on the MAD System ($\dot{W}_k = 0$), $\dot{W}_d$ was equal to the external mechanical power output ($\dot{W}_{ext}$) in this condition:

$$\dot{W}_{ext} = \dot{W}_d \qquad (16)$$

Speed-based efficiency

The speed-based η_F was assessed in the MAD System and in free swimming conditions by combining Equations 13 and 14, yielding:

$$\eta_F = (D \cdot v)/(F_{hand} \cdot v_{hand}) \qquad (17)$$

In which F_{hand} is assumed to be equal to D for a given constant speed and v_{hand} is calculated with a model proposed by Martin et al. (1981). In this model, the arm is considered a rigid segment (l) rotating at constant angular speed (ω) around the shoulder:

$$v_{hand} = \omega \cdot l \qquad (18)$$

The average ω was estimated based on the ratio of the circumference traveled by the hand in the model and its diameter ($\pi \approx 3.14$) and SF values:

$$\omega = 2\pi \cdot SF \qquad (19)$$

Thus, η_F can be calculated as follows:

$$\eta_F = v/v_{hand} \qquad (20)$$

Paddle-wheel efficiency

The "paddle-wheel" arm stroke (Froude) efficiency was calculated according to the model proposed by Zamparo et al. (2005), adapted from Martin et al. (1981), that yields the theoretical efficiency of the underwater phase only, as follows:

$$\eta_F = v/(v_{hand} \cdot 2/\pi) \qquad (21)$$

Power-based efficiency

At each step, a mean value of $\dot{W}_{ext}$ was calculated from the eight lengths swam over the MAD System and the linear relationship between $\dot{E}_{tot}$ and $\dot{W}_{ext}$ was obtained and the individual regression equations were used to calculate $\dot{E}_{tot}$ in free swimming. Since $\dot{W}_d$ was known for each swimmer in each speed from the measurements on the MAD System, Froude efficiency in free swimming could be calculated:

$$\eta_F = \dot{W}_d/\dot{W}_{ext} \qquad (22)$$

where η_F is the Froude efficiency, which represents the fraction of the $\dot{W}_{ext}$ that is converted into useful propulsive power ($\dot{W}_d$).

Statistical analysis

Descriptive statistics are reported for all variables (mean ± SD). Normality of data distribution was tested with a Shapiro-Wilk's test and a Levene's test was applied to verify the equality of the variances. The Mauchly's sphericity test was used to validate the subsequent comparison tests. A two-way repeated measures ANOVA was applied for the data comparison regarding the effects of the method and of the swimming speed on the arm stroke efficiency parameters. When any significant effect was identified, Bonferroni's *post-hoc* analysis was performed to compare the different paces, conditions or methods. If an interaction between factors occurred, the simple effect of each factor on each level of the other factor was calculated. Effect sizes were estimated using the partial

η^2 to describe the proportion of the total variance made up by the variance of the means. The ratio of variance explained of the sample was calculated for each effect and parameter estimate. Interpretation of η^2 indicates small ($\eta^2 \geq 0.02$), medium ($\eta^2 \geq 0.13$) or large effect sizes ($\eta^2 \geq 0.26$) for a two-way ANOVA and small ($\eta^2 \geq 0.01$), medium ($\eta^2 \geq 0.06$) or large effect sizes ($\eta^2 \geq 0.14$) for a one-way ANOVA according to the general rules of thumb on magnitudes of effect sizes (Cohen, 1988). In addition, Bland-Altman plots (Bland and Altman, 1986) were used to establish the agreement between the η_F estimated from the different methods.

To identify the main predictors of v_{200m}, a principal components analysis was performed to convert the set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables, reducing the number of dimensions. The two main principal components were considered for the analysis and the variables that presented eigenvalues ≥0.8 were selected for a multiple linear regression, excluding the redundant variables from the model.

For all analyses, the level of significance adopted was $p \leq 0.05$.

Results

No effects of swimming speed on the arm stroke efficiency were observed in the MAD System condition ($p>0.05$). The average difference between the speed-based and the theoretical efficiency assumed for the MAD System was 0.04±0.02 (~4%; $p<0.001$). The difference between the paddle-wheel efficiency and the theoretical assumption for the MAD System was 0.39±0.02 (~39%; $p<0.001$). When comparing the paddle-wheel model and the speed-based method, values of arm stroke efficiency were in average 0.35±0.01 higher in the latter (~35%; $p<0.001$). The individual values of arm stroke efficiency for each speed is presented in Figure 13.

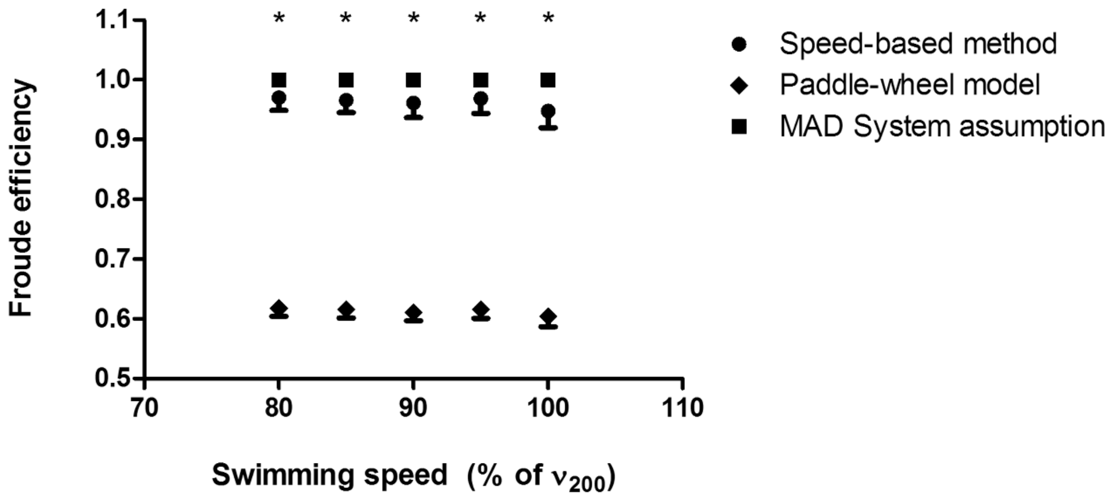

Figure 13. Values of stroke efficiency assessed in the MAD System condition by different methods in a range of speeds, from 80 to 100% of v_{200}.
*All methods were different for each swimming speed (p<0.001).

The agreement between methods is presented in Figure 14, indicating a short amplitude of the limits of agreement when comparing the speed-based method and the MAD System assumption (between -0.01 and 0.08), the paddle-wheel model and the MAD System assumption (between 0.33 and 0.37), and the paddle-wheel model and the speed-based method (between 0.36 and 0.42). Moreover, the differences seemed to be influenced by the magnitude of the averaged efficiency between methods (R^2=1; p<0.001), as indicated in the linear regression equations of each Bland-Altman plot.

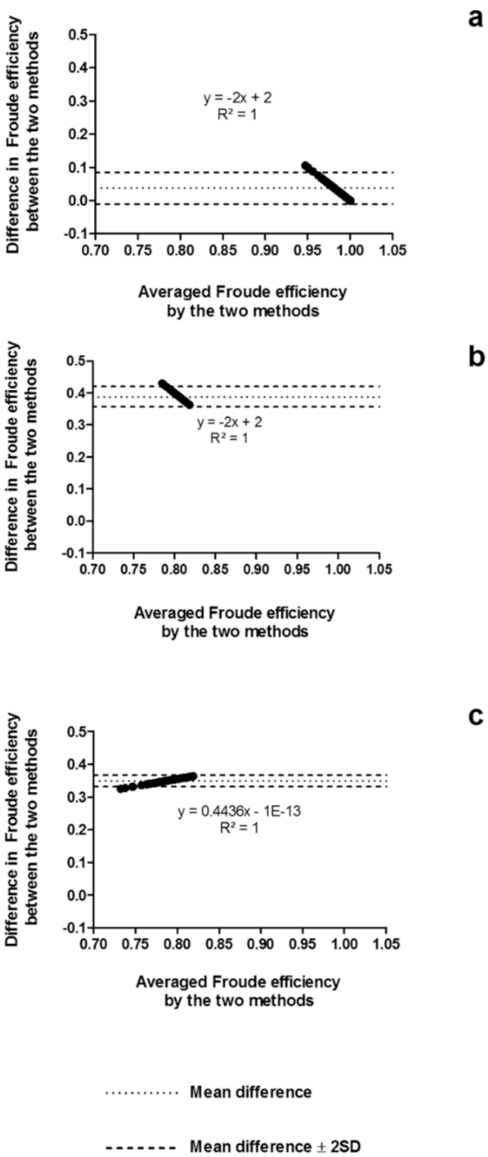

Figure 14. Bland-Altman plots testing the agreement between the speed-based efficiency and the MAD System assumption (a), paddle-wheel and MAD System assumption (b), and paddle-wheel and speed-based efficiency (c).

In free swimming, there was an interaction between swimming speed and method to assess the arm stroke efficiency (p=0.025). No differences were found in power-based efficiency between the different speeds (p>0.05). The arm stroke efficiency assessed using the speed-based and paddle-wheel methods significantly decreased from 80 to 100% of v_{200} (p<0.001). The individual comparisons of the arm stroke efficiency between the different speeds for each method are presented in Figure 15.

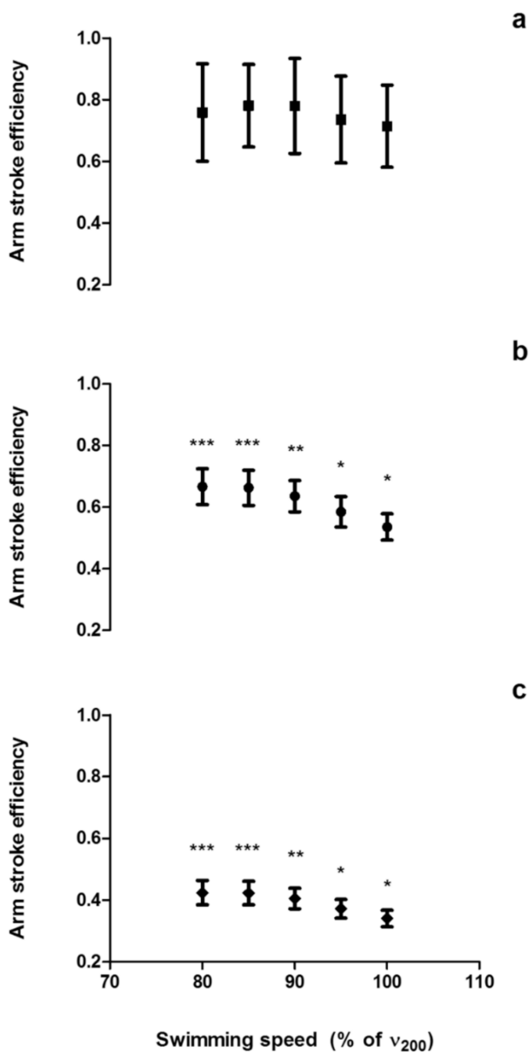

Figure 15. Froude efficiency assessed by the power-based (a), paddle-wheel (b) and speed-based (c) methods at different speeds, during the incremental protocol.
***Different from arm stroke efficiency values at 95 and 100% of v_{200m} (p<0.05).
**Different from arm stroke efficiency values at 85, 95 and 100% of v_{200m} (p<0.05).
*Different from arm stroke efficiency values at all swimming speeds (p<0.05).

The individual comparisons of the arm stroke efficiency between the different methods are presented in Figure 16.

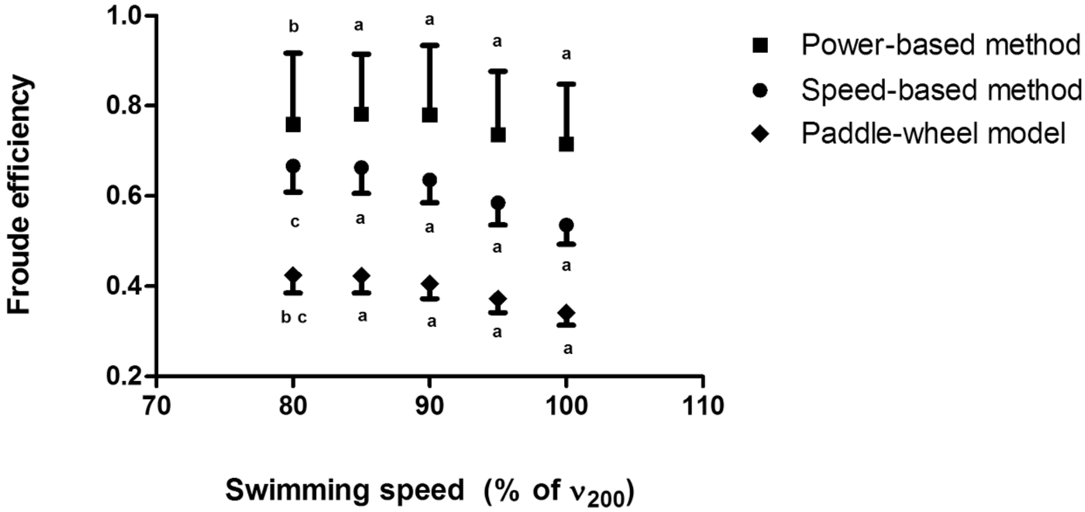

Figure 16. Froude efficiency assessed by the power-based, paddle-wheel and speed-based methods at different speeds, during the incremental protocol.
a. All methods are different.
b. Difference between the power-based method and the paddle-wheel model.
c. Difference between v/u and the paddle-wheel model.

In this condition, speed-based method was ~16% lower than the power-based method (average difference: -0.14±0.13; $p<0.001$), paddle-wheel efficiency was ~46% lower than the power-based method (average difference: -0.36±0.13; $p<0.001$) and ~36% lower than the speed-based method (average difference: -0.22±0.03; $p<0.001$). The differences between methods were within the limits of agreement and seemed to be determined by the magnitude of the averaged arm stroke efficiency between methods, as shown in Figure 17.

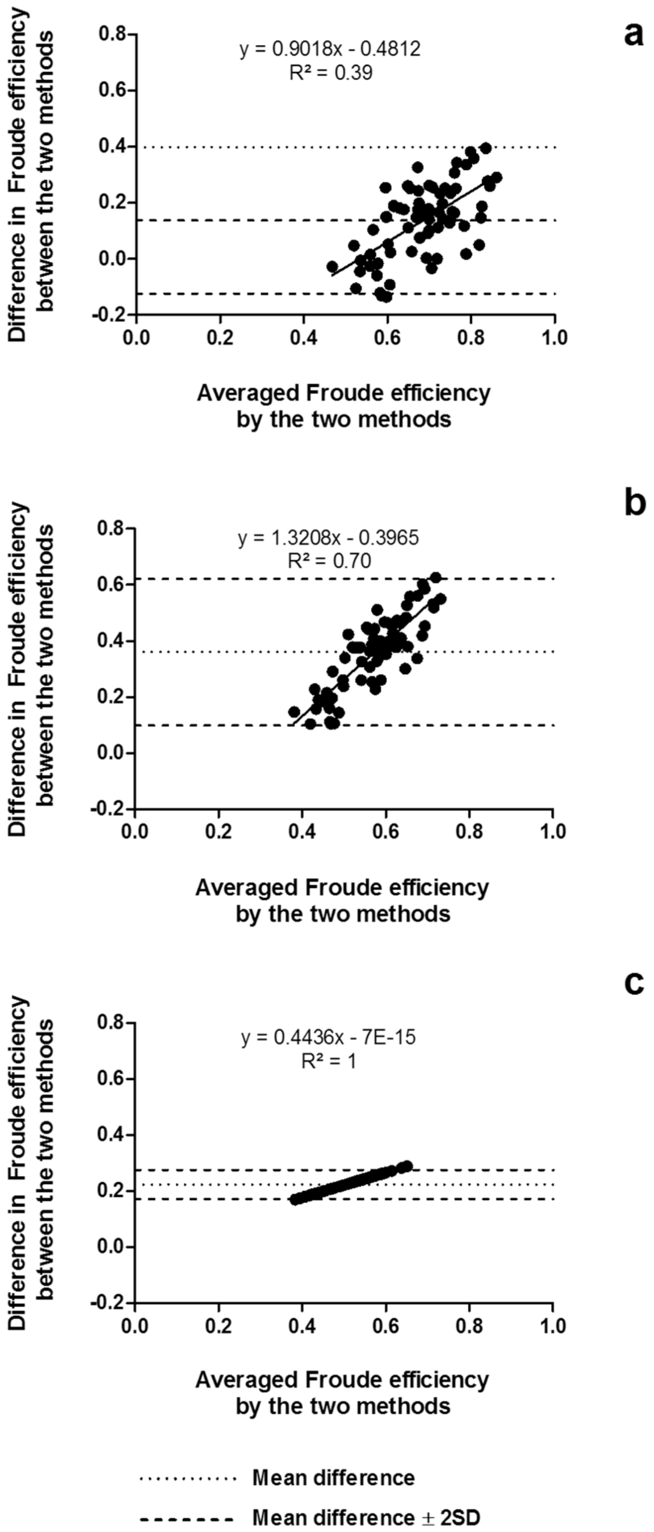

Figure 17. Bland-Altman plots testing the agreement between the speed-based and power-based efficiencies (a), paddle-wheel and power-based efficiency (b), and paddle-wheel and speed-based efficiency (c) in the free-swimming condition.

All swimming speeds were different from each other (p<0.001), as expected. Significant effects of swimming speed on D, SF and SL were observed (p<0.001). Also, swimming condition had a significant effect on SF and SL (p<0.001). Moreover, an interaction between swimming speed and swimming condition was observed for SF and SL (p<0.001).

Values of $\dot{W}_{ext}$, $\dot{W}_{d}$ and $\dot{W}_{k}$ increased with swimming speed (p<0.001). In addition, $\dot{W}_{ext}$ and $\dot{W}_{k}$ decreased in the MAD System condition in comparison to free swimming (p<0.001). The interaction between swimming speed and swimming condition for $\dot{W}_{ext}$(p<0.001) and $\dot{W}_{k}$ (p<0.001) made it possible to compare these parameters individually between the different steps and the different swimming conditions.

The mean (±SD) values of the biomechanical parameters as well as the individual differences between each step and between free swimming and MAD System conditions are reported in Table 5.

Table 5. Biomechanical parameters in free swimming and MAD System conditions. Values of $\dot{W}_{ext}$ and $\dot{W}_k$ in free swimming were obtained from the speed-based method to assess the arm stroke efficiency.

Step	Swimming speed ($\%v_{200}$ and $m \cdot s^{-1}$)		Active Drag (N)	Speed-specific drag	Stroke frequency (Hz)		Stroke length (m)		$\dot{W}_{ext}$ (W)		$\dot{W}_d$ (W)		$\dot{W}_k$ (W)	
	Both conditions		Both conditions	Both conditions	Free swimming	MAD System	Free swimming	MAD System	Free swimming	MAD System	Free swimming	MAD System	Free swimming	MAD System
1	80%	1.09±0.09 [b]	43.0±11.1 [b]	36.6±9.4	0.49±0.04 [a,b]	0.40±0.03 [a,b]	2.22±0.23 [a,c]	2.70±0.00 [a]	72±23 [a,b]	47±14 [a,b]	47±14 [b]	47±14 [b]	25±11 [a,b]	0±0 [a]
2	85%	1.15±0.09 [b]	47.7±11.7 [b]	35.9±8.3	0.53±0.04 [a,b]	0.42±0.04 [a,b]	2.20±0.17 [a,c]	2.70±0.00 [a]	85±28 [a,b]	55±16 [a,b]	55±16 [b]	55±16 [b]	30±13 [a,b]	0±0 [a]
3	90%	1.22±0.10 [b]	52.6±12.3 [b]	35.4±7.5	0.58±0.06 [a,b]	0.45±0.04 [a,b]	2.12±0.15 [a,c]	2.70±0.00 [a]	104±33 [a,b]	65±18 [a,b]	65±18 [b]	65±18 [b]	39±16 [a,b]	0±0 [a]
4	95%	1.29±0.10 [b]	57.7±13.3 [b]	34.8±6.7	0.65±0.07 [a,b]	0.47±0.04 [a,b]	1.97±0.14 [a,b]	2.70±0.00 [a]	130±42 [a,b]	75±21 [a,b]	75±21 [b]	75±21 [b]	55±22 [a,b]	0±0 [a]
5	100%	1.35±0.10 [b]	63.3±14.4 [b]	34.4±6.2	0.76±0.08 [a,b]	0.51±0.04 [a,b]	1.79±0.11 [a,b]	2.70±0.00 [a]	165±52 [a,b]	87±24 [a,b]	87±24 [b]	87±24 [b]	78±29 [a,b]	0±0 [a]

a. Different from the other condition ($p<0.05$).

b. Different from all steps ($p<0.05$).

Significant effects of swimming speed were observed for metabolic parameters, indicating that $\dot{V}O_2$, $[La^-]_{net}$ and C increase with speed ($p<0.001$). Moreover, swimming on the MAD System promoted a reduction in $\dot{V}O_2$ ($p<0.001$), $[La^-]_{net}$ ($p=0.001$), and C ($p<0.001$). The interaction between swimming speed and swimming condition allowed the individual comparisons between each step and each condition for the $\dot{V}O_2$ ($p=0.006$), $[La^-]_{net}$ ($p<0.001$) and C ($p<0.001$) The mean (±SD) values of the metabolic parameters as well as the individual differences between free swimming and MAD System conditions are presented in Figure 18. Values of $\dot{V}O_2$ ranged from 31.5±7.4 to 44.9±7.2 $mlO_2·kg·min^{-1}$ in free swimming and from 27.4±5.8 to 36.8±5.0 $mlO_2·kg·min^{-1}$ in the MAD System condition; $[La^{-1}]_{net}$ ranged from 0.7±0.5 to 4.9±2.7 $mmol·l^{-1}$ in free swimming and from 0.4±0.5 to 1.6±0.6 $mmol·l^{-1}$ in the MAD System condition; and C ranged from 0.65±0.18 to 0.85±0.20 $kj·m^{-1}$ in free swimming and from 0.55±0.13 to 0.64±0.11 $kj·m^{-1}$ in the MAD System condition.

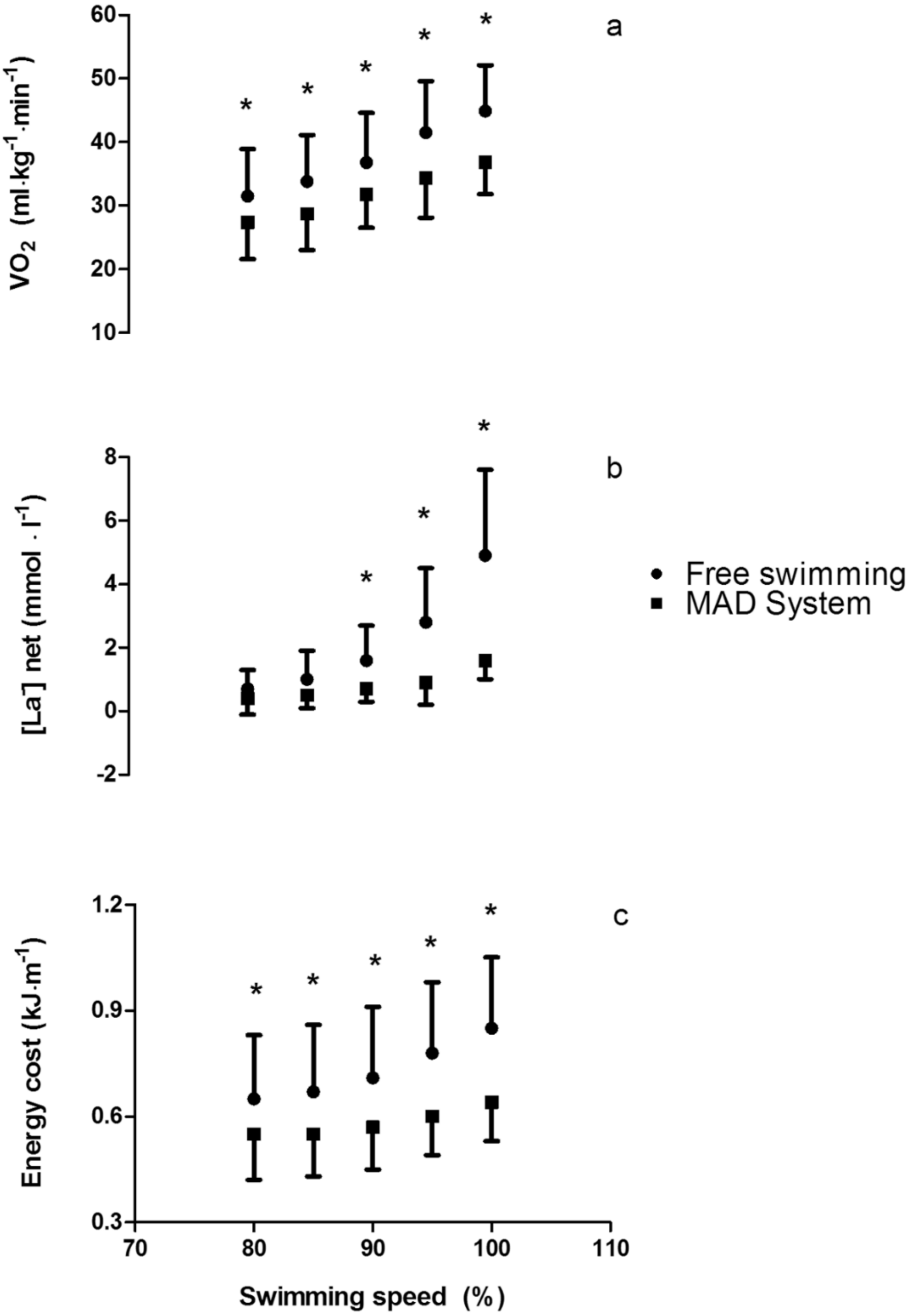

Figure 18. Individual differences in oxygen uptake (a), blood lactate concentration (b) and energy cost (c) between free swimming and MAD System conditions for each imposed speed (*p<0.05).

Swimming speed had a significant effect on $\dot{E}_{aer}$, $\dot{E}_{aner}$, $\dot{E}_{tot}$, aerobic and anaerobic contributions (p<0.001). Significant effects of swimming condition on $\dot{E}_{aer}$ (p<0.001), $\dot{E}_{aner}$ (p=0.002), $\dot{E}_{tot}$ (p<0.001), aerobic contribution (p<0.001) and anaerobic contribution (p<0.001) were also observed. Interaction between swimming speed and condition for $\dot{E}_{aer}$ (p=0.001), $\dot{E}_{aner}$ (p<0.001), $\dot{E}_{tot}$(p<0.001), aerobic contribution (p<0.001) and anaerobic contribution (p<0.001), allowed the individual comparisons between each step of the protocol and between each swimming condition, as presented in Table 6.

Table 6. Partitioning of the metabolic power input in free swimming and MAD System conditions.

Step	$\dot{E}_{aer}$ (W)		$\dot{E}_{anaer}$ (W)		$\dot{E}_{tot}$ (W)		Aerobic contribution (%)		Anaerobic contribution (%)	
	Free swimming	MAD System	Free swimming	MAD System	Free swimming	MAD System	Free swimming	MAD System	Free swimming	MAD System
1	702±222 [a c]	598±166 [a c]	15±15 [c]	9±10 [e]	716±230 [a c]	600±173 [a b]	98±1 [c]	99±1 [d]	2±1 [c]	1±1 [d]
2	759±241 [a c]	629±171 [a c]	23±25 [c]	10±10 [e]	782±255 [a c]	648±181 [a b]	97±2 [c]	99±1 [d]	3±2 [c]	1±1 [d]
3	833±260 [a b]	699±160 [a b]	39±31 [a b]	16±11 [a d]	873±283 [a b]	707±186 [a b]	96±2 [a b]	98±1 [a d]	4±2 [a b]	2±1 [d]
4	948±276 [a b]	763±186 [a b]	71±52 [a b]	23±21 [a d]	1018±316 [a b]	784±192 [a b]	94±3 [a b]	97±2 [a d]	6±3 [a b]	3±2 [d]
5	1032±270 [a b]	824±166 [a b]	130±88 [a b]	40±20 [a b]	1162±337 [a b]	877±193 [a b]	90±5 [a b]	96±2 [a b]	10±5 [a b]	4±2 [d]

a. Different from the other condition ($p<0.05$).
b. Different from all steps ($p<0.05$).
c. Different from steps 3, 4 and 5 ($p<0.05$).
d. Different from step 5 ($p<0.05$).

Among the variables selected from the principal component analysis, the redundant parameters were excluded. The eigenvalues of each variable in the first two principal components are presented in Table 7.

Table 7. Loading values of the studied parameters in the first two principal components of the set of observations.

	Eigenvalues	
	Principal component 1	**Principal component 2**
Shoulder to hand distance	0.77	0.44
Stroke frequency	0.67	-0.25
Stroke length	-0.13	0.44
Active drag	0.84*	0.45
Power to overcome drag	0.88*	0.37
Speed-specific drag	0.41	0.80**
Arm stroke efficiency	-0.87**	-0.12
External mechanical power	0.92**	0.33
Power wasted to the water	0.94*	0.30
Aerobic metabolic power	0.94*	0.07
Anaerobic metabolic power	0.77	-0.59
Total metabolic power	0.96**	-0.09
Oxygen uptake	0.88*	0.15
Blood lactate concentration	0.70	-0.64
Energy cost	0.93**	-0.10
Aerobic contribution	-0.61	0.71
Anaerobic contribution	0.61	-0.71

**Parameters selected for the prediction model.

*Redundant parameters with significant eigenvalues that were not included in the prediction model.

The selected parameters were divided into biomechanical (η_F, $\dot{W}_{ext}$ and k) and physiological ($\dot{E}_{tot}$ and C) prediction models. The multiple linear regressions indicated that all parameters were significantly determinant to the prediction models (p<0.001). Both biomechanical (R^2=0.98; p<0.001) and physiological (R^2=0.98; p<0.001) models could significantly predict the variances in v_{200} and are presented in Equations 23 and 24:

$$v_{200} = 0.003 \cdot \dot{W}_{ext} + 0.754 \cdot \eta_F - 0.012 \cdot k + 0.0873 \qquad (23)$$

$$v_{200} = 0.001 \cdot \dot{E}_{tot} - 1.643 \cdot C + 1.315 \qquad (24)$$

Discussion

This study aimed to compare the different methods to assess the arm stroke efficiency in front crawl swimming with the arms only, in two conditions: swimming on the MAD System and free swimming. The main biophysical effects of swimming on the MAD System were identified and two prediction models were established to explain the variances in v_{200}.

Arm stroke efficiency in the MAD System and free swimming conditions

Although the three ways to estimate η_F when swimming on the MAD System were significantly different, our results indicate that the speed-based method provides the closest values to the theoretical arm stroke efficiency for this condition ($\eta_F = 1$), in which the power waisted in transferring kinetic energy to the water is neglected, assuming swimming speed is constant (Toussaint et al., 1988). Values of speed-based η_F ranged from 0.9 to 1 and were, in average, ~4% lower than the theoretical η_F expected for the MAD System. This method was first reported by Martin et al. (1981) as a model to describe the hand propulsion in front crawl swimming, in which the arm is considered a rigid segment of length l, rotating at constant angular speed around the shoulder. The main assumption of this method is that the active drag and the effective force applied by the hand are the same for a given constant speed. Therefore, η_F results from the ratio of the tangential hand speed and the average forward speed, as described in Equation 20. This approach has been adapted by Zamparo et al. (2005), as a simplified paddle-wheel model, with the purpose of calculating the arm stroke efficiency during the underwater phase only, over half a stroke cycle. Although kinematical models of the arm stroke propulsion have been largely used to assess the arm stroke efficiency in front crawl swimming (Martin et al., 1981; Zamparo et al. 2005; Zamparo, 2006; Zamparo et al., 2008; Zamparo et al., 2014; Peterson Silveira et al., 2016), to our knowledge this is the first study comparing these methods to the theoretical efficiency when swimming on the MAD System.

The outcomes of the simplified paddle-wheel model were significantly lower than those of the theoretical efficiency when swimming on the MAD System (~39%) and of the speed-based method in this condition (~35%). The magnitude of the differences between the paddle-wheel and speed-based values was nearly the same in the free-swimming condition (~36%). Both speed-based and paddle-wheel methods assume that propulsion is generated by a rigid segment rotating at constant speed around the shoulder (Martin et al, 1981; Zamparo et al., 2005). The conceptual difference between these methods is that the paddle-wheel model includes a component to the equation initially proposed by Martin et al. (1981) aiming to consider only the underwater phases of the arm stroke over half a cycle (i.e. a single arm stroke), from 0 to π (Zamparo et al., 2005). However, the adaptation proposed by Zamparo et al. (2005) seems to be conflictual with the original assumptions of the model.

By assuming the arm is rotating at a constant angular speed around the shoulder, the method considers that the average angular speed of the propelling segment is the same in the aerial and underwater phases of the arm stroke and that there is not an overlap between propulsive actions generated by each upper-limb. Therefore, the initial equation proposed by Martin et al. (1981), in which η_F is based on the ratio of v_{hand} (calculated from SF values) and v (Equation 20), should not be adjusted for this purpose. In fact, the duration of the underwater and aerial phases of the arm stroke are not necessarily the same (Chollet et al., 2000) and the calculation of the arm stroke efficiency is meaningful for the propulsive phase only. Thus, although differences between the speed-based method and the theoretical efficiency assumed for the MAD System condition were small, they were possibly related to eventual propulsive gaps between pads. The only way to avoid such miscalculations of the η_F would be considering v_{hand} and v during the propulsive phases only, using the original model proposed by Martin et al. (1981).

Differently than in the MAD System condition, in which lower differences were found between the speed-based efficiency and the theoretical efficiency assumed for that condition, no “real” efficiency could be used to compare methods in free swimming. Relatively to the power-based method, a larger difference in the speed-based (~16%) and paddle-wheel values (~46%) was observed, which could be caused, at least partially, by a longer duration of non-propulsive phases in this condition, since swimmers were not constrained to generate propulsion by pushing-off fixed points. The higher values of power-based efficiency could also be related to the several assumptions of this method

(Toussaint et al., 1988), especially for considering $\dot{E}_{tot}$ as the only predictor of $\dot{W}_{ext}$, which may lead to a miscalculation.

It should be highlighted, however, that despite all methods provided significantly different values of η_F, they agreed with each other and are valid methods to measure efficiency, although not interchangeably, as indicated in Figures 14 and 17. The amplitude of the limits of agreement were shorter in the MAD System condition, which is possibly related to the "fixed" values of η_F assumed for this condition, reducing the variability in the averaged efficiency and in the differences between the methods. Furthermore, since speed-based and paddle-wheel η_F were obtained from the same parameters, the variances in η_F obtained from both methods are similar, resulting in shorter limits of agreement when comparing these methods, in both conditions. Especially in the free-swimming condition, the linear regressions provided by the agreement analysis indicated that differences between methods are determined by the magnitude of the averaged efficiency, which means that differences are higher at high efficiency values (and low swimming speeds) and closer to 0 at lower efficiency values (and higher swimming speeds).

Biophysical adaptations to enhancing efficiency

When swimming on the MAD system, the arm stroke efficiency was enhanced, since it was forced to "maximal" (Toussaint et al., 1988). Assuming $\dot{W}_d$ is the same in both conditions for a given constant speed, when swimmers are submitted to a condition in which the arm stroke efficiency is reduced, as is the case for free swimming, the $\dot{W}_k$ and $\dot{W}_{ext}$ will be higher (see Equations 15, 16 and 22). In fact, our results indicate a reduction of ~34% in $\dot{W}_{ext}$ at the lowest swimming speeds and of ~47% at v_{200} when swimming on the MAD System, relatively to free swimming at paired swimming speeds, which is in accordance with data reported in previous studies for low submaximal speeds (Toussaint et al., 1988; Toussaint et al., 1989; Toussaint 1990). The reduced values of $\dot{W}_k$ and $\dot{W}_{ext}$ when swimming on the MAD System lead to a reduction in SF (18-33%) and an increase in SL (22-51%). These results confirm that the arm stroke efficiency is directly related to the SL and inversely related to the SF, as previously reported by Zamparo et al. (2005).

The biomechanical adaptations to the MAD System condition were followed by an increase in swimming economy. When forcing swimmers to perform at "maximal" arm stroke efficiency, the energy cost, as well as the $\dot{E}_{tot}$, reduced significantly (~16-24% in the range of speeds studied). Such adaptations have been previously reported by Toussaint et al. (1988), although they neglected the anaerobic contribution by submitting swimmers to low submaximal intensities only. Our results indicate that the anaerobic contribution to the total metabolic power is not neglectable, and increases with the swimming speed, as previously reported (Capelli et al., 1998, Gastin, 2001). Moreover, the adaptions to the MAD System condition have shown that the anaerobic contribution reduces when increasing the arm stroke efficiency at a given swimming speed, suggesting that swimmers could sustain a given speed for a longer duration when enhancing efficiency.

Overall, our findings suggest that swimming on the MAD System might be a useful approach to increase the useful components of the mechanical power for a given metabolic demand, or even increasing the maximal power output as suggested by Toussaint and Vervoorn (1990). Increasing the propelling surface area could also be used for this purpose, as reported by Toussaint et al. (1989), although long-term biophysical adaptations to training in these conditions are still unclear.

Biophysical predictors of maximal swimming speed

The biomechanical prediction model was composed by η_F, $\dot{W}_{ext}$, and k, explaining 98% of the variances in v_{200m}. Therefore, the highest speeds can be achieved by the combination of high values of η_F and $\dot{W}_{ext}$ (hence high $\dot{W}_d$ and low $\dot{W}_k$), accompanied by low values of k (related to the hydrodynamic resistance), supporting the theoretical relationship provided from the combination of Equations 12 and 13 (Alexander, 1977; Daniel, 1991):

$$\dot{W}_d \approx k \cdot v^3 \tag{25}$$

Thus, by combining Equations 22 and 25, the relationship between the biomechanical predictors and swimming speed is determined:

$$v^3 \approx (\dot{W}_{ext} \cdot \eta_F)/k \tag{26}$$

A similar prediction model was reported by Zamparo et al. (2014), in which ~75% of the variability in v_{200m} could be explained by the variability in η_F and $\dot{W}_{ext}$ (assessed with an arm crank ergometer). Relatively to the prediction model reported by Zamparo et al. (2014), the quality of our prediction has increased by considering k, which is in fact another source of variability in maximal swimming speed (Zamparo et al., 2009; Zamparo et al., 2014). Another reason that could explain the higher quality of our prediction might be related to the method used to assess the $\dot{W}_{ext}$, since in our study $\dot{W}_{ext}$ was based on actual front crawl swimming assessments instead of a dryland protocol.

Two main physiological predictors were identified from the principal components analysis (C and $\dot{E}_{tot}$) and included in a regression that explained 98% of the variability in v_{200m}. The interplay between C and $\dot{E}_{tot}$ in determining maximal swimming performance is described in Equation 5, in which v is directly related to the capability of producing a high $\dot{E}_{tot}$, and inversely related to C, supporting the theoretical basis of limiting factors of swimming performance (di Prampero, 1986; Capelli et al., 1998; Zamparo et al., 2010). The two prediction models defined in our study are not independent from each other, even though they could explain the variability in v_{200m} individually. Swimming performance depends, in fact, on the interplay between biomechanical and bioenergetic parameters (Pendergast et al., 2003; Di Prampero, Pendergast & Zamparo, 2011; Pendergast & Zamparo, 2011). For instance, an increase in η_F will always be accompanied by a reduction in C for a given swimming speed (Zamparo et al., 2005; Zamparo et al., 2012).

Likewise, any increase in the $\dot{E}_{tot}$ will allow a swimmer to produce a higher $\dot{W}_{ext}$ (Toussaint et al., 1988; Zamparo & Swaine, 2012).

Conclusions

Although both methods to assess the arm stroke efficiency on the MAD System differed from the expected values for this condition ($\eta_F = 1$), the speed-based method provided the closest values ($\eta_F \sim 0.96$). The small difference between the MAD System assumption and the speed-based efficiency might be related to the assumptions of this method, that does not distinguish the propulsive and non-propulsive phases of the arm stroke. The large differences between the paddle-wheel assumption and the other methods may indicate that the way this method attempts to distinguish the underwater and aerial phases of the arm stroke is inadequate. In free swimming, all methods (power-based, speed-based and paddle-wheel model) provided different values of arm stroke efficiency, although they agree with each other.

The arm stroke efficiency was enhanced in the MAD System condition, relatively to free-swimming, which lead to mechanical adaptations that included a reduction in stroke frequency and an increase in stroke length, reducing the external mechanical power output in a range of paired swimming speeds, from 80% to 100% of v_{200m}. These effects were followed by metabolic adaptations, with a decrease in energy cost and total metabolic power input for a given speed. Moreover, η_F, $\dot{W}_{ext}$, and k (biomechanical prediction model), as well as C and $\dot{E}_{tot}$ (physiological prediction model), were the main determinants of v_{200m}, confirming the that swimming performance depends on the balance of biomechanical and bioenergetic parameters.

Acknowledgements

We would like to thank the swimmers who voluntarily participated in this study, all colleagues who helped in the data collection and analysis, KulzerTEC for providing part of the material, and CAPES Foundation (Ministry of Education of Brazil) for the financial support.

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Overall conclusion

The external mechanical power at the maximal oxygen uptake (dry-land) alone is not enough to explain the maximal swimming speed in a 200 m front crawl using the arms only. Instead, a combination of the external mechanical power and the arm stroke efficiency could explain ~75% of the variances in maximal speed. This was further confirmed by a biomechanical prediction model including the external mechanical power (in the water), the arm stroke efficiency and the speed-specific drag, which explained 98% of the variances in maximal speed in the same distance. Moreover, a physiological model including the total metabolic power and the energy cost of swimming also explained 98% of the variances in maximal speed, confirming that swimming performance depends on the balance between biomechanical and physiological parameters.

When swimming on the MAD System, a condition in which the arm stroke efficiency is forced to “maximum” values, the main biophysical adaptations were a reduction in the external mechanical power, followed by a reduction in the energy cost and in the total metabolic power for a given speed, relatively to free-swimming. These adaptations were also reflected in simple stroke parameters, with an increase in stroke length and a reduction in stroke frequency, confirming the relationship of these parameters with the arm stroke efficiency. Therefore, increasing swimming efficiency for a given speed implied an increase in swimming economy.

Methodological considerations should be taken into account when assessing the arm stroke efficiency in front crawl, including (1) adjustments to the arm stroke/leg kick contribution to swimming speed in a “full stroke” condition (using both upper and lower limbs to generate propulsion), and (2) the differences between the methods described in the literature. When increasing the stroke frequency (and speed), from very low to maximal values, swimmers increased the leg kick contribution to swimming speed. Hence, the calculation of arm stroke efficiency should include individual adjustments to swimming speed, especially in the lower speeds, instead of fixed values normally reported in the literature. Moreover, it is important to highlight that values of arm stroke efficiency should be interpreted carefully since the power-based method/MAD System assumption provided higher values than the speed-based and paddle-wheel methods. In addition, the speed-based method provided higher values than the paddle-wheel model, both in the

MAD System and free-swimming conditions. It is important to highlight, however, that despite the differences reported in this thesis, all methods presented a good agreement with each other, which means all methods could be used to estimate the arm stroke efficiency, although they are not interchangeable.

Appendix 1

UFRGS
UNIVERSIDADE FEDERAL
DO RIO GRANDE DO SUL

Bi-lateral agreement for a co-tutoring thesis in the framework of the PhD program in Science of Physical Exercise and Human Movement

Phd student Ricardo Peterson Silveira

the **Università degli Studi di Verona** (hereinafter referred as UNIVR), located in via dell'Artigliere 8, 37129 Verona, (Italia), represented by its Rector, Professor Alessandro Mazzucco,

AND

the **Universidade Federal do Rio Grande do Sul** (hereinafter referred as UFRGS) located in Av. Paulo Gama 110, Bairro Farroupilha, Porto Alegre, Rio Grande do Sul (Brazil), represented by its Rector, Professor Carlos Alexandre Netto,

In conformity with: (for the italian part)

- The Law of 3 July 1998 no. 210 art. 4 *"Norme per il Reclutamento dei ricercatori e dei professori universitari di ruolo"*;
- The UNIVR Statute, approved with D.R. no. 6435 of 7th October 1994 and modified by D.R. no. 2/2002 of 8th january 2002;
- The UNIVR Regulations on matter of reaserch doctorates settled by the University *"Regolamento del dottorato di ricerca presso l'Università degli Studi di Verona"* issued with D.R. no. 10948 of 22nd december 1999 and subsequently modified by D.R. no. 1715 of 1st July 2010.

And in conformity with: (for the foreign part)

- The resolution of August 17th 2005 no. 29/2005 about international co-tutela between UFRGS and abroad institutions

united in their desire to contribute to establishing and developing scientific co-operation between Italian and foreign teams of researchers through the mobility of their doctoral candidates

AGREE AS FOLLOWS

Article 1
Subject of the agreement

This agreement is intended to set the policy for a co-tutoring thesis between the two above mentioned Universities, in order to define conditions and guidelines for the preparation of a doctoral thesis by the student Ricardo Peterson Silveira, currently enrolled at the Università degli Studi di Verona in his 2nd year of the PhD Program in Science of Physical Exercise and Human Movement, Graduate School of Translational Biomedical sciences, Cycle 27°.

The topic of the thesis will be: Propelling Efficiency in Swimming

Project description: The aim of this project is to investigate the interplay between propelling efficiency and arm's power output in determining the maximal speed in front crawl swimming and to identify the effects of the leg kick action on the propelling efficiency of the arm stroke. This part of the project is already completed (UNIVR). The second aim of this study is to compare data of propelling efficiency as determined by 3D underwater kinematic analysis of the front crawl and the backstroke with those calculated based on models reported in the literature. This part of the project will be carried at UFRGS.

Duration: two years and half (from the 1st of June 2013 to the 31st of dicember 2015). The term of 1 year and half has to be prolonged since at UFRGS the PhD program lasts 4 years (3 years at UNIVR).

Article 2
Research periods

The research periods spent by the student in one or in the other University will vary on practical needs and will be fixed jointly by agreement between the two thesis supervisors. These periods will be more or less of equal length.

The research periods will be distributed as follows:
at the UNIVR: 18 months
at the UFRGS: 18 months (*max 18 months)* + 1 year since at UFRGS the PhD program lasts 4 years

In compliance with the rules of the PhD Program in Science of Physical Exercise and Human Movement (Graduate School of Translational Biomedical sciences, Cycle 27°), the student is required to provide a short description of the "state of the art" of his project before the end of each (solar) year so as to obtain the approval of UNIVR, be enrolled to the third year and be admitted to the Thesis defence. According to these rules the student should also provide (at the same time) a document stating that he has followed at least 60h/year of seminar/courses jointly approved by the tutors.

Article 3
Enrolment fees

The student will be compulsory enrolled at both Universities. Enrolment fees will be paid to the UNIVR while the UFRGS will exempt the student from the payment of every enrolment fee excep fixed fees established by the university's regulations on doctoral degrees in force.

Article 4
Insurance

The PhD student shall be obligatorily covered for health and accident insurance in the two countries according to the law in force in each of the countries.

Article 5
Thesis supervisors

The student will research and write the doctoral thesis under the joint supervision and responsibility of:

For the UNIVR:

- **Professor** Paola Zamparo, Department of Neurological, Neuropsychological, Morphological and Movement Sciences

For the UFRGS:

- **Professor** Flávio Antônio de Souza Castro, Department of Physical Education

Who agree to diligently fulfil the role of supervisors of the student.

The positive assessment of both thesis supervisors will be a necessary prerequisite for admission to the final examination.

Article 6
Thesis defence and examination commission

The fees for the doctoral thesis discussion will be paid only at the UFRGS, which is the institution where the PhD student will defence his doctoral thesis. The UNIVR will exempt the student from payment of every fee concerning his/her thesis defence.

The one and only oral defence of the thesis will take place at the UFRGS within 2016 (including the year of prorogation) (see last paragraph art 1).

The examination commission will be composed by an equal number of scientific representatives from both Universities including the two thesis supervisors (for a maximum of six components) and in accordance with the regulatios for doctoral degrees in force at both Institutions.

Article 7
Language

The doctoral thesis will be written and orally defended in english language. The abstract will be written in english and portugese.

Article 8
Information exchange

The contracting Institutions, through their respective thesis supervisors, undertake to notify each other of all the information and documentation useful for the purposes of organising the joint thesis that is the subject matter of this present agreement.

For information concening the organization of the present co-tutoring agreement, please refer to the following offices:

For the UNIVR:
Ufficio Dottorati di Ricerca Nazionali ed Internazionali
Via Giardino Giusti n° 2,
Verona, Italy
e-mail: dottorati.ricerca@ateneo.univr.it
Tel: 0039 045 8028092

For the UFRGS:
Pró-reitoria de Pós-Graduação da Universidade Federal do Rio Grande do Sul. Avenida Paulo Gama, 110, 7° andar – Bairro Farroupilha – CEP 90040-060
Porto Alegre – RS – Brasil
Email: propg@propg.ufrgs.br
Fone: 005551 3308 3602

Article 9
Protection of the subject matter of the thesis and publication

The protection of the subject matter of the thesis and likewise the publication, exploitation and protection of the results obtained by the student's research in the contracting Institutions will be subject to the applicable law in force and guaranteed in compliance with the specific procedures in this regard of each of the country involved n the joint thesis.

Article 10
Release of the doctoral degree

In accordance with the doctoral rules and regulations in force in each institution, each University undertakes to award a doctoral degree for the same thesis, following a favourable decision issued by the examination commission

The UNIVR will award the Ph.D. degree in Science of Physical Exercise and Human Movement

The UFRGS will award a Ph.D. degree in Human Movement Sciences

Appendix 2

UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL / PRÓ-REITORIA DE PESQUISA -

PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: Eficiência propulsiva na natação
Pesquisador: Flávio Antônio de Souza Castro
Área Temática:
Versão: 3
CAAE: 27110314.6.0000.5347
Instituição Proponente: Universidade Federal do Rio Grande do Sul
Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 648.622
Data da Relatoria: 17/04/2014

Apresentação do Projeto:
Retorno de Diligência

Projeto de doutorado
A velocidade máxima que um indivíduo pode atingir na água depende de diferentes fatores (ex.: eficiência propulsiva, potência mecânica entre outros), os quais variam de acordo com a população analisada, sendo que diferentes metodologias são utilizadas para aferir estes fatores.
O projeto visa entender as relações entre potência mecânica máxima de membros superiores, eficiência propulsiva da braçada e velocidade de nado e avaliar a acurácia e a concordância de um modelo simplificado proposto para o cálculo da eficiência propulsiva, quando comparado à análise tridimensional de vídeo.
Experimento 1:
Para a análise da eficiência propulsiva, serão convidados a participar deste estudo 10 nadadores competitivos, com no mínimo quatro anos de experiência na modalidade e treinando regularmente para competições, sendo cinco especialistas nas provas de nado livre e cinco especialistas nas provas de nado costas. O n foi baseado em calculo amostral

Será solicitado a todos os participantes que nadem tanto em estilo crawl quanto costas, em seis

Endereço: Av. Paulo Gama, 110 - Sala 317 do Prédio Anexo 1 da Reitoria - Campus Centro
Bairro: Farroupilha **CEP:** 90.040-060
UF: RS **Município:** PORTO ALEGRE
Telefone: (51)3308-3738 **Fax:** (51)3308-4085 **E-mail:** etica@propesq.ufrgs.br

velocidades de nado auto selecionadas, de muito lento (V1) a velocidade máxima (V6). Todas as tentativas serão gravadas por seis câmeras de vídeo (4 dentro d¿água e 2 fora) para a reconstrução do movimento de braçada.

Experimento 2
Para a análise da potência útil de propulsão, serão convidados a participar deste estudo 112 nadadores com diferentes níveis de experiência, divididos nos seguintes grupos: meninas praticantes de natação (n=16), meninos praticantes de natação (n=16), nadadores de elite (n=16), nadadoras de elite (n=16), triatletas (n=16), nadadores másters (n=16) e nadadores sem experiência em treinamento (n=16). A pesquisa será divulgada nas equipes e escolas de natação de Porto Alegre com o uso de cartazes. O n apresentado foi embasado por
cálculo amostral de acordo com dados da literatura.

Este projeto será realizado em 2 etapas: etapa 1 = simulação de braçada em dinamômetro; etapa 2 = nadar 25m em 6 velocidades em diferentes condições (braçada unilateral e bilateral; nado crawl) em quatro dias consecutivos.

Os pesquisadores irão apresentar TCLEs específicos para cada protocolo experimental. Para os indivíduos menores de idade (experimento 2), o TCLE sera apresentado ao responsável legal, além da apresentação de um termo de assentimento.

Objetivo da Pesquisa:
Entender as relações entre potência mecânica máxima de membros superiores, eficiência propulsiva da braçada e velocidade de nado e avaliar a acurácia e a concordância de um modelo simplificado proposto para o cálculo da eficiência propulsiva, quando comparado à análise tridimensional de vídeo.

Avaliação dos Riscos e Benefícios:
Adequados

Comentários e Considerações sobre a Pesquisa:
Pesquisadores atenderam as sugestões do CEP e o projeto encontra-se adequado para aprovação

Considerações sobre os Termos de apresentação obrigatória:

Adequados

Recomendações:

Conclusões ou Pendências e Lista de Inadequações:

Pesquisadores atenderam as sugestões do CEP e o projeto encontra-se adequado para aprovação

Situação do Parecer:

Aprovado

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Appendix 3

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ORIGINAL ARTICLE

The interplay between arms-only propelling efficiency, power output and speed in master swimmers

P. Zamparo · E. Turri · R. Peterson Silveira · A. Poli

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Abstract
Purpose To explore the interplay between arms-only propelling efficiency (η_p), mechanical power output ($\dot{W}_{tot}$) and swimming speed (V); these three parameters are indeed related through the following equation $V^3 = 1/k\eta_p\dot{W}_{tot}$ (where k is the speed-specific drag; $k = F/V^2$); thus, the larger are η_p and $\dot{W}_{tot}$ the larger is V. We furthermore wanted to test the hypothesis that a multiple linear regression between $\dot{W}_{tot}$, η_p and V would have a stronger correlation coefficient than a linear regression between $\dot{W}_{tot}$ and V alone.
Methods To this aim we recruited 29 master swimmers (21 M/8F) who were asked to perform (1) an incremental protocol at the arm-ergometer (dry-land test) to determine $\dot{W}_{tot}$ at $\dot{V}O_{2max}$ (e.g. $\dot{V}_{max}$); (2) a maximal 200 m swim trial (with a pull buoy: arms only) during which V and η_p were determined.
Results No relationship was found between $\dot{W}_{max}$ and η_p (not necessarily the swimmers with the largest $\dot{W}_{max}$ are those with the largest η_p and vice versa) whereas significant correlations were found between $\dot{W}_{max}$ and V ($R = 0.419$, $P = 0.024$) and η_p and V ($R = 0.741$, $P = 0.001$); a multiple linear regression indicates that about 75 % of the variability of V can be explained by the variability of $\dot{W}_{max}$ and η_p ($R = 0.865$, $P < 0.001$).
Conclusions These findings indicate that η_p should be taken into consideration when the relationship between $\dot{W}_{max}$ and V is investigated and that this allows to better explain the inter-subject variability in performance (swimming speed).

Keywords Front crawl · Swimming velocity · Swimming efficiency · Swimming power

Abbreviations

$\dot{E}$	Metabolic power input
EA	Elbow angle
F	Female swimmers
F_d	Drag force
HR_{max}	Heart rate at $\dot{V}O_{2max}$
K	Speed-specific drag
L	Shoulder to hand distance
M	Male swimmers
RER	Respiratory exchange ratio
SF	Stroke frequency
SL	Stroke length (distance covered per stroke)
V	Swimming speed
V_{200m}	Swimming speed in the 200 m maximal swim trial
$\dot{V}E_{max}$	Expired ventilation at $\dot{V}O_{2max}$
$\dot{V}O_{2max}$	Maximal oxygen consumption
$\dot{W}_d$	Power to overcome drag
$\dot{W}_{ext}$	External mechanical power
$\dot{W}_{int}$	Internal mechanical power
$\dot{W}_{max}$	Mechanical power output at $\dot{V}O_{2max}$
$\dot{W}_{tot}$	Total mechanical power output
η_d	Drag (performance) efficiency
η_o	Overall (mechanical) efficiency
η_P	Propelling efficiency

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Introduction

The mechanical power output ($\dot{W}_{tot}$) that can be produced to sustain locomotion (on land and in water) depends on the metabolic power input ($\dot{E}$, derived from aerobic or anaerobic energy sources) and on the overall efficiency of locomotion (η_o):

$$\eta_o = \dot{W}_{tot}/\dot{E} \quad (1)$$

However, in water only a fraction of $\dot{W}_{tot}$ can be utilized to overcome resistive forces (hydrodynamic resistance, $\dot{W}_d$) since the swimmer has to produce additional power to give water kinetic energy not useful for propulsion (e.g. Alexander 1977; Daniel 1991). The fraction of $\dot{W}_{tot}$ that can be utilized, in water, to overcome hydrodynamic resistance is termed propelling efficiency (η_p):

$$\eta_p = \dot{W}_d/\dot{W}_{tot} \quad (2)$$

$\dot{W}_d$ can be assessed based on values of drag force (F_d) and swimming speed ($\dot{W}_d = F_d \cdot V$); since, as a first approximation, F_d is proportional to the square of swimming speed:

$$F_d \approx kV^2 \quad (3)$$

and:

$$\dot{W}_d \approx kV^3 \quad (4)$$

By combining Eqs. 2 and 4 one obtains:

$$V^3 = 1/k\eta_p\dot{W}_{tot} \quad (5)$$

Equation 5 defines the relationship among η_p, $\dot{W}_{tot}$ and k (speed-specific drag) at any given speed (V): it shows that the speed of locomotion, in the aquatic environment, will be larger when $\dot{W}_{tot}$ and η_p are higher and constant k is lower.

This theoretical background is useful to understand why swimming performance bears a closer relationship to the power developed during tethered and semi-tethered swimming than to the power measured using dry-land tests (e.g. Vronstov 2011). Indeed, in the former case (in water) the mechanical power output corresponds to the product η_p $\dot{W}_{tot}$: it represents the useful power that can be applied in water for propulsion (see Eq. 2) whereas, in the latter case (on land), the power corresponds to $\dot{W}_{tot}$: hence, in theory, η_p should also be measured and taken into account when considering the effects of mechanical power output on swimming speed. Indeed, when dry-land tests are utilized to determine $\dot{W}_{tot}$ in a group of swimmers of similar anthropometric and technical characteristics, the variability of η_p (and k) can be expected to be low and hence a good (and significant) relationship between V and $\dot{W}_{tot}$ can be expected, otherwise the relationship between these two parameters can be expected to be weak or insignificant. As an example, Costill et al. (1986) reported a significant relationship between sprint speed (over a distance of 25 yards) and the mechanical power exerted in water ($R = 0.84$, $N = 76$) but not with the mechanical power exerted during a dry-land test ($R = 0.24$, $N = 76$), both assessed during all out efforts lasting 12 s (e.g. the same duration of the swim test).

A further consideration that derives from this theoretical background is that the relationship between mechanical power and swimming performance has to be evaluated during tests of comparable duration (as in the study of Costill et al. 1986). Mechanical power output indeed decreases as a function of the duration of exercise (e.g. Wilkie 1980) and the time of exhaustion (during maximal all out efforts) determines the relative contribution of the aerobic and anaerobic energy sources to total energy expenditure (e.g. di Prampero 2003; di Prampero et al. 2011). This consideration can explain why a gradual reduction in the correlation between mechanical power output (assessed by means of dry-land test or semi-tethered swim test of few seconds duration) and V is observed over increasing swimming distances: the longer the distance (and thus the exercise time); the lower the correlation between these two parameters (e.g. Vronstov 2011; Sharp et al. 1982).

Moreover, whereas $\dot{W}_{tot}$ increases with the swimming speed, propelling efficiency decreases with it. Indeed, as indicated by Zamparo (2006), propelling efficiency is proportional to the distance covered per stroke and both tend to decrease at the high speeds attained in short course events; see, as an example, the curves relating speed and stroke frequency reported by Craig and Pendergast (1979). The slope of these curves represents the distance covered per stroke which is roughly constant at low to medium speeds but decreases sharply at maximal speeds. This means that the decrease in propelling efficiency counteracts the increase in $\dot{W}_{tot}$ when the speed increases (and viceversa): thus η_p acts as a confounding factor (when not taken into account) when the relationship between $\dot{W}_{tot}$ and V is investigated.

In the literature the relationship between upper body dry-land power (or semi-tethered swimming power) and swim velocity is mainly focused on sprint swimming (25–50 m, anaerobic energy sources) (e.g. Costill et al. 1986; Dominguez-Castelles et al. 2013; Swaine and Doyle 2000); however, the correlation between these two parameters ($\dot{W}_{tot}$ and V) should be significant also at slower speeds (e.g. over the 200–400 m distances where the aerobic energy sources are more relevant in determining mechanical power output) provided that all parameters of Eq. 5 are properly determined.

On the basis of these considerations, the main purpose of this study was to explore the interplay between arms-only propelling efficiency (η_p), mechanical power output ($\dot{W}_{tot}$) and swimming speed (V) in a heterogeneous group

Table 1 Anthropometric characteristics of the swimmers and years of practice

	Age (years)	Body mass (kg)	Stature (m)	BMI ($kg \cdot m^{-2}$)	Years of practice
M (21)	33.5 ± 9.1	75.2 ± 8.8	1.80 ± 0.06	23.2 ± 2.5	7.8 ± 6.5
F (8)	28.5 ± 8.6	57.8 ± 4.2*	1.63 ± 0.03*	21.6 ± 1.3*	8.1 ± 9.1
Range	20–50	52–99	157–197	18.4–29.5	1–30

Data are means ± 1SD

* Significant differences between M and F swimmers

of swimmers during a 200 m event. A further purpose of this study was to test the hypothesis that a multiple correlation between power output, η_p and V would have a stronger correlation coefficient than the simple correlation between power output and swimming speed.

To this aim we recruited male and female master swimmers with different technical and anthropometric characteristics, whom we asked to perform two tests:

Dry-land test: an incremental protocol at the arm-ergometer (arms only) to determine the mechanical power output at $\dot{V}O_{2max}$.
Swim test: a 200 m maximal test (with a pull buoy: arms only, as during the dry-land test) during which V and η_p were determined.

Methods

Participants

Twenty-nine master swimmers (21M/8F) were recruited for this study; their principal anthropometric characteristics are reported in Table 1. Their technical level was quite heterogeneous as indicated by the large SD values in their years of swimming experience (see Table 1) but all subjects learned to swim at a young age (5–7 years), trained regularly and competed at local or national level. The purpose and objectives of the study were carefully explained to each individual and written informed consent was obtained. The study conformed to the standards set by the Declaration of Helsinki, and the local Institutional Review Board approved the procedures.

Experimental procedure

Dry-land protocol (arms only)

The swimmers were requested to complete a maximal incremental test on a modified arm-crank-ergometer (Ergoline, Cosmed, I) (see Fischer et al. 2013). The protocol consisted of a 3-min warm up (unloaded) followed by incremental steps of 10 W/min (M) or 5 W/min (F) at a cadence of 60 rpm, until voluntary exhaustion. With this test maximal oxygen uptake ($\dot{V}O_{2max}$) and the corresponding mechanical power output were determined.

Before the beginning of the test the subjects were familiarised with the equipment and the procedures and their position on the ergometer was adjusted: the distance between the saddle and the crank was arranged to allow for full arm extension; the crank axis was positioned at the same height as the shoulders; the swimmers had to keep the back straight (un-supported) and to position their feet on the ground.

During these experiments, heart rate (HR), oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$) and respiratory exchange ratio (RER) were determined on a breath by breath basis by means of a previously calibrated metabolimeter (Quark b^2, Cosmed, Italy). The values recorded during the last 30 s of the highest completed load were then computed (see Table 1). The highest completed mechanical load was then defined as $\dot{W}_{max}$.

Overall efficiency of arm-cranking (η_o) was calculated based on data of mechanical power ($\dot{W}$, W) and oxygen consumption ($\dot{V}O_2$, $l\,s^{-1}$). The latter was expressed in W ($\dot{E}$, W) according to a formula which takes into account the respiratory exchange ratio: $\dot{E}(W) = (4.94\ \text{RER} + 16.04)\ \dot{V}O_2$ 1,000. Overall efficiency of arm-cranking was calculated from the slope of the individual $\dot{E}$ vs. $\dot{W}$ relationship based on the values assessed during the last 30 s of each load: $\dot{E} = a + b\,\dot{W}$, where b (the slope) is the reciprocal of η_o. These calculations were performed by taking into account metabolic data for which RER $\leq$1 (for further details see Zamparo and Swaine 2012).

Swimming protocol (arms only)

The experiments were performed in a 25 m swimming pool. The subjects were asked to swim the 200 m at maximal speed while using a pull buoy (i e. propulsion was obtained by means of the upper limbs only); they were asked to start with a push off from the wall and were allowed to perform regular turning motions at the end of each length. The average speed was then calculated from the time taken to cover the 200 m distance and termed V_{200m}.

Table 2 The parameters collected during the "dry-land" protocol

	$\dot{V}O_{2max}$ (ml min^{-1} kg^{-1})	HR_{max} (bpm)	$\dot{V}E_{max}$ (l min^{-1})	$\dot{W}_{max}$ (W)	RER_{max}	η_o
M (21)	33.1 ± 4.6	172 ± 10	112.7 ± 21.6	135.8 ± 24.8	1.16 ± 0.07	0.21 ± 0.02
F (8)	27.2 ± 4.2[a]	165 ± 14	69.6 ± 15.2[a]	78.7 ± 14.3[a]	1.10 ± 0.05	0.20 ± 0.02
Range	19.6–39.9	145–187	35.8–157.5	55–180	1.0–1.3	0.16–0.25

Data are means ± 1SD

$\dot{V}O_{2max}$ maximal oxygen uptake, HR_{max} heart rate at $\dot{V}O_{2max}$, $\dot{V}E_{max}$ expired ventilation at $\dot{V}O_{2max}$, $\dot{W}_{max}$ mechanical power output at $\dot{V}O_{2max}$, RER_{max} respiratory exchange ratio at $\dot{V}O_{2max}$, η_o overall mechanical efficiency

[a] Significant differences between M and F swimmers

The actual speed maintained by the subjects during each length (V, m s^{-1}) was measured from the time taken to cover the middle 10 m of each length, during which the average stroke frequency (SF, Hz) was also computed from the time taken to complete a given number of strokes. The distance covered per stroke (the stroke length, SL, m) was calculated by dividing the average speed by the corresponding stroke frequency. For all these parameters (V, SF and SL) the average value over the eight lengths of the pool was computed and used in further analysis.

The arm stroke efficiency (η_P) was calculated according to the simple model proposed by Zamparo et al. (2005). The model is based on the assumption that the arm is a rigid segment of length L, rotating at constant angular speed ($\omega = 2\pi$ SF) about the shoulder and yields the average "Froude" efficiency for the underwater phase only, as follows:

$$\eta_P = (V/(2\pi \mathrm{SF}L))(2/\pi) \quad (6)$$

where V is the swimmer's speed (in the middle 10 m of each lane), SF is the stroke frequency and L is the average shoulder to hand distance (calculated as described below). Since, in this study, the swim test was conducted with the use of a pull buoy, the contribution of the legs to forward propulsion is assumed to be nil and thus no correction to the speed of progression is needed to take into account for this factor (see "Discussion" and Zamparo et al. 2005 for further details on this topic).

Video records were taken by means of an underwater camera (Sea-viewer, USA) positioned in a waterproof cylinder about 0.5 m below the water surface, frontally to the swimmer's direction. After the experiments, the data were downloaded to a PC and digitized using a commercial software package (Twin pro, SIMI, G). The elbow angle was measured at the end of the in-sweep (when the plane of the arm and forearm is perpendicular to the camera) for both sides (right and left arm) and for different arm cycles. Three to eight values of elbow angle were recorded for each subject every other lane; no differences were observed in EA as measured on the left and right side nor as a function of the distance covered: the average subject's elbow angle (EA) was then computed, on the basis of which the shoulder to hand distance (L, m) was calculated (see Zamparo et al. 2005).

Table 3 The parameters collected during the "swimming" protocol (a 200 m simulated race, with pull buoy, in a 25 m swimming pool)

	M (21)	F (8)	Range
T_{200m} (s)	187.8 ± 32.7	204.4 ± 24.9	134.5–252.2
V_{200m} (ms^{-1})	1.10 ± 0.19	0.99 ± 0.14	0.79–1.49
V (ms^{-1})	1.03 ± 0.17	0.94 ± 0.14	0.73–1.37
SF (Hz)	0.60 ± 0.07	0.58 ± 0.05	0.48–0.70
SL (m)	1.72 ± 0.29	1.62 ± 0.17	1.26–2.38
EA (°)	125 ± 11	130 ± 13	101–152
L (m)	0.59 ± 0.04	0.53 ± 0.03[a]	0.48–0.65
η_p	0.30 ± 0.05	0.31 ± 0.03	0.24–0.42

Data are mean ± 1SD

Time needed to cover the 200 m distance ($T_{200\,m}$) and corresponding speed ($V_{200\,m}$). Average values of speed (V), stroke frequency (SF), stroke length (SL), elbow angle (EA), shoulder to hand distance (L) and propelling efficiency (η_p) in the 8 lengths

[a] Significant differences between M and F swimmers

Statistical analysis

Average values are reported ±1 SD. Linear regression analyses were applied to investigate the relationship among the investigated parameters. A multiple linear regression analysis was applied to investigate the relationship between $\dot{W}_{max}$, η_p and $V_{200\,m}$. Statistical analysis was carried out by using a statistical package (SigmaPlot 11.0, US). The level of significance was set at $P \leq 0.05$. A simple t test was applied to test for differences between M and F swimmers in the investigated parameters.

Results

Data collected during the dry-land protocol are reported in Table 2. Maximal oxygen uptake was larger in M than in F swimmers ($\dot{V}O_{2max}$ = 33 and 27 ml min^{-1} kg^{-1} in M and

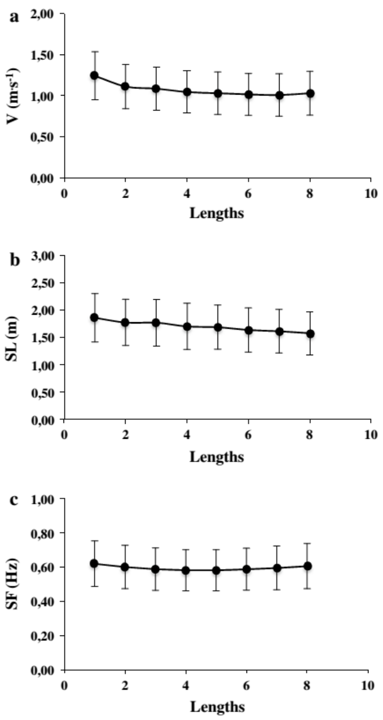

Fig. 1 Average values of speed (**a**), stroke frequency (**b**) and stroke length (**c**) as measured in the 8 lengths during the simulated 200 m race (arms only) in a 25 m pool. Data are mean ± 1SD and refer to both M and F swimmers

F, respectively) and the corresponding maximal mechanical power ($\dot{W}_{max}$) was of 136 and 78 W (in M and F, respectively). The overall efficiency of arm-cranking was similar in the two groups of swimmers (about 0.20).

Data collected during the swimming protocol are reported in Table 3. The duration of this test was of about 3–3.5 min and thus the exercise was sustained based mainly on aerobic energy sources (see "Discussion"). Stroke frequency (SF = 0.60 Hz in M and 0.58 Hz in F) and propelling efficiency (0.30 in M and 0.31 in F) were similar in the two groups and no significant differences were observed in the other parameters (with the exception of the shoulder to hand distance, *S*, that was found to be larger in M than in F).

In Fig. 1 the average values of speed (*V*, a), stroke frequency (SF, b) and stroke length (SL, c) are reported for each of the eight lengths of the pool during the simulated

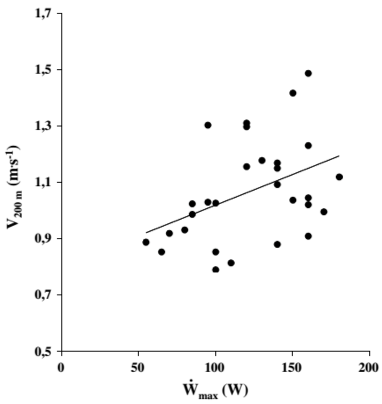

Fig. 2 The relationship between maximal power output ($\dot{W}_{max}$, dry-land test, W) and swimming speed during the 200 m maximal trial (V_{200m}, m s^{-1}): about 17 % of the variability of V_{200m} can be explained by the variability of $\dot{W}_{max}$ ($R = 0.419$, $P = 0.024$)

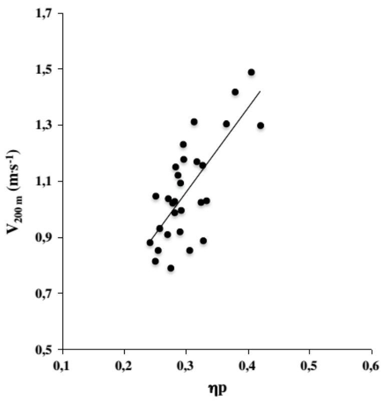

Fig. 3 The relationship between propelling efficiency (η_p) and swimming speed during the 200 m maximal trial ($V_{200\ m}$, m s^{-1}) about 55 % of the variability of V_{200m} can be explained by the variability of η_p ($R = 0.741$, $P < 0.001$)

200 m race (data refer to both M and F swimmers). These figures show that average speed was larger in the first length (due to the push off from the wall), that SF was maintained constant during the race while SL tended to decrease, due to fatigue, in the last lengths. The changes in SL mirror the changes in propelling efficiency (not shown in figure). The relationship between SL and η_p is indeed

rather good: $\eta_p = 0.151$ SL + 0.045, $N = 232$, $R = 0.899$, $P < 0.001$ (e.g. about 80 % of the variability of η_p could be explained by the variability of SL).

To analyse the relationships between $\dot{W}_{max}$, η_p and $V_{200\ m}$ the data of male and female swimmers were pooled together ($N = 29$). Figure 2 reports the relationship between maximal power output (dry-land arms only, W) and the swimming speed (arms only) during the 200 m maximal trial ($V_{200\ m}$, m s^{-1}); this relationship is well described by the following equation: $V_{200m} = 0.802 + 0.002\ \dot{W}_{max}$, $N = 29$, $R = 0.419$, $P = 0.024$. This indicates that the higher the maximal power output the faster is the swimming speed.

Figure 3 reports the relationship between propelling efficiency and swimming speed during the 200 m maximal trial; this relationship is well described by the following equation: $V_{200\ m} = 0.162 + 3.00$, η_p, $N = 29$, $R = 0.741$, $P < 0.001$. This indicates that the higher the propelling efficiency the fastest is the swimming speed.

No relationship was found between maximal power output and propelling efficiency during the swimming test ($N = 29$, $R = 0.035$, NS): not necessarily the swimmers with the highest power output are those with the higher propelling efficiency and vice versa.

A multiple linear regression taking into account all three parameters indicates that about 75 % of the variability of V_{200m} can be explained by the variability of $\dot{W}_{max}$ and η_p: $V_{200m} = -0.140 + 3.066$, $\eta_p + 0.002\ \dot{W}_{max}$, $N = 29$, $R = 0.865$, $P < 0.001$. This indicates that, as expected, both η_p and $\dot{W}_{max}$ are important factors in determining maximal speed in swimming events ($P < 0.001$ in both cases). This relationship is reported in Fig. 4.

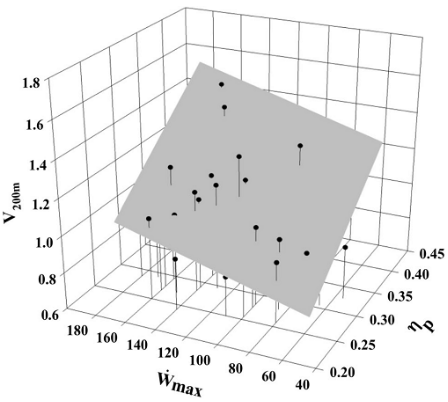

Fig. 4 The multiple linear regression between maximal power output ($\dot{W}_{max}$, dry-land test, *W*), propelling efficiency (η_p) and swimming speed during the 200 m maximal trial ($V_{200\ m}$, m s^{-1}): about 75 % of the variability of V_{200m} can be explained by the variability of $\dot{W}_{max}$ and η_p ($R = 0.865$, $P < 0.001$)

When this analysis is applied to the data of male and female swimmers separately, the relationship between $\dot{W}_{max}$, η_p and $V_{200\ m}$ is essentially the same (male swimmers: $V_{200m} = -0.120 + 3.175$, $\eta_p + 0.002\cdot \dot{W}_{max}$, $N = 21$, $R = 0.866$, $P < 0.001$; female swimmers: $V_{200m} = -0.123 + 2.039$, $\eta_p + 0.006\cdot \dot{W}_{max}$, $N = 8$, $R = 0.896$, $P = 0.017$).

By applying Eq. 5, the coefficients of the multiple regression change but the R value and the level of significance remain about the same: $V^3_{200m} = -3.411 + 12.328$, $\eta_p + 0.008\ \dot{W}_{max}$, $N = 29$, $R = 0.877$, $P < 0.001$. When the mechanical power is normalized per kg of body mass the correlation coefficient of the multiple regression is even larger ($R = 0.893$: about 80 % of the variability of V^3_{200m} can be explained by the variability of $\dot{W}_{max}$).

Discussion

Data reported in this study indicate that maximal speed in swimming is dependent not only on maximal power output (assessed in dry-land conditions) but also on propelling efficiency, as it can be hypothesized on theoretical grounds. We thus confirmed our hypothesis that a multiple correlation between $\dot{W}_{tot}$ η_p and V^3 would have a larger correlation coefficient than the simple correlation between $\dot{W}_{tot}$ and V.

Theoretically, the relationship between $\dot{W}_{tot}$, η_p and V described by Eq. 5; should have a correlation coefficient = 1. Why this is not the case can be attributed to sources of variability derived from the methods adopted in this study to determine the parameters of Eq. 5, these will be therefore discussed in detail.

Energy sources and swimming speed

The contribution of the aerobic and anaerobic energy sources to total metabolic energy expenditure differs widely according to the distance covered (or more correctly, as a function of the exercise duration): in the front crawl the world records range from about 20 s (50 m, anaerobic energy sources) to about 15 min (1,500 m, aerobic energy sources). The 400 m distance, that is swum in about 4 min (in front crawl elite swimmers), is generally taken as the competition eliciting the $\dot{V}O_{2max}$ of the swimmer; indeed, competitions over longer distances (longer race times) are swum at a fraction of $\dot{V}O_{2max}$ which is smaller the longer the exercise duration. Competitions over shorter distances (shorter race times) relay also on anaerobic (lactic and alactic) energy sources.

As indicated by di Prampero (2003) and di Prampero et al. (2011), for swim races lasting 200–300 s about 80 % of the energy requirements are derived from aerobic energy sources. The simulated 200 m race in this study lasted 188 s in M and 204 s in F and thus was indeed mainly sustained by aerobic metabolism; however, about 20 % of the energy requirements in this condition are not aerobic and this could represent a source of variability. We selected the 200 m distance (and not the 400 m one) because the swimmers had to use a pull buoy and therefore we expected that a simulated race over the 400 m distance would have been too demanding especially for those with lower technical capacities and lower swimming experience. If we had to perform these experiments with elite male swimmers (without pull buoy and without the constrains of this study) we would certainly have selected the 400 m distance instead. The values of speed reported in this study (V_{200m}) range from 0.79 to 1.49 ms^{-1}, and indicate a large variability in our sample; this was not only expected but intentional since we wanted to investigate a heterogeneous group of swimmers to better characterize the relationship between $\dot{W}_{max}$ and V.

Maximal mechanical power in land and in water

The values of $\dot{W}_{max}$ were assessed by means of a simple arm-crank ergometer. As discussed by Zamparo and Swaine (2012) there are obvious limitations to exact simulation of the swimming stroke within the laboratory and this kind of ergometer is open to criticism because it does not allow an exact replication of the swimming actions. In spite of these limitations, laboratory-based swimming ergometry has been widely used to study the physiological responses to swimming exercise and to investigate the role that muscle power has in front-crawl swimming performance (e.g. Johnson et al. 1993; Sharp et al. 1982; Swaine 1994; Takahashi et al. 1992). Points in favour of this choice are that arm-ergometers similar to that utilized in this study are of common use and simple to utilize so that these experiments can be easily replicated.

A source of variability in the determination of $\dot{W}_{max}$ can also be attributed to the fact that, in some cases, the test was terminated because of local fatigue and not because the swimmers reached their actual maximal mechanical output. Indeed, for some swimmers (especially male swimmers with large power output) the duration of the protocol was too long due to the relatively slow rate of the increments in power output (10 W/min in M and 5 W/min in F). In spite of this limitation we preferred to maintain the same protocol for all subjects; if we had to perform these experiments with a homogeneous group of elite male swimmers we would certainly have selected a different protocol (e.g. with increments of 50 W/min, as proposed by Zamparo and Swaine 2012).

As measured, $\dot{W}_{max}$ represents the external mechanical power output of the upper limbs. As indicated by Cavagna and Kaneko (1977) the total mechanical power of locomotion ($\dot{W}_{tot}$) is the sum of two terms: the power needed to accelerate and decelerate the limbs with respect to the centre of mass (the internal power, $\dot{W}_{int}$) and the power needed to overcome external forces (the external power, $\dot{W}_{ext}$). As reported by Zamparo et al. (2005) $\dot{W}_{int}$ can be estimated based on values of stroke frequency ($\dot{W}_{int} = 38.2\ SF^3$); SF in the 200 m swim test was of about 0.6 Hz, i e. lower than that adopted in the incremental test: 60 rpm = 1 Hz. We can thus expect differences in $\dot{W}_{tot}$ in the two conditions since $\dot{W}_{int}$ amounts to 8 W in the incremental test and to 38 W in the swim test; this could be considered another source of variability: when the maximal power output that can be exerted in water is calculated based on data collected on land the movement frequency should be matched, as much as possible.

The values of $\dot{W}_{max}$ reported in this study range from 55 to 180 W (0.96–2.28 W kg^{-1}), and indicate a large variability in our sample; this was not only expected but intentional since we wanted to investigate a heterogeneous group of swimmers to better characterize the relationship between $\dot{W}_{max}$ and V. In their upper range these values are comparable to those reported in the literature for elite male swimmers (175–180 W of external power for the upper limbs) and obtained with a similar protocol (e.g. Zamparo and Swaine 2012). As indicated in "Results", when the values of $\dot{W}_{max}$ are expressed per kg of body mass (to reduce the inter-subject variability) the relationship between $\dot{W}_{max}$, η_p and V^3 reach a correlation coefficient of 0.893.

In this study we assessed the dry-land power of arms-only and therefore we had to ask our swimmers to perform the swim test with arms-only and this is clearly a limitation. A more complete approach would have been to utilize a whole-body swimming ergometer, such as that described by Zamparo and Swaine (2012) to take into account also the contribution of the legs. In spite of this limitation (and in spite of work already involving a whole-body ergometer) we do think that these findings can add to our understanding of the factors that contribute to swimming speed, as indicated in the "General Discussion".

Overall and propelling efficiency

The values of overall efficiency (η_o) reported in this study (range 0.16–0.25) are comparable with those recently reported by Zamparo and Swaine (2012) by utilizing a whole-body dry-land swimming ergometer (about 0.23) and by taking into consideration the external work component of $\dot{W}_{tot}$ only, as is the case of this study. This finding is rather important since, as discussed in detail by these authors, values of 0.20–0.25 should be expected for simulated swimming in dry-land conditions as well as in actual swimming conditions. This further underlines that the low values of overall (gross) swimming efficiency reported so far in some swimming studies have to be attributed to an incomplete computation of all work components/energy losses (for a discussion on this point see Zamparo and Swaine 2012).

The efficiency calculated by means of Eq. 6 is, properly speaking, the Froude (theoretical) efficiency of the arm stroke; however, Froude efficiency and propelling efficiency in the arm stroke (front crawl) are essentially the same since the internal work is negligible (about 8 W in this study, as indicated above); the difference between these two parameters is, indeed, that Froude efficiency does not take into account this component of $\dot{W}_{tot}$ whereas propelling efficiency does (for a discussion on this point see Zamparo et al. 2005).

The model utilized in this study estimates the efficiency of the arm stroke (η_p) from the ratio of forward speed (V) to hand speed ($2\pi SFL$) since this ratio represents the theoretical efficiency of all hydraulic machines (Fox and McDonald 1992). In the equation proposed by Zamparo et al. (2005) for the front crawl a correction for the speed value is proposed to take into account that speed is sustained also by the lower limbs propulsion. In this study, however, the subjects were asked to swim with a pull buoy and thus this correction was not necessary. In this way we have reduced a possible source of variability deriving from inter-subject differences in leg propulsion/efficiency. In a recent study by Figueiredo et al. (2011) it was shown that the values calculated by means of this model and those obtained by measuring the body center of mass speed and the 3D hand speed (by means of underwater kinematic analysis) are comparable (not statistically different) thus confirming the validity of this simple model to estimate η_P in front crawl swimming. Finally, the validity of this model in estimating propelling efficiency was demonstrated and discussed in detail by Zamparo and Swaine (2012).

The values of propelling efficiency reported in this study range from 0.24 to 0.42; in their upper range are thus comparable to those reported in the literature for elite male swimmers: 0.40–0.45 (Zamparo et al. 2005; Figueiredo et al. 2011) the large variability in the η_p values was expected (we intentionally recruited for this study a heterogeneous group of swimmers) for similar reasons to those already discussed, since we wanted to demonstrate that the differences in this parameter do indeed allow us to explain why the relationship between $\dot{W}_{max}$ and V can be significant in some cases and not in others. As an example, it could be expected that in a more homogeneous group of swimmers (with similar values of η_P) the relationship between $\dot{W}_{max}$ and V would have a larger correlation coefficient than the relationship between η_P and V (i.e. the contrary of what was found in this study).

The product of overall efficiency and propelling efficiency is the drag efficiency ($\eta_d = \eta_P\eta_o$), i.e. the efficiency with which the metabolic power input is transformed into useful power output (the power to overcome hydrodynamic resistance: $\eta_d = \dot{W}_d/\dot{E}$). Thereby, the calculated values of drag efficiency range from 0.04 to 0.08 and are comparable to those reported in the literature and calculated based on values of active drag (for a discussion on this point see di Prampero et al. 2011; Zamparo et al. 2005; Zamparo and Swaine 2012).

As indicated in "Results" the relationship between SL and η_p has a large correlation coefficient ($R = 0.899$, $N = 232$, $P < 0.001$). This equation can thus be utilized to estimate propelling efficiency based on simple measures of SL.

Speed-specific drag and the validity of Eq. 5

Equation 5 indicates that another parameter influences performance in swimming and this is the speed-specific drag (k); this parameter was not considered in this study and this is the last, but not least, source of variability (see "General discussion" below). However, based on Eq. 5, k can be estimated and this calculation could give useful information on the validity of the equation itself: were the values of V_{200m}, $\dot{W}_{max}$ and η_p reported in this study correctly measured/estimated we should expect also "reasonable" values of k (i e. in the range of those reported in the literature). Based on the values of V, $\dot{W}_{max}$ and η_p (independently measured/estimated) k was calculated for each swimmer and found to amount to 25 ± 4 in F and to 34 ± 12 in M swimmers. The large SD has to be attributed, rather than to inter-individual differences, to the sources of variability discussed above (i e. we do not suggest to apply this method to estimate drag in swimming). The average values of k are indeed in the range of those reported in the literature and support, albeit indirectly, the calculations proposed in this study (e.g. the validity of Eq. 5). As an example (Zamparo et al. 2009) report data of $k = 23$ and 19 (M and F, respectively) for passive drag and $k = 43$ e 34 (M and F, respectively) for active drag. Albeit indirectly, this finding supports also the assumption made in the Introduction that $F \approx kV^2$.

General discussion

Our findings are relevant since, even if it is generally acknowledged that improving η_p and $\dot{W}_{max}$ is useful to improve performance in swimming, no studies have been conducted so far to investigate the interplay among these three factors. To our knowledge, the only other paper that attempted to investigate this topic is that of Shimonagata et al. (1999). These authors investigated the relationship between "maximum propulsion" (Po, N: the maximal force exerted during tethered swimming), "active drag" (Da, N: estimated by means of a semi-tethered swimming protocol) and maximal speed (attained during a semi-tethered swimming protocol). They found that V is significantly correlated with Po and Da (multiple regression analysis: $R = 0.84$, $P = 0.01$) but that no significant relationship can be found between Po and V or between Da and V alone. Even if they utilized values of force (and not of power output, as indicated by Eq. 5) and even if the methods they utilized for computing Po and Da can be matter of discussion, their conclusions are in line with the theoretical analysis proposed in this study (Eq. 5): swimming speed is faster as Po is higher and Da is lower.

Data reported in this paper allow greater comprehension of swimming performance (as well as of aquatic locomotion, in more general terms) since they show that the parameters entering Eq. 5 should be taken into consideration together. Indeed, even if this is theoretically known no studies have attempted so far to consider propelling efficiency when investigating the relationship between (dry-land) mechanical power output and swimming speed. Further studies should assess the effect of leg kicking on the parameters of Eq. 5 (e.g. by using a whole-body swimming ergometer) and these experiments could be replicated in different conditions (with the appropriate combination of $\dot{W}_{max}$, η_p and V values). Finally, even if, in this study, we did not investigate the relationship between $\dot{W}_{max}$, η_p and V in elite swimmers (as already discussed this was because we decided to investigate this relationship in an heterogeneous group of swimmers) we can draw general conclusions out of this study. Indeed, Fig. 4 can be utilized to identify swimmers in respect to their swimming abilities: the upper corner of the 3D plane identifies male, good level, swimmers with high values of V, $\dot{W}_{max}$ and η_p while the right corner identifies female, good level, swimmers with high values of η_p but with lower values of $\dot{W}_{max}$ (and hence of V) in respect to their male counterparts; the left corner identifies swimmers with high values of $\dot{W}_{max}$ but with low technical skills (low values of η_p, and hence of V). Hence, coaching should help swimmers to move up in this plane: indeed, V will increase both by increasing $\dot{W}_{max}$ (strength training) and/or by increasing η_p (improving technical skills by means of specific training in water). As a consequence, detraining will imply a move down on this plane since the bottom corner identifies swimmers with the lowest values of $\dot{W}_{max}$, η_p and V. As an example, in this position we can find older master swimmers since both $\dot{W}_{max}$ and η_p tend to decrease with age (e.g. Zamparo et al. 2012) but also pre-pubertal swimmers (characterized by low values of $\dot{W}_{max}$ and η_p) (e.g. Zamparo et al. 2008).

Conclusions

In conclusion, a multiple linear relationship that takes into account dry-land arms-only mechanical power output and propelling efficiency better explains swimming speed than the previously established relationship between power output (dry-land) and speed alone. Furthermore, data reported in this study explain why different results were obtained so far when investigating the relationship between dry-land $\dot{W}_{max}$ and V or between $\dot{W}_{max}$ (assessed in water) and V: in previous studies, when $\dot{W}_{max}$ was assessed by means of dry-land protocols the contribution of η_p was not accounted for. These findings further underline that $\dot{W}_{max}$ and η_p (as well as k, and hence hydrodynamic resistance) should be the focus of any intervention aimed to improve performance in swimming. Unfortunately, Eq. 5 can only be applied to the front crawl because no data are reported in the literature about the propelling efficiency in the other strokes. Further studies are needed to understand (besides arms propulsion) the role of leg propulsion and hydrodynamic resistance in determining V in the framework of Eq. 5.

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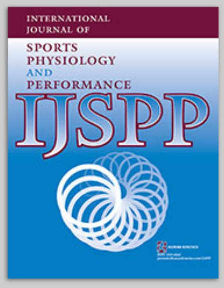
Appendix 4



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ORIGINAL INVESTIGATION

The Effects of Leg Kick on the Swimming Speed and on Arm Stroke Efficiency in Front Crawl

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ABSTRACT PDF

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Running Head: Leg kick contribution and arm stroke efficiency

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The effects of leg kick on the swimming speed and on arm stroke efficiency in front crawl

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Abstract

Purpose: to analyze the effects of swimming pace on the relative contribution of leg kick to swimming speed, and to compare arm stroke efficiency (η_F) assessed when swimming with the arms only (SAO) and while swimming front crawl (FCS) using individual and fixed adjustments to arm stroke and leg kick contribution to forward speed. **Methods:** twenty-nine master swimmers (21 males, 8 females) performed SAO and FCS at six self-selected speeds from very slow to maximal speed. The average swimming speed (v), stroke frequency (SF), stroke length (SL) were assessed in the central 10 m of the swimming pool. Then, a second-order polynomial regression was used to obtain values of v at paired SF. The percentage difference in v between FCS and SAO, for each paired SF, was used to calculate the relative contributions of the arm stroke (AC) and leg kick (LC) to FCS. Then η_F was calculated using the indirect "paddle-wheel" approach in three different ways: using general, individual, and no adjustments to AC. **Results:** the LC increased with SF (and speed) from -1±4% to 11±1% ($p<0.05$). At the lower FCS speeds, η_F calculated using general adjustments was lower than η_F calculated using individual adjustments ($p<0.05$) but differences disappear at the fastest speeds. Last but not least, η_F calculated using individual adjustments to the leg kick contribution in the FCS condition did not differ with η_F assessed in the SAO condition at all the investigated speeds. **Conclusions:** the relative contributions of the arm stroke and leg kick should be individually estimated to reduce errors when calculating arm stroke efficiency at different speeds and different swimmers.

Keywords: arm stroke efficiency, Froude efficiency, upper limbs contribution, lower limbs contribution

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Introduction

The efficiency with which an energetic input is converted into mechanical output has been reported as a measure of performance either in animal[1] or human locomotion[2]. In this regard, the fraction of the total metabolic power ($\dot{E}_{tot}$) converted into total mechanical power ($\dot{W}_{tot}$) is defined as overall or mechanical efficiency (η_o). In aquatic locomotion, $\dot{W}_{tot}$ is composed by useful and non-useful components, yielding to a cascade of efficiencies, such as the hydraulic efficiency, the Froude efficiency, the propelling efficiency, the drag or performance efficiency[3], as described in Figure 1.

While Froude efficiency is defined as the fraction of the external mechanical power ($\dot{W}_{ext}$) converted into useful propulsive power ($\dot{W}_d$, the power needed to overcome drag force), propelling efficiency is defined as the fraction of $\dot{W}_{tot}$ converted into $\dot{W}_d$. The difference between these two parameters is thus that the latter takes into account the internal mechanical power needed to move the limbs with respect to the center of mass ($\dot{W}_{int}$) while the former does not (see Figure 1). Since $\dot{W}_{int}$ is seldom measured/estimated/taken into account in swimming literature, the majority of the data reported on this topic are indeed data of “Froude efficiency”, even if they are often referred to as “propelling efficiency” values. As shown by Zamparo et al. [4], $\dot{W}_{int}$ is negligible in the arm stroke of front crawl swimming and, therefore, in this specific condition: $\eta_P \approx \eta_F$. In this paper we will define this parameter, in more general terms, as “arm stroke efficiency”. Based on the literature on this topic, arm stroke efficiency is inversely related to the energy cost of swimming[5] and it is one of the main determinants of performance[4,6]. Although difficult ways to assess this parameter are described in the literature[7], an indirect and coach-friendly way has been largely used due to its applicability, both in training routine and research[4,8,9],

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To our knowledge, only two approaches considered the relative contribution of arms and legs when calculating arm stroke efficiency in whole-body front crawl swimming: the indirect "paddle-wheel" model[4] based on values reported in previous studies[10,11] in which a contribution of 90% from the arms to propulsion (and 10% from legs) is suggested, and the method described by Gourgoulis et al.[12], based on indirect assessments of effective and resultant forces, in which the contribution of arms (~87%) and legs (~13%) were individually assessed to avoid an overestimation of efficiency in full stroke swimming. Although these values are supported in the literature for front crawl sprinting[12,13], higher relative contribution of the leg kick (~31%) in a fully tethered swimming protocol have been reported[14]. During 200-m trials at low, moderate and high stroke frequencies, values of ~11% were found[15]. However, a larger range of speeds should be considered to individually estimate arm stroke and leg kick contributions.

Thus, considering these conflicting results and the lack of information regarding the effects of individual estimation of arm stroke and leg kick contribution on the assessment of arm stroke efficiency, the aims of the present study were to analyze the effects of speed on the relative contribution of leg kick to whole-body front crawl swimming and to compare the arm stroke efficiency assessed when swimming with the arms only and while swimming front crawl using individualized and fixed adjustments to the leg kick contribution to the swimming speed. We hypotezised that relative contribution of leg kick increases with swimming speed and, therefore, the assessment of arm stroke efficiency should consider individual adjustments to leg kick contribution.

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Material and Methods

Participants

Twenty-nine master swimmers (21 males, 8 females) were recruited for this study (age: 32.3 ± 9.3 years; body mass: 69.4 ± 9.0 kg; height: 174.9 ± 8.2 cm). To test the hypothesis that leg kick contribution responds individually to swimming speed, men and women were intentionally collapsed into one heterogeneous group. The purpose and the aims of the study were carefully explained to each individual and written informed consent was obtained. The study conformed to the standards set by the Declaration of Helsinki, and the local Institutional Review Board approved the procedures.

Experimental procedure

Swimmers performed 25-m using the front crawl stroke (FCS) and the front crawl stroke while swimming with the arms only (SAO), in a randomized order, at six incremental self-selected speeds, from very slow ($V1$) to maximal speed ($V6$), resting at least 3 minutes between trials. The experiments were conducted in a 25-m indoor swimming pool and all parameters were assessed in the central 10-m to avoid the influence of the push-off start and finish. The average clean swimming speed (v; m·s^{-1}) was assessed by the ratio of the 10-m to time taken to cover it, using the head of the swimmer as reference. The stroke frequency (SF; Hz) was calculated from the number of complete strokes performed in the central 10-m and the time taken from the first and last entry of the same hand in the water, recorded by two experienced researchers using stopwatches (SEIKO digital stopwatch S141, Japan). From dividing the average speed by the corresponding stroke frequency, stroke length (SL; m) was calculated.

During the SAO condition, swimmers used a pull buoy and a rubber band around their ankles to avoid propulsion generated from the leg kick action. The arm stroke (Froude)

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efficiency was calculated according to the indirect "paddle-wheel" model[4] in which the upper arm is considered a rigid segment of length l rotating at constant angular speed ($\omega = 2\pi SF$) around the shoulder that yields the theoretical efficiency of the underwater phase only, neglecting the internal mechanical power, as follows:

$$\eta_F = (v/(2\pi \cdot SF \cdot l))(2/\pi) \quad (1)$$

Where v is the average swimming speed, SF is the stroke frequency, l is the shoulder to hand distance (calculated as described at the end of this section) and π is the ratio of the circumference traveled by the hand in the model and its diameter (~3.14).

Arm stroke efficiency in the FCS condition was also calculated according to the "paddle-wheel" model[4], in three different ways: (i) with no adjustments regarding the contribution of the arms and legs to the swimming speed (Equation 1); (ii) with a general adjustment to the arm stroke contribution, as previously described[5]:

$$\eta_F = (v \cdot 0.9/(2\pi \cdot SF \cdot l))(2/\pi) \quad (2)$$

and (iii) with an individual adjustment to the arm stroke contribution to the swimming speed:

$$\eta_F = (v \cdot AC/(2\pi \cdot SF \cdot l))(2/\pi) \quad (3)$$

Where AC is the individual contribution of the arm stroke to the swimming speed at a given speed (see below).

An underwater video camera (50 Hz; Sea-viewer, USA) positioned in a waterproof cylinder at 0.5-m below the surface was positioned on the frontal wall, to record the swimmer's transverse plane. Videos were digitized using a commercial software package (Twin pro, SIMI, G) and the elbow angle was measured at the end of the in-sweep phase (when the plane of the arm and forearm is perpendicular to the optical axis of the camera) for the right and left sides and for, at least, six different arm strokes (three from each side). As

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shown in Figure 2 and described in Equation 4, the average elbow angle between both sides was then used to calculate l by trigonometry considering the arm (from the lateral epicondyle of the humerus to the acromion process) and forearm lengths (from the center of the hand to the lateral epicondyle of the humerus) previously measured with a meter tape (0.01 cm resolution):

$$l = \sqrt{{l_{arm}}^2 + {l_{forearm}}^2 - 2 \cdot l_{arm} \cdot l_{forearm} \cdot \cos\alpha} \quad (4)$$

In which α is the elbow angle in radians, l_{arm} and $l_{forearm}$ are the arm and forearm lengths in m, respectively.

Arm stroke and leg kick contribution to swimming speed

The SF vs. v relationship was individually determined for each swimmer in both conditions (FCS and SAO), as illustrated in Figure 3, and a second order polynomial regression equation was used[16], to predict the swimming speed when swimming FCS at specific stroke frequencies corresponding to the values measured in the SAO condition for $V1, V2, V3, V4$, $V5$ and $V6$. The quality of the fit of these individual regressions was assessed by the coefficient of determination (R^2) and the standard error of the estimate (SEE). The mean ± 1SD values of R^2 and SEE observed were 0.98 ± 0.02 (0.91-1.00) and 0.02 ± 0.01 (0.00-0.05) respectively.

Then, the AC was calculated for each paired SF (from $V1$ to $V6$) based on Equation 5:

$$AC = (v_{SAO}/v_{FCS}) \cdot 100 \quad (5)$$

In which v_{SAO} and v_{FCS} are the average swimming speeds in the SAO and FCS conditions, respectively.

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Finally, the same polynomial regressions were used to estimate v_{SAO} and v_{FCS} in a range of 21 paired SF to obtain data with an increase of 2.5%, which was considered as a significant increase in swimming speed[17,18,19]. The relative contribution of leg kick (LC) to swimming speed was obtained for each paired SF from 50 to 100% of the maximal SF observed in the FCS condition, as follows:

$$LC = ((v_{FCS} - v_{SAO})/v_{FCS}) \cdot 100 \qquad (6)$$

Statistical analysis

Descriptive statistics are reported for all variables (mean ± SD). Normality of data distribution was tested with a Shapiro-Wilk's test and a Levene's test was applied to verify the equality of the variances. The Mauchly's sphericity test was used to validate the subsequent comparison tests. A two-way repeated measures ANOVA was applied for the data comparison regarding (1) the effects of pace and swimming condition on v, SF and SL; (2) the effects of pace on the leg kick contribution; and (3) the effects of self-selected pace and the method used on the arm stroke efficiency calculation. When any significant effect was identified, Fisher's least significant difference *post-hoc* analysis was performed to compare the different paces, conditions or methods. If an interaction between factors occurred, the simple effect of each factor on each level of the other factor was calculated. Effect sizes were estimated using the partial η^2 to describe the proportion of the total variance made up by the variance of the means. The ratio of variance explained of the sample was calculated for each effect and parameter estimate. Interpretation of η^2 indicates small ($\eta^2 \geq 0.02$), medium ($\eta^2 \geq 0.13$) or large effect sizes ($\eta^2 \geq 0.26$) for a two-way ANOVA and small ($\eta^2 \geq 0.01$), medium ($\eta^2 \geq 0.06$) or large effect sizes ($\eta^2 \geq 0.14$) for a one-way ANOVA according to the general rules of thumb on magnitudes of effect sizes[20]. The level of significance adopted was $p \leq 0.05$.

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Results

As a response to the increase in the self-selected speed, swimmers increased, as expected, v; SF increased in a similar manner in FCS and SAO while SL was reduced (the values of SL were lower in SAO than in FCS). Since there was an interaction between self-selected speed and swimming condition (p<0.001), v was compared between FCS and SAO conditions for each trial separately. All results regarding the effects of self-selected speed and swimming condition on the stroke parameters are presented in Table 1.

LC increased with SF (and consequently speed), as shown in Figure 4. At 100% of SF (at maximal swimming speed) it was equal to 11.4 ± 4.4 % and the AC, at this same speed was therefore 88.6 ± 4.4 %.

There was a significant effect of swimming pace (η^2 = 0.573; Observed power = 1.000; p<0.001) as well as of the way used to calculate the arm stroke efficiency (η^2 = 0.670; Observed power = 1.000; p<0.001). An interaction between swimming pace and the way used was also observed (η^2 = 0.111; Observed power = 1.000; p<0.001). Thus, the different ways to calculate arm stroke efficiency (η_F) were compared for each pace, separately.

As presented in Figure 5, η_F decreases as a function of speed (as is the case for SL). In the FCS condition, η_F calculated without any adjustment to the LC, is larger than η_F adjusted using individual and general adjustments, as well as larger than η_F in the SAO condition. At the lower speeds ($V1$-$V4$), η_F in the FCS condition, calculated using general adjustments, is lower than η_F calculated using individual adjustments but the difference disappears at the fastest speeds ($V5$-$V6$). Last but not least, η_F calculated using individual adjustments to the LC in the FCS condition did not differ with η_F assessed in the SAO condition at all the investigated speeds, meaning that methods are indeed measuring the same thing.

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Discussion

The aims of this study were to test the effects of speed on the LC and to compare arm stroke efficiency assessed in the SAO and FCS conditions. The main results indicate that speed has a significant effect on the LC, as well as on arm stroke efficiency. Moreover, data reported in this study indicate that arm stroke efficiency in the FCS condition is overestimated (compared to SAO) if not adjusted by LC, and that, at slow (but not necessarily at fast) swimming speeds, individual adjustments to the LC should be applied.

The increase in LC with swimming speed and SF, may be hydrodynamically explained. Indeed, at higher speeds associated to higher SF and lower time duration of a swimming cycle, swimmers face a shorter time period to perform the kick. So, assuming an (at least) not proportional reduction in kicking amplitude, foot velocity relative to the water will be higher compared to lower speeds and frequencies, allowing both for higher intensity of quasi-stable hydrodynamic force production during the downbeat and the upbeat. Also, it allows a much more sudden reverse of feet direction of movement, allowing a more intense vortex generation and shedding and higher propulsive effects extracted from unstable flow generated by the kick[21]. Once with the leg kick swimmers gain an extra propulsive impulse, they can reach higher speeds for the same shoulder angular velocity and efficiency is improved compared to SAO. Results also showed that specifically correcting this effect induced by the kicking action allow similar results. This means that the efficiency markers used in this study are quite sensitive to factors affecting swimming propulsion, as convenient.

To increase speed, from $V1$ to $V6$, swimmers increased their SF with a consequent decrease in SL. This pattern was observed in both conditions (FCS and SAO), as expected[22,23]. The average swimming speed and SL were larger in FCS than in SAO condition but SF was essentially the same. That reflects a similar strategy adopted by the swimmers to the task

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constraint of increasing the self-selected speed, controlling the SF in both conditions and indicates a direct effect of the flutter kick on the SL. Increases in SF and SL are expected when comparing sprint front crawl swimming with and without leg kicking[12]. Although we have not observed any effect of the swimming condition on the SF, that may have been a response to the different task constraints. In our study, swimmers were asked to perform the front crawl, either with and or without leg kicking, at a range of six self-selected speeds, instead of swimming only at the maximal swimming speed.

Our results show that the LC to FCS significantly increase with speed. At low speeds the AC and LC seem to be individually determined, whereas, at maximal speeds the inter-subject difference is rather low (small SD), as previously reported[11,12,13] at maximal swimming effort, in which the LC was ~10%. Data of 200-m trials[15] reporting an increase in LC from low to high SF in female swimmers support our findings, although male swimmers did not present the same results, reinforcing our argument that LC is individually determined and may increase with SF and speed. Also, the distance and number of trials chosen in our study allowed us to obtain a larger range of SF, from very slow to maximal speeds (and SF).

Measurements of flutter kick power[24] by towing the swimmers with an electromechanical motor, at six different speeds, showed a decrease in power when increasing the towing speed, suggesting that the capability to produce power by the legs reduces in speeds above the maximal flutter kick speed. The paradoxical results found in our study may be related to other adaptations that occur when swimming the FCS, such as the ones regarding swimming coordination, economy and the efficiency cascade. Furthermore, the already suggested unstable flow propulsive effect of the crawl flutter kick, particularly expected at the higher velocities, may gain with increased translational swimming velocity,

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allowing exploiting different hydrodynamic mechanisms not accessible at maximal kicking swimming velocity only.

A coordinative adaptation on leg kicking occurs as a response to the increase in front crawl swimming speed, changing from a two-beat to a six-beat pattern[18]. It is not clear, however, whether the adaptations in the leg kick pattern is related to its contribution to swimming speed, but our findings showing the increasing LC suggests so. Also, at low swimming speeds, the role of the leg kick is mostly related to the maintenance of a horizontal body position, reducing the frontal projected area and drag forces whereas its propulsive role seems to increase following the changes on arm to leg coordination from two to four or six beats per stroke[25].

Higher net energy expenditure, as well as higher energy cost to cover a given distance, is observed when comparing leg kicking at surface and the front crawl stroke[5]. Thus, economy seems to be one of the main reasons that lead swimmers to adopt a given leg kicking pattern, as well as a given AC and LC, according to the pace they are supposed to swim. Efficiency, in its different forms, may also be a determinant factor when it comes to adopting the optimal leg kick pattern and contribution to swimming speed. Previous findings[26] showed that legs produced higher power output than arms during an all-out 30-s simulated swimming test, what is in line with the higher energy expenditure observed in human swimming[5]. However, they found that leg kick has lower propelling, overall and performance efficiencies than swimming front crawl. Thus, a lower fraction of the metabolic power is converted into mechanical power, what may be related to a higher internal mechanical power[4] as well as to a lower fraction of the total mechanical power and metabolic power output that are actually transformed into useful power to overcome drag[27].

Considering the relative contribution of arms and legs to the average tethered force when swimming FCS, AC and LC of 70.3% vs. 29.7%, for males, and 66.6% vs. 33.4%, for

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females, were previously reported[14] during a 30-s all-out tethered swimming protocol. However, the relative contribution of arms and legs to the average tethered force when swimming FCS not necessarily represents the relative contribution to the swimming speed. Also, besides assessing the contribution of arms and legs only at maximal effort, considering the sum of the arms only and leg kicking conditions as a reference, the authors probably overestimated the average force of the actual front crawl swimming, since there was a force deficit when comparing swimming with the whole body and the sum of the other two conditions.

Therefore, changing the AC and LC seems to be an intrinsic strategy adopted by swimmers to optimize the economy and efficiency at a given speed, and to cope with velocity generation requirements, reducing the LC at lower speeds and increasing it at higher speeds. Adaptive movement patterns emerge as a function of the organism's propensity to minimize metabolic energy expenditure with respect to task, environment and organism constraints to action[28]. Indeed, motor organization in swimming will occur in response to one of those three constraints: organismic (e.g. gender, expertise, anthropometry, physiological requirements, swimmer's discipline), environmental (e.g. active and wave drag, propelling efficiency) and task constraints (e.g. task goal, instructions given to the swimmer, imposed pace and distance)[29,30].

The large standard deviations in LC observed in the present study at low swimming speeds may thus: (1) reflect the heterogeneity of the subjects and (2) confirm the necessity of an individualized estimation of AC and LC, considering the pace and inter-individual effects on it, instead of assuming a given fixed value; on the other hand, at maximal swimming speeds, also suggested by the few studies that assessed the differences in maximal swimming

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speed between FCS and SAO conditions[11-13], the LC seems to be rather constant and on the range of 10-12%.

One of the main issues on assessing propelling (or Froude) efficiency in swimming is the fact that the most used approach reported in the literature refer to the arm stroke only. These values of arm stroke efficiency should thus be compared to our SAO values since the legs are supported by a pull buoy and do not contribute to propulsion. Other approaches for assessing the arm stroke efficiency in front crawl swimming have been used, based on the concepts previously described for the front crawl stroke[31] and for the analysis of locomotion in "rowing animals"[32]. These indirect approaches consider the ratio of the average swimming speed to the hand speed ($\eta_F = v_{swim}/v_{hand}$) and may be assessed by a 2D simplified model[4], as the one used in the present study, or a 3D model[9], in which arm stroke efficiency is considered as the ratio of the horizontal speed of the center of mass to the 3D resultant hand speed ($\eta_F = v_{CM}/v_{3Dhand}$). Indirect assessments of effective and resultant forces generated by the hands have also been used to assess the arm stroke efficiency in a previous study[12] in which individual adjustments to the arm stroke contributions to swimming speed were considered to avoid overestimation of the arm stroke efficiency during full stroke swimming.

Although the assessment of arm stroke efficiency with the "paddle-wheel" model[4] relies on the assumption that the upper-limbs are a rigid segment of length l moving at constant speed, it is a coach-friendly approach that may be applied to assess the arm stroke efficiency not only in the SAO but also in the FCS conditions by considering the AC. Furthermore, a previous study[9] reported similar average values of arm stroke efficiency between the method used in the present study and a 3D model. Moreover, despite AC has been often assumed[11] as 90%, independently of the pace or the level of the swimmers, our

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results suggest that the AC and LC should be individually estimated, at least at lower swimming speeds, since both depend on the swimming pace. In fact, when individual adjustments to the AC were used, arm stroke efficiency did not differ between FCS and SAO conditions, at paired SF. Furthermore, our data show that, when assuming a AC of 90%, arm stroke efficiency is underestimated only at the lower speeds, from $V1$ to $V3$, since no differences were observed at the highest speeds.

Using polynomial regressions to predict swimming speed at a given SF can be a limitation of the method used to estimate AC and LC in the present study, since swimmers did not necessarily perform at those specific speeds or SF. However, we attempted to reduce this limitation by predicting speeds nearly within the range of SF (and speeds) that they actually performed in both conditions. Regarding the use of a pull-buoy in the SAO and the use of the leg kick in the FCS, a leg-raising effect has been reported for both conditions[12,33], although a slightly larger trunk incline (11.46 ± 1.51° vs. 10.01 ± 2.56°) has been observed at maximal swimming speed in SAO than in FCS [12]. Thus, the contribution of leg kick to swimming speed may not be related only to the propulsion generated by the lower limbs, but also to a reduction in resistive drag[34].

Practical applications

Data reported in this study, using coach-friendly methods, may help coaches and scientific community to better understand and evaluate arm stroke efficiency in front crawl swimming, with no constraints regarding the lower limbs. Our results show that the contribution of the leg kick action in front crawl stroke increases with speed and should be considered in the calculation of arm stroke efficiency. In addition, the methods used in this study could be considered by coaches and practitioners to assess changes in front crawl performance related to the arm stroke or leg kick actions. Our findings could also be

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considered when prescribing training according to the arm stroke and leg kick contributions to swimming speed.

Conclusion

As a general effect, leg kicking action leads to an increase in stroke length (and consequently speed) at comparable stroke frequencies. Moreover, the percentage contribution of the flutter kick to forward speed increases with the swimming pace. Thus, regarding the assessment of arm stroke efficiency, the contribution of arms and legs should be individually estimated in order to reduce the errors when analyzing different speeds and different swimmers.

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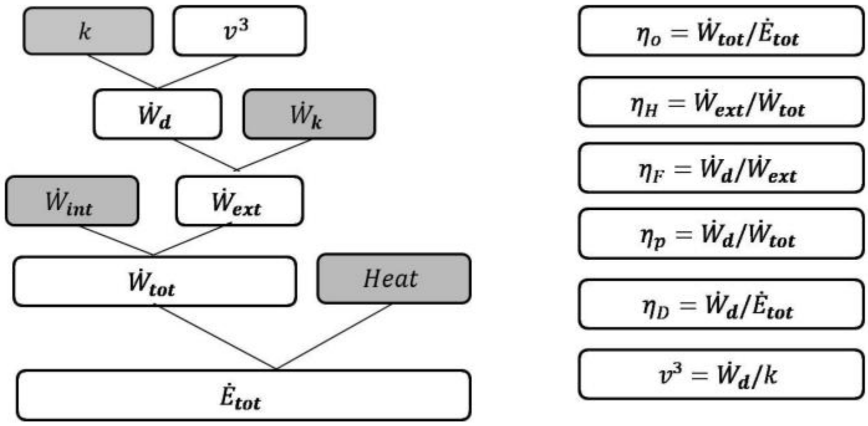

Figure 1. Useful and non-useful components of the cascade of efficiencies. $\boldsymbol{\eta_o}$: overall efficiency; $\boldsymbol{\eta_H}$: hydraulic efficiency; $\boldsymbol{\eta_F}$: Froude efficiency; $\boldsymbol{\eta_P}$: propelling efficiency; $\boldsymbol{\eta_D}$: drag efficiency; $\boldsymbol{\dot{E}_{tot}}$: total metabolic power input; $\boldsymbol{\dot{W}_{tot}}$: total mechanical power output; $\boldsymbol{\dot{W}_{int}}$: internal mechanical power; $\boldsymbol{\dot{W}_{ext}}$: external mechanical power; $\boldsymbol{\dot{W}_d}$: power needed to overcome drag (useful propulsive power); $\boldsymbol{\dot{W}_k}$: power that does not contribute to generate propulsion; $\boldsymbol{k}$: speed-specific drag coefficient; $\boldsymbol{v}$: swimming speed.

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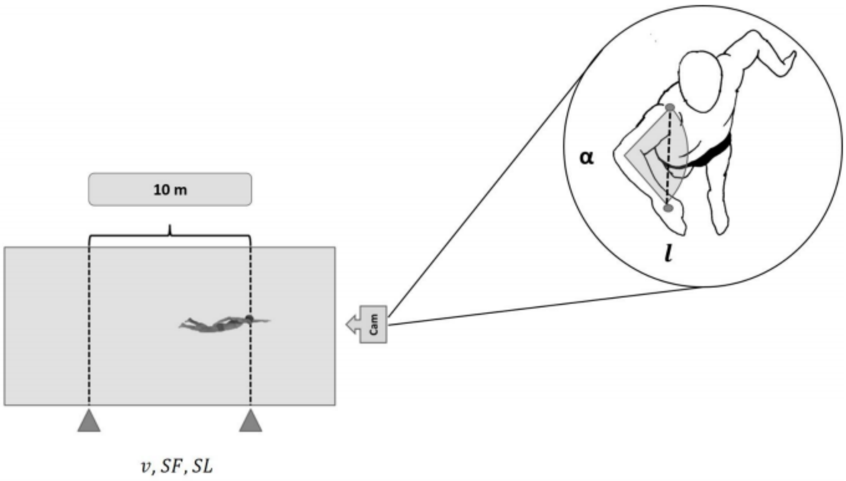

Figure 2. Stroke parameters assessed in the central 10 m of the swimming pool, as well as from a frontal camera recording the frontal plane of the swimmer. $\boldsymbol{v}$: average swimming speed; $\boldsymbol{SF}$: average stroke frequency; $\boldsymbol{SL}$: average stroke length; $\boldsymbol{\alpha}$: elbow angle at the end of the in-sweep phase; $\boldsymbol{l}$: shoulder to hand distance.

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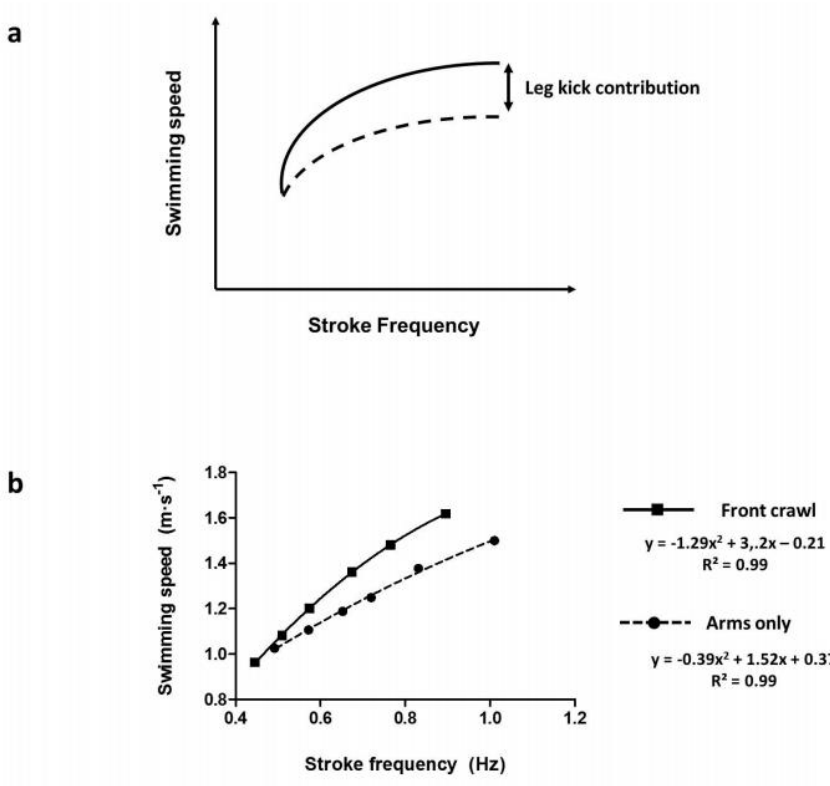

Figure 3. Stroke frequency (SF) vs. speed (v) relationship determined for the whole-body front crawl stroke (FCS) and swimming front crawl with the arms only (SAO) plotted to determine the contribution of the leg kick to forward speed (LC; the percentage difference in v between FCS and SAO at a given SF).

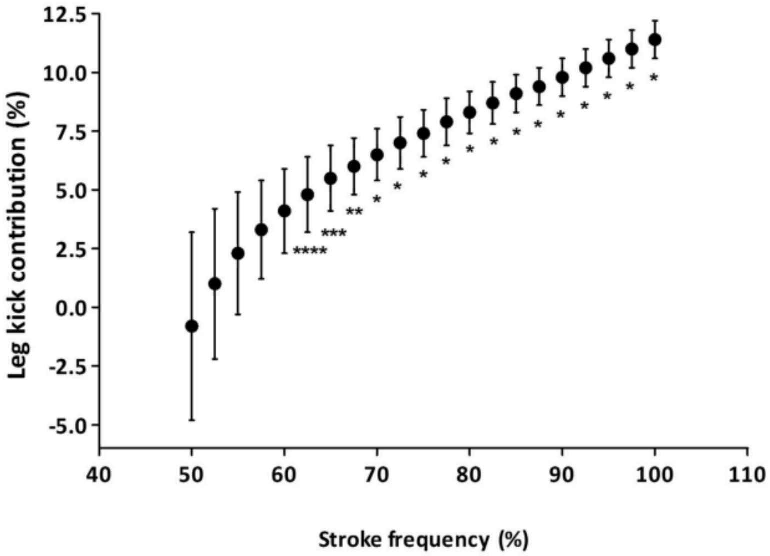

Figure 4. Relative contribution of the leg kick when swimming whole-body front crawl (FCS) in a range of 21 paired stroke frequencies (SF). Data are presented as Mean ± 1SE.

*Increased speed is different from the values corresponding to the range of 50 to 100% of the maximal SF ($p<0.05$).

**Increased speed is different from the values corresponding to the range of 52.5 to 100% of the maximal SF ($p<0.05$).

***Increased speed is different from the values corresponding to the range of 55 to 100% of the maximal SF ($p<0.05$).

****Increased speed is different from 57.5 to 100% of the maximal SF ($p<0.05$).

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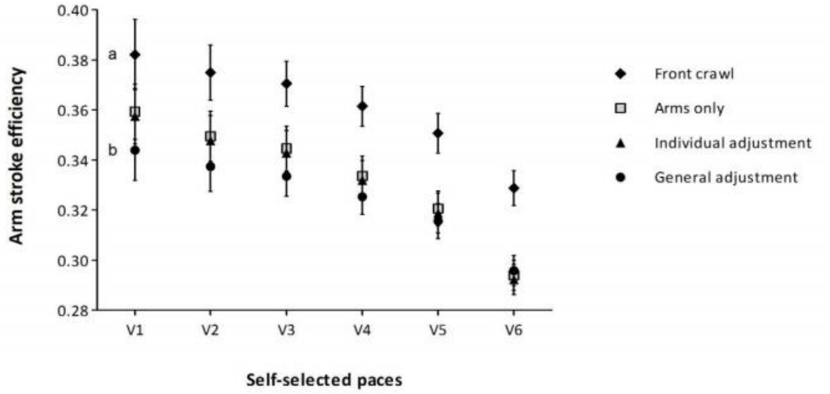

Figure 5. Arm stroke efficiency (η_F) at each self-selected speed. The data regarding front crawl swimming with the arms only (SAO) condition was individually adjusted for stroke frequencies equal to the ones observed in the front crawl stroke (FCS). Data are presented as Mean ± 1 SE, black lozenges are non-adjusted FCS values, black triangles are the SAO values, gray squares are individually-adjusted FCS values and black circles are FCS values adjusted assuming 90% of contribution from the arms to swimming speed.

[a.] η_F is different from all the other methods in each and every self-selected speed ($p<0.05$);

[b.] η_F is different from the SAO and the individually-adjusted FCS values at the first, second and third self-selected speed ($p<0.05$).

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Table 1 Stroke parameters (mean±SD) across the different self-selected paces and conditions.

Trial	v_{FCS} (m·s[-1])	v_{SAO} (m·s[-1])	SF_{FCS} (Hz)	SF_{SAO} (Hz)	SL_{FCS} (m)	SL_{SAO} (m)
V1	0.93 ± 0.10 [a]	0.87 ± 0.09	0.45 ± 0.07	0.44 ± 0.05	2.13 ± 0.41	1.98 ± 0.29
V2	1.02 ± 0.11 [a]	0.94 ± 0.10	0.49 ± 0.07	0.48 ± 0.06	2.09 ± 0.34	1.96 ± 0.29
V3	1.09 ± 0.11 [a]	1.03 ± 0.11	0.53 ± 0.06	0.54 ± 0.06	2.08 ± 0.29	1.92 ± 0.30
V4	1.19 ± 0.13 [a]	1.10 ± 0.13	0.59 ± 0.07	0.60 ± 0.07	2.03 ± 0.23	1.85 ± 0.22
V5	1.29 ± 0.14 [a]	1.18 ± 0.15	0.66 ± 0.08	0.67 ± 0.09	1.97 ± 0.22	1.77 ± 0.21
V6	1.43 ± 0.16 [a]	1.28 ± 0.18	0.78 ± 0.10	0.78 ± 0.10	1.84 ± 0.21	1.64 ± 0.18
Effect of speed						
Significance	p<0.001		p<0.001		p<0.001	
Effect size	0.934		0.897		0.538	
Observed power	1.000		1.000		1.000	
Effect of condition						
Significance	p<0.001		p=0.891		p<0.001	
Effect size	0.702		0.001		0.631	
Observed power	1.000		0.052		1.000	
Interaction						
Speed vs. condition						
Significance	p<0.001		p=0.212		p=0.190	
Effect size	0.418		0.051		0.051	
Observed power	1.000		0.436		0.518	

v_{SFC}: average swimming speed when swimming front crawl; v_{SAO}: average swimming speed when swimming front crawl with the arms only; SF_{FCS}: stroke frequency when swimming front crawl; SF_{SAO}: stroke frequency when swimming with the arm stroke only; SL_{FCS}: stroke length when swimming front crawl; SL_{SAO}: stroke length when swimming front crawl with the arms only.

[a]. Individual difference between FCS and SAO conditions (p<0.01).