University of Porto
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Biophysical Analysis of the 200 m Front Crawl

The interplay between the biomechanical, energetic, coordinative, and muscular factors

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Abstract

Biophysics, the area of confluence of physiology and biomechanics, has developed into one of the most attractive areas of study in swimming. However, a lack of research in this field is evident, especially in competitive distance events. The purpose of this thesis was to conduct a biomechanical, energetic, coordinative and muscular characterization of the 200 m front crawl event, aiming to understand the interplay among these four domains and its relationship with performance. The experimental protocol consisted in 200 m front crawl at race pace, as well as 50, 100 and 150 m at the previous 200 m lap paces. Biomechanical (speed, stroke length, stroke rate, intracycle velocity variation of the centre of mass in x, y and z axes, propelling efficiency), energetic (total energy expenditure and energy cost), coordinative (inter-arm coordination) and muscular (muscular activity and frequency) factors were assessed during the 200 m swim and blood samples were collected before and after each test. Results identified three components of a 200 m front crawl swim: the first 50 m lap, the second and third laps, and the fourth lap. Speed, stroke length, stroke rate, and propelling efficiency decreased, total energy expenditure, energy cost, inter-arm coordination muscular activity amplitude and frequency (decrease of frequency spectrum) increased, and intracycle velocity variation of the centre of mass maintained stable. Significant interplay was observed between the biomechanical, energetic, coordinative, muscular domains and the relative contribution of the assessed factors was closely related to the task constraints, especially fatigue, as the major changes occurred from the first to the last lap of the 200 m front crawl event.

Key words: Swimming, front crawl, intracycle velocity variation, energy cost, inter-arm coordination, electromyography

Resumo

A biofísica é a área de confluência da fisiologia e biomecânica, e tornou-se uma das áreas de maior interesse no estudo da natação pura desportiva. No entanto, a falta de investigação neste domínio é evidente, especialmente em distâncias competitivas. O propósito desta tese foi realizar uma caracterização biomecânica, energética, coordenativa e muscular dos 200 m crol, com o objetivo de entender a interação entre estes quatro domínios e sua relação com a *performance*. O protocolo experimental consistiu em 200 m crol à máxima velocidade em situação de competição simulada, bem como 150, 100 e 50 m, às intensidades correspondentes às respectivas passagens na prova simulada de 200 m. Os fatores biomecânicos (velocidade, distância de ciclo, frequência gestual, variação intracíclica da velocidade do centro de massa nos eixos x, y e z, eficiência propulsiva), energéticos (dispêndio energético e custo energético), coordenativos (coordenação inter-braços) e musculares (atividade muscular e frequência) foram avaliados durante 200 m crol, e amostras de sangue foram coletadas antes e após cada teste. Os resultados identificaram três componentes durante os 200 m: os primeiros 50 m, os segundos e terceiros 50 m, e os últimos. A velocidade, distância de ciclo, frequência gestual e eficiência propulsiva diminuiu, o gasto energético total, o custo da energia, a coordenação inter-braços, amplitude e frequência da atividade muscular (diminuição do espectro de frequências) aumentou, e a variação de intracíclica de velocidade do centro de massa mantêve-se estável. Foi observada uma interação significativa entre os fatores biomecânicos, energéticos, coordenativos e musculares, e a sua contribuição relativa ao longo do esforço esteve associada às condicionantes da tarefa, especialmente o aparecimento de fadiga, uma vez que as principais alterações ocorreram nos primeiros e últimos 50 m dos 200 m crol.

Palavras-chave: Natação, crol, variação intracíclica de velocidade, custo energético, coordenação inter-braços, eletromiografia

Résumé

La biophysique, champ de confluence de la physiologie et de la biomécanique, est devenue un des domaines des plus intéressants dans l'étude de la nage. Cependant, la recherche dans ce champ s'avère déficiente, surtout pour ce qui est de l'étude des compétitions sportives de natation. Le but de la présente thèse était d'effectuer une caractérisation biomécanique, énergétique et musculaire de l'épreuve de 200 m crawl, afin de permettre de comprendre l'intéraction entre ces quatre domaines et leur relation avec la performance. Le protocole expérimental a consisté dans 200 m crawl au rythme de course, ainsi que dans 50 m, 100 m et 150 m au même rythme que les distances intermédiaires du 200 m. Des facteurs biomécaniques (vitesse, distance par cycle, fréquence gestuelle, variation intracyclique de la vitesse du centre de la masse dans les axes x, y et z, efficience propulsive), des facteurs enérgétiques (dépense energétique totale et coût énergétique), des facteurs de coordination (coordination des bras) et des facteurs musculaires (activité musculaire et fréquence) ont été évalués lors de l'épreuve de natation de 200 m et des échantillons de sang ont été prélevés avant et après chaque épreuve. Les résultats ont permis d'identifier trois composantes de la nage de crawl de 200 m: la première longueur de 50 m, la deuxième et troisième longueurs, et la quatrième longueur. La vitesse, la distance par cycle, la fréquence gestuelle et l' efficience propulsive ont diminué, tandis que la dépense énergétique totale, le coût de l'énergie, la coordination entre bras, l'amplitude de l'activité musculaire et la fréquence (diminution du spectre de fréquence) ont augmenté. La variation intracyclique de la vitesse dans le centre de la masse est restée stable. Une interaction significative a été observée entre les domaines biomécanique, énergétique, de coordination et musculaire. La contribution relative des facteurs évalués a été étroitement liée aux contraintes de l'exercice, spécialement la fatigue, dans la mesure où les changements les plus importants sont survenus de la première à la dernière longueur de l'épreuve de 200 m crawl.

Mots clés: natation, crawl, variation intracyclique de la vitesse, coût de l'énergie, coordination des bras, électromyographie.

Zusammenfassung

Die Biophysik, d. h. jene Wissenschaft, die Physiologie und Biomechanik verbindet, hat sich in den letzten Jahren zu einem der attraktivsten Forschungsfelder innerhalb der Erforschung des Schwimmens entwickelt. Gleichwohl bleiben weiterhin Lücken zu füllen, gerade was die Erforschung des Sportschwimmens betrifft. Ziel dieser Dissertation war es, den Ablauf des 200-m-Kraulen unter biomechanischen, energieekönomischen, koordinativen und muskulären Gesichtspunkten zu analysieren und dadurch die Wechselwirkung dieser vier Bereiche und ihre Beziehung zum Leistungsverhalten zu verstehen. Das Experimentalprotokoll bestand aus 200-m-Kraulen im Renntempo sowie aus 50-, 100- und 150-m-Tests, deren Geschwindigkeiten den Teiletappen der vorhergehenden 200-m-Runde entsprachen. Biomechanische (Geschwindigkeit, Schlaglänge, Schlagfrequenz, intrazyklische Geschwindigkeitsschwankungen des Masseschwerpunkts auf der x-, y- und z-Achse, Antriebseffizienz), energieöknomische (gesamter Energieaufwand und Energieverbrauch), koordinative (Armkoordination) und muskuläre (Muskelaktivität und Muskelfrequenz) Faktoren während des 200-m-Schwimmens wurden untersucht und Blutproble wurden vor und nach jedem Test gesammelt. Das Ergebnis ermöglicht es, drei Komponenten beim 200-m-Kraulen zu unterscheiden: die erste 50-m-Bahn, die zweite und dritte Bahn und die vierte Bahn. Geschwindigkeit, Schlaglänge, Schlagfrequenz und Antriebseffizienz ließen nach, während der gesamte Energieaufwand, der Energieverbrauch, die Armkoordination, die Muskelaktivität im Hinblick auf Amplitude und Frequenz (Abnahme des Frequenz-Spektrums) zunahmen. Die intrazyklischen Geschwindigkeitsschwankungen des Masseschwerpunkts blieben stabil. Zwischen den biomechanischen, energieökonomischen, koordinativen und muskulären Faktoren konnten signifikante Wechselwirkungen beobachtet werden. Der relative Anteil der bewerteten Faktoren war eng mit Aufgabenbewältigungshemmnissen, vor allem mit Müdigkeit, verbunden, da die wichtigsten Änderungen von der ersten bis zur letzten Bahn des 200-m-Kraulens auftraten.

Schlagwörter: Schwimmen, Kraulen, intrazyklische Geschwindigkeitsschwankungen, Energieverbrauch, Armkoordination, Elektromyographie

List of Abbreviations

Aer	aerobic energy system
AnAl	anaerobic alactic energy system
AnL	anaerobic lactic energy system
AnS	anaerobic contribution
APAS	Ariel Performance Analysis System
BB	biceps brachii
BF	biceps femoris
C	energy cost of exercise
CM	whole body centre of mass
CRP	continuous relative phase
CV	coefficient of variation
D	hydrodynamic drag
d	Cohen effect size for t-statistics
EMG	electromyography
$\dot{E}_{tot}$	total energy expenditure
F	F-statistics
f	Cohen effect size for F-statistics
FCR	flexor carpi radialis
FI	spectral indices
Freq	frequency analysis of the electromyographic signal
IdC	index of coordination
iEMG	integral of the electromyographic signal
IVV	intracycle velocity variation
KF	kick frequency
$[La^-]$	blood lactate concentrations
$[La^-]_b$	basal blood lactate concentrations
max	maximum
min	minimum
n	number of subjects
P	probability
PM	pectoralis major
PCr	phosphocreatine
PO_2	oxygen partial pressure
r	correlation coefficient
r^2	determination coefficient
RF	rectus femoris

RMS	root mean square
SD	standard deviation
SE	standard error
SF	stroke frequency
SL	stroke length
SR	stroke rate
STATA	Data Analysis and Statistical Software
t	time
TA	tibialis anterior
TB	triceps brachii
TD	time delay
UT	upper trapezius
v	velocity, speed
vmin	maximum velocity
vmax	minimum velocity
$\dot{V}O_2$	volume of oxygen consumed
$\dot{V}O_{2b}$	basal volume of oxygen consumed
$\dot{V}O_{2max}$	maximal volume of oxygen consumed
$\dot{V}O_{2peak}$	maximal peak of oxygen consumed
W_{tot}	total mechanical work
W_d	mechanical work to overcome hydrodynamic resistance
W_{int}	internal mechanical work
W_{ext}	external mechanical work
x	horizontal axis
y	vertical axis
z	lateral axis
3D	three-dimensional
3Du	three-dimensional hand speed
$\Delta[La^-]$	difference between the maximal $[La^-]$ values measured after the test and those measured after the warm-up
ΔSL	difference between the values measured at the end and those measured in the beginning of the effort
ΔSpeed	difference between the values measured at the end and those measured in the beginning of the effort
ΔSR	difference between the values measured at the end and those measured in the beginning of the effort
η_F	froude efficiency
η_m	mechanical efficiency

η_o	overall efficiency
η_p	propelling efficiency
η_T	theoretical efficiency
τ	time constant

Chapter 1. General Introduction

The goal of competitive swimming is to travel the race distance as fast as possible. The identification of the variables that contribute to, and hence predict, swimming performance is one of the main aims of the swimming "science" community. Biomechanics, Physiology/Energetics, Biophysics, EMG, Anthropometry, Psychology, Medicine, Instruments, Evaluation, Education, Training and other factors are the main scientific approaches that are used to understand swimming (Vilas-Boas, 2010). It has been proposed that of these factors, biomechanics and physiology/energetics are the areas with the greatest potential to assist swimmers to enhance their performance and achieve high-levels in competitive swimming (Barbosa et al., 2010; Fernandes et al., 2009; Toussaint & Hollander, 1994; Zamparo et al., 2011).

The importance of biomechanics and physiology/energetics is understandable as swimming is characterized by the intermittent application of propulsive force to overcome a velocity-dependent water resistance, or drag. Propulsion is generated by the combination of arms, legs and trunk movements, which are dependent on the swimmer's technique. As opposed to land-based competitions, where the energy cost of locomotion does not vary a great deal with technique, swimming technique can vary the energy cost of swimming significantly (di Prampero, 1986). The swimming technique results in intracycle velocity variations of propulsion and, consequently, of velocity (for review see Vilas-Boas et al., 2010). These variations in propulsion, drag and, thus, instantaneous velocity contribute to the highly variable performance in swimming (Barbosa et al., 2010; Toussaint & Beek, 1992) and result in a particular mean velocity for various swimming distances.

The mean velocity in swimming is the product of the number of stroke cycles per minute (stroke rate, SR) and the distance the body travels per stroke (stroke length, SL), which are both velocity-dependent (Craig & Pendergast, 1979;

Craig et al., 1985). Coupling the biomechanics with physiology/energetic (Figure 1) shows that to attain a given velocity requires a given metabolic power output ($\dot{E}_{tot}$) that is also velocity-dependent (Barbosa et al., 2010; Capelli et al., 1998; di Prampero, 1986; Fernandes et al., 2006; Pendergast et al., 2003; Zamparo et al., 2011), as represented in the following equation:

$$v_{max} = \dot{E}_{tot-max} \cdot C^{-1} \quad (1)$$

where v_{max} represents maximal swimming velocity, $\dot{E}_{tot\text{-}max}$ maximal total energy expenditure corrected for body mass and C energy cost.

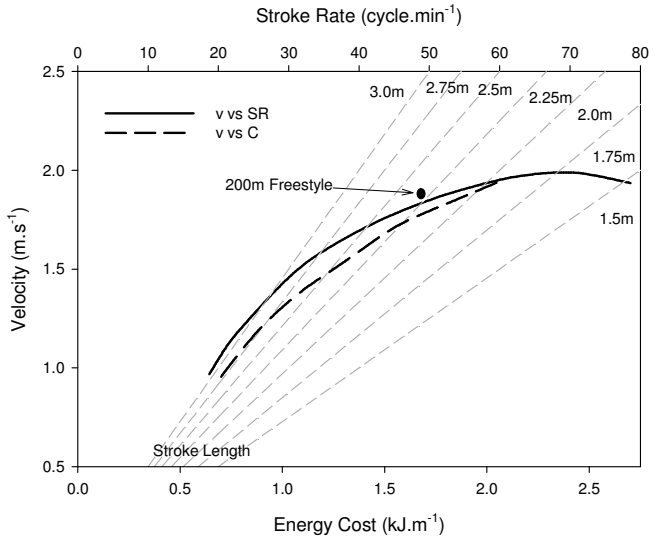


Figure 1. Stroke rate-velocity relationship and velocity-energy cost relationship. The dot represents the 200 m freestyle event. The inset indicates the theoretical changes of stroke rate and stroke length, which result in an increase of velocity.

The swimming velocity can also be described by the equation proposed by Pendergast et al. (1978):

$$v = \dot{E}_{tot} \cdot (\eta_p \cdot D^{-1}) \quad (2)$$

where v represents swimming velocity, $\dot{E}_{tot}$ total energy expenditure, η_p propelling efficiency, and D the hydrodynamic drag.

The above referred relationships show that maximal swimming performance depends on the interplay between biomechanical (eq. 1) and bioenergetics (eq. 2) factors. Previous studies have used these relationships to model the biophysics of swimming performance (Barbosa et al., 2010; Pendergast et al., 2006; Toussaint & Hollander, 1994), demonstrating that successful competitive swimming performance requires that a talented swimmer has developed his/her technique and physical conditioning to a high level (Smith et al., 2002).

Among the many approaches used in swimming research, the Biophysics of swimming has developed into one of the most attractive areas. Vilas-Boas (2010) reported that 5.6% and 1.4% of studies in swimming used the Biophysical approach in swimming as determined from the Biomechanics and Medicine in Swimming Symposia (the most important swimming congress, that takes place every four years) and Pubmed, respectively. Several of these researches have used incremental and intermittent protocols to understand the biophysical aspects of swimming as a function of velocity. Although a large spectrum of velocities has been studied, which helps to understand the relationship between important factors in swimming, researches failed to evaluate the specificity of specific competitive events. The current Thesis addressed specifically the factors that are critical to the 200 m freestyle event.

The experimental accomplishments of this work are presented in Chapters 2 to 11 of this Thesis. Additionally, a general discussion elaborates the results obtained from these individual studies with their integration in Chapter 11, and a discussion of the specialized literature related the studies include in this thesis appears in Chapter 12. The main conclusions, and suggestions for future research, are then presented in Chapters 13 and 14, respectively.

This research examined the front crawl technique, the most common stroke performed in official swimming events, and the one that allows the highest swimming velocity. Thus, the front crawl is the most important swimming technique to be used in competitions. As a consequence of its importance, front

crawl is the most widely used stroke in training and practice. Furthermore, it was study the 200 m event, which is the most common distance in competitive swimming. This event is scientifically interesting as it is a very unique competitive distance where both aerobic and anaerobic energy sources contribute significantly to the energetics (Capelli et al., 1998; Reis et al., 2010; Troup, 1991). In addition, appearance of fatigue during the 200 m event regarding biomechanical parameters influences both velocity and energetics (Alberty et al., 2005; Craig et al., 1985; Psycharakis & Sanders, 2008). Thus, studying the 200 m front crawl can help to understand the link between several factors that determine swimming performance. The aim of this Thesis was to understand the interplay among biomechanics, energetic, coordinative and, muscular factors that determine the 200 m front crawl performance.

Swimming performance corresponds to the time to cover specific distances, which equals mean velocity, and is a consequence of the average of the changes in instantaneous velocity. Instantaneous velocity is not constant during the stroke cycle and can be measured as the intracycle velocity variation (IVV). IVV is normally computed from the movements of the hip during free-swimming (Alberty et al., 2008; Alves et al., 1996; Schnitzler et al., 2010; Seifert, Leblanc, et al., 2010). However, the hip does not reflect the whole-body centre of mass kinematics during all of the components of the motion (**Appendix I**), thus, the motion of the center of mass is a better criterion variable. To analyze the kinematics properly, a greater accuracy and reliability in the computed video data should be used. This can only be accomplished by using a calibration volume in the video records during the measurements with the number and location of measurement points that ensure its validity and reliability (**Appendix II**).

Due to the cyclic application of propulsion, increases in the instantaneous velocity occur when the propulsive force of the swimmer exceeds the drag, while decreases in velocity occur when the drag exceeds the propulsive force. So, it is important to analyze the changes in IVV across the 200 m event to

examine the effects of fatigue and relation with performance. These data were used to develop an understanding of the hand kinematics that contribute to the increase or decrease of IVV (**Chapter 2**).

In front crawl swimming, the arm stroke and leg kick provide the propulsive force to overcome the body's drag. Propulsion is mainly provided by the arm stroke with a contribution of about 85 to 90% of the total (Bucher, 1975; Deschodt et al., 1999; Hollander et al., 1988). Nevertheless, leg kick has great importance in the body stabilization (Yanai, 2003). Therefore, a study was conducted to investigate kinematic and electromyographic changes during the 200 m front crawl, and to determine the effects of fatigue on the technique and muscle activation (**Chapter 3**).

As velocity also depends on the energy supply, $\dot{E}_{tot}$ (measured directly) and the energy cost of swimming (C, calculated as $\dot{E}_{tot}/v$) were studied (**Chapter 4**). For $\dot{E}_{tot}$, the computations of the three energy pathways were taken into account. For this, oxygen consumption ($\dot{V}O_2$) was measured directly during the effort, as well as the rate of change of $\dot{V}O_2$ at the onset of the swim ($\dot{V}O_2$ kinetics) (**Appendix IV**). Since C is highly dependent on the swimmers' propelling efficiency (η_p), it was also aimed to compute this parameter from the three-dimensional velocity of the hand during the stroke cycle (**Chapter 4**).

Previous biophysical swimming research has observed the relationship between IVV and C for all the swimming techniques (Alves et al., 1996; Barbosa et al., 2005; Barbosa, Lima, et al., 2006; Kjendlie et al., 2004; Vilas-Boas, 1996). However, all these studies used a swim test with a progression in velocities, and not during a competitive swim of a fixed distance, which was not studied before. To our knowledge, this relation (IVV vs. C) has not been previously studied during a competitive swimming distance and is presented in **Chapter 5**.

Due to the propulsion oscillations within the stroke and the relationship of SR and SL to velocity, the coordination and motor control in the swimming stroke is a recent topic of interest. This has been proposed as the beginning of the cascade that influences swimming performance (Barbosa et al., 2010). To address this issue, the continuous relative phase was used to characterize and understand the changes that occur in motor control during the 200 m swim. This was examined by studying the inter-arm temporal-spatial coupling and evaluation of the different solutions that swimmers have in the coordination of the phases of the stroke. Also, a profile cluster analysis was performed and all of these results are presented in **Chapter 6**.

As previous studies highlighted the index of coordination (IdC) proposed by Chollet et al. (2000) as the preferential tool to understand the coordination changes of the swimmers' that are faced with several constraints, a study was done using this tool to characterize the 200 m and understand the changes in the IdC relative to the different arm-stroke phases (**Chapter 7**). In addition, IdC was assessed by digitization rather than the subjective observation initially proposed.

Inter-arm coordination was also suggested to influence energy cost (C), since the latter depends on the timing between the actions responsible for the external work (Seifert, Komar, et al., 2010). A high positive correlation between these parameters was previously reported in incremental intermittent protocols (Fernandes et al., 2010; Komar et al., 2010; Seifert, Komar, et al., 2010). Consequently, Barbosa et al. (2010) suggested that C is inversely related to the propelling efficiency, as described in the following equation:

$$C = \left(\frac{W_{tot}}{\eta_P}\right)\eta_o^{-1} \quad (3)$$

where C is defined as the total energy expenditure required to displace the body over a given unit of distance, η_P is the propelling efficiency, η_o represents the overall efficiency and W_{tot} indicates the total mechanical work per unit of

distance.

Following this, the total mechanical work has been divided into the internal work (W_{int}), due to the velocity changes of the body segments respecting to the body CM, and the external work (W_{ext}), related to the position and speed changes of the CM relative to the environment (Alexander & Goldspink, 1977; Barbosa et al., 2010; Zamparo, Pendergast, et al., 2005), which could be expressed by the IVV of the CM (Minetti et al., 1993). Knowing this, a study aiming to understand the relationships among the changes in IdC with biomechanical factors (such as IVV and η_p) and energetic factors (such as C) were included in this Thesis (**Chapter 8**).

Motor coordination changes occur due to the response of the swimmer to the constraints imposed on its actions (Newell, 1986), and are adjusted (optimized) to maximize the movement efficiency (Sparrow et al., 2000; Sparrow & Newell, 1998); this optimization is attained by efficient muscle work (Wakeling et al., 2010; Wakeling et al., 2011). In **Chapter 9**, new insights about the impact of fatigue on muscle activity were studied using electromyographic techniques (EMG). The treatment of the raw EMG data included both amplitude and frequency analysis. These data were used to understand if muscle fatigue occurs during the swim, how fatigue evolves regarding the repetitive submaximal contractions and evaluation of the enrollment of upper and lower body muscles.

Briefly, the purpose of this Thesis was to understand the changes in biomechanical, energetics, coordinative and muscular factors, as part of the complex human biophysical phenomena of locomotion and general behaviour, to obtain the best performance in the competitive swimming distance. Propulsive and drag forces acting on the swimmer's body are major performance determinants, and are affected by technique, propelling efficiency, motor organization, and motor control. In addition, the force generators (the muscles) as well as energy expenditure of exercise influence swimming

performance. This way, a case study was conducted to analyse these factors (biomechanical, energetics, coordinative and muscular) during a 200 m front crawl (**Chapter 11**).

The interplay of the biomechanical, energetic, coordinative and muscular factors was determined using theoretical models based on the experimental data. Finally, the relative weight of the factors that contributed to each of the 50 m laps performance, as well as for the 200 m swim performance, were determined, and the interplay among them was analysed in **Chapter 12**. This chapter fulfills the biophysical structure, dynamics, and function, which allow an integrated visualization throughout the course of “conformational” changes.

Chapter 2

Intracycle velocity variation of the body centre of mass in Front crawl

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Abstract

Our aim was to assess the 3D intracycle velocity variation (IVV) of the body centre of mass (CM) during 200 m front crawl event to characterise it, and analyse its relation with the segmental hand kinematics and the velocity (v) changes. Ten high level male swimmers performed 200 m front crawl at maximal intensity. Two above and four under water cameras were used to record one complete non-breathing cycle, for each 50 m lap, and APASystem was used for imaging processing. The coefficient of variation was calculated to assess the IVV in the horizontal (x), vertical (y) and lateral (z) axes; hand kinematics was also computed. IVV remained stable across the 200 m, and correlations were found between vx and vmaxx ($r = 0.55$), vminx ($r = 0.68$), IVVx ($r = -0.45$) and IVVz ($r = -0.45$), all for $p \leq 0.01$. In addition, IVVx was related to the backward horizontal amplitude normalized to stroke length ($r = 0.54$), IVVy with hand angular velocity ($r = -0.40$), and IVVz with the elbow angle range in the pull phase ($r = -0.37$), all for $p < 0.05$. This study highlights the stability of the IVV (x, y, z), the inverse relation of the IVV (x, z) with v, the direct relation of the vmaxx and vminx with v, and the influence of the hand kinematics in the IVV.

Key words: Swimming, Biomechanics, Intracycle Velocity Variation, Three-dimensional, Front crawl

Introduction

The total mechanical work in aquatic locomotion is the sum of the work needed to overcome drag and intertial forces (external work), and the work needed to accelerate and decelerate the limbs regarding the body centre of mass (CM) (internal work) [4]. External work is related to the position and velocity changes of the CM and is expressed by its intracycle velocity variation (IVV), occurring as propulsive and drag forces change during swimming [31]. Thus, increases in the IVV imply higher work to swim at a certain velocity [24,32]. The IVV is discriminative of skill level [34,38,42], has been positively associated with energy expenditure [5,8,42], is considered as an indicator of swimming efficiency (for a review see [42]), and might be influenced by inter-arm coordination [2,34,35]. The lowest IVV values were found for front crawl [8,13,28], which is considered the most efficient conventional swimming technique, due to the higher continuity of the limbs' propulsive actions [5].

The 200 m race is one of the most interesting Olympic swimming events, and has been studied regarding the general stroke parameters [2,14,26], coordination mode [2,22], technical aspects [20], neuromuscular activity [6] and from a bioenergetics perspective [11,23]. In these studies, it was described that fatigue evolves during the 200 m effort. In addition, Psycharakis et al. [33] studied the role of the IVV in each 50 m lap and for the 200 m mean values that do not express the specificity of the task, particularly the individual evolvement of fatigue; complementarily, Alberty et al. [2] purposed that in fatigue conditions, changes occur in the stroke parameters (SL and SF), as well as in inter-arm coordination, to maintain the IVVx constant. However, Tella et al [40], in spite of showing a decrease of the time-frequency analysis of the intracycle acceleration during fatigue, only decrease in SF was observed. Concerning the kinematic changes of the hand, Deschodt [16] observed a decrease in the maximal forward coordinate and maximal depth of the hand during a 6 × 50 m set at maximal velocity performed by well-trained swimmers; conversely, Aujouannet et al. [6] found a stability of the underwater fingertip trajectory during a set of 4 x 50 m at maximal velocity performed by high level swimmers.

Studies that combined IVV and hand kinematics were conducted only for butterfly technique by Martins-Silva and Alves [29] and Barbosa et al. [7], who showed that high segmental velocities in all directional components of the most propulsive phases are associated to decreases of IVV, but no data is available for front crawl regarding this topic.

The aim of this study was to assess the three-dimensional IVV of the CM during a 200 m maximal front crawl event to analyse: (a) its variations across the event as fatigue occur; (b) its relationship with velocity changes during the race; (c) the hand kinematics that significantly influence it. It was hypothesized that: (a) IVV would be stable during the 200 m; (b) presents, a negative influence to velocity; and (c) higher stroke length and longer effective underwater pattern of the hand implies a decrease of the horizontal IVV, higher amplitude depths leads to an increase of the vertical IVV, and an efficient hand pattern technique tends to minimize the lateral IVV.

Methods

Experimental procedure

Ten high level male swimmers volunteered to participate in this study (mean (SD)): age 21.6 (2.4) yrs; height 185.2 (6.8) cm; arm span 188.7 (8.4) cm; body mass 76.4 (6.1) kg. All swimmers (mean performance in a 200 m race = 91.6 (2.1)% of the 25 m pool world record) had 11.0 (3.5) yrs experience as competitive swimmers. All subjects gave their written informed consent before participation. The study was approved by the local ethics committee and performed in accordance with the ethical standards proposed by Harriss and Atkinson [25].

After a moderate intensity individual warm-up, totalling 1000 m, swimmers performed a 200 m front crawl simulated race, at maximal intensity, from a push off start (to eliminate the influence of the dive in the analysis of the first stroke cycle). Six synchronised video cameras (Sony® DCR-HC42E, Tokyo, Japan) were used to record the event (four under and two above water); the above water angle between cameras was approximately 100º, while the angles

between adjacent underwater cameras varied from 75º to 110º. Three-dimensional reconstruction of twenty-one digitised body landmarks (50 Hz) was computed using DLT [1], a calibration frame (3 x 2 x 3 m for the horizontal, vertical and lateral directions; 30 calibration points) and a 6 Hz low pass digital filter. Twenty-one body landmarks, particularly the 7th cervical, mandible (mental protuberance), humeral heads, ulnohumeral joints, radiocarpal joints, 3rd dactylions, trochanter major of femurs, tibiofemoral joints, talocrural joints, calcanei and acropodion, and the Zatsiorsky anatomical model adapted by de Leva [15], were used. The calibration setup, the accuracy and reliability of the calibration procedures and digitisation have been described before [21]. One complete arm stroke cycle (at mid-pool and without breathing), for each 50 m of the 200 m front crawl, was recorded. Test sessions took place in a 25 m indoor pool (1.90 m deep and at 27.5ºC), and swimmers were instructed to avoid breathing while swimming through the calibrated space.

Data analysis

The IVV of the CM in three directions (x, y, z) was computed as the coefficient of variation of the instantaneous velocity-time data for each axis [42]. Maximum and minimum velocity within the stroke cycle (vmax and vmin, respectively), for x, y and z axes, were computed from the instantaneous velocity-time data. The velocity (x, y and z) was obtained from the intracycle velocity (x, y and z) data and the relative vmax and vmin (in all the axes) were calculated as a percentage of horizontal velocity. Mean horizontal velocity was calculated by dividing the swimmer's mean CM horizontal displacement by the time spent to complete one stroke cycle, stroke frequency (SF) was considered the inverse of the time to complete one stroke cycle, and stroke length (SL) was obtained through the horizontal displacement of the CM during one stroke cycle.

The following kinematic variables were computed through x, y and z positions of specific landmarks: (i) the backward displacement amplitude (distance between the most forward point and the most backward point) and slip amplitude (distance between entry and exit of the hand) of the hand, and both variables normalized to the SL values: (ii) the vertical motion of the upper limb

(represented by the fingertip in y direction referenced to water surface); (iii) the lateral motion of the upper limb (calculated as the absolute z displacement of the fingertip with reference to the swimmer's CM); (iv) the three-dimensional elbow angle (quantified as the arc-cosine of the dot product of the upper arm and lower arm unit vectors) calculated in four time moments within the underwater stroke cycle, entry of the hand in the water (A), beginning of finger backward movement (B), finger vertically aligned with the shoulder (C), and exit of the water (D); (v) the elbow angle range during the pull (B to C) and push (C to D) phases; (vi) the hand angular velocity (was derived through a digitising procedure and considered to be the mean angular speed of the line from the midpoint of the wrist to the fingertip projected onto the xy plane of the external reference system).

Statistical analysis

Mean (SD) computations for descriptive analysis were obtained for all variables (normal distribution of the data was verified with Shapiro–Wilk's test). A one-way repeated measures ANOVA was used to compare the studied parameters throughout the 200 m. When a significant F-value was obtained, Bonferroni post-hoc was performed to locate the pairwise differences between the means. To assess the relationship between horizontal velocity and the other variables for the whole race distance and for each of the four laps, Pearson's product–moment correlation coefficient was calculated. The 200 m and its four laps involved a repeated measurements design, and a within-subjects correlation coefficient was reported to account for the lack of independence among the repeated measurements by removing the variation between subjects [9]. Also, a between subjects correlation coefficient was implemented [10]. The effect size (f) for each variable was calculated according to Cohen [12]. All statistical analysis was performed using STATA 10.1 (StataCorp, USA) and the level of statistical significance was set at $p \leq 0.05$.

Results

Figure 1 presents the changes in velocity, vmax, vmin, vmax/v and vmin/v for x, y and z axes throughout the swimming event. Swimmers' vx decreased from the first to the remaining laps ($F_{(3,27)} = 24.58$, $p < 0.001$, $f = 1.26$). SL remained constant for the first three laps (2.29, 2.21 and 2.19 m, respectively), whereas a decrease was observed in the final 50 m (2.12 m) ($F_{(3,27)} = 4.56$, $p = 0.01$, $f = 0.32$). SF decreased significantly from 0.68 Hz in first lap to the other laps (0.63, 0.61 and 0.64 Hz, respectively) ($F_{(3,27)} = 5.08$, $p = 0.006$, $f = 0.39$). The vmaxx and vminx were concomitant with the vx behavior presented differences from the first to the other remaining laps ($F_{(3,27)} = 4.40$, $p = 0.01$, $f = 0.46$ and $F_{(3,27)} = 1.80$, $p = 0.01$, $f = 0.46$, respectively). No significant changes were found for the other velocity variables analysed throughout the 200 m race.

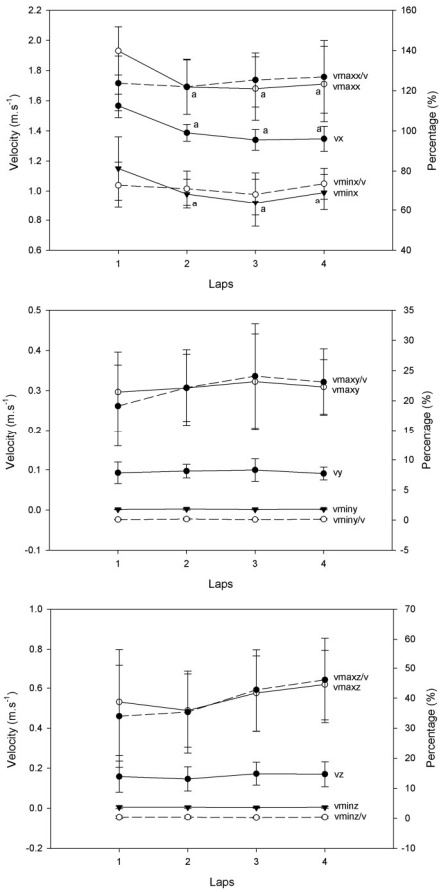


Figure 1. Mean velocity (v), maximal velocity (vmax), minimum velocity (vmin), vmax/v and vmin/v of the centre of mass in the horizontal (top panel), vertical (middle panel) and lateral (bottom panel) axes during the 200 m. [a] Statistically different from the Lap 1, $p \leq 0.05$.

Table 1 shows the mean (SD) values and repeated ANOVAs performed for IVV in x, y and z axes.

Table 1. Mean (SD) values and significance levels of the repeated measures ANOVA for the intracycle velocity variation (IVV) in x, y and z axes.

Variables	Lap 1	Lap 2	Lap 3	Lap 4	$F_{(3,27)}$	p	f
IVVx	0.21 (0.04)	0.20 (0.04)	0.24 (0.04)	0.23 (0.06)	1.60	0.21	0.18
IVVy	0.76 (0.10)	0.76 (0.10)	0.73 (0.11)	0.78 (0.10)	0.82	0.49	0.00
IVVz	0.80 (0.06)	0.84 (0.04)	0.84 (0.04)	0.83 (0.03)	2.18	0.12	0.24

Correlations computed between vx and IVV in all directions of motion are shown in Table 2. The within-subject correlation values showed a significant inverse relationship between vx and IVV in x and z axes. Referring to the different laps, an inverse relationship was also observed between vx and IVVx for the first lap, and between vx and IVVy for the first and last 50 m.

Table 2. Correlation coefficients (p) for the correlations between horizontal velocity (vx) and intracycle velocity variation in x, y and z axes (IVVx, IVVy and IVVz, respectively).

Variable	Correlations with vx					
	Within subject correlation	Between subject correlation	Lap 1	Lap 2	Lap 3	Lap 4
IVVx	-0.45 (0.01)	-0.19 (0.61)	-0.69 (0.03)	-0.26 (0.47)	-0.16 (0.65)	-0.32 (0.37)
IVVy	-0.12 (0.52)	-0.24 (0.53)	-0.64 (0.04)	0.08 (0.82)	0.23 (0.53)	-0.63 (0.05)
IVVz	-0.45 (0.01)	-0.14 (0.71)	-0.17 (0.63)	-0.26 (0.46)	0.01 (0.97)	-0.40 (0.25)

Table 3 shows the correlations between vx and vmax, vmin, vmax/v and vmin/v for x, y and z axes, being observed that vx was directly influenced by vmaxx and specially by vminx.

Table 3. Correlation coefficients (p) for the correlations between horizontal velocity (vx) and maximum velocity (vmax), minimum velocity (vmin), relative maximum velocity (vmax/v) and relative minimum velocity (vmin/v) for x, y and z axes.

Variable	Correlations with vx					
	Within subject correlation	Between subject correlation	Lap 1	Lap 2	Lap 3	Lap 4
vmaxx	0.55 (0.001)	0.30 (0.40)	-0.24 (0.50)	0.08 (0.84)	0.56 (0.09)	0.33 (0.35)
vminx	0.68 (<0.001)	0.55 (0.10)	0.72 (0.02)	-0.34 (0.33)	0.64 (0.04)	0.61 (0.05)
vmaxy	-0.16 (0.38)	-0.26 (0.50)	-0.47 (0.17)	-0.10 (0.78)	0.10 (0.79)	-0.25 (0.48)
vminy	0.01 (0.94)	-0.03 (0.92)	0.18 (0.62)	-0.24 (0.51)	0.18 (0.61)	0.46 (0.18)
vmaxz	-0.12 (0.52)	0.15 (0.67)	-0.04 (0.91)	-0.17 (0.63)	0.44 (0.20)	-0.04 (0.90)
vminz	-0.12 (0.52)	0.40 (0.25)	-0.20 (0.58)	-0.38 (0.28)	0.57 (0.09)	0.23 (0.52)
vmaxx/v	-0.34 (0.06)	-0.15 (0.68)	-0.68 (0.03)	-0.36 (0.30)	0.08 (0.83)	-0.17 (0.64)
vminx/v	0.39 (0.03)	0.41 (0.23)	0.61 (0.06)	-0.53 (0.11)	0.51 (0.13)	0.33 (0.35)
vmaxy/v	-0.43 (0.01)	-0.39 (0.33)	-0.55 (0.09)	-0.22 (0.55)	-0.05 (0.90)	-0.45 (0.18)
vminy/v	-0.07 (0.72)	-0.08 (0.83)	0.11 (0.77)	-0.26 (0.47)	0.09 (0.79)	0.37 (0.29)
vmaxz/v	-0.33 (0.07)	-0.01 (0.99)	-0.12 (0.75)	-0.26 (0.47)	0.31 (0.38)	-0.26 (0.47)
vminz/v	-0.23 (0.21)	0.39 (0.27)	-0.22 (0.54)	-0.40 (0.25)	0.52 (0.12)	0.14 (0.69)

Analysing deeply the IVV (x, y and z) to identify the segmental velocities that could influence it, the following significant within subject correlation coefficients over the 200 m front crawl were assessed: (i) IVVx was related to the SL ($r = -0.37$, $p = 0.04$), SF ($r = -0.34$, $p = 0.05$) and backward horizontal amplitude normalized to SL ($r = 0.54$, $p = 0.001$); (ii) IVVy was correlated with fingertip depth ($r = 0.35$, $p = 0.04$), and hand angular velocity ($r = -0.40$, $p = 0.02$); (iii) the lateral IVV was influenced by the angle of the elbow when hand is vertically align with the shoulder ($r = -0.35$, $p = 0.04$), the elbow angle range in the pull phase ($r = -0.37$, $p = 0.04$), SL ($r = -0.47$, $p = 0.01$), and backward amplitude normalized to SL ($r = 0.36$, $p = 0.04$). In addition, table 4 shows the mean (SD) of the hand kinematics parameters that significantly influence IVV during the

200 m front crawl, stressing the decrease of the hand angular velocity and maximum finger depth, the increase of the backward horizontal amplitude normalized to SL and the stability of the elbow angle when hand is vertically align with the shoulder and elbow range of the pull phase.

Table 4. Mean (SD) values and significance levels of the repeated measures ANOVA for the hand kinematic parameters (hand angular velocity, ratio backward amplitude to stroke length, maximal finger depth, elbow angle when hand-shoulder vertically align and elbow angle in the range of pull phase).

Parameter	Lap 1	Lap 2	Lap 3	Lap 4	$F_{(3,27)}$	p	f
Hand angular velocity (degree.s^{-1})	2.73 (0.42)	2.50 (0.26)	2.43 (0.26)[a]	2.38 (0.25)[a]	5.18	0.006	0.40
Backward amplitude/ SL	0.71 (0.06)	0.71 (0.08)	0.73 (0.07)	0.75 (0.07)[a,b]	4.50	0.01	0.18
Max. finger depth (m)	0.72 (0.06)	0.71 (0.06)	0.70 (0.05)	0.69 (0.06)[a]	4.90	0.008	0.17
Elbow angle: hand-shoulder (º)	102.2 (13.4)	101.2 (15.5)	96.8 (12.5)	95.9 (10.7)	2.24	0.11	0.16
Elbow angle: range of pull (º)	47.6 (14.7)	51.7 (14.9)	51.6 (17.5)	53.0 (14.4)	1.06	0.38	0.03

[a,b] Statistically significant differences from the first and second lap, respectively. $p<0.05$

Discussion

The purpose of this study was to examine the three-dimensional IVV of the CM throughout a 200 m front crawl maximum effort to establish its relationship with vx, and observe the kinematic variables that most influence it. The main findings were that the swimmers maintained a stable IVV (x, y and z) during the 200 m front crawl, and that the IVV (x and y) was inversely correlated with the vx, i.e., as higher is the IVV in the x and y axes, the lower is horizontal velocity. It was also observed that vx is highly influenced by vmaxx and vminx. The IVV has been considered an indicator of efficiency, and the three-dimensional approach of hand kinematics gave new insights on the IVV-related parameters that could be used to achieve higher improvements of the swimming performance, in agreement with the established hypothesis.

Maximum and minimum instantaneous velocity

As expected, vx generally decreased throughout the 200 m distance, being significantly higher in the first lap than in the subsequent three laps; concomitant changes in SL and SF were observed, particularly the increase in the SF in the fourth lap to maintain the vx as SL decreased (in accordance with previous results [2,14,26,33]). In addition, vmaxx and vminx were significantly higher in the first lap than the other three laps. As pointed out by Psycharakis et al. [33], it would be logical to expect swimmers to produce higher vmaxx and vminx at the early stages of the race, and it is possible that the swimming technique deteriorates, as the swim progressed, due to factors such as fatigue [20] that could have had a negative effect on their ability to produce large propulsive forces and/or to minimize resistive forces [23]. In the y and z directions, vmax and vmin seem to be stable across the four laps.

Swimming performance (as indicated by vx) had a strong linear relationship with both vmaxx and vminx when considering the repeated measures throughout the 200 m, as reported previously [33]. However, in each lap, vminx showed to be more determinant to a higher vx than vmaxx, as reported before [27,39]. Contrary to the absolute vmaxx value, its relative value was not associated with vx throughout the event. However, a negative correlation was found in the first, meaning that in the early stage of the race, where swimmers are not yet influenced by fatigue, vmaxx should be close to mean vx. This would result in a lower IVVx, as it is inversely related with performance during the course of the 200 m effort.

The relative vmaxx and vminx were 24 and 27% higher and lower than vx, respectively. These values are in accordance with data reported in other front crawl studies [2,13], resulting in a higher variation of velocity than the reported by Psycharakis et al. [33]. These differences could be due to velocity and stroke mechanics differences.

Intracycle velocity variation

The IVV (x, y and z), as hypothesised, was found to be stable in the course of the 200 m front crawl effort, which is in accordance with Psycharakis et al. [33]

and Alberty et al. [2]. This seems to be attained by a coordinative adaptation of the upper limbs, bringing the propulsive actions closer together when velocity increases or fatigue occurs [2,22,34], particularly through an increase of SF [36], as observed in our study. This suggestion was reinforced by significant relation between IVV and the stroke mechanics; an inverse relationship between SL and SF with IVVx was found across the 200 m. The SL and SF changes observed over the effort influence the propulsive impulse production [3], which is related to the inter-arm coordination. In this way, it influences the lag time between propulsive phases of each arm, which was associated to the stability in the IVVx at several swimming paces for high level swimmers [34].

IVVx showed an inverse moderate relationship with the vx throughout the 200 m effort, meaning that as vx decreased, IVVx increased, which is probably due to a decrease in the vminx. This parameter showed to be strongly related to vx during the course of the race and in each lap. Craig and Pendergast [23] reported a direct relationship between velocity and IVVx in a n x 25 m incremental protocol until maximum; however, swimmers were instructed to perform with a low stroke frequency and maximising stroke length. This task constraint would explain the obtained direct relationship, which might influence the inter-arm coordination selected by the swimmers (promoting a higher lag time between propulsive phases) [34,35], but also decreasing the duration over which the propulsive force act per distance unit [3], and lowering hand speed [41]. The observed relationship between the IVVx and vx for the first lap could be due to the higher vx attained in the beginning of the event, contrarily to the suggestion of Barbosa et al. [8]. The inverse relationship between IVVy and vx observed in the first and fourth laps, indicate a possible influence of the SF, as it were the laps with higher values.

The negative relationship between vx and IVVz could be explained by the necessity of maintaining a higher velocity of the hand during the sideway movements, which is a characteristic of high skilled swimmers [41]. The significant contribution of lift forces in human swimming was shown by several authors (for review see [41]), suggesting that differences between an excellent and a moderate swimming technique might be a result of the extent to which lift

forces are used, which should influence the movement along the z axis of the CM.

The above-mentioned inverse relation between IVV (x and z) and vx throughout the race is in opposition to the inexistence of relation reported before [33]. Our results suggest that swimming with lower IVVx and IVVz for a given mean vx would be more economical, as these parameters showed a negative relation with the SL (and so, with efficiency), which influences inversely economy [23,41]; this data seems to be in accordance with Barbosa et al. [8] who found a direct relationship between IVVx and energy cost in front crawl. However, energy cost increases with velocity increase [18,19]. These data were obtained in an incremental test and cannot be compared to a single 200 m bout, where fatigue is a major determinant of technique towards the end of the race. Investigations should be conducted towards the relationship between IVV and energy cost during race distances to understand the management of these variables in maximal competitive efforts. In addition, no relationships were observed in the between subject correlations, evidencing the homogeneity of the swimmers tested in the current study. As this could also have masked other possible relationship, further research focusing on swimmers of different levels would be useful.

Regarding the influence of the hand kinematics in the IVV, the inverse relation between IVVx and SF was in accordance with Martins-Silva and Alves [29] and Barbosa et al. [7], as it suggests an increase of hand velocity. The observed SF increase when the event comes to the end, results in increasing the relative duration of the propulsive phases [2,3], however as observed, a increase in backward amplitude relative to SL occurs, as well as a direct relation with the IVVx, reflecting a decrease in propelling efficiency [23] and confirming the necessity of an effective force aplication to minimize IVVx. These results are in opposition with Deschodt et al. [17], which reported a positive influence of the backward amplitude in vx, but for a 25 m sprint. In the 200 m front crawl event the catch-up inter-limb coordination is usually used [2,22], i.e., it is evident a higher relative time between propulsive actions due to longer gliding time [37], allowing a higher decrease in vminx. The characteristics of a 25 m maximum

velocity protocol would also influence the IVV (y and z), as SF rise, increasing also the hand angular velocity and decreasing IVVy by increasing the minimum velocity, and so, diminishing backward amplitude normalized to SL and IVVz.
The IVVz stability is justified, as the angle of the elbow when the hand is vertically below the shoulder remained stable over the effort and negatively influences IVVz. For the same elbow position a shorter angle would make the hand cross the medial line of the body, and would increase IVVz. Furthermore, the angle range during the pull phase showed a positive relation with IVVz, as in this phase important medial-lateral movements happen at high velocities [20,30,41]. The reported inverse relationship between IVVy and vx (observed in the first and fourth laps) is justified as IVVy showed an inverse relationship with the hand angular velocity. The highest SF were observed in the first and last lap, and the swimmers that presented lower SF had higher IVVy and lower vx. SF was more important in these laps due to the higher vx obtained in the first lap, and due to the fatigue effect in the last 50 m [2,6,23]. In addition, a higher SF leads to lower propelling efficiency [23,41], and less efficient technique with straighter movements leading to the observed deeper hand trajectory, as reported before [16]. During the 200 m bout the IVVy was inversely influenced by the maximal depth coordinate of the finger. Deschodt et al. [17], although in sprint, found a negative relation between the maximal depth coordinate of the finger and velocity. These findings might suggest a negative influence of the IVVy in the vx, as it was found for the first and last lap of the 200 m effort. This underlines the importance of minimizing superfluous movements in the y axis.

Conclusion

This study evidenced a stable IVV across the 200 m front crawl race, using different methodological calculation approaches. As velocity, SL and SF changed during the effort, they probably contribute for a stabilization of the IVV. The importance of the vmaxx and vminx in the vx was found, being also inversely influenced by the IVVx and IVVz. However, the relationship changed

when each 50 m lap were considered de per si, reflecting the influence of fatigue as the effort develops.

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Chapter 3

Kinematic and Electromyographic Changes During 200 m Front Crawl at Race Pace

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Abstract

The purpose of this study was to analyse eventual kinematic and electromyographic changes during a maximal 200 m front crawl at race pace. Ten male international level swimmers performed a 200 m maximal front crawl test. Images were recorded by two above and four under water cameras, and electromyographic signals (EMG) of 7 upper and lower limbs muscles were analysed for one stroke cycle in each 50 m lap. Capillary blood lactate concentrations were collected before and after the test. The variables of interest were: swimming speed, stroke length, stroke and kick frequency, hand angular velocity, upper limb and foot displacement, elbow angle, shoulder and roll angle, duration of stroke phases, and EMG for each muscle in each stroke phase. Generally, the kinematic parameters decreased, and a relative duration increases for the entry and pull phases and decreases for the recovery phase. Muscle activation of flexor carpi radialis, biceps brachii, triceps brachii, peitoral major and upper trapezius increased during specific stroke phases over the test. Blood lactate concentration increased significantly after the test. These findings suggest the occurrence of fatigue, characterised by changes in kinematic parameters and selective changes in upper limbs muscle activation according to muscle action.

Key words: Swimming, Technique, Front crawl, Segmental kinematics, Muscle activity, Blood lactate

Introduction

In front crawl swimming, the production of propulsive forces to overcome a velocity-dependent water resistance (i.e. hydrodynamic drag force) is mainly generated by the arm stroke motion. The contribution of the arm action to the total front crawl propulsion generated in front crawl is estimated to be about 85% (Deschodt, Arsac, & Rouard, 1999; Hollander, de Groot, & Van Ingen Schenau, 1988). Nevertheless, propulsion generation in swimming is not yet fully understood (Sanders, 1999; Toussaint, Van den Berg, & Beek, 2002), it is know that propelling forces are strongly linked to kinematic hand parameters, as observed in different models of hand force calculation (Berger, Hollander, & de Groot, 1999; Gourgoulis, Antoniou, Aggeloussis, Mavridis, Kasimatis, Vezos, Boli, & Mavromatis, 2010; Sanders, 1999; Toussaint, et al., 2002). It was also suggested that swimming speed (*v*) could be partly explained by hand displacements in the horizontal (aligned with the direction of the motion) and vertical axes during the arm stroke (Deschodt, et al., 1999), with hand speed being one of the main factors predicting swimming speed (Suito, Ikegami, Nunome, Sano, Shinkai, & Tsujimoto, 2008).

Studies regarding the effect of fatigue on the arm stroke kinematics during high intensity swimming are limited. Deschodt (1999) reported a significant decrease in horizontal wrist displacement in a 6 × 50 m front crawl set at maximal speed. In addition, Suito, et al. (2008) showed that hand speed and peak angular velocity of shoulder adduction were significantly reduced from the first to the second half of an all-out 100 m front crawl, in agreement with the reports of Toussaint, Carol, Kranenborg, & Truijens (2006). On the other hand, Aujouannet, Bonifazi, Hintzy, Vuillerme, & Rouard (2006) found unchanged spatial fingertip's trajectory, despite the occurrence of fatigue, during a protocol of 4 x 50 m front crawl at maximal intensity.

These alterations in kinematic parameters due to fatigue may be associated with eventual changes in muscle activation. For instance, an increase in the average muscular activity was found after an exhaustive 400 yards front crawl test for the shoulder external rotators (supraspinatus, infraspinatus, and teres

minor), and internal rotators (subscapularis) muscles (Monteil, Rouard, Dufour, & Troup, 1993). Furthermore, some authors found increases in the integrated EMG of the deltoid muscle during swimming at a speed of 1.3 and 1.4 $m.s^{-1}$ in a swimming flume (Wakayoshi, Moritani, Mutoh, & Miyashita, 1994), and of the flexor carpi ulnaris (considering the whole stroke cycle) and triceps brachii (during the insweep and outsweep phases) over a 4 x 100 m protocol conducted at 85% of the 100 m front crawl speed (Rouard, Billat, Deschodt, & Clarys, 1997). More recently, Stirn, Jarm, Kapus, & Strojnik (2011) evaluated muscle fatigue in upper body muscles during a 100 m all-out front crawl; although no changes in EMG amplitude of the pectoralis major, latissimus dorsi and triceps brachii muscles were found, it increased for the triceps brachii and the lower part of the latissimus dorsi.

Although the contribution of the lower limbs to the total propulsion in front crawl is known to be low (Deschodt, et al., 1999; Hollander, et al., 1988), the kick plays an important role in providing stability for the whole stroke by facilitation of body position, optimizing propulsion and minimizing resistance (Maglischo, 2003), as well as in assisting an economical body roll, as it is linked to the hydrodynamic forces (Yanai, 2003), implying physiological changes (e.g. oxygen consumption) (Ogita, Hara, & Tabata, 1996). In addition, proper kicking is required as a foundation for development of good coordination in the global front crawl technique (Sanders, 2007). In this way, the changes that might occur in the lower limbs actions during high-intensity swim should be taken into account.

In spite of the above-mentioned findings, to the best of our knowledge, no studies have been conducted to analyse the changes of such kinematic and electromyographic parameters during a high intensity swim competition distance. The present study aimed to investigate kinematic and electromyographic changes during a maximal 200 m front crawl at race pace.

Methods

Participants

Ten international level male front crawl swimmers (mean, *s* of 21.6, *s*=2.4 years old; 76.4, *s*=6.1 kg of body mass; 1.85, *s*=0.07 m of height; 1.89, *s*=0.08 m of arm span), 200 m specialists (91.6, *s*=2.1% of the 25 m pool world record average speed), volunteered to participate in the study. All principles of the Declaration of Helsinki were considered and the local ethics committee approved the study. All swimmers provided written informed consent.

Swimmers were marked with white half spheres attached to a black complete swimsuit, allowing manual digitisation for further three-dimensional reconstruction. Twenty-one anatomical landmarks were used: the vertex of the head, 7th cervical vertebra, mandible (mental protuberance), and the right and left tip of the third distal phalanx of the finger, wrist axis, elbow axis, shoulder axis, hip axis, knee axis, ankle axis, fifth metatarsophalangeal joint, and the tip of the first phalanx.

Data collection

After a moderate intensity individual warm-up totalling 1000 m, subjects underwent a 200 m maximal front crawl test, using a push off start and open turns to eliminate the influence of the dive in the analysis of the first stroke cycle and due to the EMG apparatus. One complete non-breathing stroke cycle, at mid-pool, was recorded for each 50 m of the 200 m front crawl. The stroke cycle was defined as the period between two consecutive hand entries of the right hand. Swimmers were instructed to avoid breathing while swimming through the calibrated space. The swimming test was recorded by six synchronised video cameras (Sony® DCR-HC42E) four under and two above the water. All cameras recorded the motion of the swimmer at a sampling frequency set at 50 fields per second and an electronic shutter speed of 1/250 s. The recorded swimming space was calibrated using a frame of the following dimensions: 3.0 m length (*x*), 2.0 m height (*y*), and 3.0 m (*z*) width (accuracy and reliability established by Figueiredo, Vilas Boas, & Fernandes, 2011). Three-dimensional

reconstruction of the twenty-one body landmarks, digitised manually and frame by frame using APAS (Ariel Dynamics Inc), was computed using DLT (Abdel-Aziz & Karara, 1971), Zatsiorsky anatomical model adapted by de Leva (1996), and a 6 Hz low pass digital filter. Tests were conducted in a 25-m indoor swimming pool (27.5º C).

The EMG activity was measured at a sampling frequency of 1000 Hz, with a 16-bit analog to digital conversion (BIOPAC System, Inc). The EMG signal of seven muscles (flexor carpi radialis, FCR; biceps brachii, BB; triceps brachii, TB; pectoralis major, PM; upper trapezius, UT; biceps femoris, BF; and rectus femoris, RF), which have been shown to have high activity during front crawl swimming (for review see Clarys & Cabri, 1993), was recorded from the right side of the body using bipolar (inter-electrode distance of 2 cm) Ag–AgCl circular surface electrodes, with preamplifiers (AD 621 BN). The electrodes were placed parallel to the direction of muscle fibres on the surface of the muscle belly according to international standards (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Before electrode fixation, the skin surface was shaved, abraded, and cleaned with alcohol. Afterwards, electrodes were covered with an adhesive bandage (Opsite Flexifix®) to avoid contact with water (de Jesus, Figueiredo, Goncalves, Pereira, Vilas-Boas, & Fernandes, 2011; Rouard & Clarys, 1995). All cables were fixed to the skin by adhesive tape to minimise the perturbation of the natural movement and interference with the signal. In addition, swimmers wore a complete swimsuit (Fastskin, Speedo®) with a cable entrance opened in the medium-dorsal position; over the water, a steel cable was extended with a sheave to which the cables corresponding to each one of the electrodes were fixed. A reference electrode was attached to the skin of the patella. The total gain of the amplifier was set at 1100 with a common mode rejection ratio of 110 dB (de Jesus, et al., 2011). To synchronise EMG and video, an electronic flashlight signal / electronic trigger was marked simultaneously on the video and EMG recordings.

Capillary blood samples (5 µl) were collected from the ear lobe to assess rest and post exercise blood lactate by means of a portable lactate analyser (Lactate Pro, Arkray, Inc.). Blood lactate was measured before and at 1, 3, 5,

and 7 min after the test; the peak value was used for further analysis as an indicator of exercise intensity.

Data analysis

Kinematical data analysis was done using APAS (Arial Dynamics, Inc.). The mean horizontal speed was calculated by dividing the swimmer's mean whole-body centre of mass (CM) horizontal displacement by the time spent to complete one stroke cycle. Stroke frequency (SF) was the inverse of the time to complete one stroke cycle. Stroke length (SL) was the horizontal displacement of the CM during one stroke cycle. Angular speed of the hand was derived through a digitising procedure and considered to be the mean angular speed of the line from the midpoint of the wrist to the fingertip projected onto the *xy* plane of the external reference system. Kick frequency (KF) was the inverse of the time to complete one kick cycle, defined as the period between two consecutive maximum vertical coordinates of the right foot.

The backward displacement amplitude and slip amplitude were calculated through the difference between the coordinates of the most forward point and the most backward position of the fingertip, and of the entry and exit of the fingertip, respectively (Figure 1). The vertical motion of the upper limb was represented by displacements of the fingertip, wrist, and elbow. The *y* displacement of the first phalanx tip was representative of the foot's vertical motion. Both the *y* direction motion of the upper limb and foot were referenced to an external point. The lateral motion of the upper limb was calculated as the absolute *z* displacement, referenced to the swimmer's CM.

Shoulder roll angle was determined by the arc-tangent (Sy/Sz), where Sy and Sz are the y and z components of the shoulder unit vector, i.e., the angle between the unit vector of the line joining the shoulders, projected onto the yz plane (the plane perpendicular to the swimming direction) and the horizontal.

The three-dimensional elbow angle was calculated in four time moments within the underwater stroke cycle (Figure 1): (i) entry of the hand in the water (*A* - entry); (ii) beginning of finger backward movement (*B* – first back); (iii) finger vertically aligned with the shoulder (*C* – shoulder x); (iv) end of backward

movement (*D* – end back). These time moments were calculated based on the horizontal displacement of the finger and shoulder during the stroke cycle. The elbow angle range during the pull and push phases was calculated as: *C*-*B* and *D*-*C*, respectively.

Four separate phases were identified within every stroke cycle (Figure 1), from the swimmer's horizontal (*x*) and vertical displacement (*y*) of the finger and noting the time corresponding to these displacements: entry, pull, push, and recovery (Chollet, Chalies, & Chatard, 2000; Seifert, Chollet, & Bardy, 2004). Time was expressed in seconds and as a percentage of the stroke cycle. Kick cycle phases were calculated based on the vertical displacement of the foot: the downbeat, from the maximal to minimum vertical coordinates; and, the upbeat, from the minimum to maximal vertical coordinates.

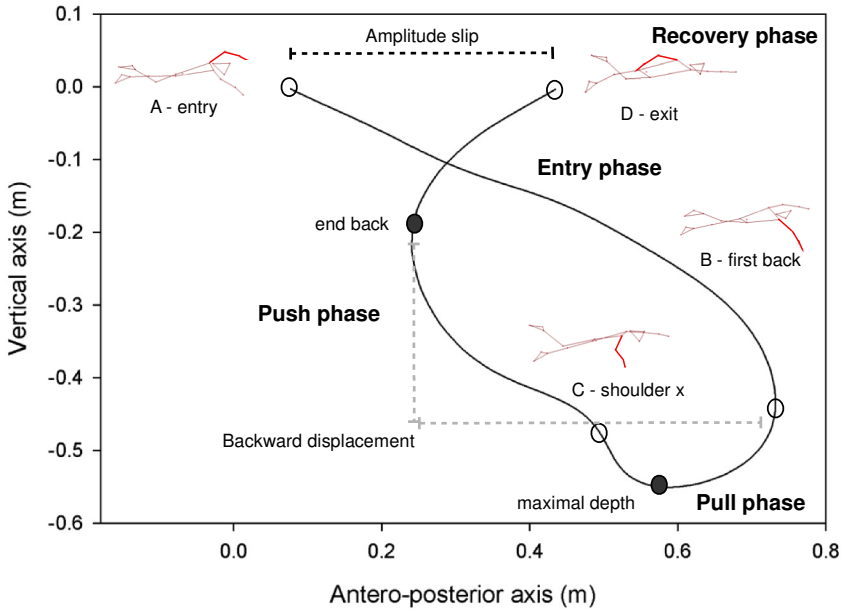


Figure 1. Example of the underwater trajectory of the right hand.

The EMG data analysis was performed using the MATLAB 2008a software environment (MathWorks Inc., Natick, Massachusetts, USA). The raw EMG signals were band-passed filtered (8-500 Hz), full-wave rectified and smoothed with a 4th order Butterworth filter (10 Hz) for the linear envelope. The integration of the rectified EMG (iEMG) was calculated, per unit of time, to eliminate the stroke phases duration effect (iEMG/t). The signal was partitioned in 40 ms

windows to find the maximal iEMG value for each swimmer over every stroke cycle in the mid-pool. To normalise the results, iEMG/t was expressed as a percentage of iEMG maximum value obtained during the 200 m (Caty et al., 2007).

Statistical analysis

All data were checked for normality and expressed as means and standard deviations (*s*). The compound symmetry, or sphericity, was checked using the Mauchley test (Winter, Eston, & Lamb, 2001). A one-way repeated measures analysis of variance (ANOVA) was used to assess changes in the measured variables over the four laps during the race. When significance was determined, post-hoc comparisons were conducted with Bonferroni analysis. A repeated measures *t-test* was used to compare blood lactate concentration between the beginning and end of the effort. Statistical significance was set at $P < 0.05$. All statistical tests were performed using STATA 10.1 software (StataCorp, Inc.). Effect size between laps and between beginning and end of the 200 m were computed with Cohen's *f* and Cohen's *d*, respectively. The criteria for interpreting the effect size were based on Cohen's (1988) suggestion that *f* effect sizes of 0.1 are small, 0.25 moderate, and 0.4 large and *t* effect sizes of 0.2 are small, 0.5 moderate, and 0.8 large.

Results

Mean (*s*), *P*- and *F*-values of the repeated measures ANOVA and *f* are displayed in Table 1 for the variables tested. Changes in race parameters were observed as denoted by the significance level and large effect sizes. Swimming speed, hand angular v, SL, SF, maximal depths of finger, wrist and elbow, elbow angle at the end back, shoulder roll and KF significantly diminished along the 200 m. Whereas, maximal elbow width showed a significant increase.

Table 1. Mean (*s*) data and statistical comparisons between the laps across the 200 m front crawl for the following variables: race parameters, arm, elbow angle, shoulder roll and foot.

Parameter	Lap 1	Lap 2	Lap 3	Lap 4	$F_{3,27}$	*P*	*f*
Speed ($m.s^{-1}$)	1.57 (0.08)	1.39 (0.06)[a]	1.34 (0.07)[a]	1.35 (0.06)[a]	24.58	<0.001	1.26
Stroke length (m)	2.29 (0.23)	2.21 (0.17)	2.19 (0.13)	2.12 (0.13)[a,b,c]	4.55	0.01	0.32
Stroke frequency (Hz)	0.68 (0.09)	0.63 (0.06)	0.61 (0.05)[a]	0.64 (0.05)	5.08	0.006	0.39
Hand angular v ($rad.s^{-1}$)	0.048 (0.007)	0.044 (0.005)	0.042 (0.005)[a]	0.042 (0.004)[a]	5.18	0.006	0.40
Backward amplitude (m)	1.62 (0.12)	1.57 (0.14)	1.59 (0.11)	1.59 (0.11)	0.96	0.43	0.00
Backward amplitude/SL (m)	0.71 (0.06)	0.71 (0.08)	0.73 (0.07)	0.75 (0.07)[a,b]	4.50	0.01	0.18
Amplitude slip (m)	0.56 (0.27)	0.57 (0.32)	0.56 (0.33)	0.58 (0.31)	0.06	0.98	0.00
Max. finger depth (m)	0.72 (0.06)	0.71 (0.06)	0.70 (0.05)	0.69 (0.06)[a]	4.90	0.008	0.17
Max. wrist depth (m)	0.57 (0.06)	0.56 (0.06)	0.55 (0.05)	0.54 (0.06)[a]	4.50	0.001	0.18
Max. elbow depth (m)	0.36 (0.04)	0.35 (0.04)	0.34 (0.04)	0.33 (0.06)[a,b]	6.98	0.001	0.21
Max. finger width (m)	0.34 (0.05)	0.35 (0.09)	0.35 (0.09)	0.38 (0.07)	1.13	0.35	0.07
Max. wrist width (m)	0.33 (0.04)	0.34 (0.06)	0.33 (0.07)	0.34 (0.04)	0.41	0.75	0.00
Max. elbow width (m)	0.31 (0.05)	0.33 (0.06)	0.34 (0.05)	0.35 (0.05)[a]	4.79	0.008	0.23
Finger width range (m)	0.35 (0.08)	0.35 (0.10)	0.33 (0.10)	0.35 (0.05)	0.75	0.53	0.00
Wrist width range (m)	0.29 (0.05)	0.30 (0.08)	0.27 (0.08)	0.27 (0.06)	1.30	0.29	0.09
Elbow width range (m)	0.22 (0.05)	0.23 (0.05)	0.23 (0.05)	0.23 (0.05)	1.03	0.39	0.03
Elbow angle: entry (º)	149.4 (12.1)	145.1 (14.0)	149.1 (11.4)	146.0 (12.8)	1.61	0.21	0.10
Elbow angle: first back (º)	149.7 (11.2)	152.9 (6.8)	148.4 (10.6)	149.0 (8.1)	1.85	0.16	0.13
Elbow angle: shoulder x (º)	102.2 (13.4)	101.2 (15.5)	96.8 (12.5)	95.9 (10.7)	2.24	0.11	0.16
Elbow angle: end back (º)	143.0 (3.3)	142.6 (7.6)	141.3 (6.6)	136.3 (4.8)[a,b]	5.57	0.004	0.43
Elbow angle: range of pull (º)	47.6 (14.7)	51.7 (14.9)	51.6 (17.5)	53.0 (14.4)	1.06	0.38	0.03
Elbow angle: range of push (º)	40.8 (14.9)	41.4 (19.1)	44.4 (14.8)	40.3 (12.6)	0.56	0.64	0.00
Shoulder roll (º)	107.6 (15.8)	114.2 (13.2)	118.9 (9.4)[a]	114.1 (15.7)	3.12	0.04	0.25
Kick frequency (Hz)	2.02 (0.21)	1.87 (0.21)	1.85 (0.20)[a]	1.91 (0.22)	2.80	0.05	0.26
Depth Right foot (m)	0.47 (0.03)	0.47 (0.05)	0.48 (0.03)	0.48 (0.04)	0.11	0.96	0.00

[a,b,c] Significantly different from the first, second and third lap, respectively. $P<0.05$.

Mean (*s*) relative and absolute durations of stroke phases for each lap, as well as the propulsion/non-propulsion ratio, are presented in Figure 2 (left and right panel, respectively). The entry and pull phases presented an increase of the relative duration along the 200 m ($F_{3,27} = 5.25$, $P = 0.005$, $f = 0.23$; $F_{3,27} = 3.37$, $P = 0.03$, $f = 0.36$, respectively), while a decrease was observed for the recovery phase ($F_{3,27} = 9.08$, $P < 0.001$, $f = 0.37$). Absolute durations of the entry phase increased progressively from the first lap ($F_{3,27} = 7.56$, $P < 0.001$, $f = 0.33$), whereas an increase in the push phase was observed only in the last 50 m ($F_{3,27} = 4.13$, $P = 0.02$, $f = 0.47$). Although the push and recovery phases did not presented significant differences ($F_{3,27} = 2.37$, $P = 0.09$, $f = 0.29$; $F_{3,27} = 2.67$, $P = 0.07$, $f = 0.19$, respectively) *P*-values were lower than 0.10 and the effect size was medium.

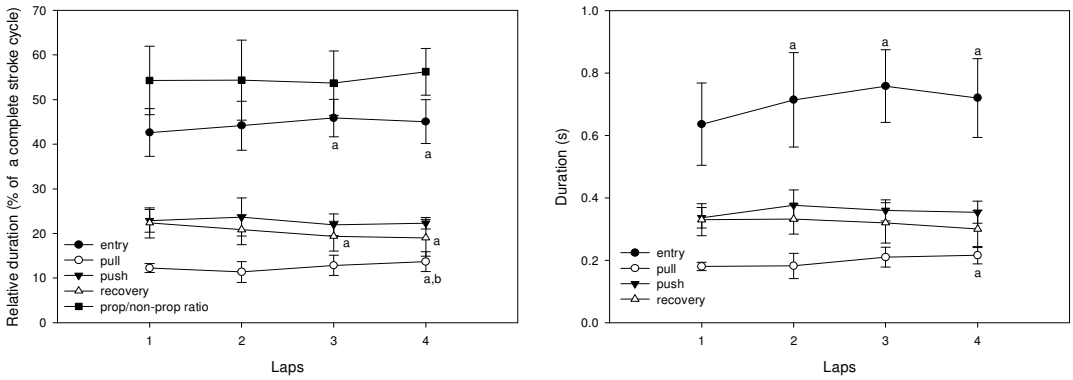


Figure 2. Stroke phase relative durations and propulsion/non-propulsion ratio (left panel), and stroke phase absolute durations (right panel). Mean (*s*) values are indicated over the 200 m front crawl. [a,b] Significantly different from the first and second lap, respectively. $P < 0.05$.

Figure 3 shows upper body muscles activation (FCR, BB, TB, PM, and UT) separated by phase and lap.

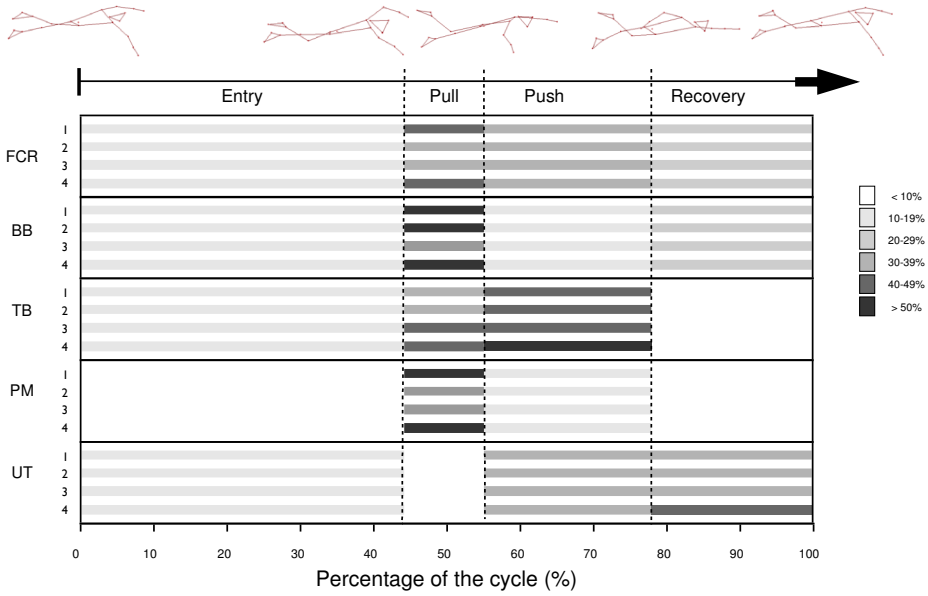


Figure 3. Upper limb muscles iEMG during each stroke phase across the 200 m front crawl (1 to 4 represents the laps). FCR – flexor carpi radialis, BB – biceps brachii, TB – triceps brachii, PM – pectoralis major, and UT – upper trapezius. The stick figure represents the key points that define the phases.

FCR presented differences during the entry, pull and push phases between the second and third with the fourth lap ($F_{3,27} = 7.14$, $P = 0.001$, $f = 0.42$; $F_{3,27} = 9.01$, $P < 0.001$, $f = 0.43$; $F_{3,27} = 3.32$, $P = 0.04$, $f = 0.32$, respectively); BB for

the pull phase between the third and fourth lap ($F_{3,27}$ = 3.30, P = 0.04, f = 0.27); TB for the push phase between the first and fourth lap ($F_{3,27}$ = 3.21, P = 0.04, f = 0.16); PM for the pull phase between the third and fourth lap ($F_{3,27}$ = 4.60, P = 0.01, f = 0.30); and UT for the recovery phase between the first and second with the fourth lap ($F_{3,27}$ = 5.19, P = 0.01, f = 0.29). iEMG mean (s) values of lower limbs muscles activation (BF and RF) are presented in Figure 4; no statistical significant differences were found along the 200 m effort.

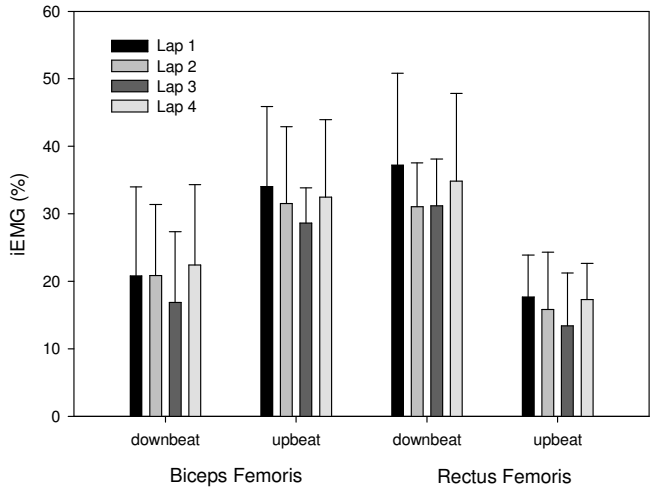


Figure 4. Mean±s values of the lower limb muscles iEMG during downbeat and upbeat phases of the kick over the four laps of the 200 m front crawl maximal effort.

Blood lactate increased from 1.07, s = 0.21 mmol.L^{-1} at rest to 11.12, s = 1.65 mmol.L^{-1} after the test (t = -21.27, P < 0.001, d = -9.01).

Discussion

This study aimed to analyse if the changes in kinematic variables and muscle activity in response to a high-intensity swimming test would reflect evidence of fatigue, confirmed by the measured blood lactate after the 200 m.

Stroke parameters management changed along the 200 m front crawl event as expected, as in the literature (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005; Craig, Skehan, Pawelczyk, & Boomer, 1985; Psycharakis & Sanders, 2008). SL decreased along the test with statistical meaning in the last

50 m lap, and SF decreased in the third lap in comparison to the first one, and augmented at the end of the effort to compensate the decrease in the SL (allowing maintenance of speed) (Alberty, Potdevin, Dekerle, Pelayo, Gorce, & Sidney, 2008; Alberty, et al., 2005; Craig, et al., 1985).

Concomitant with velocity decrease, angular velocity of the hand diminished along the 200 m; once the upper limb is assumed to be the main generator of propulsive force, therefore decreases in swimming velocity are likely to be caused by reduced hand velocity, as found for the 100 m front crawl (Suito, et al., 2008; Toussaint, et al., 2006). This change of hand angular velocity has implications on the time duration of the stroke phases, as the pull phase is increased in relative and absolute values, but without higher propulsive force generation. The increase in relative duration of the pull phase, and the decrease in relative duration of the recovery phase, is in agreement with the results of Alberty, et al. (2005) also during a 200 m test.

Backward amplitude was higher than the value reported by Deschodt, et al. (1999), probably because of the different protocol velocities, as it changes the SR-SL relationship (Craig, et al., 1985), and lower velocities are associated with higher SL (Barden, Kell, & Kobsar, 2011). However, backward amplitude remained statistically stable, suggesting that the most forward point augmented, possibly due to a higher glide, in accordance with the increase in relative and absolute duration of the entry phase. When backward amplitude was normalised to SL, an increase in the last lap was observed, suggesting a decrease of the propelling efficiency (cf. Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011), as a higher relative duration of the pull phase as hand angular velocity decreased, but with lower propulsive impulses as SF increase (Alberty, Sidney, Pelayo, & Toussaint, 2009).

The measured depths were similar to the values previously described for 25 m maximal intensity swimming (Deschodt, et al., 1999; McCabe, Psycharakis, & Sanders, 2011; Payton, Bartlett, Baltzopoulos, & Coombs, 1999). A decrease of the depths was observed from the first to the last lap, resulting in a tendency for an absolute decrease in elbow angle at shoulder x point (not statistically different, but with a medium size effect). This occurred due to the elbow width

increased, although with the same range. The values presented by the maximal finger width were in accordance with the literature (McCabe, et al., 2011; Payton, et al., 1999). The observed changes in the depth could be due to changes in SF, as the shoulder roll presents the same pattern (significant decrease in the third lap), and have been linked to each other (Cappaert, 1999; Psycharakis & Sanders, 2010; Yanai, 2003). The magnitudes of shoulder roll in the present study were similar to those reported by Psycharakis & Sanders (2008) and McCabe, et al. (2011), at least for the first lap, where the velocities were higher. However, the speed was constant during the last three laps, the shoulder roll increased in the last lap, and yet the depths decreased. In this phase (pull) the PM and BB showed a great importance and an increase of the activation as previously reported (Rouard, et al., 1997; Rouard & Clarys, 1995), suggesting that the attained stability was done by increasing the muscle effort, based on the dominant contribution of shoulder adduction during this phase (Suito, et al., 2008). A high activation of the TB in this phase suggests the antagonist action to maintain joint stability and supplement prime movers action (Rouard, et al., 1997). It would be of interest to understand if less skilled swimmers perform in the same way or have great kinematical changes.

In the push phase, the elbow angle at end back point values were slightly lower than the ones presented by McCabe, et al. (2011); however the measurement protocols were different, as this late have implemented bouts of 25 m at maximum speed. The decrements in this parameter across the effort suggest a reduction of the power output (Berger, et al., 1999; Gourgoulis, et al., 2010), and also a decrease in the propulsive forces produced in the push phase. It is suggested that TB fatigues, although the push phase duration was stable, because of the decrease of angular hand velocity. TB activation during the push phase increased significantly along the 200 m, in agreement with the results of Aujouannet, et al. (2006). The increase in EMG signal amplitude occurs in response to muscle fatigue, to maintain the swimming speed through an additional recruitment of muscle fibres (Merletti, Knaflitz, & De Luca, 1990).

As SF increased in the last lap, changes occurred in the relative duration of the recovery phase, as previously observed (Alberty, et al., 2008; Seifert, et al.,

2004), but with a decrease (medium effect size) of the absolute duration (Barden, et al., 2011). Concomitant with this changes the activation of the UT muscle occurred in the last lap, resulting from the successive sub-maximal repetitions (bringing the upper limb out of the water to the initial position to start a new stroke cycle), and decreasing the time between contraction and relaxation. The augmented activation of FCR during the catch, pull and push phases throughout the test is likely to confirm the important role of this muscle in stabilising the wrist during these phases, as previously reported for the wrist flexor muscles (Caty, et al., 2007), since the higher load is underwater, presenting evidence of fatigue (Rouard, et al., 1997).

The deterioration of stroke mechanics is described in the literature, and was related to local fatigue due to high lactate levels (Figueiredo, et al., 2011; Toussaint, et al., 2006). The observed post exercise blood lactate values are similar to those found by other authors after 200 m front crawl swimming event (Alberty, et al., 2005; Craig, et al., 1985; Vescovi, Falenchuk, & Wells, 2011), confirming the high intensity achieved by the participants during the test, and suggesting the appearance of fatigue.

Regarding the lower limbs, KF decreased in the third lap, as in the SF, suggesting that swimmers maintained the same arm-leg coordination. The lower limbs seem to follow the upper limbs frequency, as the first ones have a lower importance in the propulsion (Deschodt, et al., 1999; Hollander, et al., 1988), which is reflected in the level of activation of both BF and RF muscles in comparison to the upper limb muscles in their main phases. As a consequence, BF and RF do not show electromyographic and kinematic evidences of fatigue, as their level of activation remained the same, predominantly in the downbeat (RF) and upbeat (BF) kick, as they are agonistic/antagonistic muscles; their depth remained also the same, in spite of changes in KF. Kick depth values were slightly higher than those presented by McCabe, et al. (2011), probably because in sprinting the KF is so much higher that it reduces the amplitude of the kick. In addition, the slightly higher activity of the BF and RF in the first lap of the upbeat and downbeat phase (respectively), suggest that the higher speed in the first lap could be associated with higher lower limbs use; this would lead

to a higher body position, decreasing frontal drag, and consequently requiring less work for upper limbs would be needed (as found by Rouard, Quezel, & Billat, 1992).

Conclusion

Changes in the spatial and temporal kinematics occurred during the 200 m front crawl. In addition, muscular activation of the upper limb muscles increased during the event in the phases in which they were required. These changes evidenced fatigue that was indicated by high blood lactate at the end of the event. The lower limb kinematics and muscle activity remained quite stable only changing their KF in response with SF changes, but not showing signs of fatigue.

Acknowledgments

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Chapter 4

An energy balance of the 200 m front crawl race

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Abstract

The purpose of the present study was to determine the relative contribution of the aerobic (Aer), anaerobic lactic (AnL) and alactic (AnAl) energy sources during each of the four laps of a 200 m front crawl race. Additionally, energy cost (C) and arm stroke efficiency were also computed. Ten international swimmers per- formed a 200 m front crawl swim, as well as 50, 100, and 150 m at the 200 m pace. Oxygen consumption was measured during the 200 m swim and blood samples were collected before and after each swim; the C of swimming was calculated as the ratio of E_{tot} to distance (where E_{tot} = Aer + AnL + AnAl). Arm stroke efficiency was calculated by kinematic analysis as the speed of center of mass to the ratio of 3D hand speed. For the 200 m the contributions were 65.9% (Aer), 13.6% (AnL), and 20.4% (AnAl) whereas for each lap they were 44.6, 73.2, 83.3 and 66.6% (Aer), 14.1, 5.0, 4.4 and 28.1% (AnL) and 41.3, 21.8, 12.3 and 5.2% (AnAl) for the four laps, respectively. For the 200 m as a whole C was 1.60 kJ m^{-1} whereas C = 1.71, 1.56, 1.44 and 1.70 kJ m^{-1} for each consecutive lap, respectively. Arm stroke efficiency ranged from 0.40 to 0.43 and was significantly lower in the last lap as compared to the first ($P = 0.002$), suggesting the occurrence of fatigue. The decrease in arm stroke efficiency was mirrored by an increase in C as can be expected on theoretical grounds.

Key words: Swimming, Front crawl, Energy contribution, Biomechanics, Arm stroke efficiency

Introduction

Competitive swimming events over different distances (from 50 m to 1500 m) are characterized by different durations (and intensities) and can be described in terms of the specific relative contribution of aerobic and anaerobic energy sources to overall energy expenditure (e.g. Capelli et al. 1998; Capelli 1999; di Prampero 2003; Laffite et al. 2004; Reis et al. 2010; Zamparo et al. 2000). The power and capacity of the immediate (ATP-PCr), short-term (anaerobic glycolysis), and long-term (oxidative phosphorilation) systems of energy production are indeed major factors in determining swimming performance and a large part of training is devoted to the improvement of the different energy production systems (Toussaint and Hollander 1994).

Indeed, as proposed by di Prampero (1986), maximal performance in swimming (v_{max}), as well as in other forms of locomotion, depends on the maximal metabolic power of the athlete ($\dot{E}_{tot\text{-}max}$) and on his/her energy cost (economy) of locomotion (C):

$$v_{max} = \dot{E}_{tot-max}/C \quad (1)$$

As indicated above, $\dot{E}_{tot\text{-}max}$, can be computed based on measures / estimates of the aerobic, anaerobic lactic and anaerobic alactic energy contributions, whereas C (i.e. the amount of metabolic energy spent to cover one unit of distance, kJ · m^{-1}; di Prampero 1986) depends on biomechanical factors such as the mechanical efficiency (η_m), the propelling efficiency (η_p) and the mechanical work to overcome hydrodynamic resistance (W_d):

$$C = W_d/(\eta_P \times \eta_m) \quad (2)$$

Hence, for a given $\dot{E}_{tot\text{-}max}$, a subject with a good propelling efficiency and a low hydrodynamic resistance (and hence with a low C) will outrun a subject with a poor η_P and a large W_d (and hence with an high C). On the other hand, a subject with an elevated $\dot{E}_{tot\text{-}max}$ could outrun a swimmer with a better C but

characterized by a lower maximal aerobic and/or anaerobic power (e.g. di Prampero et al. 2010). Therefore, the swimmer's propelling (and overall) efficiency plus his/her capability to overcome drag, as well as $\dot{E}_{tot\text{-}max}$, are the factors to be taken into account when a complete energy balance of a given swimming race has to be computed.

Last but not least, propelling efficiency depends on technique and is affected by fatigue (Troup 1991; Toussaint et al. 2006; Zamparo et al. 2005a). During a competitive swimming event it could indeed be expected that when the subject develops fatigue, his/her technique is impaired and his/her propelling efficiency is decreased thus leading to an increase in his/her energy cost (detrimental to performance).

This "cascade", which is expected on theoretical grounds, has not been demonstrated in swimming yet, at least in swimming races. Indeed, $\dot{E}_{tot\text{-}max}$ and C are generally determined for the total duration of the event and not for the single laps (e. g. Capelli et al. 1998; Zamparo et al. 2000) and the papers which investigate metabolic parameters generally do not take into account biomechanical parameters and *viceversa*. Exceptions are those that relate the C and speed fluctuations (e. g. Alves et al 1996; Barbosa et al. 2005, 2008; Vilas-Boas 1996).

Recently, the aerobic and anaerobic contributions to $\dot{E}_{tot\text{-}max}$ were evaluated in each 100 m of the 400 m front crawl (Lafitte et al. 2004) and an attempt was made to relate kinematic variables to metabolic data even if no direct measures of propelling efficiency were made. The aim of the present study was to determine the relative contribution of the three energy sources during each of the four laps of a 200 m front crawl race. Additionally, C and arm stroke efficiency were computed in order to investigate their role in the development of fatigue in this swimming race.

Materials and Methods

Subjects

Ten international level male swimmers volunteered to participate in this study.

Subjects' average (SD) age, height, arm span, body mass and percentage of body fat were 21.6 (2.4) yr, 185.2 (6.8) cm, 188.7 (8.4) cm, 76.4 (6.1) kg, and 10.1 (1.8)%, respectively. The participants had an average of 11.9 (3.5) yrs of competitive experience and an average performance in the 200 m short-course front crawl swim of 109.3 (2.1) s. All subjects gave their written informed consent before participation. The study was approved by the local ethics committee and was performed according to the Declaration of Helsinki.

Experimental design

All swimmers were tested in the competitive period of the training season. To minimize any overtraining effects on test performance, swimmers avoided stressful training during the days before the test. On the testing day each swimmer performed an individual warm-up, which consisted of low- to moderate-intensity 1000 m aerobic swimming. Following the warm-up, swimmers performed a 200 m maximum front crawl swim replicating their competition pacing and strategy. All tests were conducted in a 25 m indoor pool; a push start and open turns, without gliding, were performed. During these tests, oxygen consumption was measured as indicated below; moreover, video records were taken in order to measure propelling efficiency (see below). After, at least, 90 min of rest interval, each swimmer performed a 50 m front crawl test at the same swimming speed as in the previous 200 m (controlled by a visual light pacer - TAR 1.1, GBK-Electronics, Aveiro, Portugal - with a flash every 5 m). Twenty-four hours later, each swimmer performed a 150 m and a 100 m test, with at least 90 min interval between. At the end of each test blood lactate accumulation was measured (this protocol was first publically proposed in a scientific meeting by Vilas-Boas and Duarte 1991). To simulate as much as possible the 200 m test conditions, swimmers used the respiratory snorkel and valve system also in the 50, 100 and 150 m tests. The swimming speed (v) for each lap was calculated by the ratio between distance and corresponding times by means of a stopwatch.

Data collection

Oxygen uptake (VO_2) was recorded by means of the K4b² telemetric gas exchange system (Cosmed, Roma, Italy), during the 200 m front crawl test. This equipment was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (as validated by Keskinen et al. 2003). Expired gas concentrations were measured breath-by-breath and averaged every 5 s (cf. Sousa et al. 2010). Net VO_2 was calculated by subtracting the resting VO_2 (assumed to be equal to 5 $ml \cdot kg^{-1} \cdot min^{-1}$) from the measured VO_2. Before, and after, the 50, 100, 150 and 200 m tests capillary blood samples (5µl) were collected from the ear lobe to assess rest and post exercise blood lactate (La_b) by means of a portable lactate analyzer (Lactate Pro, Arkray, Inc.). Lactate was measured at 1, 3, 5, and 7 min post test, and the peak value was used for further analysis.

Data Analysis

The 200 m race can be considered a "square wave" exercise of intensity close to, or above, maximal aerobic power; at this intensity the energy contribution of all the three energy sources should be taken into account (Capelli et al. 1998; Zamparo et al. 2010). For each 50 m lap these contributions were calculated as follows.

1) Aerobic contribution. The aerobic contribution (*Aer*, kJ) in each of the four 50 m laps was calculated from the time integral of the net $\dot{V}O_2$ vs. time relationship in the appropriate time ranges. This energy contribution (*Aer*, ml O_2) was then expressed in kJ assuming an energy equivalent of 20.9 $kJ \cdot lO_2^{-1}$ (Zamparo et al. 2010).

2) Anaerobic contribution. The anaerobic contribution (*AnS*, kJ) was obtained by the sum of the energy derived from lactic acid production (*Anl*, kJ) plus that derived from phosphocreatine (*PCr*) splitting in the contracting muscles (*AnAl*, kJ). In turn:

Lactic contribution:

$$Anl = b[La]_{bnet} \cdot M \quad (3)$$

where $[La]_{bnet}$ is the net accumulation of lactate after exercise, *b* is the energy equivalent for lactate accumulation in blood (2.7 ml $O_2 \cdot mM^{-1} \cdot kg^{-1}$ as proposed by di Prampero 1978) and *M* (kg) is the mass of the subject. $[La]_{bnet}$ (mM) was calculated as the difference in $[La]_b$ before and after each lap. In the first lap: $[La]_{bnet\,50} = [La]_b$ 50 m – $[La]_b$ rest; in the second lap: $[La]_{bnet\,100} = [La]_b$ 100 m – $[La]_b$ 50 m; in the third lap: $[La]_{bnet\,150} = [La]_b$ 150 m – $[La]_b$ 100 m; in the fourth lap: $[La]_{bnet\,200} = [La]_b$ 200 m – $[La]_b$ 150 m. This energy contribution (*Anl*, ml O_2) was then expressed in kJ assuming an energy equivalent of 20.9 kJ $\cdot$ lO_2^{-1} (Zamparo et al. 2010).

Alactic contribution:

$$AnAl = PCr\,(1 - e^{-t/\tau}) \cdot M \quad (4)$$

where t is the time duration, τ is the time constant of *PCr* splitting at work onset (23.4 s, as proposed by Binzoni et al. 1992), *M* (kg) is the mass of the subject and *PCr* is the phosphocreatine concentration at rest. The latter was assumed to be equal to 27.75 mM $\cdot$ kg^{-1}, an average of the values reported in the literature (see Prampero et al. 2003).

The energy derived from the utilisation of the *PCr* stores (*AnAl*) was estimated assuming that, in the transition from rest to exhaustion, the *PCr* concentration decreases by 27.75 mM $\cdot$ kg^{-1} muscle (wet weight) in a maximally active muscle mass (assumed to correspond to 50% of body mass). *AnAl* can be expressed in kJ by assuming a P/O_2 ratio of 6.25 and an energy equivalent of 0.468 kJ $\cdot$ mM^{-1} (cf. Capelli et al. 1998). When the *AnAl* stores are completely exploited the energy derived (for a subject of 70 kg of body mass) amounts to: [(27.75 $\cdot$ 0.5M) / 6.25] $\cdot$ 0.468 = 72.7 kJ. The *AnAl* contribution for each lap was then calculated as the difference in *AnAl* before and after each lap. In the first lap: $AnAl_{50}$ =

AnAl 50 m – *AnAl* rest; in the second lap: $AnAl_{100}$ = *AnAl* 100 m – *AnAl* 50 m; in the third lap: $AnAl_{150}$ = *AnAl* 150 m – *AnAl* 100 m; in the fourth lap: $AnAl_{200}$ = *AnAl* 200 m – *AnAl* 150 m.

On the basis of these data overall, $\dot{E}$ was computed and *C* was calculated as the ratio between $\dot{E}$ and average *v*.

Kinematic analysis

Each swimmer's performance was recorded with a total of six stationary and synchronized video cameras (Sony® DCR-HC42E) at 50 Hz, four below and two above the water. Twenty-one landmarks (Zatsiorsky's model adapted by de Leva 1996), that define the three-dimensional position and orientation of the rigid segments, were manually digitized using Ariel Performance Analysis System (Ariel Dynamics, Inc.). Kinematic data were processed with a digital filter at 6 Hz and stored on a computer for offline analysis. One stroke cycle for each of the 50 m lap was analyzed. The setup and calibration utilized in this study has been described in detail by Figueiredo et al. (2009), where the accuracy and reliability of the calibration procedure and digitization process was also reported.

From these data, the center of mass position as a function of time was computed; the speed of the center of mass (v_{cm}) was calculated by dividing the horizontal displacement of center of mass in one stroke cycle over its total duration. Additionally, stroke length (SL, m · cycle^{-1}) was determined through the horizontal displacement of the center of mass during a stroke cycle and stroke frequency (SF, cycle·min^{-1}) was determined from the time needed to compete a stroke cycle. From the kinematic data, the 3D hand speed was computed as the sum of the instantaneous 3D speed of the right and left hand during the underwater phase (3Du) and was utilized in further analysis.

The propelling efficiency of the arm stroke was estimated in two ways:

1) from the ratio of the speed of the center of mass to 3D average hand speed, since this ratio represents the theoretical efficiency in all fluid machines (Fox and McDonald 1992) and in "rowing animals" (Alexander, 1983):

$$\eta_T = v_{cm}/3Du \quad (5)$$

2) according to the model proposed by Zamparo et al. (2005b). This 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 efficiency for the underwater phase only, as follows:

$$\eta_F = (v/(2\pi \cdot SF \cdot L)) \cdot 2\pi \quad (6)$$

where *v* is the average speed of the swimmer, SF the stroke frequency (in Hz) and the term L is the average shoulder-to-hand distance, which was calculated trigonometrically by measuring the upper limb length and the average elbow angle during the insweep of the arm pull. In turn, elbow angle was measured from kinematic data, in the insweep phase, in the point at which the hand was right above the shoulder (as suggested by Zamparo et al. 2005b).

Equation 6 was not "corrected" for the contribution of the legs to propulsion (as originally proposed by Zamparo et al. 2005b) in order to allow a comparison with data of η_T (for which this contribution was also not taken into account too). Therefore, in both cases, the efficiency values are values of Froude/Theoretical efficiency (internal work is not considered/computed in both cases) of the arm stroke only. For a more detailed discussion see di Prampero et al. (2010) and Zamparo et al. (2010).

Statistical Analysis

Average (SD) computations for descriptive analysis were obtained for all variables (normal Gaussian distribution of the data was verified by the Shapiro–Wilk's test). A one-way repeated measures ANOVA was used to compare the analysis of the kinematical parameters along the 200 m. When a significant F-value was achieved, Bonferroni post hoc procedures were performed to locate the pairwise differences between the averages. The efficiency method agreement was assessed by pairwise T-test, linear regression analysis, Pitman's test of difference in variance, and the Bland–Altman plot. This

statistical analysis was performed using STATA 10.0, being set the level of significance at 0.05.

Since a limited sampled is used, effect size was computed with Cohen's f. It was considered a (Cohen 1988): (1) small effect size if $0 \leq |f| \leq 0.10$; (2) medium effect size if $0.10 < |f| \leq 0.25$ and; (3) large effect size if $|f| > 0.25$. To determine the tests reliability (50, 100 and 150 m) of the SF and rest blood lactate values between the different swims, a one-way repeated measures ANOVA was used. The reliability was for the SF for the 1st lap ($F_{(3,27)} = 2.11$, $P = 0.12$, $f = 0.19$), for the 2nd lap ($F_{(2,18)} = 2.26$, $P = 0.13$, $f = 0.13$), and for the 3rd lap ($F_{(1,9)} = 2.98$, $P = 0.12$, $f = 0.10$). Also for rest blood lactate no differences were found $F_{(3,27)} = 0.34$, $P = 0.80$, $f = 0.13$.

Results

Kinematical analysis

Table 1 shows the average (SD) values of the assessed biomechanical parameters in each 50 m lap of the 200 m front crawl. Swimming v_{cm} ranged from 1.57 to 1.33 $m.s^{-1}$ decreasing significantly from the first lap to the other laps ($F_{(3,27)} = 24.72$, $P < 0.001$, $f = 1.04$). SL remained constant for the first three laps, whereas a decrease in SL was observed in the 4th lap ($F_{(3,27)} = 4.55$, $P = 0.01$, $f = 0.33$). SF only presented differences between lap 1 to lap 3 ($F_{(3,27)} = 4.55$, $P = 0.006$, $f = 0.39$).

Table 1. Average (SD) speed of the center of mass (v_{cm}), stroke length (SL), stroke frequency (SF), three-dimensional hand speed (3Du), η_T and η_F values in each 50 m lap of the 200 m front crawl.

	v_{cm} ($m.s^{-1}$)	SL ($m.cycle^{-1}$)	SF ($cycles.min^{-1}$)	3Du ($m.s^{-1}$)	η_T	η_F
1st 50m	1.57	2.29	40.91	3.65	0.43	0.41
	(0.08)	(0.23)	(5.24)	(0.21)	(0.02)	(0.04)
2nd 50m	1.39[a]	2.21	37.78	3.35[a]	0.42	0.40
	(0.06)	(0.17)	(3.42)	(0.15)	(0.02)	(0.05)
3rd 50m	1.34[a]	2.19	36.64[a]	3.23[a]	0.42	0.41
	(0.07)	(0.13)	(2.80)	(0.23)	(0.02)	(0.03)
4th 50m	1.33[a]	2.12[a]	37.72	3.31[a]	0.41[a]	0.40
	(0.06)	(0.14)	(2.64)	(0.26)	(0.01)	(0.04)

[a, b, c] Different from the 1st, 2nd and 3rd lap, respectively. P<0.05

Concomitant with the decrease in v_{cm}, a significant reduction in 3Du was found from the 1st lap to the others ($F_{(3,27)} = 18.19$, $P < 0.001$, $f = 0.69$), being these values approximately twice the values of v_{cm}. However, the decrease in v_{cm} was higher than the decrease in 3Du, which leads the ratio $v_{cm} \cdot 3Du^{-1}$ (the theoretical efficiency) significantly lower in the 4th lap compared to the others ($F_{(3,27)} = 6.64$, $P = 0.002$, $f = 0.40$).

Arm stroke efficiency was also calculated as proposed by Zamparo et al (2005b). These values (η_F) were found to be close to the η_T ones (per parwise T-test $P = 0.125$, $d = 0.24$) and positively correlated ($\eta_F = 0.927$, $\eta_T + 0.0204$; N = 40; R = 0.444; $P = 0.004$); however, the values of η_F remained stable during the four laps of the 200 m ($F_{(3,27)} = 0.71$, $P = 0.56$, $f = 0.14$). The Bland-Altman plot of the difference in efficiency values against the average efficiency is reported in Figure 1. The average difference was rather low (95%IC -0.021 to 0.002) with limits of agreement (average ± 1.96SD) ranging from -0.082 to 0.062. The Pitman test of difference in variance showed that the correlation coefficient of the difference versus average of the two measurements was 0.669 ($p < 0.001$) indicating that the difference between the two methods tends to increase the higher the efficiency values.

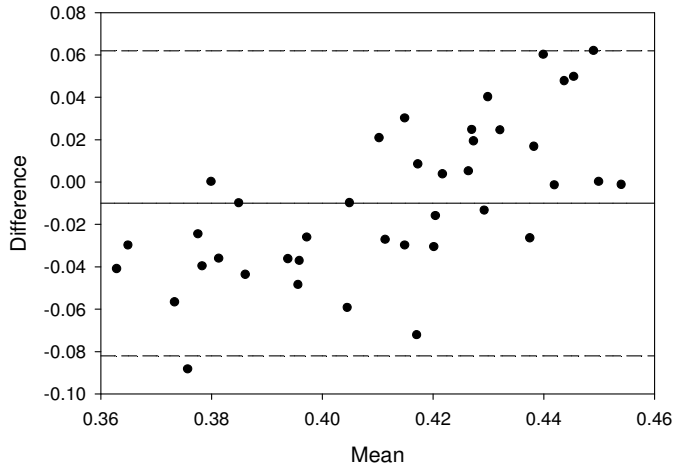


Figure 1. Bland and Altman plot of comparison between both estimates for propelling efficiency of the arm stroke. Average difference line (solid line) and 95% IC (dashed lines) are indicated.

The average (SD) values of lactate measured at rest and after the 50, 100, 150 and 200 m test where 1.07 (0.21), 3.47 (0.74), 4.18 (1.13), 4.92 (1.10) and

11.12 (1.65) mM, respectively. From these data the anaerobic lactic contribution was determined as described in the methods section.

The average (SD) values of E_{tot} are reported in Table 2 along with the aerobic (*Aer*), anaerobic lactic (*AnL*) and anaerobic alactic (*AnAl*) contribution during the four laps in terms of energy (kJ) and power (kW). In the same table are also reported the times and the corresponding velocities for each lap; the contribution of the three energy sources was also computed based on the total 200 m distance and is reported on the last row of Table 2. The contribution of the *Aer* energy sources (kJ), was stable in the last three laps and significantly lower in the 1st one compared to the others ($F_{(3,27)}$ = 110.515, $P < 0.001$, f = 1.36). Indeed, in the 1st lap the contribution of the *AnAl* and *AnL* (1st lap different from the 2nd and 3rd) energy sources was predominant ($F_{(3,27)}$ = 925.91, $P < 0.001$, f = 5.69 and $F_{(3,27)}$ = 66.131, $P < 0.001$, f = 1.73, respectively). As indicated in table 2, *AnAl* (kJ) decreased as a function of time, being highest in the 1st lap and lowest in the last one. On the contrary, the contribution of *AnL* (kJ) was highest in the final lap compared to the others ($F_{(3,27)}$ = 66.131, $P < 0.001$, f = 1.73). Total energy expenditure (E_{tot}, kJ), was higher in the 1st and 4th lap ($F_{(3,27)}$ = 19.578, $P < 0.001$, f = 0.59) compared to the 2nd and 3rd laps. In terms of power, the contribution of the three energy sources to $\dot{E}_{tot}$ (kW) was similar to that described above; however, differences in $\dot{E}_{tot}$ were found not only between the 1st and 4th lap, but also between the 2nd and 3rd one ($F_{(3,27)}$ = 29.137, $P < 0.001$, f = 0.80).

In Table 2, are also reported the values of energy / power as calculated for the total 200 m distance. These data can also be obtained by summing the contribution of the four laps (in terms of energy, E) or by averaging them (in terms of power, $\dot{E}$).

Finally, average v and time were not significantly different in the 2nd to the 4th lap, whereas the 1st lap was covered at a significantly higher v and lower time ($F_{(3,27)}$ = 31.519, $P < 0.001$, f = 1.25 and $F_{(3,27)}$ = 30.753, $P < 0.001$, f = 1.23, respectively).

The percentage contributions of *Aer*, *AnL* and *AnAl* to E_{tot} are reported in Figure 2 for the four laps (lines plot) and for the total distance (histogram), also in this

case it is apparent that the data calculated over the 200 m distance correspond to the average value of the four laps. For the 200 m swim the contributions were of 65.9%, 13.6% and 20.4% for the aerobic, anaerobic lactic and anaerobic alactic energy sources, respectively. The aerobic contribution was lower in the 1st lap compared to the others, whereas the *AnAl* contribution decreased from the 1st to the last lap. Finally, the lactic contribution was higher in the first and last lap compared to the others.

Table 2. Average (SD) speed (*v*), time (t), aerobic (*Aer*), anaerobic lactic (*AnL*), anaerobic alactic (*AnAl*) contributions and total energy expenditure (E_{tot}) values sources in the four 50 m laps of the 200 m and of the 200 m front crawl. Results in kJ and kW.

	v (m/s)	*Aer* (kJ)	*AnL* (kJ)	*AnAl* (kJ)	E_{tot} (kJ)
1st 50m	1.56 (0.08)	38.22 (6.87)	12.05 (3.34)	35.01 (2.53)	85.28 (9.07)
2nd 50m	1.40 [a] (0.07)	57.00 [a] (6.06)	3.84 [a] (2.03)	17.01 [a] (2.04)	77.84 [a] (7.09)
3rd 50m	1.36 [a] (0.06)	59.92 [a] (6.11)	3.40 [a] (2.92)	8.79 [a,b] (1.13)	72.10 [a] (8.78)
4th 50m	1.38 [a] (0.05)	56.53 [a] (5.31)	24.24 [a,b,c] (6.03)	4.44 [a,b,c] (0.51)	85.21 [b,c] (10.35)
Sum		211.68 (22.16)	43.52 (8.24)	65.24 (4.98)	320.44 (31.90)
200m	1.42 (0.05)	210.61 (22.20)	43.42 (7.80)	65.24 (4.98)	319.27 (31.60)
	t (s)	*Aer* (kW)	*AnL* (kW)	*AnAl* (kW)	$\dot{E}_{tot}$ (kW)
1st 50m	32.22 (1.62)	1.19 (0.24)	0.38 (0.11)	1.09 (0.08)	2.66 (0.36)
2nd 50m	35.83 [a] (1.78)	1.60 [a] (0.19)	0.11 [a] (0.06)	0.48 [a] (0.06)	2.18 [a] (0.24)
3rd 50m	36.90 [a] (1.53)	1.63 [a] (0.17)	0.09 [a] (0.08)	0.24 [a,b] (0.03)	1.96 [a] (0.26)
4th 50m	36.36 [a] (1.36)	1.56 [a] (0.16)	0.67 [a,b,c] (0.18)	0.12 [a,b,c] (0.01)	2.35 [a,b,c] (0.33)
Average		1.49 (0.17)	0.31 (0.06)	0.48 (0.04)	2.29 (0.26)
200m	141.30 (4.74)	1.49 (0.17)	0.31 (0.06)	0.46 (0.04)	2.23 (0.23)

[a, b, c] Different from the 1st, 2nd and 3rd lap, respectively. P<0.05

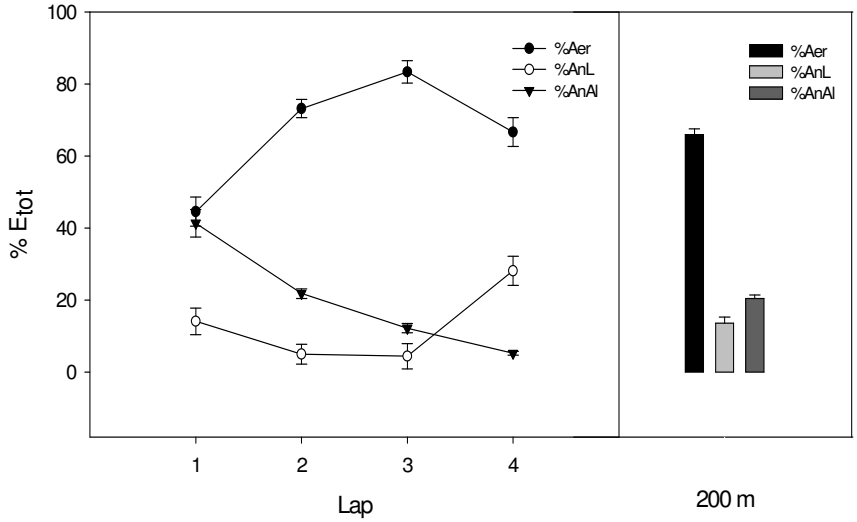


Figure 2. Percentages of the total metabolic power output (%E_{tot}) derived from aerobic (%*Aer*), anaerobic lactic (%*AnL*) and anaerobic alactic (%*AnAl*) energy sources in the four 50 m laps of the 200 m and of the 200 m front crawl.

The energy expenditure needed to cover a unit distance (*C*) was calculated from the ratio of E_{tot} and distance for each of the four 50 m laps. The average (SD) values are reported in Figure 3; *C* was higher in the 1st and 4th lap compared to the 2nd and 3rd ($F_{(3,27)}$ = 19.578, $P < 0.001$, $f = 0.61$); these differences could be attributed to the fact that, in the 1st lap, the subjects swum at a higher *v* compared to the others, leading to a much higher E_{tot}, whereas in the 4th lap a possible effect of fatigue has to be taken into account. Indeed, in the last lap both SL and η_T were found to be lower than in the previous ones (cf. Table 1 and Table 2).

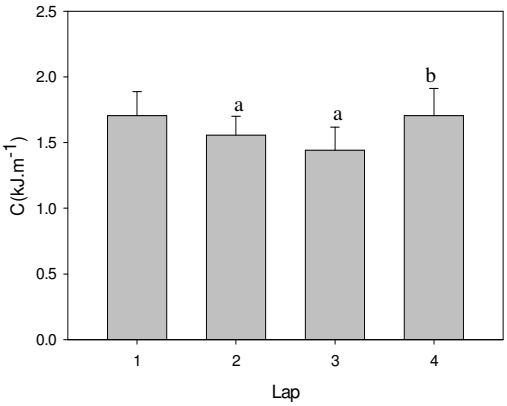


Figure 3. Energy cost of swimming (*C*) in the four laps of the 200m front crawl. Bars indicate standard deviations. [a, b, c] Different from the 1st, 2nd and 3rd lap, respectively. P<0.05

Since equation 2 can be applied only at a given speed (η_p, W_d and C change with the speed), the influence of fatigue on C could be investigated only at constant v. Hence, in Figure 4 the values of C are plotted as a function of the values of η_T for the three last laps only (indeed no statistical differences in v were found in these conditions). Data were interpolated using a linear function to give an empirical description of a possible relationship between the variables. Although not statistically significant, this relationship indicates that higher values of C correspond to lower values of propelling efficiency, as it can be expected on theoretical basis (equation 2).

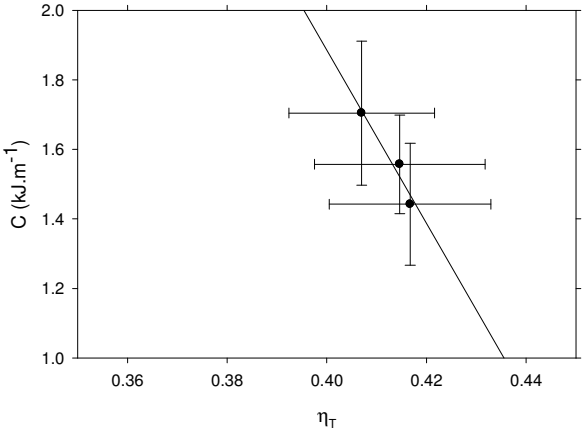


Figure 4. Energy cost of swimming (C) as a function of the η_T (v_{cm}·3Du^{-1}) in the three last laps of the 200m front crawl. Bars indicate standard deviations. Data are interpolated by the following equation: C = 24.917, η_T + 11.853; N = 3; R = 0.97; P = 0.157.

On theoretical basis it could also be expected that SL is related to propelling efficiency. The average (SD) values of SL are reported in Figure 5 as a function of η_T. The relationship between these parameters is indeed significant (P = 0.03). As indicated in the Table 1, both SL and arm stroke efficiency decrease from the 1st to the last lap, suggesting the occurrence of fatigue. Indeed, the swimmers were not able to maintain the same SL and efficiency during the entire duration of the race. This figure also indicates that it is possible to estimate the arm stroke efficiency from values of SL, which are easily measurable with a stopwatch from the poolside.

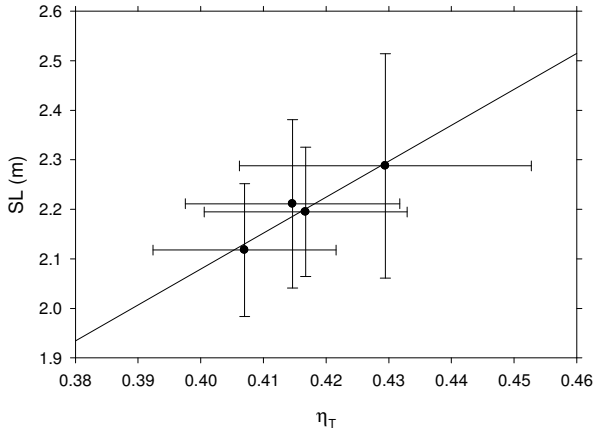


Figure 5. Stroke length (SL) as a function of the η_T in the four laps of the 200m front crawl. Bars indicate standard deviations. Data are interpolated by the following equation: SL = 7.256, η_T – 0.823; N = 4; R = 0.97; P = 0.03.

Discussion

In the present study the relative contribution of *Aer*, *AnL* and *AnAl* energy sources to total energy expenditure was estimated in the 200 front crawl, as well as in each 50 m lap of this race. Moreover, *C* and arm stroke efficiency (assessed by means of two independent methods) were also computed in order to investigate their changes during the course of the race (which would be related to the development of fatigue). The following discussion will focus first on the energy sources contribution in the total 200 m as well as in each 50 m lap. The data of arm stroke efficiency and C will then be discussed, as well as their relationship in the development of fatigue.

Energy sources contribution

1) The 200 m as a whole

As reviewed by Gastin (2001) the aerobic pathway has an important role in performance capacity during high intensity exercises lasting about 2 min, as it is the case of the 200 m front crawl race. The %*Aer* contribution calculated in this study (65.9 ± 1.57%) is similar to that reported by Ogita (2006) for a 2-3 min bout (65%), by Troup (1991) for a 200 m maximal swim (65%), by Capelli et al.

(1998) for a 200 yards maximal swim (61%) and by Zamparo et al. (2000) for a 200 m maximal swim (72%; in young male and female swimmers).

The anaerobic contribution calculated in this study was of 34.0 (1.40)% (*AnS*) being 13.6 (1.71)% and 20.4 (0.91)% from the *AnAl* and *AnL* energy sources, respectively. In other studies the *AnS* contribution was of 35% (Troup 1991) in high level swimmers (200 m maximal swim), of 28.9% (Zamparo et al. 2000) in young male and female swimmers (200 m maximal swim), and of 39% (Capelli et al. 1998) in elite swimmers (200 yards maximal swim) whereas Ogita et al. (2006) reported an *AnS* contribution of 30% for a 2-3 min bout. Only in another study (Capelli et al. 1998) the contribution of the *AnL* and *AnAl* energy sources was computed separately; compared to our data the *AnL* values reported by these authors resulted to be lower and the *AnAl* values larger (24.7% and 13.8%, respectively). Reis et al. (2010) found for the 200 m 13% for the *AnL* contribution.

For sake of comparison, for the 400 m race, Rodríguez and Mader (2003), Laffite et al. (2004) and Reis et al. (2010) reported an %*Aer* contribution of 83.2%, 81.1% and 95% respectively; over the distances of 50 and 100 yards Capelli et al. (1998) reported an %*Aer* contribution of 15.3% and 33.3%, respectively. Also, Rodríguez and Mader (2003) calculated an %*AnL* of 10.2% for the 400 m race and Capelli et al. (1998) of 58.9% and 47.2% over the distances of 50 and 100 yards Finally, Rodríguez and Mader (2003) reported an *AnAl* contribution of 5.8% for the 400 m and Capelli et al. (1998) found contributions of 25.8% and 19.6% over the distances of 50 and 100 yards, respectively.

The differences in the percentage contributions reported in this and other studies have to be attributed to the studied samples and their performance level, but also to the methods adopted to estimate the *Aer*, *Anl* and *AnAl* energy sources. Indeed, as indicated by Gastin (2001), the methods by which energy release is determined have a significant influence on the relative contribution of the energy systems during periods of maximal exercise. As an example, in some studies *Aer* is directly measured (by means of indirect calorimetry methods), whereas on others it is estimated by the use of backward

extrapolation techniques (e. g. Lafitte et al. 2004). As far as the *AnI* energy sources are regarded, differences could arise from differences in peak blood lactate concentration as well as by the use of different values of the lactate to energy equivalent (2.7-3.3 $mlO_2 \cdot mM^{-1} \cdot kg^{-1}$). The estimates of the *AnAl* energy sources are, however, the most "variable" ones, due to the several assumptions involved in such calculations, particularly the wide range of resting values of *PCr* reported in the literature (see Prampero et al. 2003), the percentage of muscle involved in swimming and so on.

Last but not least, most of the studies reported in the literature do not take into account the three energy systems but just the *Aer* and *AnL* ones (e. g. Lafitte et al. 2004, Ogita 2006). This, of course, has a direct influence on the relative contribution values.

2) Each 50 m lap considered separately

To our knowledge there is no literature that tried to compute a complete energy balance of each of the four 50 m lap of a 200 m front crawl race. Laffite et al. (2004) carried out a similar study for each 100 m lap of the 400 m front crawl race but the *Aer* values reported were calculated by using backward extrapolation techniques and the *AnAl* contribution was not taken into account.

As it would be expected on theoretical grounds, our data indicate that the *Aer* contribution increases from the first (44.6 ± 4.00%) to the last lap (66.6 ± 3.99%), while the *AnAl* contribution decreases from 41.3 (3.76)% to 5.2 (0.51)%, from the first to the last lap. These data are indeed similar to those that can be computed on subjects performing all out swimming races over the 50, 100, 150 and 200 m distances (see discussion above) where, however, a decrease in *AnL* could also be observed, from the 50 to the 200 m distance. Data reported in this study, on the contrary, indicate that the *AnL* contribution increases in the last lap, compared to the 2nd and 3rd. This *AnL* pattern is in agreement with the findings of Laffite et al. (2004) and Coelho et al. (2008) for the 400 and 100 m front crawl, respectively.

These data therefore suggest that a pacing strategy is adopted during the race with a distribution of the effort which is not an "all out" for the entire duration of

the race. These data also indicate that appropriate training stimuli should be proposed based on the different energy sources contributions in the different phases of this swimming race, allowing addressing a competition strategy according to quantitative data.

The data reported in this study give, indeed, a theoretical basis for the common practice since, for the 200 m race, training the aerobic power is considered of utmost importance and improving lactic production and accumulation is highly demanded. Our data, however, also indicate that importance should be given to anaerobic alactic workouts owing to the fact that the *AnAl* contribution in the 200 m effort is not negligible in the 1st 50 m lap and during the whole event (about 22%).

Arm stroke Efficiency

Theoretical (Froude) efficiency essentially depends on the speed components of the fluid at the inlet and outlet sections and this is true for all fluid-machines: pumps, turbines, propellers, fans, water-wheels and paddle-wheels (Fox and McDonald 1992). As an example, the theoretical efficiency of a paddle-wheel can be calculated from the ratio of the average horizontal speed of the boat (*v*) to the tangential speed of the blades (the rim speed, *u*): *v* is less than *u* because only part of the shaft power input goes into "useful" motion (forward displacement) whereas the remaining fraction is wasted in giving "un-useful" energy to the water. As indicated by Alexander (1983), the ratio of horizontal speed (*v*) to tangential speed (*u*) is proportional to the theoretical efficiency also in "rowing" animals that move in water by producing power strokes, during which an appendage is accelerated backwards, and recovery strokes, during which the appendage returns to its original position moving forward. Front crawl swimmers can indeed be considered as "fluid machines" (or wave making bodies) that obtain the thrust necessary to proceed at a given speed with a “rowing type” movement of their upper limbs.

The best way to calculate theoretical efficiency of the arm stroke is to compute the instantaneous horizontal speed of the body centre of mass as well as the instantaneous 3D hand speed (the tangential speed of the “two moving blades”)

over a complete stroke cycle. This was done in this study by means of a 3D kinematical analysis. The so calculated values of theoretical efficiency ($\eta_T = v_{cm} \cdot 3Du^{-1}$) are in agreement with the values calculated with the simple model proposed by Zamparo et al. (2005b): $\eta_F = (v / (2 \pi SF L)) (2 / \pi)$) in which both the speed of the center of mass (v_{cm}) and the angular speed of the arms ($2 \pi SF$) are assumed to be constant, as an average over a complete stroke cycle. Even these are both strong assumptions, the data reported in this study indicate that these approximations are quite reasonable since in both cases the values of arm stroke efficiency range from 0.34-0.47 indicating that less than 50% of the mechanical power produced by the muscles can be utilized, in this stroke, for effective propulsion.

In the literature only two other papers attempted to calculate Froude (Theoretical) efficiency from measures of horizontal speed of the body and hand speed (Toussaint et al. 2006 and Seifert et al. 2010). However, in those studies, a “one side” 2D kinematic analysis was performed and thus this ratio was calculated by taking into account the contribution of one arm “at the time”. Thus, these data are not directly comparable with those reported in the present study. Since this is not the principal aim of the study, for a comparison among the data of arm stroke efficiency reported in the literature, the reader is referred to Zamparo et al. (2010) and di Prampero et al. (2010).

As shown along the text, theoretical efficiency significantly decreased along the four laps of a 200 m race. The decrease in efficiency indicates a less effective propulsion generating pattern because a relative higher hand speed is necessary for force generation at a given horizontal speed. Our results suggest that during the race, swimmers adapt their SF and SL, and eventually their arm coordination, to match the required propulsive force to the speed commensurate with the power output that can be generated. This decrease in efficiency is probably indicative of a reduction in stroke technique quality at the end of the race, when the swimmer becomes fatigued (Wakayoshi et al. 1995), higher lactate accumulation occurs (our data, see also Wakayoshi et al. 1996) and neuromuscular fatigue takes place (as indicated by EMG data, see

Figueiredo et al. 2010). According to equation 2, this decrease in efficiency suggests a possible increase in energy cost along the race.

Energy Cost of Swimming

In the swimming literature, data of *C* at supra-maximal speeds are scarce. Indeed, to compute this parameter both the aerobic and anaerobic (lactic and alactic) energy sources should be measured/estimated and this is not an easy task, as indicated above. It goes without saying that a source of difference in the values of *C* necessarily depends on how these contributions are calculated (and this was previously discussed). Other sources of difference (for a given speed and stroke) would be the age, gender and technical level of the swimmers, since these parameters strongly influence *C* (see equation 2) by affecting either the hydrodynamic resistance (W_d) or the propelling efficiency (η_p) (e. g. Zamparo et al. 2010; di Prampero et al. 2010).

For the front crawl and over speeds or distances similar to those of this study, Costill et al. (1985) reported values of 1.16 $kJ \cdot m^{-1}$ in elite male swimmers at a speed of 1.42 $m \cdot s^{-1}$; Capelli et al. (1998) reported values of *C* of 1.28 (0.11) $kJ \cdot m^{-1}$ for elite male swimmers (over a 182.9 m distance); Zamparo et al. (2000) reported values of about 1.3 and 1.0 $kJ \cdot m^{-1}$ for young male and female swimmers, respectively, at a speed of 1.4 $m \cdot s^{-1}$; Fernandes et al. (2006) reported values of 0.94 (0.13) $kJ \cdot m^{-1}$ in highly trained swimmers at a speed of 1.40 (0.06). Finally, Fernandes et al. (2008) reported values of 1.26 (0.04) and 0.77 (0.08) $kJ \cdot m^{-1}$, respectively in elite male and female swimmers, at a speed of 1.55 (0.02) and 1.39 (0.02) $m \cdot s^{-1}$.

The values of *C* reported in this study are larger than those reported above: *C* = 1.60 (0.13) $kJ \cdot m^{-1}$ (at an average speed of 1.42 $m \cdot s^{-1}$) when the entire 200 m distance is taken into consideration whereas *C* = 1.71 (0.18), 1.56 (0.14), 1.44 (0.17) and 1.70 (0.21) $kJ \cdot m^{-1}$ for each consecutive lap, respectively. The observed differences in *C* between our and previous studies are essentially attributable to methodological differences and to the "sample" itself. As an example, in the study of Fernandes et al. (2006) the contribution of the *AnAl* stores to total energy expenditure was not taken into account and both females

and males were evaluated. On the other hand, the *AnAI* contribution as calculated by Capelli et al (1998) and Zamparo et al. (2000) is lower than that reported in this study, and so on.

It is therefore more interesting to discuss, rather than the absolute values of *C*, its changes during the four laps. The differences in *C* we observed from the first to the last lap can be partially attributed to differences in the average speed attained by the swimmers: *v* was indeed significantly higher in the first lap (1.56 ± 0.08 $m \cdot s^{-1}$) compared to the others (1.40 ± 0.02 $m \cdot s^{-1}$, on the average) and this explain the larger values of *C* observed in the first 50 m, considering the theoretical cubic relationship of power with speed in swimming (di Prampero 1986). In fact, it was previously shown that a *v* increase leads to a higher E_{tot} (Toussaint and Hollander 1994; Wakayoshi et al. 1995; Fernandes et al. 2006). Since no significant differences in speed were found among the 2nd, 3rd and 4th laps other reasons than changes in speed should be taken into consideration.

As indicate above, the determinants of *C* (for a given speed, stroke, technical skill and gender) are the hydrodynamic resistance and the propelling efficiency. Since both parameters are expected to change with fatigue (i. e. η_p is expected to decrease and W_d to increase), the energy cost should also be expected to change (increase) during a race. This was indeed the case and particularly so between the 3rd and 4th lap. Moreover, as expected on theoretical grounds, the values of *C* in the last three laps were found to be related (even if not to a significant level) to the values of theoretical efficiency: the lower η_T, the higher *C* (Figure 3). This finding is particularly interesting since the sample was very homogenous (same gender, stroke, technical level and speed) and thus the range of η_T and *C* values was very small.

Conclusions

The methodological approach adopted in this study made it possible to calculate the relative contribution of the three energy source systems in each 50 m lap of a 200 m front crawl race. When a comparison with data from literature was possible (for the total 200 m) our data confirmed the findings reported in

previous studies: 65% aerobic and 35% anaerobic. The understanding of the energetics of competitive swimming for each of the 4 laps of the 200 m race attempted in this study contributes to improve the application of appropriate training stimuli to the appropriate energy system and to address a competition strategy according to quantitative data. In this study it was also possible to investigate the effect of fatigue along the course of the 200 m race: as fatigue develops SR increases, SL and efficiency decrease and this brings about an increase in *C*, as it could be expected on theoretical basis.

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Chapter 5

Energy cost and body centre of mass' 3D intracycle velocity variation in swimming

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Abstract

The purpose of this study was to examine the relationship between the energy cost (C) and the 3D intracycle velocity variation (IVV; horizontal - x, vertical - y and lateral - z axes) throughout the 200 m front crawl event. Ten international level swimmers performed a maximal 200 m front crawl swim followed by 50, 100 and 150 m bouts at the same pace as in the 200 m splits. Oxygen consumption was measured during the bouts and blood samples were collected before and after each one. The C was calculated for each 50 m lap as the ratio of the total energy expenditure (three energy pathways) to distance. A respiratory snorkel and valve system with low hydrodynamic resistance was used to measure pulmonary ventilation and to collect breathing air samples. Two above water and four underwater cameras videotaped the swim bouts and thereafter APAS was used to assess the centre of mass IVV (x, y and z components). The increase in C was significantly associated with the increase in the IVV in x for the first 50 m lap ($R = -0.83$, $P < 0.01$). When considering the whole event, the within subject correlation coefficient showed to be significant for the IVV in x and z components ($R = -0.34$, $P = 0.03$ and $R = -0.34$, $P = 0.03$, respectively). It is concluded that IVV relationship with C in a competitive distance does not presents the direct relationship found in the literature for incremental protocols.

Key words: Biophysics, Energetics, Front crawl, Kinematics

Introduction

Swimming is characterised by the intermittent application of propulsive forces to overcome a velocity-dependent water resistance (i.e. hydrodynamic drag force). Swimming propulsion is produced by a combination of trunk, arms and legs movements resulting in non-uniform body movement, evidencing intracycle velocity variation (IVV; Barbosa et al. 2010b; Vilas-Boas et al. 2010). As the four conventional techniques use different combinations of trunk, arm and leg actions, its IVV is quite different among them (Craig and Pendergast 1979). The swimming velocity (v) is the product of the stroke frequency (SF) by the distance the body moves through the water within each stroke cycle (SL). The generation of a given v requires a certain metabolic power output (E_{tot}) that is also velocity-dependent (di Prampero 1986). Front crawl has been considered the most efficient swimming technique due to the higher continuity of the arms propulsive actions (Barbosa et al. 2010b; Vilas-Boas et al. 2010). Moreover, when compared to the others swimming techniques, the IVV in front crawl has been considered very low or even negligible (Alves et al. 1996; Craig and Pendergast 1979; Holmer 1983; Kjendlie et al. 2004), whereby its energetic profile considered the lowest from all swim techniques (Barbosa et al. 2006a; Holmer 1974). Meanwhile, several authors pointed out that an increased IVV leads to a higher amount of mechanical work, lowering swimming efficiency, as compared to uniform movement; an increase of 10% of v within a stroke cycle result in an additional work demand of about 3% (Nigg 1983) which seems to be due to the necessity of overcoming the hydrodynamic drag force (Toussaint and Beek 1992). In this sense, the magnitude of IVV is considered as a valid estimator of swimming efficiency (Vilas-Boas et al. 2010).

The number of studies regarding the relationships between the energetics and the biomechanical domains in competitive swimming is increasing (Vilas-Boas 2010). Alves et al. (1996) observed a significant relationship between the hip's horizontal IVV (IVVx) and the energy cost (C) of backstroke swimming at submaximal velocities. The same authors studying front crawl, did not report any relationship between C and IVVx, as well as Kjendlie et al. (2004) when

comparing children and adults during 4 x 25 m front crawl at submaximal velocities. For the breaststroke, Vilas-Boas (1996) found a non-significant correlation between C and hip's IVVx, but performing individual correlations both variables were highly correlated. Concerning the butterfly, Barbosa et al. (2005) concluded that high IVV was well related with lower swimming efficiency (inducing an increase in the C). Additionally, Barbosa et al. (2006b) found that C increases were strongly related to IVVx for all swim techniques, when partial correlations controlling the effect of v, were computed.

The above reported studies were assessed the IVV vs. C relationships thought progressive and intermittent protocols using a large swim velocity range (Alves et al. 1996; Barbosa et al. 2005; Vilas-Boas 1996). Moreover, IVV was evaluated for an anatomical landmark (i.e., hip) (Alves et al. 1996; Vilas-Boas 1996) or the body centre of mass (Barbosa et al. 2005; Barbosa et al. 2006b). Nevertheless, in both situations, studies adopted a mono-planar assessment (i.e., IVV's horizontal component), not including a multi-planar one.

Complementarily, several works were published regarding the stroke mechanics variations (Craig et al. 1985; Seifert and Chollet 2009; Barbosa et al. 2010a), segmental or body kinematics (Figueiredo et al. 2009; Psycharakis et al. 2010) and energetical variables (Ribeiro et al. 2010; Fernandes et al. 2006; Reis et al. 2010). A topic that is of strong interest for the swimming research community is the energetics and biomechanical profile variations, however, to our knowledge, no attempt was made to assess the relationships between C and IVV throughout a swimming event.

The purpose of this study was to examine the relationships between the centre of mass' IVV in the three axes of motion (horizontal - x, vertical - y and lateral - z) and the C of locomotion throughout the 200 m freestyle event. It was hypothesized that no relationship would be found between IVV (x, y and z) and C, since there is a low range of velocity changes during a swimming event, allowing IVV stability.

Materials and Methods

Subjects

Ten highly trained competitive male swimmers volunteered to participate in this study (mean ± 1SD: aged 21.6 ± 2.4 years; height 185.2 ± 6.8 cm; arm span 188.7 ± 8.4 cm; body mass 76.4 ± 6.1 kg; percentage of adipose tissue 10.1 ± 1.8%). All swimmers (mean performance over a 200 m freestyle event = 91.6 ± 2.1% of the 25 m pool world record) had 11.0 ± 3.5 years experience as competitive swimmers. All subjects gave their written informed consent before participation. The study was approved by the local ethics committee and was performed according to the Declaration of Helsinki.

Experimental design

On the testing day each swimmer performed an individual warm-up, which consisted of low- to moderate-intensity 1000 m aerobic swimming. Thereafter, swimmers performed a 200 m maximal front crawl bout. All tests were conducted in a 25 m indoor swimming pool, being performed push start and open turns without gliding. After 90 min of active rest interval, swimmers performed a 50 m front crawl bout at the same speed obtained in the 200 m bout. Twenty-four hours later, swimmers performed a 150 m and 100 m bouts, with a 90 min active recovery. Swim pacing for the 50, 100 and 150 m bouts was controlled by a visual light pacer placed in the bottom of the pool (TAR 1.1, GBK-Electronics, Aveiro, Portugal). At the end of each test blood lactate accumulation was measured. To simulate as much as possible the 200 m test conditions, swimmers used the respiratory snorkel and valve system also in the 50, 100 and 150 m swims.

Data collection and analysis

The 200 m bout was recorded with six stationary and synchronised video cameras (Sony, DCR-HC42E, Tokyo, Japan): (i) four below (optical axes ranged from 75º to 110º) and; (ii) two above the water surface (optical axes was ~100º). The recorded space was calibrated with a volume (3 x 2 x 3 m for the

horizontal, vertical and lateral directions) and thirty calibration points. Synchronization of the images was attained using a pair of lights observable in the field of view of each camera. One stroke cycle for each 50m lap was analysed. Twenty-one anatomical landmarks were used: the vertex of the head, 7^{th} cervical vertebra, mandible (mental protuberance), and the right and left tip of the third distal phalanx of the finger, wrist axis, elbow axis, shoulder axis, hip axis, knee axis, ankle axis, fifth metatarsophalangeal joint, and the tip of the first phalanx. Three-dimensional reconstruction of the twenty-one body landmarks, digitised manually and frame (50 Hz) by frame was obtained using APAS (Ariel Performance Analysis System, Ariel Dynamics, Inc., USA), and computed using DLT (Abdel-Aziz & Karara, 1971). Zatsiorsky anatomical model adapted by de Leva (1996), widely used in the literature (e.g. Barbosa et al. 2005; Figueiredo et al. 2011), was used, adjusting the mean relative CM positions and radii of gyration to reference them to the position of joint centers. After residual analysis for a wide range of cut-off frequencies, 6Hz was selected as the optimal cut-off frequency for the smoothing of the data using a low pass digital filter incorporated in the software. Root Mean Square (RMS) reconstruction errors of 12 validation points on the calibration frame, which did not served as control points, were, respectively for *x*, *y* and *z* axes: (i) 3.9, 3.7 and 3.3 mm for above the water view and (ii) 3.4, 2.5 and 3.2 mm for the underwater view (for more detailed analysis cf. Figueiredo et al. 2011). These results showed good accuracy as previously observed (Gourgoulis et al. 2008). To determine the reliability of the digitizing process a swimmer was digitized ten times for all the six video cameras through the stroke cycle. Small standard deviation for the repeated digitisations indicated acceptable reliability for velocity being 0.03, 0.02 and 0.03 $m \cdot s^{-1}$ for vx, vy and vz, respectively, similar to the ones reported by Psycharakis and Sanders (2009).

CM' velocity (v_{cm}) was calculated dividing the horizontal displacement of CM in one stroke cycle over to its total duration. The SL was determined through the horizontal displacement of the CM during the stroke cycle. The SF was determined from the time needed to compete a stroke cycle. To analyse the centre of mass' IVV in the three axes it was computed the coefficient of

variation (SD/mean) as suggested before (Barbosa et al. 2005; Figueiredo et al. 2009; Vilas-Boas et al. 2010). The use of the coefficient of variation seems to be the only sensitive approach to the mean swimming velocity and to the dispersion of the instantaneous velocity throughout the stroke cycle, and not to a single or couple of instantaneous moments; therefore, mathematically, is the more accurate method to the quantification of IVV (Vilas-Boas et al. 2010). In addition, the coefficient of variation is cited in the scientific literature as a reliable statistic to distinguish the economy of swimming (Alves et al. 1996; Barbosa et al. 2005; Nigg 1983; Vilas-Boas 1996).

Oxygen uptake (VO_2) was recorded by means of the telemetric gas exchange system (K4b², Cosmed, Rome, Italy) continuously during the 200 m front crawl test. This equipment was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system previously validated (Keskinen et al. 2003). Expired gas concentrations were measured breath-by-breath and averaged every 5 s. Net VO_2 was calculated subtracting the resting VO_2 from the measured VO_2.

Before and after each test capillary blood samples (5 µl) were collected from the ear lobe to assess rest and post exercise (at 1, 3, 5, and 7min) blood lactate ($[La]_b$) by means of a portable lactate analyser (Lactate Pro, Arkray, Inc., Japan), that has been show to be accurate (Baldari et al. 2009). The v for each lap was calculated by the ratio between distance and time using a stopwatch.

C was obtained through the ratio between $\dot{E}_{tot}$ and mean v, $\dot{E}_{tot}$ was considered as the sum of the three energy sources (aerobic, alactic and lactic) as previously proposed (Capelli et al. 1998; Figueiredo et al. 2011; Zamparo et al. 2011). The aerobic contribution (*Aer*) in each of the four 50 m laps was calculated from the time integral of the net VO_2 vs. time relationship (equivalent of 20.9 kJ $\cdot$ lO_2^{-1}, assuming a respiratory quotient of 0.98). The anaerobic contribution was obtained by the sum of the energy derived from glycolysis (*Anl*) plus that derived from phosphocreatine (*PCr*) splitting in the contracting muscles (*AnAl*). In this sense, lactic contribution was considered as:

$$Anl = b[La]_{bnet} \cdot M \quad (1)$$

where $[La]_{bnet}$ is the net accumulation of lactate after exercise, *b* is the energy equivalent for lactate accumulation in blood (2.7 ml O2 · mM^{-1} · kg^{-1} as used before, di Prampero et al. 1978) and *M* is the mass of the subject. Afterwards, *AnI* was then expressed in kJ assuming an energy equivalent of 20.9 kJ · lO_2^{-1} (for review see Zamparo et al. 2011).
Alactic contribution was considered as:

$$AnAl = PCr\ (1 - e^{-t/\tau}) \cdot M \quad (2)$$

where t is the time duration, τ is the time constant of *PCr* splitting at work onset (considered to be 23.4 s, as proposed by Binzoni et al. 1992), *M* is the mass of the subject and *PCr* is the phosphocreatine concentration at rest. The latter was assumed to be equal to 27.75 mM · kg^{-1} muscle (wet weight) in a maximally active muscle mass (Figueiredo et al. 2011; Prampero et al. 2003). *AnAl* was expressed in kJ by assuming a P/O_2 ratio of 6.25 and an energy equivalent of 0.468 kJ · mM^{-1} according to Capelli et al. (1998) and Zamparo et al. (2011) for swimming maximal velocities. The *AnAl* contribution for each lap was then calculated as the difference in *AnAl* before and after each lap.

Statistical Analysis

Mean (± 1SD) computations for descriptive analysis were obtained for all variables selected (data normal distribution verified with Shapiro–Wilk's test). A one-way repeated measures ANOVA was used to compare the kinematical variables along the 200 m event. When a significant F-value was achieved, Bonferroni post-hoc procedure was performed to locate the pairwise differences. Linear regressions between the energetic (C) and biomechanical (IVV in x, y and z axes) variables were computed, as well as their coefficients of determination for each lap. Partial correlations between IVV (x, y and z) and C, controlling the effect of v, for each lap were also computed. To further analyse the relationship between energetic and biomechanical variables over the 200 m, since involves a repeated measurements design, a within subjects correlation coefficient was reported, which accounts for the lack of independence among

the repeated measurements by removing the variation between subjects, as proposed by Bland and Altman (1995a).

Also, a between subjects correlation coefficient for repeated measurements design (Bland and Altman 1995b) was reported for the mean values of the 200 m, examining whether subjects with a high value on IVV (x, y and z) also tend to have a high value on C. All statistical analysis was performed using STATA 10.1 (StataCorp, USA) and the level of statistical significance was set at $P \leq 0.05$. Since a limited sampled is used, effect size was computed with Cohen's f. It was considered a (Cohen 1988): (1) small effect size if $0 \leq |f| \leq 0.10$; (2) medium effect size if $0.10 < |f| \leq 0.25$ and; (3) large effect size if $|f| > 0.25$.

Results

Figure 1 shows the mean (SD) values of the biomechanical parameters assessed in each 50m lap of the 200m front crawl event. The *v* decreased significantly from the first lap to the remain ones ($F_{(3,27)} = 24.58$, $P < 0.001$, $f = 1.26$). The SL remained constant for the first three laps, whereas a decrease was observed in the 4th lap ($F_{(3,27)} = 4.56$, $P = 0.01$, $f = 0.32$). SF only presented differences between lap 1 to lap 3 ($F_{(3,27)} = 5.08$, $P = 0.01$, $f = 0.39$).

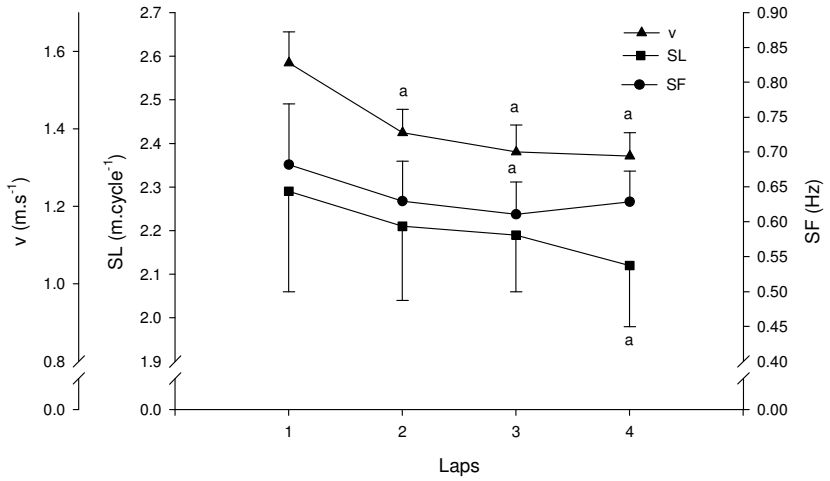


Figure 1. Mean (SD) values of velocity (v), stroke length (SL) and stroke frequency (SF) for the 200 m Front crawl event. [a, b, c] Significantly different from the 1st, 2nd and 3rd lap, respectively. P < 0.05.

Figure 2 presents the relationships between C and IVV (x, y and z) for each 50 m lap. The relationship between C and IVVx in the first 50 m lap was statistically significant (R = -0.83, *P* = 0.003) evidencing that decreases in the IVVx promoted increases in the C. All the other relationships computed for the other axes of motion (y and z axes) and for the second, third and fourth 50 m laps showed to be non-significant.

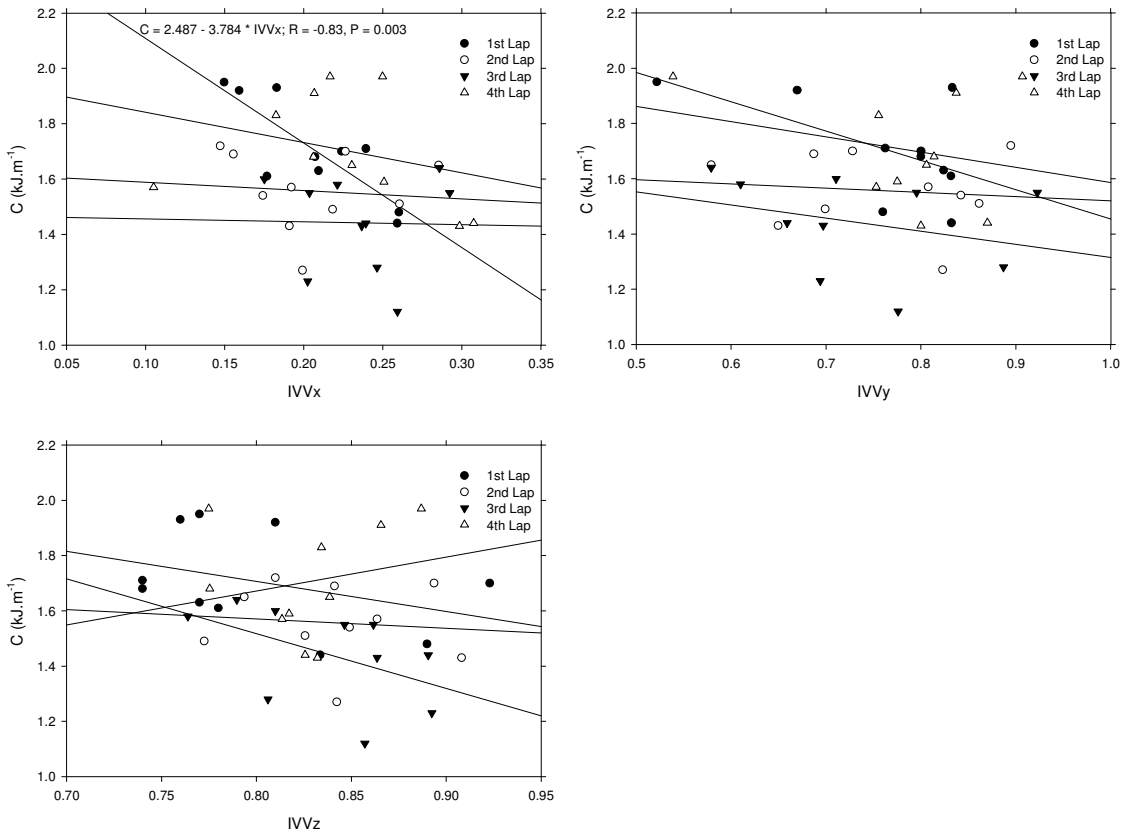


Figure 2. Energy cost (C) as a function of intracycle velocity variation (IVV) in horizontal (upper left panel), vertical (upper right panel) and lateral (lower panel) axes in the four laps of the 200 m Front crawl event. Lines represent linear regression analysis (N = 10), P < 0.05.

As v is a co-variable of C and IVV, partial correlation values between IVV (x, y and z) and C for each 50 m lap of the 200 m front crawl event were computed (Table 1). Thus when controlling the v effect the same trend was observed as the linear regressions: only the relationship between C and IVVx in the first 50 m lap was significant (R = -0.65, *P* = 0.05). So, during this competitive event, increases in IVVx were explained by increases in C, but just in the first lap.

Table 1. Partial correlation values (N = 10), controlling the swimming velocity effect, between intracycle velocity variation (IVV) in horizontal (x), vertical (y) and lateral (z) axes and the energy cost (C) for each 50 m lap of the 200 m Front crawl event.

	IVVx vs. C	IVVy vs. C	IVVz vs. C
1st Lap	R = -0.65 (*P* = 0.05)	R = -0.07 (*P* = 0.85)	R = -0.46 (*P* = 0.21)
2nd Lap	R = -0.10 (*P* = 0.79)	R = -0.11 (*P* = 0.78)	R = -0.11 (*P* = 0.78)
3rd Lap	R = -0.01 (*P* = 0.98)	R = -0.33 (*P* = 0.39)	R = -0.49 (*P* = 0.18)
4th Lap	R = -0.19 (*P* = 0.62)	R = -0.05 (*P* = 0.91)	R = 0.50 (*P* = 0.17)

To further study the relationship of the energetics and biomechanical variables throughout the 200 m event, within and between subjects correlation coefficients were computed (Table 2). Data showed an inverse relationship between C and IVV (x, z) during the 200 m within the same swimmer.

Table 2. Within (N = 40) and between (N = 10) subjects correlation coefficient values between intracycle velocity variation (IVV) in horizontal (x), vertical (y) and lateral (z) axes and the energy cost (C) for the 200 m Front crawl event (taking in consideration the four studied laps).

Axis	Within subjects C vs. IVV	Between subjects C vs. IVV
x	R = -0.34 (*P* = 0.03)	R = -0.33 (*P* = 0.39)
y	R = 0.07 (*P* = 0.70)	R = -0.35 (*P* = 0.38)
z	R = -0.34 (*P* = 0.03)	R = -0.27 (*P* = 0.48)

Discussion

The purpose of this study was to examine the relationships between the body centre of mass' IVV in the x, y and z axes with the C during the 200 m front crawl event. The IVVx was inversely associated with C singly for the first lap when analysing each 50 m length. IVVx and IVVz were also inversely related with C, when considering the within subject correlation for the repeated measures during the 200 m event.

Previous studies have found a direct relationship between IVVx and C, indicating that IVV could be a valid estimator of efficiency (Barbosa et al. 2005). However this was found for a wider range of v; to the best of our knowledge, there is no study about IVV changes throughout a competitive event, where v changes in a much lower range. During the 200 m front crawl event the v and

the stroke parameters associated (i.e. SF and SL) changed, which is in accordance with previous reports (Alberty et al. 2005; Craig et al. 1985). The v of the 1st lap was higher than the other ones, meaning that a higher water resistance had to be overcome, since water resistance is related to v^2. As the v is maintained for the rest of the event, changes in the SF and SL occurs as a response to muscular fatigue (Figueiredo et al. 2010a; Caty et al. 2006; Stirn et al. 2011).

In the first lap, the association between C and IVVx was of 69%, which evidences that swimmers who performed faster had a higher C (di Prampero 1986), and lower propelling efficiency (Toussaint et al. 1988a) presenting lower / higher maximal / minimal v peaks and also apply a better coordination (Seifert and Chollet 2009; Seifert et al. 2010b). The latter means less time spent between propulsive phases, and consequently lower IVVx. However, even when velocity effect was controlled a significant inverse relationship between IVVx and C was found. At submaximal intensities, for the same velocity, the best swimmers are characterized as being more economic (i.e., presenting a lower C) (di Prampero 1986; Fernandes et al. 2006), having higher arm stroke efficiency (Seifert et al. 2010b; Toussaint 1990), SL (Craig et al. 1985; Seifert et al. 2010b), and higher lag time between propulsive actions (Seifert et al. 2010b), implying a higher IVVx. The presented relationship between IVVx and C suggests that swimmers: (i) were not fatigued, since they swam at a submaximal intensity for the first lap, as their goal is to achieve the best performance over the 200 m; (ii) may adopt different coordinative strategies to reach the same goal, particularly at the SF values observed (Potdevin et al. 2006), and at early stages of the event, which result in C variations (Seifert et al. 2010a).

In all the remaining laps, no association was found between C and IVV (x, y and z), even when partial correlations were computed. This might be explained by the fact that in aquatic locomotion, total mechanical work is the sum of the work needed to overcome external forces (external work) and to accelerate and decelerate the limbs with respect to the centre of mass (internal work) (Barbosa et al. 2010b; Zamparo et al. 2005). External work is related to the position and

velocity changes of the CM, being IVV an estimation of it. Internal mechanical work is linked to the segmental kinematics, as SL and SF, which change during the course of the race (cf. Figure 1). It was reported by Zamparo et al. (2005) that internal work has a cubic relationship with the SF (W_{int} = 38.2 SF^3); so, as it changes throughout the 200 m event, also the total mechanical work vary. Indeed, if total mechanical work increases for the same overall efficiency, C rises as well (Overall efficiency = W_{tot} x C^{-1}). Since IVV does not take into account internal mechanical work, it might have a significant influence in the small v range when comparing to other incremental protocols (Barbosa et al. 2005; Fernandes et al. 2006).

The C determinants (for a given v, technique, skill and gender) are the work to overcome hydrodynamic resistance (W_d) and the propelling efficiency (η_p), both expected to change with the appearance of fatigue. During a race it is expected that η_p decrease and W_d increase, and in this way that the C also increase (Figueiredo et al. 2011). In 200 m front crawl v diminish during the course of the event, η_p also decreases as observed before (Figueiredo et al. 2011). However, SF increased in the fourth lap, augmenting internal mechanical work (probably increasing C as well), but also increasing continuity of the propulsive actions (probably diminishing IVV) (Alberty et al. 2005; Figueiredo et al. 2010b). The W_d decrease also with the decrease of v (Toussaint et al. 1988b); nevertheless, the W_d that each swimmer must produce to overcome hydrodynamic resistance at a given v is widely variable and dependent on individual morphology and technique (Vilas-Boas 1996; Chatard et al. 1990).

At the muscle level, classic experiments have shown that contraction type, length and speed, as well as fiber type and the recruitment pattern, influence force generation and, therefore, metabolic cost, reflecting the effect of different contraction parameters (Sih and Stuhmiller 2003). In the 200 m particular effort Caty et al. (2006) and Figueiredo et al. (2010a) found that muscular fatigue occur in the main muscles involved in swimming, which is expected also to influence C more than IVVx.

Psycharakis et al. (2010) found greater magnitude in the IVVy and IVVz axes than in IVVx, but their role and influence is not yet fully understood. In fact, in

spite of their possible influence on the IVVx and v, there is no relationship with the C within each lap. This might be related to the fact that, when normalizing the SD used to calculate the coefficient of variation of the IVVy and IVVz to the horizontal v, the variations decrease to values ranging from 0.04 to 0.06 (unpublished data from our group), being much smaller than the IVVx producing perhaps small effect in the C.

When analysing each subject throughout the 200 m event (within subject correlation) it was possible to observe a significant inverse relationship, of medium effect, between C and IVV (x, y). These results showed the same relation as in the first lap, although a low variance is explained probably due to the influence of v changes in the IVV. It is suggested that the v changes and fatigue had a higher effect in the C rather than in the IVV, since C is variable (Figueiredo et al. 2011) and IVV is stable (Psycharakis et al. 2010) during this event. Also, that several factors influence C more than IVV during a competitive event. In addition, in the between subjects correlation computed for the overall 200 m (mean values), it was not observed that swimmers with higher C values had higher IVV (x, y and z) values.

Conclusion

It is concluded that for each lap no relationship occurs between IVV and C, unless for the first lap in the swimming direction, where the rises in IVV determine a lower C. In whole 200 m the same tendency was found but for the x and z axis, reflecting the specificity of this swimming event. In the future, other factors should be taken into account/studied (e.g., changes in coordination, peripheral fatigue) in order to better understand the occurred changes.

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Chapter 6

Individual profiles of spatio-temporal coordination in high intensity swimming

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Abstract

The aim of this study was to assess the inter-subject variability in the inter-arm coordination in front crawl performed at high intensity. First, it was analysed the role of fatigue in the selected biomechanical and coordinative parameters. Second, inter-subject variability was assessed amongst the swimmers to establish a coordination profile. The inter-arm continuous relative phase was used to analyse upper limbs coupling during two arm stroke cycles for each 50 m lap of the 200 m front crawl event. Ten male competitive swimmers swam 200 m front crawl at race pace. Two above water and four underwater cameras videotaped the test and APAS was used to assess the 3D anatomical points position and to calculate, afterwards, the angular position, velocity, and continuous relative phase. The kinematics of two arm stroke cycles were filtered and normalised to the total cycle duration. A significant decreased, caused by fatigue, was observed in the biomechanical and coordinative (temporal) parameters. The topography of the mean continuous relative phase curve showed a higher inter-subject variability between two groups (63.1° *vs.* 76.0°; $p<.05$), suggesting that several profiles of inter-limb coordination may exist. Two clusters arise from the coordination profiling, explained mainly by the organismic constraints (swimmer's specialty).

Key words: Motor control, Cluster analysis, Fatigue, Swimming

Introduction

Dynamical systems approach of motor control allows focusing on the stability of spatio-temporal patterns of bodily parts coordinated with each other and the environment (e.g., Beek, Peper, & Stegeman, 1995; Kelso, 1995; Schoner & Kelso, 1988). In humans, it emphasizes the importance of inter- and intra-limb coordination, being this late considered as an important dimension of human motor behavior (Swinnen et al., 1997), in which cyclical motor coordination tasks have received increasing attention (Donker, Beek, Wagenaar, & Mulder, 2001; Lee, Swinnen, & Verschueren, 1995; Seifert, Leblanc, Chollet, & Delignieres, 2010; van Emmerik & Wagenaar, 1996). In human's locomotion, inter-limb coordination has been mostly investigated during walking or running (e.g., Diedrich & Warren, 1995; Donker, et al., 2001; van Emmerik & Wagenaar, 1996; Wagenaar & Beek, 1992; Wagenaar & van Emmerik, 2000), i.e., in situations where the arms do not contribute to propulsion, but to the trunk stabilisation (Wannier, Bastiaanse, Colombo, & Dietz, 2001). However, in aquatic locomotion (front crawl), 85% of propulsion is due to the arms actions (Bucher, 1975; Deschodt, Arsac, & Rouard, 1999; Hollander, De Groot, Van Ingen Schenau, Kahman, & Toussaint, 1988), and inter-arm coordination acquire a higher importance in the study of coordination; in fact, it is linked to the swimming velocity, and it changes due to the breathing actions, floating (external forces) and balance of the body segments (Chollet, Chalies, & Chatard, 2000; Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010; Yanai, 2003).

Two elementary modes of coordination resulted from the study of rhythmic movements (Kelso, 1984; Kelso & Jeka, 1992): (i) in-phase coordination designates the simultaneous contraction of homologous muscles (e.g. flexing or extending the arms simultaneously) and, (ii) anti-phase coordination designates the simultaneous activation of non-homologous muscle groups (e.g. flexing one arm and extending the other one). The late can be assessed by the relative phase between limbs (Beek, et al., 1995). This line of research was initiated on phase transitions in rhythmic finger and hand movements (Kelso, 1984; Kelso,

Holt, Rubin, & Kugler, 1981) and their coordination dynamics modeling (Haken, et al., 1985). It was found that coordinated finger movements result in in-phase and anti-phase coordination modes, and have a differentiated stability according to movement frequency.

Inter-limb coordination emerges due to changes in the constraints imposed on action, rather the acquisition or prescriptions for action (Kugler, Kelso, & Turvey, 1980; Newell, 1986), and three types of constraints were distinguished (Newell, 1986): organismic, environmental, and task. Organismic constraints are structural or functional, associated with the actor, such as body anthropometry. Environmental constraints are external to the organism and are not manipulated by the experimenter. Task constraints refer to the goal of the activity and have been classified into three categories: the task goal, the rules or instructions specifying the response dynamics, and the implements or machines specifying the response dynamics. In aquatic locomotion, several inherent environmental constraints must be considered, such as the density or temperature of the fluid, the direction of water flow (causing drag force), the underwater visibility, and waves on the surface of the water. For studying swimming performance, two environmental constraints are constantly applied to the swimmer's body while displacing on water: drag force and the energy wasted in accelerating masses of water without resulting in propulsion (Toussaint & Beek, 1992). If these environmental constraints are inherent to the swimming locomotion, fatigue, in other hand, evolves quite dependable of the task and internal pacing of each swimmer. Fatigue in human performance can be defined as any exercise-induced decrease in the power produced (Bigland-Ritchie & Woods, 1984; Taylor & Gandevia, 2008) that, in maximal swimming exercise, is evidenced by decrease in speed. Adaptive movement pattern emerge as a function of the organism to conserve metabolic energy, and of the demands arising from constraints, as fatigue (Sparrow & Newell, 1998); thus, individuals naturally adopt a preferred coordination mode (Sparrow, Hughes, Russel, & Le Rossignol, 2000; Sparrow & Newell, 1998), as observed by Seifert, et al. (2010) in swimming relating to specialty.

As each individual perform differently (regarding his organismic constraints) to achieve the same goal, there is no single optimal pattern of coordination, rather several solutions to each motor problem, reflecting inter-individual variability (Newell & Corcoss, 1993). Inter-individual variability shows the different pattern of coordination adopted by each individual for the exploration of different possible motor solutions in relation to the constraints encountered, and permits coordination profiling (Button, Davids, & Schöllhorn, 2006). Cluster analysis is an increasingly common technique to detect and group similar patterns within high dimensional datasets, and one significant advantage of coordination pattern clustering is that no a priori assumptions about the structure of the dataset are required to identify similar patterns (Rein, Button, Davids, & Summers, 2010).

Coordination in aquatic locomotion, particularly in front crawl swimming has been lately studied using a coordinative tool designated Index of Coordination, that was proposed by Chollet et al. (2000) based on temporal changes (Seifert, Chollet, & Rouard, 2007; Seifert, Toussaint, et al., 2010). Using that parameter, the changes of motor coordination with different paces have been a topic of interest (Schnitzler, Seifert, Ernwein, & Chollet, 2008; Seifert, Chollet, & Allard, 2005; Seifert, Toussaint, et al., 2010); however, its use could be completed with spatial data to enable spatial–temporal analysis, as well as to be calculated in a continuous way, it will give information about instantaneous changes (Glazier, Wheat, Pease, & Bartlett, 2006; Hamill, Haddad, & Mc Dermott, 2000). Thus, the calculation of the continuous relative phase (CRP) (Hamill, van Emmerik, Heiderscheit, & Li, 1999; Kelso, 1995; Kurz & Stergiou, 2002) would provide information on the type of relationship (in-phase or anti-phase) between a pair of joints and the relative amount of coupling (from in-phase to anti-phase mode of coordination), and, even more relevant, it will enable an intra-cycle analysis through the swimming cycle for a better understanding of the inter-limb coordination dynamics.

The aim of this study was to examine individual coordination profiling during a 200 m maximal front crawl effort. We hypothesized that a common behavior regarding the influence of fatigue and a higher inter-individual difference in the

coordination parameters.

Material and Methods

Participants

Ten male competitive swimmers volunteered to participate in this study. Their main characteristics were 21.6 (2.4) years old, 185.2 (6.8) cm of height, 188.7 (8.4) cm of arm span, 76.4 (6.1) kg of body mass, 10.1 (1.8)% of adipose tissue, 11.0 (3.5) years of competitive swimming background and a performance over the 200 m freestyle event of 91.6 (2.1)% of the short course world record. Before testing, participants read and signed an informed consent form according to the local ethics committee and Declaration of Helsinki (2000).

Experimental procedure

Before the experimental trial, swimmers performed an individual warm-up, totalling 1000 m. Afterwards, 21 markers were placed on anatomical landmarks defining three-dimensional position and orientation of the head, torso, arms, forearms, hands, thighs, shanks and feet (Zatsiorsky model adapted by de Leva, 1996). The experimental trial consisted on performing a 200 m maximum front crawl. Two arm movements, taken in the central part of the pool, were evaluated to avoid start and turn effects. To eliminate the effects of breathing on the variables studied, swimmers were asked to execute non-breathing cycle while swimming through the calibrated space.

Video analysis and stroking parameters (velocity, stroke rate, stroke length)

Six digital video cameras, four under (optical axes of adjacent cameras varied from 75º to 110º) and two above-water (optical axes of adjacent cameras ~100º) were used to record the trial. Underwater and above-water views were three-dimensional reconstructed using a calibration volume (3 x 2 x 3 m and 30 calibration points), DLT algorithm (Abdel-Aziz & Karara, 1971) and a low pass digital filter of 6 Hz. A flashing light was used to synchronise all the cameras.

Landmarks were digitised manually and frame-by-frame at a frequency of 50 Hz, using Ariel Performance Analysis System (Ariel Dynamics, Inc., USA). The above described procedures enabled to calculate the average swimming speed ($m.s^{-1}$, as the horizontal displacement of the centre of mass in one stroke cycle over its total duration), the stroke length (m, as the horizontal displacement of the centre of mass in one stroke cycle) and the stroke frequency (Hz, as the time needed to complete a stroke cycle).

Inter-arm coordination

Three-dimensional segment angles were calculated between arm's centre of mass and trunk, and angular velocities from positional data. The continuous relative phase (CRP) between inter-arm (arm's centre of mass - shoulder - trunk) angles was analysed from two arm movements for each 50 m lap, taken from the central part of the swim pool to avoid start and turn effects. The stroke cycle was considered to begin in the entry of the right hand and to finish in the re-entry of the right hand, and was normalised to its duration, in percentage. In accordance with Hamill, et al. (2000), the data on angular displacements and angular velocities were normalised (θ_{norm} and ω_{norm}, respectively) in the interval [-1, +1] as follows (Fig. 1):

$$\theta_{norm} = \frac{2\theta}{\theta_{max} - \theta_{min}} - \frac{\theta_{max} + \theta_{min}}{\theta_{max} - \theta_{min}} \quad (1)$$

where θ_{max} and θ_{min} are the maximum and minimum angular position within one complete cycle, respectively.

$$\omega_{norm} = \frac{2\omega}{\omega_{max} - \omega_{min}} - \frac{\omega_{max} + \omega_{min}}{\omega_{max} - \omega_{min}} \quad (2)$$

where ω_{max} and ω_{min} is the maximum and minimum angular velocity within one complete cycle, respectively. Angular velocity was obtained through differentiating displacement data.

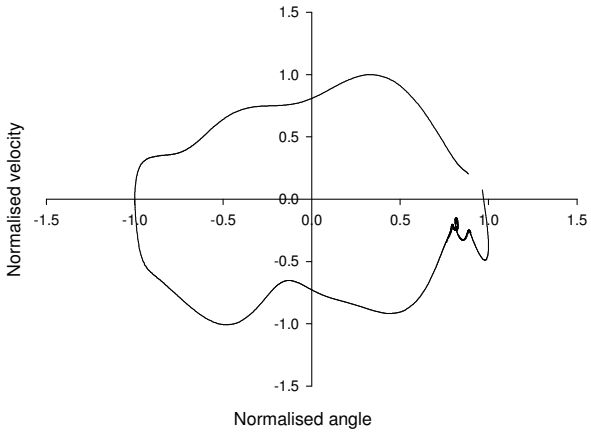


Figure 1. Phase portrait.

Phase angles (θ) were calculated using the following formula and graphical representation (Fig. 2):

$$\emptyset = tan^{-1}(\omega_{norm}/\theta_{norm}) \quad (3)$$

where the θ_{norm} and ω_{norm} are the data on angular displacements and angular velocities normalized, respectively.

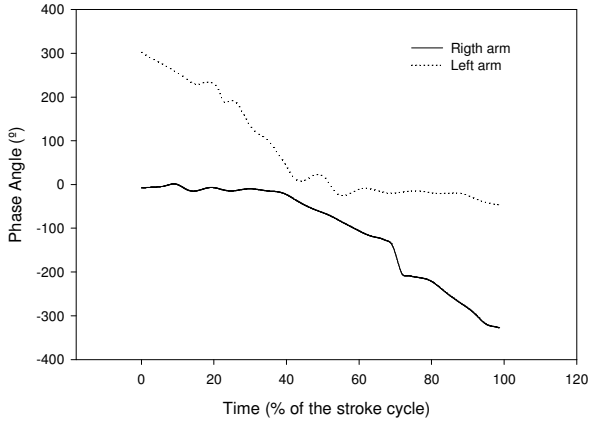


Figure 2. Phase angle for right and left side.

The coupling was quantified by CRP angle. CRP was defined as the difference between the normalised phase angles of two segment motions throughout the arm swimming cycle. In each coupling, the distal segment was subtracted from

the proximal. A CRP of 0° indicated that the respective segments were in-phase, and, as the CRP increased, the segments would be more out-of-phase until a CRP of 180° would indicate an anti-phase coupling. A positive CRP indicated that the proximal segment had a greater phase angle while a negative CRP indicated that the distal segment had a greater phase angle. CRP was computed as:

$$CRP = right\ shoulder\ phase\ angle - left\ shoulder\ phase\ angle \quad (4)$$

Nevertheless, two coordination modes are theoretically possible (in-phase - 0° - and anti-phase - 180°). However, it was used the range of 0º < CRP < 360º because when information about the coordination between segments is required, this approach is considered more suitable (Wheat & Glazier, 2006).
Complementarily, and following Bardy, Oullier, Bootsma & Stoffregen (2002), Diedrich and Warren (1995), Seifert, Delignieres, Boulesteix & Chollet (2007), and Seifert, et al., (2010), a lag of ± 30° was accepted in this study for the determination of a coordination mode. Therefore, an in-phase mode was assumed to occur for 210° < CRP < 30°, while the anti-phase mode was taken to be between 150° < CRP < 180°.

Inter-subject coordination profiling

Coordination profiling between the swimmers was established by a cluster hierarchical analysis, as proposed before (Ball & Best, 2007; Button, et al., 2006; Rein, et al., 2010) to classify different participant profiles. In swimming, cluster analysis has been already used to classify: (i) the characteristics of subject' physical fitness, as critical velocity or anaerobic working capacity in breaststroke (Abe, et al., 2006); (ii) the backstroke start, regarding to the body segment vector of the swimmers (Wilson & Howard, 1983); (iii) the aerial style of the diving start (Seifert, et al., 2010); (iv) the diving start profiles, taken in account the start in his whole duration, i.e., from block phase to swimming phase to 15m (Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010); and,

(v) groups of swimmers according to their reactions to the swimming training (Avalos, Hellard, & Chatard, 2003).

Statistical analysis

Differences between laps

Normality of the distribution and the variance homogeneity were checked. Comparisons between laps were performed using a one-way repeated measures ANOVA. The comparison was done for: (i) the stroking parameters (speed, stroke frequency, stroke length, and arm angular velocity); (ii) the mean continuous relative phase (CRP_{mean}), (iii) the standard deviation of the continuous relative phase (CRP_{SD}); (iv) the time spent in in-phase mode; (v) the continuous relative phase at the catch (when the hand starts the backward movement) and at the exit (when the hand get out of the water) of the underwater hand path (CRP_{catch} and CRP_{exit}, respectively) for the right (R) and left (L) hand; (vi) the maximum peak of the continuous relative phase values (CRP_{max}); (vii) the minimum peak of the continuous relative phase values (CRP_{min}); (viii) the difference between maximum and minimum peaks of CRP values (CRP_{dif}); (ix) the time of the glide and propulsive phases; and (x) the time at which the catch and exit points of the hand underwater path occurred for right and left hand (R_{catch}, R_{exit}, L_{catch}, L_{exit}).

Since a n = 10 sampled was used, effect size was computed with Cohen's *d* and Cohen's *f* for t-test and repeated measures ANOVA, respectively. It was considered (i) small effect size if $0 \leq |d| \leq 0.2$ or $0 \leq |f| \leq 0.1$; (ii) medium effect size if $0.2 < |d| \leq 0.5$ or $0.1 < |f| \leq 0.25$ and; (iii) large effect size if $|d| > 0.5$ or $|f| > 0.25$ (Cohen, 1988).

Inter-subject coordination profiling

Cluster analysis to classify swimmers

As higher inter-subject variability of CRP was expected, cluster hierarchical analysis using the squared Euclidean distance dissimilarity measure and the Ward linkage method was applied to determine several profiles within the studied swimmers. Eleven variables were used to classify the recreational

swimmers: mean CRP, intra-cyclic SD of CRP, % of time spent in in-phase mode of coordination, the CRP at the beginning and at the end of the cycle, the maximum peak, the first minimum peak and the second minimum peak of CRP values, the times at which the maximum peak, the first minimum peak and the second minimum peak of CRP occurred.

Cluster validation

According to Breiman (1996) and Rein, et al. (2010), the number of clusters and classification of the subject within the cluster were validated by bootstrapping procedure (called "bagging" when it is applied to dendrogram and machine learning; Breiman, 1996). One bagging procedure corresponds to construct the dendrogram, then to repeat this operation on all subject – 1 (one excluded at the time) and examine whether obtained classifications are stable or not. For example, if we remove the subject 1, we observed if each subject remained in his initial cluster or if he switched from one cluster to another one. In addition, the variables which significantly differentiated the clusters were determined using the Fisher information. Fisher information corresponds to the ratio between inter-cluster (J_b) and intra-cluster (J_w) distances:

$$Fisher\ information = J_b/J_w \tag{5}$$

where J_b and J_w corresponds to:

$$J_b = \sum_g N_g d^2(\mu_g, \bar{X}) \tag{6}$$

where N_g is the number of element in the cluster $_g$, d is the chosen distance, μ_g is the centre of cluster $_g$ (i.e. the mean of all points in $_g$), and $\bar{X}$ is the centre of all the points (i.e., the mean of all the points).

$$J_w = \sum_g \sum_{i \epsilon C g} d^2(x_i, \mu_g) \tag{7}$$

where C_g are the points in cluster $_g$, x_i is the value for each point.

The higher the Fisher information, the more discriminative are the variables. Based on the Fisher information, the cluster analysis was repeated several times, removing each variable one by one. A variable was considered significantly discriminative when the composition of the dendrogram (number of cluster and classification of the subject in the cluster) did not change in comparison to the initial result. All tests were conducted with Minitab 15.1.0.0 ® software (Minitab Inc., Paris, France, 2006) with a conventional significance level of $p < .05$.

Results

Fatigue effect

Swimmers showed a significant decrease in speed (13.8%), stroke frequency (5.1%), stroke length (6.9%) and angular velocity (13.3%) along the 200 m concomitant with the increase at blood lactate (11.12 ± 1.65 $mmol.l^{-1}$), suggesting the appearance of fatigue. However, no differences were found between laps in the spatial coordinative parameters, with the exception of the R_{glide}, R_{catch}, R_{exit} and and L_{exit} temporal parameters that increased from the beginning to the end of the 200 m event (Table 1).

Table 1. Effect of fatigue on the stroking parameters (Average (SD))

Parameters	Lap 1	Lap 2	Lap 3	Lap 4	$F_{(3,27)}$	p	f
v ($m.s^{-1}$)	1.57 (0.08)	1.39 (0.06)[a]	1.34 (0.07)[a]	1.35 (0.08)[a]	24.58	<0.001	1.26
SL (m)	2.29 (0.23)	2.21 (0.17)	2.19 (0.13)	2.12 (0.13)[a,b,c]	4.55	0.01	0.32
SF (Hz)	0.68 (0.09)	0.63 (0.06)	0.61 (0.05)[a]	0.64 (0.05)	5.08	0.006	0.39
R_{ω} ($m.s^{-1}$)	2.73 (0.42)	2.50 (0.26)	2.43 (0.26)[a]	2.38 (0.25)[a]	5.18	0.006	0.40
L_{ω} ($m.s^{-1}$)	2.83 (0.36)	2.61 (0.31)[a]	2.52 (0.17)[a]	2.44 (0.16)[a]	9.42	<0.001	0.53
R_{glide} (%)	43.1 (5.5)	44.4 (5.6)	45.5 (4.8)	46.1 (4.6)[a]	5.57	0.004	0.21
R_{prop} (%)	35.4 (3.3)	35.2 (3.4)	34.8 (2.9)	36.3 (2.2)	1.55	0.23	0.10
L_{glide} (%)	41.4 (4.8)	42.3 (6.5)	43.5 (6.3)	42.2 (6.0)	1.15	0.35	0.05
L_{prop} (%)	33.1 (3.9)	33.7 (4.7)	34.8 (4.0)	36.0 (4.3)	2.53	0.07	0.18
R_{catch} (%)	43.1 (5.5)	44.4 (5.6)	45.5 (4.8)	46.1 (4.6)[a]	5.57	0.004	0.23
R_{exit} (%)	78.5 (3.7)	79.6 (3.7)	81.0 (3.7)[a]	81.7 (3.9)[a,b]	11.84	<0.001	0.33
L_{catch} (%)	95.9 (5.6)	96.1 (7.0)	97.7 (5.8)	96.7 (5.7)	0.88	0.46	0.12
L_{exit} (%)	29.1 (3.3)	29.9 (4.0)	32.6 (4.0)[a,b]	32.6 (3.9)[a,b]	11.31	<0.001	0.41
$CRP_{catch}R$ (º)	120.4 (48.9)	120.4 (32.9)	116.7 (32.2)	128.3 (21.7)	0.51	0.68	0.11
$CRP_{exit}R$ (º)	182.5 (24.6)	194.1 (20.2)	188.9 (17.9)	189.4 (18.9)	1.01	0.40	0.02
$CRP_{catch}L$ (º)	264.8 (28.9)	274.3 (39.2)	285.3 (50.4)	276.2 (32.2)	1.26	0.31	0.09
$CRP_{exit}L$ (º)	180.4 (14.7)	173.8 (18.2)	167.6 (15.4)	182.8 (16.0)	1.75	0.18	0.24
CRP_{min} (º)	71.7 (24.4)	75.8 (30.2)	73.8 (24.4)	82.7 (11.6)	0.91	0.45	0.00
CRP_{mean} (º)	188.1 (7.5)	186.8 (8.5)	190.1 (7.1)	190.7 (4.8)	1.88	0.16	0.15
CRP_{max} (º)	308.8 (25.4)	311.1 (30.6)	329.4 (23.1)	320.4 (13.8)	2.69	0.07	0.29
CRP_{SD} (º)	66.7 (11.1)	67.3 (13.1)	71.6 (11.6)	67.6 (7.6)	1.30	0.29	0.09
CRP_{dif} (º)	237.0 (39.9)	235.3 (44.3)	257.7 (46.8)	237.7 (17.4)	1.59	0.22	0.15

[a,b,c] Statistical different from first, second and third lap, respectively. $p < .05$

Inter-subject coordination profiling

The dendrogram enabled to classify the swimmers in two coordination profiles: six subjects composed cluster #1 and four subjects composed cluster #2. Eleven variables significantly explained the difference between the two clusters. The Fisher information was used to classify these variables from the most discriminative to the less discriminative variables: L_{glide}, L_{catch}, CRP_{min}, L_{prop}, $CRP_{catch}L$, CRP_{SD}, R_{glide}, R_{catch}, SF, R_{exit}, $CRP_{catch}R$, v, SL, L_{exit}, R_{prop}, CRP_{max}, $CRP_{dif,}$ CRP_{mean}, and $CRP_{exit}L$ (Table 2). The most discriminative variables were the ones with the highest Fisher information, all variables with a Fisher information value of or above 0.72 presented differences between the clusters; these variables were: L_{glide}, L_{catch}, CRP_{min}, L_{prop}, $CRP_{catch}L$, CRP_{SD}, R_{glide}, R_{catch}, SF, R_{exit}, $CRP_{catch}R$ (Table 2).

Table 2. Difference between cluster's parameters (Average (SD)), p < .05

Parameters	Cluster 1	Cluster 2	t	p	*d*	Inter-cluster distance	Intra-cluster distance	Fisher
v ($m.s^{-1}$)	1.43 (0.04)	1.38 (0.03)	1.89	0.10	1.53	0.005	0.01	0.45
SF (Hz)	0.67 (0.04)	0.60 (0.05)	2.47	0.04	1.78	0.05	0.14	0.76
SL (m)	2.15 (0.08)	2.29 (0.19)	-1.67	0.13	1.18	36.2	47.4	0.35
R_{ω} ($m.s^{-1}$)	2.46 (0.28)	2.60 (0.18)	-0.93	0.38	0.63	0.05	0.48	0.11
L_{ω} ($m.s^{-1}$)	2.60 (0.29)	2.59 (0.08)	0.04	0.97	0.05	<0.001	0.44	0.00
$CRP_{catch}R$(º)	135.6 (16.3)	100.2 (35.3)	2.39	0.04	1.57	3647.9	5066.6	0.72
$CRP_{exit}R$ (º)	186.7 (17.2)	191.6 (15.7)	-0.45	0.66	0.33	57.2	2219.9	0.03
$CRP_{catch}L$(º)	257.4 (28.8)	301.7 (16.1)	-2.76	0.03	2.00	4693.3	4916.0	0.95
$CRP_{exit}L$ (º)	177.0 (8.7)	174.8 (6.4)	0.43	0.68	0.31	11.7	502.5	0.02
CRP_{min} (º)	87.8 (11.3)	58.4 (14.5)	3.63	0.007	2.61	2078.5	1259.2	1.65
CRP_{mean} (º)	190.1 (6.3)	187.1 (6.3)	0.74	0.48	0.53	21.8	318.7	0.07
CRP_{max} (º)	313.2 (19.7)	325.1 (14.3)	-1.03	0.33	0.74	338.7	2559.3	0.13
CRP_{SD} (º)	63.1 (8.5)	76.0 (5.0)	2.70	0.03	1.95	398.1	436.8	0.91
CRP_{dif} (º)	312.2 (19.7)	323.1 (14.3)	-0.94	0.37	0.68	284.1	2559.3	0.11
R_{glide} (%)	42.2 (2.9)	48.7 (4.9)	-2.66	0.03	1.92	101.2	114.6	0.88
R_{prop} (%)	36.2 (2.3)	34.2 (3.5)	1.10	0.31	0.80	9.6	63.8	0.15
L_{glide} (%)	38.9 (3.3)	47.6 (3.5)	-4.00	0.004	2.88	181.2	90.7	2.00
L_{prop} (%)	36.5 (2.7)	31.2 (1.2)	3.63	0.007	2.62	68.1	41.4	1.64
R_{catch} (%)	42.2 (2.9)	48.7 (4.9)	-2.66	0.03	1.92	101.2	114.6	0.88
R_{exit} (%)	78.4 (2.6)	82.9 (3.4)	-2.39	0.04	1.72	48.5	67.8	0.72
L_{catch} (%)	93.2 (4.4)	101.8 (1.7)	-8.59	0.006	2.65	177.0	105.9	1.67
L_{exit} (%)	29.7 (3.9)	33.0 (1.7)	-1.56	0.16	1.13	25.5	84.4	0.30

Cluster #1 was characterized by a flatter CRP curve (Fig. 3, left panel) and a more symmetric coordination profile (Fig. 4, left panel), whereas cluster #2 was characterized by the highest CRP variability (Fig. 3, right panel), the longest time of the cycle spent in glide and the most asymmetric coordination profile (Fig. 4, right panel).

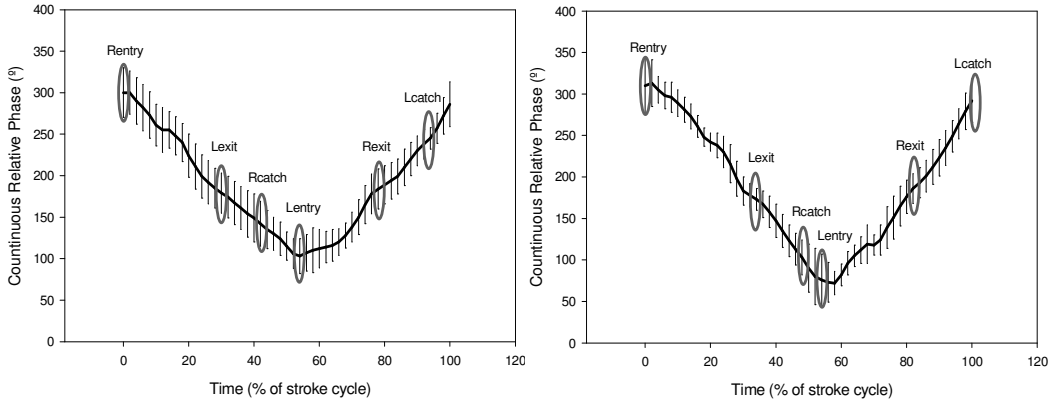


Figure 3. Continuous relative phase between right shoulder and left shoulder through a complete cycle for the cluster 1 (left panel) and cluster 2 (right panel).

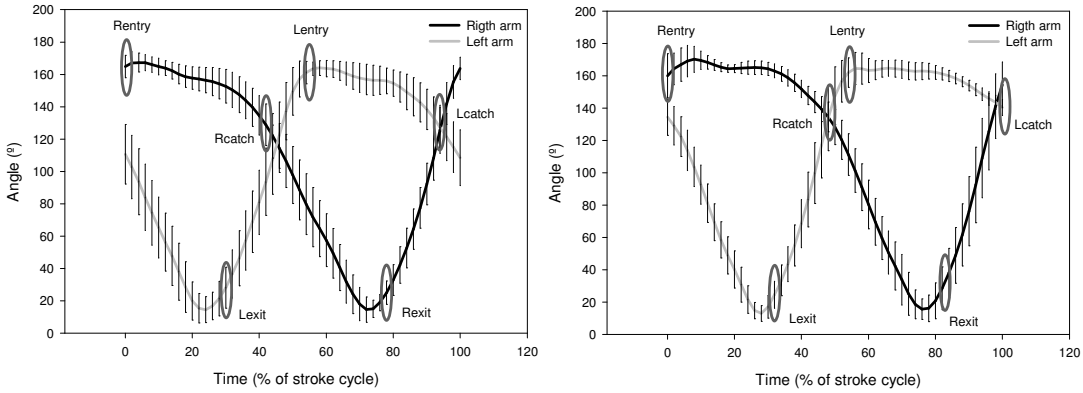


Figure 4. Variations of the right and left shoulder angles through a complete cycle for the cluster 1 (left panel) and cluster 2 (rigth panel).

Discussion

Effect of fatigue

The decrease observed in the *v*, SF, SL, and arm angular *v* along the 200 m evidenced, concomitant with the post exercise lactate, the fatigue induced by this high intensity effort, as previously shown for the same swimming distance (Bonifazi, Martelli, Marugo, Sardella, & Carli, 1993; Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2010; Pelayo, Mujika, Sidney, & Chatard, 1996). Coordinative spatial parameters showed no differences across the four laps of the 200 m event, but differences were observed in the temporal parameters. As suggested by Aujouannet, Bonifazi, Hintzy, Vuilerme, & Rouard (2006) this could be due to the very high performance level and homogeneity of the group of the swimmers tested, suggesting a stable spatial pattern that is not easily changed even by the impairments imposed by fatigue. The increase of temporal parameters under fatigue was specially marked by an increase of the R_{glide} time and of occurrence time for the R_{catch}, R_{exit}, and L_{exit}. This occurs as the swimmers increase the relative duration of the propulsive phases, which suggests a compensation for the decline of the force generating capacity (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005; Alberty, Sidney, Pelayo, & Toussaint, 2009). In accordance with the increase of the phases relative time duration, we also found a decrease in the angular velocity of the

arm, which also reflects fatigue and contributes to the reduction of the propulsive force generation, responsible for the decrease in speed; this reduced propulsive force production under fatigue conditions was previously referred (Figueiredo, et al., 2010; Suito et al., 2008; Toussaint, Carol, Kranenborg, & Truijens, 2006). In fact, the 200 m event, when performed at maximum intensity, is considered to be an exhausting effort (Aujouannet, et al., 2006; Bonifazi, et al., 1993; Pelayo, et al., 1996), and impairments of motor control resulting from fatigue may be expected (Alberty, et al., 2005; Alberty, et al., 2009). These constraints may explain the observed asymmetries, particularly resulting in the increase of the R_{glide} and R_{catch} not matched with correspondent contralateral evidences (Barden, Kell, & Kobsar, 2011; Potts, Chralton, & Smith, 2002; Seifert, et al., 2005).

The results of the continuous relative phase along the effort suggest that the intrinsic anti-phase coordination pattern is strongly preserved throughout the effort. Similar strong coupling relationships have also been noted between the arm and leg in various rhythmic activities, as walking, creeping and swimming (Wannier, et al., 2001). The present findings are limited to the study of two arm stroke cycles for each 50 m lap and therefore critical notions related to the analysis of coordination dynamics, might be influenced. However, its use to represent performance outcomes is commonly used in performance-oriented sports research (Glazier, Davids, & Bartlett, 2003; Nikodelis, Kollias, & Hatzitaki, 2005), particularly in Biomechanics, where technical limitations do not allow the recordings of more than one cycle, when dealing with a whole-body three-dimensional approach (Figueiredo, Vilas-Boas, Maia, Goncalves, & Fernandes, 2009; Psycharakis, Naemi, Connaboy, McCabe, & Sanders, 2010).

Inter-subject coordination profiling

In this study, as expected, all swimmers used an anti-phase coordination mode. In the front crawl swimming technique the arms are temporally coupled in an intrinsic anti-phase synchronisation mode, which seems to be strongly preserved despite of the environmental constraints and skill level (Nikodelis, et al., 2005). However, in spite of CRP_{mean} have not showed differences between

the two clusters, CRP_{SD}, mostly because of the CRP_{min}, showed to be different between clusters, which means that cluster #1 has a flatter CRP curve, evidencing lower variability. Differences noted in the CRP_{catch} between clusters pointed out also a different tendency to have higher or lower time in glide phase.

Bilateral asymmetry in elite front crawl swimming has been reported before (Barden, et al., 2011; Nikodelis, et al., 2005; Potts, et al., 2002; Psycharakis & Sanders, 2008; Seifert, et al., 2005). This last study reported asymmetries for swimmers of all levels, showing that arm coordination asymmetry vary greatly among swimmers and that technique asymmetry was associated with the handedness and unilateral breathing pattern of swimmers, being predominantly propulsion-based. It has also been reported that swimmers might apply larger propulsive forces when pulling with the dominant arm (Barden, et al., 2011; Potts, et al., 2002). We observed that the underwater phases of the right arm were longer, probably because the studied swimmers were right-handed; this can be related to differences in the magnitude, duration, timing, or direction of propulsive forces between the underwater phases of the dominant and non-dominant arm (Psycharakis & Sanders, 2008). Sadeghi, Allard, Prince, & Labelle (2000) reviewed the symmetry and limb dominance in gait analysis and suggested that the dominant limb might be used mainly for propulsion and the non-dominant for control and support. Barden, et al. (2011) found that the degree of bilateral asymmetry does not increase in relation to augmented exercise intensity; in fact, there results showed that arm asymmetry decreased with increasing exercise intensity, and that the decreases in asymmetry were proportional for both the power (underwater) and recovery (above water) phases of the stroke cycle, corroborating that higher degrees of anti-phase inter-limb coupling (i.e. less bilateral asymmetry) occur at faster speeds in front crawl swimming (Nikodelis, et al., 2005). However, the presence of a higher external power imbalance when nearing exhaustion (about 8%) between the left and right arm was also observed before (Potts, et al., 2002). In our study asymmetries seems to be stable or slightly increased, as changes occur, R_{glide} increase, but L_{prop} had a tendency to increase ($p=0.07$). Notwithstanding, Potts,

et al. (2002) results, these ones where found at exhaustion but during an incremental protocol, and the present results evidenced the occurred fatigue, but with a decrease in velocity. The present study results evidence the need of the profiling study, as arm coordination asymmetry varies greatly among swimmers, which could augmented the imbalance between propulsive and non-propulsive forces, increasing intracycle velocity variation and energy cost for the same average speed.

Swimmers of cluster #2 had higher values of R_{glide} and L_{glide} that shows a prevalence of swimming with more glide time and a tendency for higher SL, comparing with the counterparts of cluster #1. This could be explained by the swimmer's specialty, i.e., an organismic constraints, since the swimmers in this cluster also perform well at the 400 and 800 m competitive events. These competitive distances are associated with higher SL (Craig, Skehan, Pawelczyk, & Boomer, 1985) and a preference to higher glide than in shorter distances, implying higher propelling efficiency values than the sprinters (Cappaert, Bone, & Troup, 1992; Seifert, Komar, et al., 2010). It was also observed a longer relative duration of the left arm propulsion, since swimmers presented a left preference breathing side. Such results expressed that the fact that those swimmers have a unilateral breathing pattern led to asymmetric coordination (as presented by Barden, et al., 2011). In spite of being carried out only in non-breathing cycles, Seifert, Chehensse, Tourny-Chollet, Lemaitre, & Chollet (2008) showed that even in this condition, swimmers use a coordination mode similar to front crawl breathing cycles, that is part of their usual repertoire, emphasizing the powerful role of learned breathing laterality. These conclusions were attained even when the swimmer did not need to turn his head to breathe, evidencing that unilateral breathing disturbs arm coordination, and that all the stroke key points studied occurred at a later time within the stroke cycle.

Conversely, swimmers belonging to cluster #1 were more symmetric, and balanced, contributing for this higher SF than the one presented by cluster #2. Yanai (2003) and Psycharakis & Sanders (2008) demonstrated that swimmers reduced the amplitude of body roll as they increase the stroke frequency. This is expected from the sprinters, as the case of the swimmers in cluster #1, which

use higher SF to achieve higher speed, and also a more continuous inter-limb coordination (Seifert, et al., 2010). In spite of the differences between clusters, probably marked by swimmers' specialty, no differences where found between clusters for the hand speed, contrarily to the reported before by McCabe, Psycharakis & Sanders (2011), probably because all the swimmers are 200 m specialist.

Conclusion

This study highlighted the changes caused by the fatigue induced on the 200 m front crawl maximal effort being evident significant changes in the coordinative, kinematical and physiological parameters. In spite of these changes were common between swimmers, it was possible to identify individual adaptations clustered in two groups. Differences in the general biomechanical parameters to achieve the same velocity, presenting different combinations between SL and SF, which as due or promote asymmetries, which were also caused by their inherent breathing pattern. It was possible to determine that their difference was manly due to their specialty, as sprinters or distance swimmers.

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Chapter 8

Inter-limb coordinative structure in a 200 m front crawl event

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Introduction

Technical performance in swimming has traditionally been evaluated through changes in velocity, stroke rate and stroke length. However, this approach does not provide specific information on the effectiveness of motor organization. Coordination emerge as a consequence of constrains imposed on action, reflecting a propensity towards self-organizing optimality in biological systems [1]. In the front crawl technique, the two arms move rhythmically in anti-phase inter-limb relationship, which reflects an intrinsic coordination mode [2], being one of the most important factors contributing to the generation of propulsive forces [3].

To assess the coordinative parameters in front crawl, Chollet et al. [4] proposed the Index of Coordination (IdC), a tool that measures the inter-arm lag time between propulsive phases. Following these authors, the three major patterns of arm coordination are the catch up, the superposition and the opposition modes, being the coordination employed by the swimmer determined by the relative contributions of each phase (entry/catch, pull, push and recovery) to the total duration of the arm stroke cycle.

The aim of the present study is to assess the IdC during a 200m front crawl maximal effort, as well as to understand its interplay with the stroking parameters. The relative contribution of the arm stroke phases will also be assessed and discussed.

Methods

Six male competitive swimmers volunteered to participate in this study (20.3 ± 2.8 years old, 69.4 ± 4.8 kg, 177.2 ± 5.9 cm, 183.3 ± 7.0 cm of arm span and 10.0 ± 2.6% of fat mass). All participants signed a written informed consent in which the experimental protocol was described.

Swimmers were monitored in a 200m front crawl maximal test, when passing through a specific pre-calibrated space (calibration frame with dimensions of 3 x 2 x 3 m for the horizontal, vertical and lateral directions). Thirty points of

calibration were used and the synchronisation of the images was obtained using a pair of lights visible in the field of view of each video camera.

Six stationary video cameras were used, being two above and four underwater (Sony® DCR-HC42E). One complete arm stroke cycle, without breathing, was analysed for each length of 50 m, being assumed a six-beat kick synchronization. Test session took place in a 25 m indoor pool, being used push starts in order to minimize the starting effect.

The video images were digitized with APASystem (Ariel Dynamics, USA) at a frequency of 50 Hz, manually and frame by frame in order to have a more objective analysis. Twenty-one anatomical reference points were used. Image coordinates were transformed to 3D object-space coordinates using the DLT algorithm and then filtered using a low pass digital filter of 6 Hz. Each movement was then divided in four distinct phases defined as follows [4]: (i) entry/catch, which corresponds to the time between the entry of the hand into the water and the beginning of its backward movement; (ii) pull, corresponding to the time between the beginning of the backward movement of the hand and its entry into the plane vertical to the shoulder (initial part of the propulsion); (iii) push, the time between the positioning of the hand below the shoulder and its exit from the water and (iv) recovery, corresponding to the time between the exit of the hand and its next entry into the water.

The duration of each phase was measured with a precision of 0.02 s and was expressed as a percentage of the duration of a complete stroke cycle. The duration of the propulsive and non-propulsive phases were the sum of pull and push, and of catch and exit phases, respectively.

The average horizontal velocity (v) was assessed by dividing the displacement of the centre of mass in one stroke cycle for its total duration. Stroke rate (SR) was assessed through the inverse of its time duration, being stroke length (SL) considered the horizontal displacement of the centre of mass during a stroke cycle.

Statistical analysis

After the normality was checked, mean (SD) was computed for all variables. A one way repeated measures ANOVA, with Tukey post-hoc test was used to compare all the variables. Additionally, Pearson correlation coefficients were computed between IdC and the other biomechanical and coordinative parameters. The level of significance was set at $p < 0.05$.

Results

In Table 1 it is possible to observe the mean (SD) values of the general biomechanical parameters (v, SR and SL) and of the coordinative organization parameters (IdC and stroke phases) for the four laps of the 200m front crawl test.

Table 1. Mean (SD) values of the velocity, stroke rate, stroke length, index of coordination (IdC), entry/catch, pull, push, recovery, propulsive phases and non-propulsive phases in the four laps of the 200m front crawl.

	velocity ($m.s^{-1}$)	stroke rate (stroke $.min^{-1}$)	stroke length (m. $stroke^{-1}$)	IdC (%)	entry/ catch (%)	pull (%)	push (%)	recovery (%)	propulsive (%)	non-propulsive (%)
1st	1.64	49.08	2.01	-13.1	37.7	23.1	14.1	25.1	37.2	62.8
50m	(0.04)	(3.04)	(0.15)	(2.7)	(4.9)	(1.4)	(1.2)	(3.7)	(2.6)	(2.6)
2nd	1.48	43.88	2.03	-13.5	39.0	12.4	24.3	24.4	36.6	63.4
50m	(0.07)[a]	(3.18)[a]	(0.11)	(3.8)	(5.1)	(1.6)	(3.4)	(3.1)	(4.0)	(4.0)
3rd	1.46	44.34	1.98	-13.9	39.3	12.4	23.8	24.5	36.2	63.8
50m	(0.05)[a]	(2.45)[a]	(0.12)	(3.2)	(5.1)	(2.1)	(1.9)	(3.1)	(3.7)	(3.7)
4th	1.40	44.33	1.89	-11.7	37.8	13.5	24.9	23.8	38.4	61.6
50m	(0.08)[a,b,c]	(2.37)[a]	(0.15)[b]	(3.9)[a,b,c]	(5.2)	(2.9)	(4.7)	(2.4)	(4.3)[b,c]	(4.3)[b,c]

[a, b, c] Significantly different from the first, second and third laps, respectively ($p < 0.05$)

In table 2 there are presented the coefficients of correlation between the IdC and all the other biomechanical and arm stroke phase variables.

Table 2. Correlation's matrix obtained between index of coordination (IdC) and velocity, stroke rate, stroke length, entry/catch phase, pull phase, push phase, recovery, propulsive phases and non-propulsive phases.

	velocity ($m.s^{-1}$)	stroke rate (stroke. min^{-1})	stroke length (m. $stroke^{-1}$)	entry/ catch (%)	pull (%)	push (%)	recovery (%)	propulsive (%)	non-propulsive (%)
IdC (%)	ns	ns	ns	-0.78	0.54	0.78	ns	0.97	-0.97

Discussion

The purpose of this research was to study the behaviour of IdC through a 200m maximal front crawl effort and its relationship with the general biomechanical parameters. Moreover, as differences in the visual determination of IdC depends on the operator expertise [5], the assessment was done through digitization.

IdC staid in the catch-up mode during the whole effort. In the fourth lap it was observed an IdC increase possible due to fatigue (as previously observed in 100m race [6]). In this fatigue stages, swimmers tend to increase their propulsive continuity, as observed elsewhere [7]. However, it further reflected more time spent during the propulsive phase than greater force generation as the v and SL decreased in the last 50m of the 200m. These facts could be explained by the development of local muscular fatigue [8], reflecting a declining capacity to deliver power output [9]. Nonetheless, no changes were noticed for the SR, being the swimmers unable to increase it in order to compensate the SL decrease as suggested before (eg. [10]). These facts lead to an increase of the relative duration of the propulsive phases, reflecting the inability to generate enough propulsive force, as a consequence temporal structure changed [6].

Additionally, in the non-propulsive phases, IdC only was related with the entry/catch phase, implying that the relative time duration between the entry and the beginning of the pull phase has a great negative influence on the coordination mode, which should be diminished specially under fatigue conditions.

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Chapter 9

Relation between efficiency and energy cost with coordination in aquatic locomotion

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Medicine and Science in Sports and Exercise (submitted)

Abstract

The aim of this study was to establish the relationships between the intracycle velocity variation (IVV) and Froude efficiency (η_T) accepted as indicators of swimming efficiency, energy cost (C), and index of coordination (IdC) throughout a 200 m freestyle race. Ten male international level swimmers performed a maximum 200 m front crawl swim. Performance was recorded with four below- and two above-water synchronized cameras for four non-breathing stroke cycles (one for each 50 m). Oxygen consumption was measured continuously during the effort, and blood samples were collected before and after the test. IdC, body centre of mass' IVV (x, y and z) and η_T were also calculated. For assessing C swimmers performed also 50, 100 and 150 m at the same pace as in the 200 m splits to capture blood lactate samples after each 50 m lap of the 200 m. Swimmers attained a stable IVV (x, y, and z), as fatigue development along the 200 m effort induced a decrease in velocity, stroke length, stroke frequency, η_T, and an increase of IdC (evidencing a coordination change). Direct relationships between C and IdC for the second and fourth lap were found: $r = 0.63$ and $r = 0.69$ ($P < 0.05$), respectively. Computing partial correlation, also IdC and η_T in the first lap were significantly correlated ($r = -0.63$, $P < 0.05$). IdC and η_T showed to be significant for the within subjects correlation ($r = -0.45$, $P = 0.01$), and IdC and C for the between subjects correlation ($r = 0.66$, $P = 0.04$). Patterns of coordination modified during the 200 m event in response to the task constraints, observed by the changes in the other studied parameters and allowing the IVV stability along the effort.

Key words**:** Biophysics, Front crawl stroke, Arm coordination, Propelling efficiency, Intracycle velocity variation, Energetics

Introduction

Intracycle velocity variation (IVV) has been used to characterize swimming technique, whereby its magnitude was considered an indicator of swimming efficiency (for review see Vilas-Boas et al. 36). The Froude efficiency or propelling efficiency (see Toussaint et al. 34) is relevant in all propulsion in a fluid, and it is quantified as the mechanical power needed to overcome drag relative to total mechanical power produced (including power wasted in giving a kinetic energy change to the fluid used to push-off from). Therefore, both IVV and Froude efficiency could be useful tools for the technical training of swimmers, enabling optimizing swimmers' movement coordination. Coordination emerges as a consequence of the constraints imposed on action (22), and it is characterized by qualitative reorganizations of the movement in the course of practice. To assess effective motor organization in front crawl, Chollet et al. (11) proposed the Index of Coordination (IdC), considered as the lag time between propulsive and non-propulsive phases that influence acceleration and deceleration of the body centre of mass (CM).

In expert swimmers, arm coordination shifts from catch-up (IdC<0%), opposition (IdC=0%), to superposition (IdC>0%) modes concomitant with increased levels of swimming speed (11, 28, 29). It is suggested that such adaptive movement patterns emerge as a function of the organism's propensity to conserve metabolic energy, and of the demands arising from the environmental constraints (32). Schnitzler et al. (27) suggested that when swimming at higher speed, coordination is focused not only on generating more propulsion, but also on minimizing drag and stabilizing IVV; for example: when a swimmer overlaps his propulsion (IdC>0%), he enables higher mean propulsion than the mean propulsion of swimming when no overlap occurs; i.e. the average propulsion of only one arm (3). Also, in exhaustive conditions, where the force producing capacity may be compromised by the developing fatigue, the IdC increases when velocity decreases (2, 3).

Recently, the link between efficiency parameters and IdC was studied (26, 27). The stability of the IVV was observed at different swimming paces, and it was

suggested that IdC changes might ensure this stability. Alberty et al. (2) also studied the nature of the temporal modifications in the front crawl technique under exhaustive conditions, and observed stability of the IVV in spite of IdC changes. Seifert et al. (31) analyzed both propelling efficiency and IdC in two different expertise groups, and found that, among several parameters, the Froude efficiency was directly related with IdC, though the link between them was not explored. In these pioneer studies, 25 m sprints were used for assessing propelling efficiency and coordination, and IVV was obtained only for the swimming direction (horizontal axis), and from a fixed point (normally the hip) rather than from the body CM. In fact, the front crawl IVV assessment in the lateral and vertical directions seems also to be relevant, since they were reported to be greater than the variations in the swimming direction (24). Only Figueiredo et al. (15) related IVV in the three axes of motion with IdC, and observed a positive correlation with the IVV in vertical and lateral directions.

In addition, inter-arm coordination was also suggested to influence energy cost (C), since the latter depends on the timing between the actions responsible for the external work (30); a high positive relation between these parameters was evidenced before in incremental intermittent protocols (14, 30). Thus, it is suggested (5) that C is not only related to the Froude or propelling efficiencies, as described in the following equation:

$$C = \left(\frac{W_{tot}}{\eta_P}\right)\eta_o^{-1} \quad (1)$$

where C is defined as the total energy expenditure required to displace the body over a given unit of distance, η_P is the propelling efficiency, η_o represents the overall efficiency and W_{tot} indicates the total mechanical work per unit of distance. The total mechanical work has been divided into the internal work (W_{int}), due to the speed changes of the body segments respecting to the body CM, and the external work (W_{ext}), related to the position and speed changes of the CM relative to the environment. However, the IVV is not null, as the swimmer does not move at a constant velocity. Variations of propulsive and

resistive forces, and asymmetries in power production of each arm, lead to variations in the swimming velocity in each stroke cycle that is influenced complementarily by the arms' motion. Barbosa et al. (6) found a direct relationship between the horizontal IVV and the C in an incremental front crawl protocol ranging from low to high swimming intensities.

The aim of this study was to establish the relationships between some well accepted efficiency parameters (IVV and Froude efficiency), C, and inter-arm coordination (assessed by IdC) throughout a 200 m freestyle race. It was hypothesized that, during the race, fatigue develops, which leads to a higher IdC, as well as to a speed drop. In addition, it will also be observed if fatigue also leads to a deterioration of technique, leading to a decrease in propelling efficiency that would influence IVV.

Methods

Subjects

Ten well-trained swimmers (21.6 ± 2.4 yr), specialists on the 200 m freestyle event, volunteered for this study. Height, arm span, body mass and percentage of adipose tissue were 185.2 (6.8) cm, 188.7 (8.4) cm, 76.4 (6.1) kg, and 10.1 (1.8)%, respectively. The subjects had an average of 11.9 (3.5) yrs of competitive experience. Their performances in the 200 m freestyle were 109.3 (2.1) s, corresponding to an average speed representing 91.6 (2.1)% of the average speed of the short course pool men world record. Swimmers were informed of the experimental procedure, and of the potential risks and benefits of the study.. Swimmers gave a written consent to participate, and the protocol was reviewed and approved by the local ethics committee according to the Declaration of Helsinki (2000). During the testing period, subjects were asked to avoid stressful training programs, adapting the intensity and the total volume of training. Swimmers were accustomed to use a snorkel.

Experimental Procedures

Following the self-selected swim of 1000 m warm-up that included snorkel swimming, swimmers performed a 200 m maximum front crawl test using a

push start and open turns without glide, replicating their competition pacing and strategy. All tests were conducted in a 25 m indoor pool, and each subject swam alone in one lane, avoiding pacing or drafting effects. After 90 min of active rest interval, swimmers performed a 50 m front crawl test and, 24 h later, a 150 m and a 100 m tests, with 90 min active rest interval in-between. Both 50, 100 and 150 m tests were conducted at the same swimming speed as in the previous 200 m (controlled by a visual light pacer, placed in the bottom of the pool, with a flash every 5 m, TAR 1.1, GBK-EIectronics, Aveiro, Portugal).

Data Collection

Kinematics

Performance was recorded with a total of six stationary and synchronized video cameras (Sony, DCR-HC42E, Tokyo, Japan), four below and two above the water. The space recorded was calibrated with a volume with dimensions of 3 x 2 x 3 m for the horizontal (*x*), vertical (*y*) and lateral (*z*) directions, being the *x* direction aligned with the forward direction of the swimmers displacement. Thirty points of calibration were used, and the synchronization of the images was obtained using a pair of lights observable in the field of view of each camera. The angle between the optical axes of the two surface cameras was approximately 100º, while the angles between the optical axes of adjacent underwater cameras varied from 75º to 110º. One stroke cycle for each 50 m lap was analyzed.

Energetics

Oxygen uptake ($\dot{V}O_2$) was recorded through the K4b² telemetric gas exchange system (Cosmed, Roma, Italy), during all the 200 m front crawl effort, which was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (14, 18). Expired gas concentrations were measured breath-by-breath and averaged every 5 s. Net $\dot{V}O_2$ was calculated by subtracting the resting $\dot{V}O_2$ (measured just before the beginning of the exercise) from the measured $\dot{V}O_2$.

Before, and after, the 50, 100, 150 and 200 m tests, capillary blood samples

(5µl) were collected from the ear lobe to assess rest and post exercise blood lactate (La_b) using a portable lactate analyzer (Lactate Pro, Arkray, Inc.). Lactate was measured at 1, 3, 5, and 7 min post test, and the peak value was used for further analysis.

Data Analysis

Kinematics

Twenty-one landmarks (Zatsiorsky's model adapted by de Leva, (13) - defining the three-dimensional position and orientation of the head, torso, upper arms, forearms, hands, thighs, shanks and feet - were manually digitized at 50 Hz using a specific software (Ariel Performance Analysis System, Ariel Dynamics, Inc., San Diego, USA). Direct Linear Transformation algorithm (1) was used for three-dimensional reconstruction and a digital low-pass filter at 6 Hz was used for data smoothing. The calibration setup and the accuracy and reliability procedures have been already described in detail (16). The low errors in the calculations suggested very good reconstruction accuracy and reliability, and negligible image distortion and refraction. To determine the reliability of the digitizing process, a swimmer was digitized 10 times for all the six video cameras through the stroke cycle. Small standard deviation for the repeated digitisations indicated acceptable reliability for velocity being 0.03, 0.02 and 0.03 $m \cdot s^{-1}$ for x, y and z, respectively.

One complete stroke cycle in the mid-section of the swimming pool was analyzed for each 50 m lap, and the CM position as a function of time was computed. The mean velocity (v) was calculated by dividing the horizontal displacement of the CM in one stroke cycle over its total duration, and the instant swimming velocity by dividing the horizontal displacement of the CM in one frame over its duration. In addition, stroke length (SL) was determined through the horizontal displacement of the CM during the stroke cycle, and the stroke frequency (SF) was determined from the time needed to complete a stroke cycle.

Intracycle Velocity Variation

To analyze the IVV of the CM in the 3 axes of movement (x, y, z) the coefficient of variation was computed as proposed before (5, 16):

$$IVV = \frac{\sqrt{\sum_i (v_i - \bar{v})^2 F_i / n}}{\sum_i v_i F_i / n} \quad (2)$$

where IVV represents intracycle velocity variation of the center of mass, $\bar{v}$ mean swimming speed, v_i instant swimming speed, F_i absolute sample frequency and n is the number of observations.

Propelling Efficiency

The three-dimensional hand speed was computed as the sum of the instantaneous three-dimensional speed of the right and left hand during the underwater phase (3Du). From the ratio of the speed of CM to 3Du, since this ratio represents the theoretical efficiency in all fluid machines (19) and in rowing animals (4), propelling efficiency as:

$$\eta_T = \frac{\bar{v}}{3Du} \quad (3)$$

where η_T is the average theoretical efficiency over a stroke cycle, $\bar{v}$ mean swimming speed and 3Du the three-dimensional average hand speed. The computed efficiency values are values of Froude/Theoretical efficiency (internal work is not considered/computed) of the arm stroke only (cf. 40 for a more detailed discussion).

Index of coordination

IdC assessment requires the identification of key points in the stroke cycle (11), particularly the entry and catch (A) of the hand in the water (time between the entry of the hand into the water and the beginning of its backward movement), the pull (B; time between the beginning of the backward movement of the hand and its entry into the vertical plane of the shoulder), the push (C; time between

the positioning of the hand below the shoulder to its exit from the water) and the recovery (D; time between the final point of the push phase and its following entry into the water). Each phase, within every stroke cycle, was determined from the swimmer's horizontal and vertical displacement of the hand, and noting the time corresponding to these displacements. The duration of each phase was expressed as a percentage of the duration of a complete stroke. The duration of the propulsive and non-propulsive phases was the sum of pull and push phases, and of the catch and exit phases, respectively. The duration of a complete arm-stroke was the sum of the propulsive and non-propulsive phases and the IdC expressed the time gap between the propulsion of the two arms as a percentage of the duration of the complete arm-stroke cycle, and was the mean of IdC_{left} (equation 4) and IdC_{rigth} (equation 5) (2, 3, 28):

$$IdC_{right} = \frac{(Time_{end\ of\ phase\ C\ for\ right\ arm} - Time_{beginning\ of\ phase\ B\ for\ left\ arm}) * 100}{Duration_{complete\ stroke\ cycle}} \quad (4)$$

$$IdC_{right} = \frac{(Time_{end\ of\ phase\ C\ for\ right\ arm} - Time_{beginning\ of\ phase\ B\ for\ left\ arm}) * 100}{Duration_{complete\ stroke\ cycle}} \quad (5)$$

Energetics

The contribution of the three energy sources (10, 38) in each 50 m lap of the 200 m front crawl race were assessed as follows. The aerobic contribution (Aer) was calculated from the time integral of the net $\dot{V}O_2$ vs. time relationship in the appropriate time ranges. The anaerobic contribution was obtained by the sum of the energy derived from lactic acid production (Anl, equation 6) and phosphocreatine (PCr, equation 7) splitting in the contracting muscles (AnAl).

$$Anl = b[La]_{bnet} \cdot M \quad (6)$$

where $[La]_{bnet}$ is the net accumulation of lactate after exercise, b is the energy equivalent for lactate accumulation in blood (2.7 ml $O_2 \cdot mM^{-1} \cdot kg^{-1}$ as proposed before (5, 6, 14, 18)) and M (kg) is the mass of the subject. $[La]_{bnet}$ (mM) was calculated as the difference in $[La]_b$ before and after each lap.

$$AnAl = PCr\ (1 - e^{-t/\tau}) \cdot M \quad (7)$$

where t is the time duration, τ is the time constant of PCr splitting at work onset (23.4 s, see Zamparo et al. (38)), M (kg) is the mass of the subject and PCr is the phosphocreatine concentration at rest. The latter was assumed to be equal to 27.75 mM · kg^{-1}, an average of the values reported in the literature.

The energy derived from the utilization of AnAl was estimated assuming that, in the transition from rest to exhaustion, the PCr concentration decreases by 27.75 mM · kg^{-1} muscle (wet weight) in a maximally active muscle mass. AnAl can be expressed in kJ by assuming a P/O_2 ratio of 6.25 and an energy equivalent of 0.468 kJ · mM^{-1} (cf.(10)). The AnAl contribution for each lap was then calculated as the difference in AnAl before and after each lap. On the basis of these data, Ė was computed and C was calculated as the ratio between Ė and average v.

Statistical Analysis

Average (SD) computations for descriptive analysis were obtained for all variables (normal Gaussian distribution of the data was verified by the Shapiro–Wilk's test). The compound symmetry, or sphericity, was checked using the Mauchley test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure when the epsilon correction factor was < 0.75 or according to the Huyn–Feld procedure when the epsilon correction factor was > 0.75 (37). A one-way repeated measures ANOVA was used to compare the analysis of the kinematical parameters along the 200 m. When a significant F-value was achieved, Bonferroni post hoc procedures were performed to locate the pairwise differences between the averages. Pearson correlation and partial correlation was used to analyze the relationship between variables for each lap. However, since the measurements per 50 m lap during the 200 m involve a repeated measurements design, a within subjects correlation coefficient was reported, which accounts for the lack of independence among the repeated

measurements by removing the variation between subjects (8). Also, a between subjects correlation coefficient was reported (9). The referred statistical analysis was performed using STATA 10.1 (StataCorp, USA). The level of significance was set at 0.05 and effect size was computed with Cohen's *f*. The effect size was considered (1) small if $0 \leq |f| \leq 0.1$; (2) medium if $0.1 < |f| \leq 0.25$ and; (3) large if $| |f| > 0.25$ (12).

Results

Swimming v decreased significantly from 1.57 to 1.35 $m.s^{-1}$ (first to the last lap) ($F_{(3,27)} = 24.58$, $P < 0.001$, $f = 1.26$). SL remained constant for the first three laps (2.29, 2.21 and 2.19 m, respectively), whereas a decrease was observed in the final lap (2.12 m) ($F_{(3,27)} = 4.56$, $P = 0.01$, $f = 0.32$). SF decreased significantly from 0.68 Hz in first lap to the other laps (0.63, 0.61 and 0.64 Hz, respectively) ($F_{(3,27)} = 5.08$, $P = 0.006$, $f = 0.39$). To further study the changes in the in v, SL and SF, each parameter was expressed as a percentage of the value observed in the first lap (Figure 1). Speed decreased from the first to the last lap by 13.8%. SF (-5.8%) also decreased, but a non-significantly increase in the last lap of the test was observed. SL decreased non-significantly during the first laps, and a decrease of 6.9% was observed in the last lap (see Figure 1).

Figure 2 presents the remaining kinematical parameters studied. The η_T was significantly lower in the fourth lap compared to the others ($F_{(3,27)} = 6.98$, $P = 0.001$, $f = 0.42$). Conversely, IdC was found to be higher in the fourth lap than in the first and second ones ($F_{(3,27)} = 5.10$, $P = 0.006$, $f = 0.36$). The IVV in the x, y and z axes stayed stable during the whole 200 m effort ($F_{(3,27)} = 1.60$, $P = 0.21$, $f = 0.18$; $F_{(3,27)} = 0.82$, $P = 0.49$, $f = 0.00$; $F_{(3,27)} = 2.18$, $P = 0.11$, $f = 0.30$).

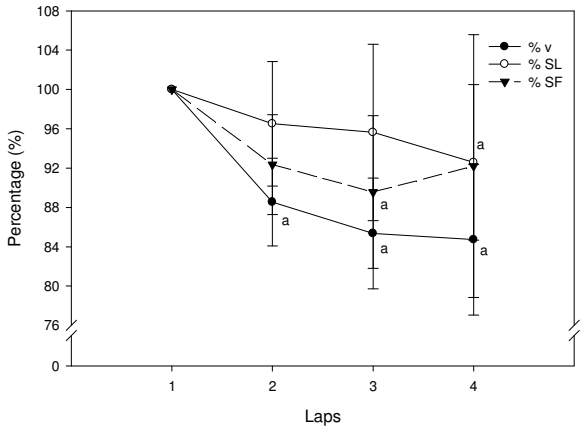


Figure 1. Mean and SD lap-averaged values expressed as percentage of the first lap value for swimming speed (%v), stroke length (%SL), and stroke frequency (%SF) for the 200 m swim. [a] Different from lap 1, $p < 0.05$.

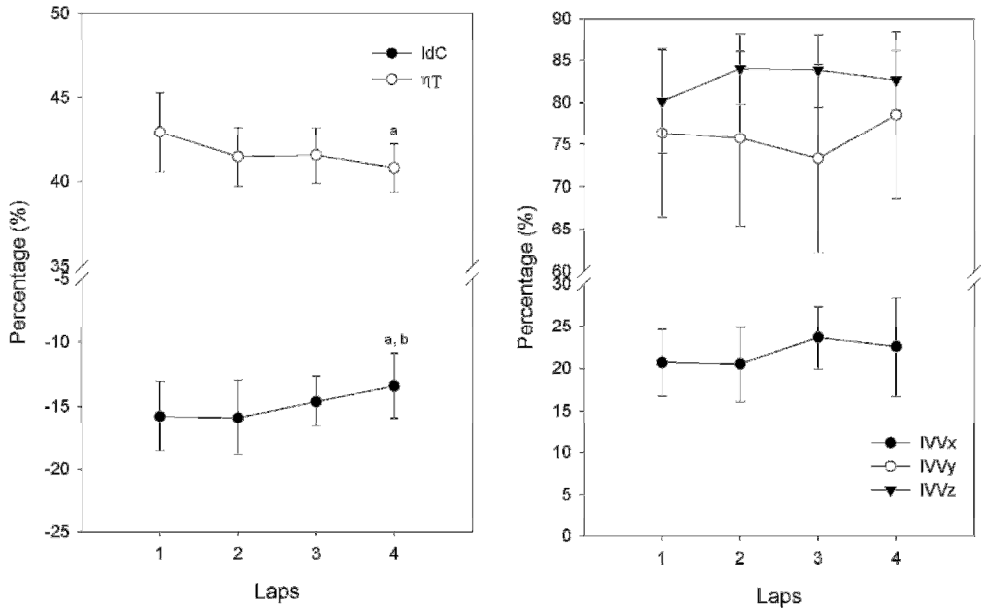


Figure 2. Mean and SD lap-averaged values for Index of Coordination (IdC) and Propelling efficiency (η_T) (left panel), and Intracycle Velocity Variation (IVV) in x, y and z axes (right panel) for the 200 m swim. [a, b, c] Different from the 1st, 2nd and 3rd lap, respectively. $P<0.05$.

Figure 3 presents the relationships between IdC, IVV (x, y and z), η_T and C for each 50 m lap of the 200 m front crawl effort. A direct relationship between IdC and C for the second and fourth lap was found: $r = 0.63$ and $r = 0.69$ ($P < 0.05$), respectively. All the other relations showed to be non-significant.

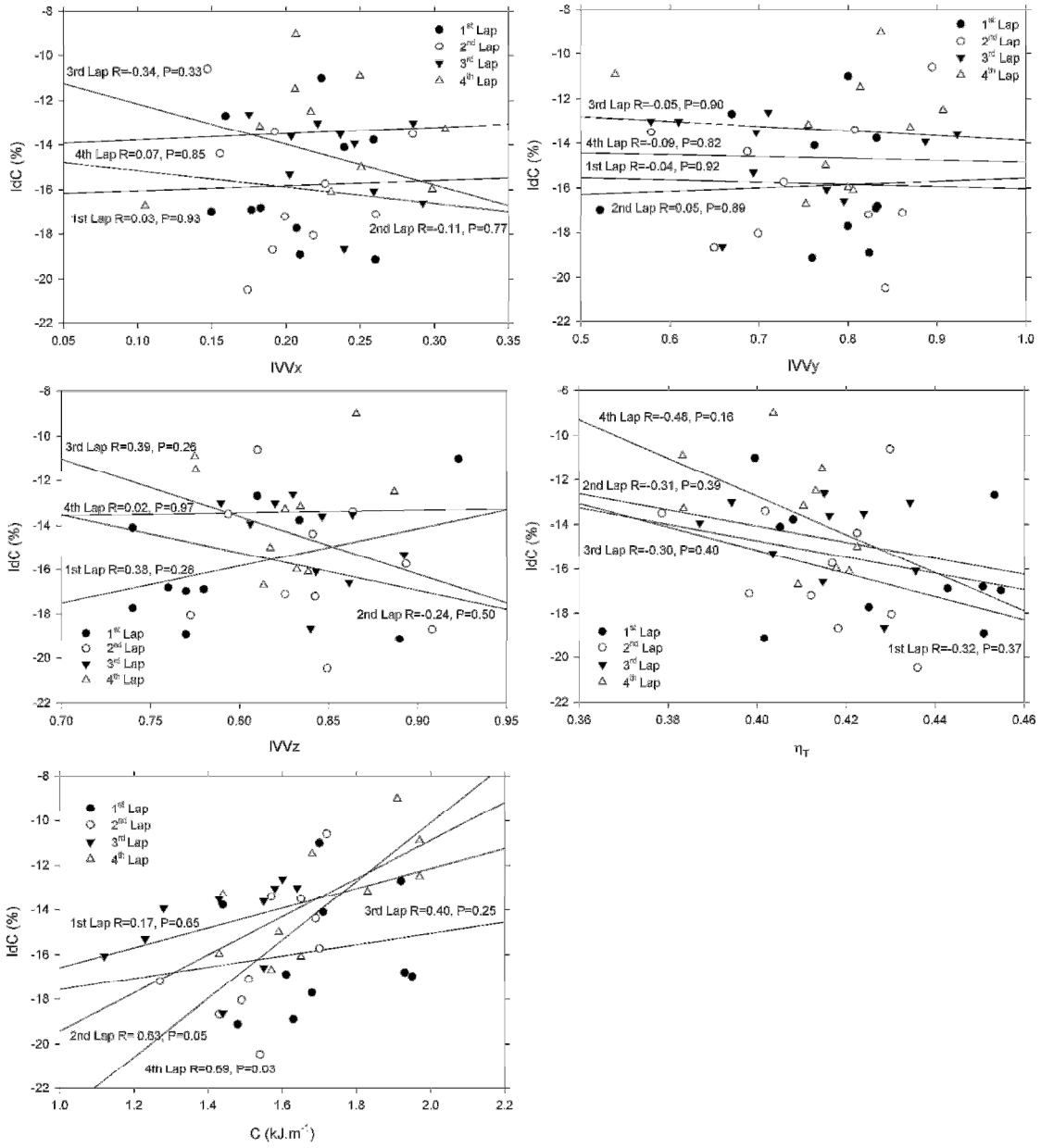


Figure 3. Index of Coordination (IdC) as a function of intracycle velocity variation (IVV) in horizontal (upper left panel), vertical (upper right panel) and lateral (lower left panel) axes, propelling efficiency (η_T) (lower right panel) and energy cost (C) (lower panel) in the four laps of the 200 m freestyle event.

Table 1 presents the partial correlation values between IdC, IVV (x, y and z) and η_T for each 50 m lap of the 200 m front crawl event, controlling the swimming speed. Only partial correlations between IdC and C in the second and fourth lap and IdC and η_T in the first lap were significant. So, during this

competitive event, in general terms, increases in IdC were not associated to increases in IVV (x, y and z) and η_T.

Table 1. Partial correlation values (p-value) between Index of coordination (IdC), Intracycle velocity variation (IVV) in horizontal (x), vertical (y) and lateral (z) axes, propelling efficiency (η_T) and energy cost (C) for each 50 m lap of the 200 m, controlling the swimming speed variable.

	IVVx vs. IdC	IVVy vs. IdC	IVVz vs. IdC	η_T vs. IdC	C vs. IdC
Lap 1	0.56 (0.12)	0.40 (0.29)	0.53 (0.14)	-0.63 (0.05)	-0.52 (0.15)
Lap 2	-0.09 (0.82)	0.05 (0.91)	-0.23 (0.52)	-0.38 (0.32)	0.63 (0.05)
Lap 3	-0.31 (0.42)	-0.23 (0.56)	-0.61 (0.08)	-0.22 (0.56)	0.45 (0.22)
Lap 4	0.13 (0.73)	0.04 (0.97)	0.10 (0.80)	-0.46 (0.22)	0.70 (0.04)

To further study the relationship between variables during the 200 m front crawl, within and between subjects correlation coefficient were computed (Table 2); it was observed an inverse relationship between IdC and η_T for the within subjects correlation, meaning that the increase in IdC within the same individual is associated with a decrease in η_T during the 200 m. A significant correlation between subjects for the variables IdC and C was also found, evidencing that subjects with a high value on IdC also tend to have a high value of C.

Table 2. Within and between subjects correlation coefficient values (p-value) between Index of Coordination (IdC) and intracycle velocity variation (IVV) in horizontal (x), vertical (y) and lateral (z) axes propelling efficiency (η_T) and the energy cost (C) for the 200 m front crawl.

Variable	Correlations with IdC	
	Within subject correlation	Between subject correlation
IVVx	0.14 (0.46)	-0.06 (0.87)
IVVy	-0.04 (0.84)	0.04 (0.91)
IVVz	0.30 (0.10)	-0.31 (0.42)
η_T	-0.45 (0.01)	-0.36 (0.36)
C	0.01 (0.99)	0.66 (0.04)

Discussion

Stability in the IVV values (x, y and z) was observed across the swimming effort, which is in accordance with previous data (24). This seems important, as the increase in IVV will increase work, as reported theoretically and experimentally in incremental swimming protocols (6). Propulsive efficiency (η_T) decreased in

the last lap due to fatigue (18, 35), as fatigue evolved during the 200 m front crawl. A decrease in speed was observed, as well as a decrease in SL and SF, in different rates depending on the stage of the effort (2, 25).

As the above-mentioned changes occurred, inter-limb coordination adapted, as an optimization mechanism to obtain as much speed possible given the dwindling power output, increasing the IdC (as observed previously, (2, 3, 17). Glazier et al. (20) stated that an effective front crawl swimming technique must be sufficiently flexible and adaptable to enable emerging patterns of coordination to be modified according to constraints impinging on the swimmer. All the results presented along the 200 m effort are in accordance with the literature, but the present study's major interest is the interplay between these variables.

The direct relationship between IdC and C for the second and fourth lap of the 200 m effort was expected since IdC is related to SF, and propulsive efficiency to SL, and a lower application of forces per arm-stroke cycle (3, 21) would increase C for the same average v. A dimensional analysis of C has the property of N ($J \cdot m^{-1} = Nm \cdot m^{-1} = N$), and so IdC will increase when more relative force is required. In fact, with the development of fatigue, average force production per stroke is reduced. Nevertheless, bringing the strokes closer together or overlap them has the effect of increasing the average propulsive force where the average force per stroke remains constant, or even diminishes slightly (3). Barden et al. (7) showed that in different intensity bouts of 200 m front crawl, a substantial increase in stroke rate occurs at the critical speed, which is related to a disproportionate decrease in the duration of the recovery phases of the stroke cycle, such that the propulsive/recovery ratio increases significantly (33). Similarly, in constant swimming speed tests, SF and IdC gradually increased, indicating that the duration over which the propulsive force acted per distance unit augmented. Apparently, this is an effective compensation mechanism for the reduction in force capacity due to the build up of fatigue (3).

The non-significant relationship obtained between IVVx and IdC were in accordance with previous results on high-level swimmers (26), suggesting an

adaption of inter-limb coordination in order to attain lower C (32). Furthermore, stability of the IVV is observed, as C and IVV show a positive relationship throughout an incremental intermittent protocol to obtain $\dot{V}O_2max$ (6). The IVV measured for the other axes of motion (y and z) showed no relationship with IdC, suggesting that the vertical and lateral motion of the CM as quantified by the IVV are not influenced by the mode of coordination adopted by the swimmers.

IVVx represents an overall outcome in the sense that it relates to the spacing in time of propulsive and resistive 'pulses'. If these 'pulses' are well coordinated, such that maxima for propulsion and drag coincide, it will lead to minimized acceleration of the CM, i.e., two sinuses with a 180º phase shift, one representing propulsion and the other drag, would lead to zero acceleration when both have the same amplitude. To enhance coordination such that propulsive and resistive pulses are matched, the swimmer may use the IVVx, since it is directly coupled to variations in the optic flow (i.e. the variations in speed with which the pool floor appears and disappears under the swimmer). Hence, using visual information, the propulsive and resistive actions of the swimmer could be coordinated to reduce energy loss due to excessive intracycle velocity variations of the CM and thus explaining for the observed invariance of the IVV in the present study.

In addition, IdC showed to be inversely related to η_T in the first lap, meaning that an increase in IdC is associated with a decrease in η_T, in the beginning of the 200 m effort. Such results are understandable since the IdC is strongly related with the SF (11, 23), implying that IdC increased concomitant with SF. This is associated with lower average propulsion per stroke while the time averaged propulsion remains the same (3). It could be speculated that the reduced capacity to generate effective propulsion per stroke is compensated by higher hand speeds while 'slip' occurs, and, consequently, the stroke length will reduce. This fact would explain why stroke length is considered as an indicator of propulsive efficiency (18, 33) hence, during the last lap the $\eta_{\square}$ is expected to decrease, as it does. This suggestion is further supported by the observation that IdC simultaneously increases with a decrease of η_T, which is in line with the

fact that an increase in IdC (2, 17) is associated with a decrease in η_T (18, 35) in fatigued conditions. In the between subject correlation, it was found that the swimmers with higher IdC have higher C that also reflects a lower η_T, which might reflect that the preferred coordination mode of each swimmer is influenced by several constraints (22, 29, 32), particularly the type of training (30).

Conclusion

This study highlighted the changes in motor organization during a 200 m effort conducted at self-selected race pace. It appears that irrespective the speed changes along the effort, IVV was maintained at a constant level. It is suggested that IVV may be coupled to visual feedback providing cues for keeping it constant, which will have an energy efficiency boosting effect. It was also evidenced that the relationship between the studied variables is highly dependent on fatigue evolvement.

Acknowledgments

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Chapter 9

Upper and lower limbs muscular fatigue during the 200 m front crawl

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Abstract

The aim of this study was to investigate how upper and lower limbs muscle fatigue evolves in the 200 m front crawl swimming race. Surface electromyographic signals (EMG) were collected from the flexor carpi radialis, bicpes brachii, triceps brachii, pectoralis major, upper trapezius, tibialis anterior, biceps femoris, and rectus femoris muscles of ten international level swimmers; four underwater cameras were used for kinematical analysis. In addition, capillary blood samples were collected before and after the test. Swimming speed and stroke length decreased from the beginning to the end of the effort, whereas stroke frequency increased after an initial decrease to maintain speed, as this was correlated to the SF decrease ($R = 0.70$, $P < 0.05$). Concomitant with the decrease in speed, the blood lactate increased to 11.12 (1.65) $mmol.L^{-1}$. EMG amplitude of the flexor carpi radialis, bicpes brachii, triceps brachii, upper trapezius, and tibialis anterior increased by 20 - 25%, as well as the spectral indices (decrease of frequency spectrum) by 40 - 60%, presenting evidence of sub-maximal fatigue. Lower limb muscles (biceps femoris and rectus femoris) did not presented signals of fatigue, showing a lower stimulus than the upper limbs muscles. It was concluded that the 200 m front crawl event induced significant fatigue in the upper limbs, and that fatigue phenomena evolves differently in each muscle studied.

Key words: Swimming, Fatigue, EMG, Amplitude, Frequency

Introduction

Fatigue has received attention in sports sciences mainly due to its effects on athletes' performance, where several models have been presented to explain the fatigue process during exercise, as the neuromuscular model (Abbiss and Laursen 2005). Fatigue refers to an "acute impairment of performance that includes both an increase in the perceived effort necessary to exert a desired force and an eventual inability to produce this force" (Enoka and Stuart 1992). The cause of fatigue appear to be multifactorial, due to the impairment of several sites or processes (Enoka and Duchateau 2008), and is related to the characteristics of the exercise or tasks (Enoka 1995; Gandevia et al. 1995). During tasks with sustained maximal contraction, the decline in performance is concomitant with the increase in fatigue. For sub-maximal contraction tasks, the onset of fatigue is probably not associated with its end (Enoka and Duchateau 2008), and the target force can still be maintained (Sogaard et al. 2006). To better evaluate the fatigue process, continuous monitoring of muscle activity allow obtaining amplitude and frequency responses of the electromyographic signal (EMG) (Dimitrov et al. 2006; Lowery and O'Malley 2003; Masuda et al. 1999; Merletti et al. 1990). In this way, fatigue for sub-maximal contraction could be reflected by an increase of the amplitude EMG signal and a decrease of frequency spectrum (Enoka and Duchateau 2008). Whereas, for maximal contraction, a decrease both in amplitude EMG signal and frequency spectrum are reported (Taylor and Gandevia 2008).

In competitive swimming, fatigue has been studied by analysing different kinematic and physiological parameters. For example, during 200 m maximal front crawl swimming, the anaerobic metabolism is highly stimulated (Figueiredo et al. 2011b), causing high lactate concentration in blood (Capelli et al. 1998; Vescovi et al. 2011) and having an impact in the appearance of fatigue (Allen et al. 2008). The evidence of fatigue was shown by the decrease of isometric and tethered forces measured before and after four 50 m bouts simulating the 200 m front crawl (Aujouannet et al. 2006), and by the decrease in hand speed and arm stroke propelling efficiency during the 200 m front crawl (Figueiredo et al.

2011b). Concomitantly, changes in stroke length and stroke frequency occurred to maintain speed along the 200 m front crawl event (Alberty et al. 2005; Craig et al. 1985; Psycharakis and Sanders 2008), and the relative duration of the non-propulsive phases within a stroke is reduced with respect to the propulsive phases in the last laps of the 200 m, reflecting a change in inter-arm coordination (Alberty et al. 2005; Figueiredo et al. 2010).

However, regarding EMG, swimming fatigue literature is scarce. In the amplitude domain some, studies presented an increase in the muscular activity regarding fatigue (Monteil et al. 1993; Rouard et al. 1997; Wakayoshi et al. 1994). In the frequency domain, Aujouannet et al. (2006) and Caty et al. (2006) reported a decrease in the frequency analysis of EMG of upper limb muscles, both for isometric contraction done before, during and after a 200 m front crawl test. Recently, Stirn et al. (2011) evaluated muscle fatigue with amplitude and frequency analysis in upper body muscles (pectoralis major, latissimus dorsi and triceps brachii) during 100 m all-out front crawl, having the mean power frequency of all muscles significantly decreased by 20–25%, and EMG amplitude of the triceps and the lower part of the latissimus muscles increased. No study concerned lower limb muscles.

In most of humans' activities, like walking and running, arms do not contribute to propulsion, but to the stabilisation of the trunk (Wannier et al. 2001). In opposition, in front crawl swimming 85% of propulsion is due to the upper limbs (Deschodt et al. 1999; Hollander et al. 1988); in fact, in swimming, lower limbs present a lower propelling efficiency (Pendergast et al. 2003; Zamparo et al. 2002), acting mostly as stabilizers in spite of the great muscle mass involved, which might be important to consider in swimming fatigue assessment. The aim of this study was to investigate how muscle fatigue evolves in the 200 m front crawl swimming by means of the amplitude and frequency analysis regarding the involvement of different muscles of upper and lower limbs. We hypothesized an increase in amplitude signal and a decrease in spectral parameters resulting of repetitive sub-maximal contractions, which evolves in a non-linear process of fatigue occurring differently for the upper and lower body muscles. More, we hypothesized that changes in muscular recruitments are related to the

involvement of the muscles during the swimming cycle, especially in regard to the contribution of the upper and lower limbs muscles to the propulsion.

Methods

Subjects

This study was performed on ten highly trained male front crawl specialists. Their characteristics (average (SD)) were 21.6. (2.4) yr of age, 1.85 (0.07) m of height, 1.89 (0.08) m of arm span, 76.4 (6.1) kg of body mass, and 10.1 (1.8) % of adipose tissue. Swimmers had 11.9 (3.5) yr of competitive experience and an average performance in the 200 m front crawl swim of 109.2 (2.3) s corresponding to an average speed representing 91.6 (2.1)% of the short course pool men world record. All subjects were informed about the methods and aims of the study, and gave their written consent as approved by the local ethics committee and in accordance with the Declaration of Helsinki (2000). Measurements were carried out in the competitive period of the training season with no stressful training during the days before the test.

Experimental design

On the testing day, each swimmer performed an individual warm-up (1000 m), as in competition, which consisted of low to moderate intensity swimming. Following the warm-up, swimmers performed a 200 m front crawl at maximum intensity, as in competition. At the end of the test, blood lactate accumulation was measured. Due to the measurement equipment that was attached to the swimmers, it was used push-off starts and open turns. All tests were conducted in a 25 m and 27.5ºC indoor pool.

Data collection

Four underwater stationary and synchronized digital video cameras (Sony® DCR-HC42E, Tokyo, Japan) were used to record swimmer's movement during the 200 m front crawl swimming. The video analysis of the swimming cycles were digitized manually and frame by frame (50 Hz) (Ariel Performance

Analysis System, Ariel Dynamics Inc., USA). The digitization from the four cameras was reconstructed with the help of a calibration volume (3 x 2 x 3 m, and 20 calibration points) and the DLT algorithm (Abdel-Aziz and Karara 1971). Kinematic data was filter with a cut-off frequency of 6 Hz. The accuracy and reliability of coordinate reconstruction were in general similar to or better than other studies that used similar calibration volumes (Figueiredo et al. 2011a).

Before and after the test, capillary blood samples (5µl) were collected from the ear lobe to assess rest and post exercise blood lactate concentrations by means of a portable lactate analyzer (Lactate Pro, Arkray, Inc., Kyoto, Japan). Blood lactate was measured at 1, 3, 5, and 7 min post-test, and the peak value was used for further analysis in order to evaluate a physiological marker of exercise intensity.

For EMG data collection, muscles were selected according to their main function, anatomic localisation and literature results: flexor carpi radialis (FCR), biceps brachii (BB), triceps brachii (TB) pectoralis major (PM), upper trapezius (UT), rectus femoris (RF), biceps femoris (BF) and tibialis anterior (TA) muscles (Clarys and Cabri 1993; Stirn et al. 2011). The skin of the swimmer was shaved and rubbed with an alcohol solution. Recording of the muscle activity was unilateral using disposable Ag–AgCl circular surface electrodes, with preamplifiers (AD 621 BN) placed in a bipolar configuration with 2.0 cm of inter-electrodes distance, in line with the muscle's fibre orientation. Electrodes were placed in the midpoint of the contracted muscle belly as suggested by Clarys and Cabri (1993), and covered with an adhesive bandage (Opsite Flexifix) to avoid contact with water (de Jesus et al. 2011; Rouard and Clarys 1995). A reference electrode was attached to the skin surface of the patella. All cables were fixed to the skin by adhesive tape to minimise the perturbation of the natural movement and interference with the signal. Additionally, swimmers wore a complete swimsuit (Fastskin, Speedo). The total gain of the amplifier was set at 1100 with a common mode rejection ratio of 110 dB. The data were sampled at 1000 Hz with a 16-bit analog to digital conversion (BIOPAC System, Inc., Santa Barbara, USA), being stored on computer for later analysis. To

synchronise EMG and video, an electronic flashlight signal / electronic trigger was marked simultaneously on the video and EMG recordings.

Data treatment

Kinematic and Physiological Analysis

The swimming cycle was defined as the time during two consecutive right hand entries. Stroke frequency (SF) was assessed through the inverse of stroke duration (obtained from the number of frames), and the stroke cycle (SL) was assessed from the horizontal displacement of the hip during a stroke cycle. Average speed was calculated by multiplying SL by SF. In addition, the difference between the beginning and the end of the effort was computed for the speed, SF, SL and blood lactate concentrations (ΔSpeed, ΔSF, ΔSL, and ΔLa^-, respectively).

EMG Amplitude Analysis

The EMG data analysis was performed using the MATLAB 2008a software environment (MathWorks Inc., Natick, Massachusetts, USA). For the amplitude analysis, raw EMG's were band-passed (8-500 Hz), rectified to obtain the full wave signals, and smoothed with a 4^{th} order Butterworth filter (10 Hz) for the linear envelope. The integration of the rectified EMG was calculated for each stroke and reported per unit of time, to eliminate the stoke cycle duration effect (iEMG/T). The signal was partitioned in 40 ms windows to found the maximal iEMG value (iEMGmax). To normalise the results, iEMG/T was expressed as a percentage of iEMGmax (Caty et al. 2007).

EMG Frequency Analysis

For the frequency analysis, spectral indices were calculated (Dimitrov et al. 2006). These spectral indices have showed to be most accurate in detecting changes in muscle power during dynamic contractions (Gonzalez-Izal et al. 2010), and were proposed to overcome the relatively low sensitivity of the median frequency and the mean frequency not adapted to dynamical contractions. These indices were assessed as in the following equation:

$$FI = \frac{\int_{f1}^{f2} f^{-1} \cdot PS(f) \cdot df}{\int_{f1}^{f2} f^{k} \cdot PS(f) \cdot df} \quad (1)$$

where k was 5, PS(f) was the spectral power for the currency frequency f, and f1 = 8 Hz and f2 = 500 Hz (the high and low-pass frequencies of the amplifier filter).

Spectral moment of order -1 emphasise the increase in low and ultra-low frequencies in the EMG spectrum, attributable to the increase of negative after-potentials, expressing muscular fatigue, and the signal spectral moment of order 5 emphasise the effect of decreases in the high frequencies, attributable to the increased duration of the intracellular action potentials, and the decreased action potential propagation velocity (Dimitrov et al. 2006). The FI indicates fatigue as it increases, representing frequency decrease.

Frequency and amplitude parameters were obtained for each stroke cycle, defined by video analysis, of the 200 m in the mid-section of the swimming pool and then averaged for each of the eight 25 m lap that composed the 200 m. To analyse the changes from the beginning to the end of the effort, a normalization of the results between subjects was done: all the values (FI or iEMG) were expressed as a percentage of the initial values.

Statistical Analysis

Average (SD) computations for descriptive analysis were obtained for all variables (normal Gaussian distribution of the data was verified by the Shapiro–Wilk's test and sphericity checked using the Mauchley test (Winter et al. 2001). A one-way repeated measures ANOVA was used to compare the analysis of the kinematical and EMG parameters along the 200 m for the eight 25 m laps. When a significant F-value was achieved, Bonferroni post hoc procedures were performed to locate the pairwise differences between the means. Statistical analysis was performed using STATA 10.1 (StataCorp LP, Lakeway, USA), and the level of significance set at 0.05. Effect size was computed with Cohen's *d* and Cohen's *f* for t-test and repeated measures ANOVA, respectively. The

effect size was considered small if $0 \leq |d| \leq 0.2$ or $0 \leq |f| \leq 0.1$, medium if $0.2 < |d| \leq 0.5$ or $0.1 < |f| \leq 0.25$, and large if $|d| > 0.5$ or $|f| > 0.25$ (Cohen 1988).

Results

Figure 1 shows the mean (SD) values of the kinematic parameters for each 25 m lap of the 200 m front crawl. Swimming speed decreased from 1.58 (0.08) to 1.43 (0.11) $m.s^{-1}$ with significant differences from the first two laps to the other laps ($F_{7,63} = 9.76$, $P < 0.001$, $f = 0.81$). SL remained constant for the first five laps, whereas a significant SL decrease was observed in the seven and eight laps (2.31 m to 2.17 m; $F_{7,63} = 3.72$, $P = 0.002$, $f = 0.31$). SF only presented differences between lap 1 and laps 3, 4, 5 and 6 ($F_{7,63} = 4.57$, $P < 0.001$, $f = 0.38$). The speed decrease was correlated to the SF decrease and not to SL (Table 1). Concomitant with the decrease in swimming speed, the blood lactate increased from the rest to the post blood lactate peak of the 200 m front crawl from 1.07 (0.21) to 11.12 (1.65) $mmol.L^{-1}$ ($t = -21.27$, $P < 0.001$, $d = -9.01$). The increase of the blood lactate was not associated with any of the changes occurred in the kinematical measures (ΔSpeed, ΔSL, ΔSF).

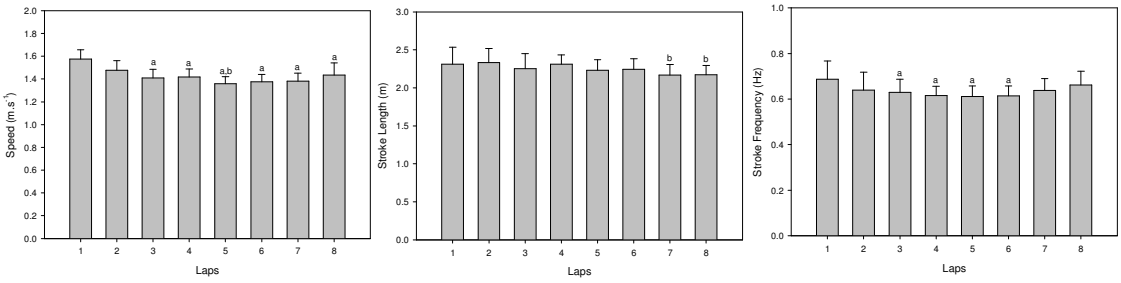


Figure 1. Average (SD) of swimming speed (left panel), stroke length (middle panel), and stroke frequency (right panel) for the eight 25 m laps of a 200 m front crawl. [a,b] Statistically different from the Lap 1 and 2, respectively. $P < 0.05$.

Table 1. Correlation matrix between the changes of speed (ΔSpeed), stroke length (ΔSL), stroke frequency (ΔSF), and blood lactate (ΔLa) from the beginning to the end of the 200 m front crawl.

	ΔSpeed	ΔSL	ΔSF	ΔLa
ΔSpeed	-			
ΔSL	0.10	-		
ΔSF	0.70*	-0.63*	-	
ΔLa	-0.05	0.20	-0.17	-

*P<0.05

EMG results indicated significant increases of both amplitude and frequency parameters for the FCR, BB, TB, UT and TA; and a increase in frequency parameters without changes in amplitude for the PM, BF and RF (Figure 2).

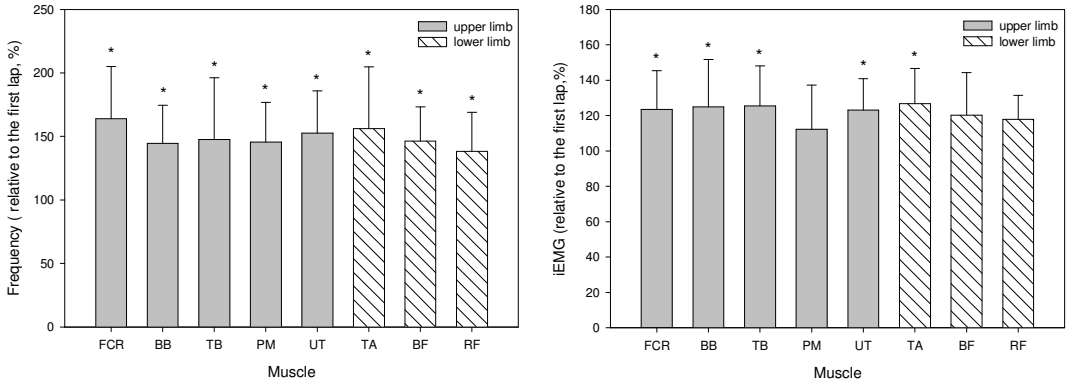


Figure 2. Average (SD) frequency (left panel) and amplitude (right panel) ratio between the last 25 m and the first 25 m lap values. *P < 0.05.

To observe the progress of fatigue on the studied muscles, the changes of the iEMG and the FI were analysed across the eight 25 m laps of the 200 m front crawl (Figure 3). In addition, as some muscles (TB and TA) did not present the expected differences in the iEMG, as showed between the beginning and end of the effort, correlation coefficients were computed between those muscles iEMG and the 200 m's laps. TB and TA showed a direct relationship with the laps (R = 0.78 and R = 0.70, P < 0.05, respectively), indicating an increase of the amplitude parameters over the effort, as showed in Figure 2.

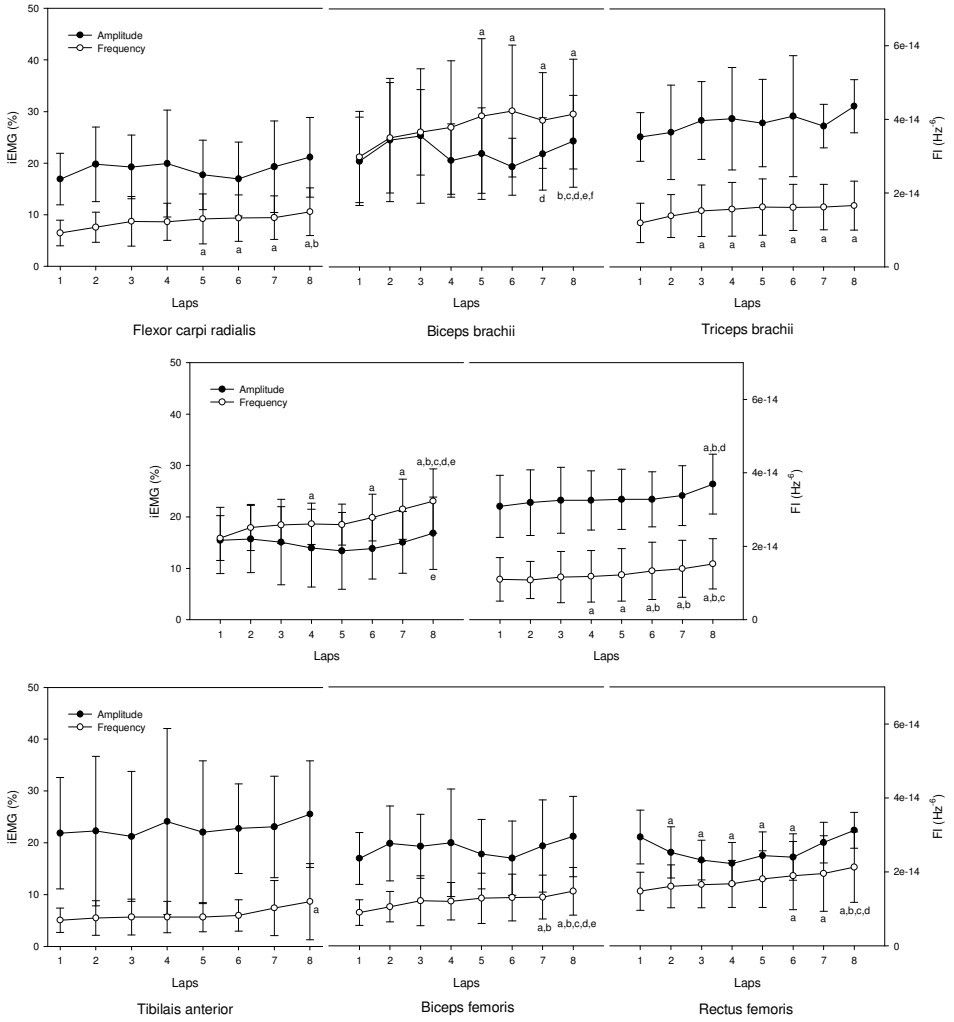


Figure 3. Average (SD) amplitude and frequency EMG parameters for upper body (upper and middle panel) and lower body (lower panel) muscles in eight 25 m laps of a 200 m front crawl. [a,b,c,d,e] Statistically different from the Lap 1, 2, 3, 4 and 5, respectively. $P < 0.05$.

Globally, results indicated that changes during the 200 m effort affected more the frequency (FI) than the amplitude (iEMG) results, and that it was possible to distinguish several pattern of changes during the 200 m, linear increase or decrease for the medium laps following by an increase. To analyse the inter-individual variations of fatigue, coefficient of variation (SD / mean) was computed for each lap and each muscle (Figure 4), and correlation coefficients between the coefficient of variation and the laps were established to understand their tendency across the 200 m (Table 2). It seems that the inter-individual differences remained similar from one muscles to another with similar values for FI and iEMG and from one lap to another, with the exception of the UT and RF,

with regular increase of the coefficient of variation of the FI and decrease of iEMG among the laps.

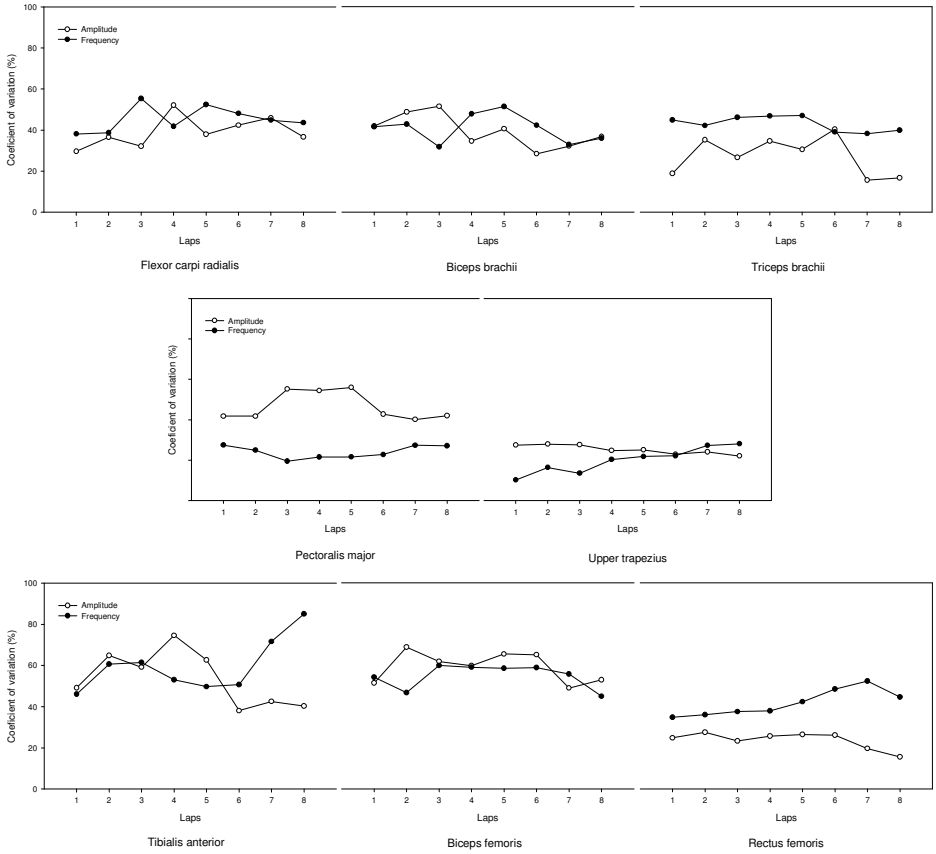


Figure 4. Inter-individual variations (coefficient of variation) for amplitude and frequency EMG parameters in front crawl among the 8 laps of the 200 m front crawl for upper body (upper and middle panel) and lower body (lower panel).

Table 2. Correlation coefficients between coefficient of variation for amplitude and frequency EMG parameters and the laps across the 200m front crawl.

	FCR	BB	TB	PM	UT	TA	BF	RF
Frequency	0.27	-0.23	-0.60	0.18	0.96*	0.65	-0.12	0.86*
Amplitude	0.45	-0.67	-0.23	-0.18	-0.92*	-0.54	-0.29	-0.68

FCR: flexor carpi radialis, BB: biceps brachii, TB: triceps brachii, PM: pectoralis major, UT: upper trapezius, RF: rectus femoris, BF: biceps femoris, and TA: tibialis anterior. *P < 0.05.

To complete muscle fatigue analysis, a correlation between frequency and amplitude parameters (FI and iEMG) of the studied muscles with the kinematical variables (speed, SL and SF) was computed (Table 3). Numerous negative correlations were obtained for FI with speed, SL and SF; in fact, SL

was inversely related to FI for all muscles. In addition, the upper limb muscles that presented muscle fatigue (FCR, BB, TB, UT) were inversely related to speed, meaning that at higher speeds a higher muscle firing rate was achieved; SF was only correlated to BB and TB frequency parameters. Few correlations were obtained between iEMG and stroke parameters, being speed not related with iEMG; the muscles that did not presented fatigue (PM, RF and BF) had a direct relationship with the SF, and SL was only negatively correlated with amplitude of UT.

Table 3. Correlation coefficients between muscle frequency and amplitude with kinematical variables, speed, stroke length (SL) and stroke frequency (SF).

	Frequency			Amplitude		
Muscles	Speed	SL	SF	Speed	SL	SF
FCR	-0.78*	-0.83*	-0.41	-0.11	-0.24	0.03
BB	-0.89*	-0.70*	-0.64*	0.02	-0.13	0.13
TB	-0.91*	-0.73*	-0.64*	-0.57	-0.58	-0.32
PM	-0.55	-0.85*	-0.12	0.52	-0.17	0.76*
UT	-0.76*	-0.82*	-0.40	-0.38	-0.79*	0.05
TA	-0.31	-0.83*	0.17	-0.11	-0.44	0.14
BF	-0.47	-0.89*	0.01	0.53	-0.29	0.84*
RF	-0.62	-0.89*	-0.18	0.49	-0.41	0.87*

FCR: flexor carpi radialis, BB: biceps brachii, TB: triceps brachii, PM: pectoralis major, UT: upper trapezius, RF: rectus femoris, BF: biceps femoris, and TA: tibialis anterior. *$P < 0.05$.

Discussion

The aim of this study was to investigate how muscle fatigue evolves in the 200 m front crawl maximal swimming by means of the amplitude and frequency analysis of the involvement of different upper and lower limbs muscles. The high blood lactate concentrations, the decrease of swimming speed, and the changes in SL and SF confirmed the reaching of fatigue at the end of the 200 m effort. The post-exercise blood lactate concentration was similar to previous studies (Capelli et al. 1998; Pelayo et al. 1996; Vescovi et al. 2011), confirming that the 200 m is one of the competitive events with significant anaerobic contribution. The observed decreases of speed and SL, and SF, changes were in accordance to previous results (Alberty et al. 2005; Craig et al. 1985;

Psycharakis and Sanders 2008). The negative relationship between ΔSL and ΔSF refelected the swimmers strategy to maintain the speed (Alberty et al. 2008; Alberty et al. 2005; Craig et al. 1985). The correlations between speed and SF decreases confirmed Termin and Pendergast (2000) results, reveling that SF is the first determinant of motor organization in swimming (Seifert et al. 2007; Alberty et al. 2008).

The reaching of fatigue by the kinematic and physiological parameters was associated to changes in the muscular activation. The comparison between the beginning and the end of the 200 m indicated increases of iEMG and FI (frequency spectrum decrease) for the upper limb muscles (FCR, BB, TB and UT) and only for TA lower limb muscle, confirming the greater involvement of the upper limbs muscles regarding the lower limb ones. These results suggested that in spite of swimming at maximum effort, the muscles under observation were involved at a sub-maximum level. The increase of iEMG was already observed in other kind of maximal swimming efforts: i) 400 yards for the external rotators and internal rotators muscles (Monteil et al. 1993); ii) swimming at a speed of 1.3 and 1.4 ms^{-1} up to exhaustion for the deltoideus (Wakayoshi et al. 1994); iii) test of 4x100 m at 85% of the 100 m front crawl best performance for the flexor carpi ulnaris muscle considering the whole stroke cycle, and for the triceps brachii in the insweep and outsweep phases (Rouard et al. 1997); and, iv) more recently, by Stirn et al (2011), in a 100 m all-out front crawl for the triceps brachii and latissimus dorsi muscles. Similar results were observed in other sports activities such as cycling (Housh et al. 2000; Watanabe et al. 2009) and running (Kellis and Liassou 2009; Patras et al. 2009). Most of these studies interpreted the increase in the EMG activity amplitude as a sign of neuromuscular fatigue due to decreased muscle fiber propagation velocity, increased motor unit firing rate, increased motor units recruitment and increased motor units synchronization (Gandevia 2001; Lowery and O'Malley 2003).

More, the increase of iEMG among the 200 m test is different from one muscle to another indicating different kind of reaching of fatigue. For example, the TB and TA muscles present a constant increase of amplitude towards the end of

the effort as fatigue is reached. Other muscles (e.g. BB) were characterized by a broken process with an increase of iEMG and a decrease of frequency only ate the end of the 200 m.

The reaching of fatigue at the end of the 200 m front crawl was also associated to a decrease of the frequency spectrum (increase of the FI) for all the muscles studied, as previously shown for dynamic fatiguing contractions (Dimitrov et al. 2006; Gonzalez-Izal et al. 2010; Mileva et al. 2009). The shift of the spectrum toward the lower frequencies could be associated to changes in the action potential duration and afterpotential magnitude (Dimitrova and Dimitrov 2003), to motor unit recruitment (Gazzoni et al. 2004), to short-term motor unit synchronization (Farina et al. 2002), to muscle characteristics, like percentage of fast-twitch fibers that have been shown to fatigue more rapidly than muscles with a greater percentage of slow-twitch fibers (Morris et al. 2010) conducting to a decrease in muscle fiber conduction velocity (Farina et al. 2004; Lowery et al. 2002; Merletti et al. 1990), and more type 1 fibers (fatigue resistant) being recruited in order to maintain force production (De Luca 1997). The decrease in muscle fiber conduction velocity is, then, due to an accumulation of metabolic products such as lactic acid, which reduces intracellular pH and decreases the excitability of the muscle fiber membrane (Allen et al. 2008; Masuda et al. 1999). Although pH was not directly measured during our test, the high maximal blood lactate values collected after the 200 m test implyed a noteworthy pH decrease, which could contribute to the decrease of frequency contents of the studied muscles (Linssen et al. 1996). In spite of all these facts, the changes in frequency were similar in all muscles, as also found by Stirn et al. (2011), but with a higher range, which could be due to higher duration of the effort (about the double) in the current study. The highest change in frequency for FCR could be related to their important role in maintaining the stability of the wrist during the whole swimming cycle (Caty et al. 2007).

The associated iEMG and FI increases was observed for upper limb muscles with fatigue reflecting the sub-maximal level of contractions of the studied muscles. Past research showed that forces generated by the upper limbs during swimming do not represent the muscular maximum load. Swaine (2000)

reported maximal mean peak power output values of 304 (22) W and mean power output during 30 s of 260 (55) W in simulated arm swimming, whilst in 100 m front crawl swimming arms only, Toussaint et al. (2006) reported average values of 170.7 (21.8) W. Additionally, Morouço et al. (2011) found a maximal peak of 232.6 (63.2) N and average of 92.8 (33.7) N in 30 s tethered swimming, corresponding to 445.6 (121.3) W and 178.2 (64.70) W (respectively), assuming the reported speed for 50 m of 1.92 $m.s^{-1}$, where this late was highly correlated to the speed of the 200 m front crawl event (R = -0.82), and Caty et al. (2007), in semi-tethered swimming, found an average power of 68.84 (11.88) W for a 25 m sprint. In this way, forces produced during front crawl can be roughly estimated as sub-maximal.

The increase of FI with a stable iEMG for the lower limb muscles (RF and BF) reflected its lower involvement along the 200 m distance. This lower activity, comparing to other upper body muscles (TB and BB), was already found in front crawl sprint (Bollens et al. 1988; Cabri et al. 1988), and reflects its lower contribution in the swimming propulsion. Zamparo et al. (2002) noted that 117.1 (10.9) W of total power is required to swim at 1 $m.s^{-1}$ just with leg-kick, whereas during maximal whole body swimming only 14.6 W are due to the lower limbs (Hollander et al. 1988); in fact, only about 10% of propulsion seems to be due to the kick (Deschodt et al. 1999). Additionally, lower limbs have a higher energy cost comparing to the upper limbs and whole body swimming, evidencing a lower propulsive efficiency (Pendergast et al. 2003; Zamparo et al. 2005; Zamparo et al. 2002). However, the lower limbs can sustain greater power output than the upper limbs during simulated swimming and a lower decline of the power output in an all-out 30 s test than the upper limbs (Swaine 2000). All these facts converge to the idea that the lower limbs have a lower activity (stimulus) during swimming the whole front crawl stroke than the upper limbs (Bollens et al. 1988; Cabri et al. 1988; Clarys 1985) and are more able to sustain effort, i.e., to be less fatigable.

The contribution of the muscular activation to the stroke parameters appeared different for the upper and lower limb muscles. Results indicated that stroke parameters are strongly negatively related to FI and few related to iEMG. The

upper body muscles that presented sub-maximal fatigue (FCR, TB, BB, UT) also presented a negative relationship of FI with the swimming speed. These correlations reflected that lower speeds corresponded to lower muscle firing rate. The inverse relationship between FI and SL observed for all muscles could reflect that the applied sub-maximal swimming forces required lower firing muscle frequencies with higher participation of the fibers type I. Only PM, RF, BF presented a positive relationship of the iEMG with SF, indicating that higher SF resulted in higher iEMG, as previously found by Cabri et al. (1988). In cycling, Thomas et al. (2010) concluded that fatigue was associated to pedaling rate rather than pedal speed, increasing muscle shortening speed. This finding supported the notion that the time available for muscle excitation and relaxation kinetics is a major contributor to fatigue, justifying why swimmers preferred to swim front crawl at the lowest SF (or the longest SL), which do not require an increase in oxygen uptake (McLean et al. 2010).

Lastly, it seems that the inter-individual differences remained similar, or at least without a clear tendency to increase or decrease, for all the studied muscles, both for amplitude and frequency analysis. An exception was the UT that for amplitude and frequency analysis, where it was observed small, however constant changes, which revealed a decrease and increase, respectively, for the amplitude and frequency. This seems to be due to the constant arm stroke phase recovery that occurs above water, and therefore the load exerted on the muscle is more similar in each arm stroke, revealing this linear tendency along the effort and a higher similarity between subjects. The changes in the inter-individual differences over the effort could be due to changes in the pace of each swimmer, and/or to differences in technique, which may imply a higher recruitment of some muscles and would have influence in the amplitude and frequency analysis.

Conclusion

In summary, the changes observed in the kinematic (speed, SL and SF) and physiological parameters (La^-) confirmed the presence of muscular fatigue after

the maximal 200 m front crawl. Additionally, the changes of amplitude and frequency EMG parameters (iEMG and FI) were concomitant with the kinematic and physiological assessed parameters, in agreement with the detected fatigue appearance in upper limbs. It was not detected fatigue lower limbs, as the contribution to the propulsion is lower, and so is the stimulus. Notwithstanding the results obtained, changes in EMG signal amplitude and frequency could not be attributed solely to fatigue process, which suggest that fatigue in swimming in the severe intensity domain should be further investigated controlling some of the kinematic variables.

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Chapter 10

Biophysical Analysis of the 200 m Front Crawl Swimming: a Case Study.

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Abstract

The performance of one swimmer during 200 m front crawl swim was analysed, integrating coordinative, biomechanical, electrophysiological and bioenergetical data. A male swimmer (participant at the 2008 Olympic Games and national record holder) swam 200 m for the assessment of the intracyclic velocity variation (IVV) in x, y and z axes, arm coordination, oxygen uptake and neuromuscular activity. Afterwards, the swimmer performed 50, 100 and 150 m at the 200 m pace for blood lactate kinetics analysis. This study highlighted the stability of the IVVx, continuity of arm coordination in the last 100 m, as the electromyographic data evidenced a significant fatigue involvement. Moreover, oxygen consumption rate values decreased as blood lactate concentrations rate and absolute values increased along the effort.

Key words: EMG, Intracyclic velocity variation, Arm coordination, Energy expenditure, Biophysics.

Introduction

Propulsive and drag forces acting on the swimmer's body are major performance determinants, being affected by technique, motor organisation and control. However, the muscular activity, as well as the energy expenditure of exercise, are also swimming influencing parameters (Clarys and Cabri, 1993; Fernandes et al., 2006). In this sense, to understand the real involvement of the above parameters in swimming, a biophysical approach is needed (Pendergast et al., 2006), combining data from different areas. The 200m front crawl is dependent on both anaerobic and aerobic energy systems, implying higher levels of fatigue (Costill et al., 1992). However, the interactions between the performance influencing factors in this specific event were not yet discussed. The aim of the present study was to analyse the 200m front crawl maximal effort, performed by an elite Olympic swimmer, assessing the intracyclic velocity variation of the centre of mass, arm coordination, energy expenditure and neuromuscular activity.

Methods

A male swimmer, 2008 Olympic Games participant and 200 m front crawl national record holder (21 years old, 71 kg of body mass, 180 cm of height, 182 cm of arm span and 8.8% of body fat mass) volunteered to participate in the present study. The test session took place in a 25 m indoor swimming pool.

Briefly, the subject, after a moderate intensity individual warm-up, performed a 200m font crawl test at maximal intensity (as in competition), with push in-water start. The swimmer was monitored when passing through a specific pre-calibrated space with dimensions of 3 x 2 x 3m for the horizontal (x), vertical (y) and lateral (z) directions. Thirty points of calibration were used, and the synchronisation of the images was obtained using a pair of lights observable in the field of view of each one of the six video cameras (Sony® DCR-HC42E). The angle between the optical axes of the two surface cameras was approximately 120º, while the angles between the optical axes of adjacent

underwater cameras varied from 75º to 110º. Two complete arm stroke cycles, without breathing, for each 50m of the 200m front crawl were digitised using the APASystem (Ariel Dynamics, USA) at a frequency of 50 Hz, manually and frame by frame. Zatsiorsky and Seluyanov's model, adapted by de Leva (1996) was used. Twenty one body landmarks were digitised in each frame to represent the endpoints of the head, torso, upper arms, forearms, hands, thighs, shanks and feet. Direct Linear Transformation algorithm was used for three-dimensional reconstruction, as well as a 6 Hz low pass digital filter for the smoothing of the data. The velocity (v) was calculated by dividing the displacement of centre of mass (CM) in one stroke cycle for its total duration. Additionally, stroke rate (SR) was assessed through the inverse of its time duration, and stroke length (SL) was determined through the horizontal displacement of the CM during a stroke cycle.

To analyse the intracyclic velocity variation (IVV) for the x, y and z axes of the CM, was calculated through the coefficient of variation of the $v_{(t)}$ distribution.

Arm movement was broken into four phases (entry/catch, pull, push and recovery) (Chollet et al., 2000), using the above referred digitised model. The duration of the propulsive phase was considered to be the sum of the pull and push phases, and the duration of the non-propulsive phase the sum of the entry/catch and recovery phases. Arm coordination was quantified using the Index of Coordination (IdC) proposed by Chollet et al. (2000), measuring the lag time between the propulsive phase. The IdC was calculated for two complete arm strokes per 50m, and expressed as a percentage of complete arm stroke duration.

For the total energy expenditure (Ė) assessment, oxygen uptake (VO_2) was recorded breath-by-breath by the K4b² telemetric gas exchange system (Cosmed, Roma, Italy), during the 200 m front crawl exercise. Artefacts were manually eliminated and data were averaged every 5 s (cf. Sousa et al., in press). After 90 min of rest interval, the swimmer performed a 50 m front crawl test to assess blood lactate concentration [La^-], at the same swimming v as the previous 200m (controlled by a visual light pacer - TAR 1.1, GBK-Electronics, Aveiro, Portugal - with a flash every 5 m). Twenty-four h later, the swimmer

performed 150 m and 100 m, with 90 min interval between tests, in order to simulate as much as possible the 200m test conditions, also using a respiratory snorkel and valve system. Capillary blood samples (5 µl) were collected from the ear lobe, at rest, as well as at 1, 3, 5, and 7 min of recovery, to assess rest and post exercise [La^-] (Lactate Pro, Arkray, Inc.). It was ensured, by measuring, that swimmer had similar blood lactate concentration rest values prior to each test.

The $\dot{E}$ corrected for body mass was calculated using the VO_2 net (difference between the average value of each 50m length and the rest value), and the blood lactate net (difference between the value measured in two consecutive lengths), transformed into VO_2 equivalents using a 2.7 $mlO_2.kg^{-1}.mmol^{-1}$ constant (di Prampero et al., 1978). Anaerobic alactic energy sources were assumed to be negligible in this type of effort (Rodriguez and Mader 2003).

For the muscular analysis active differential surface EMG recordings were used of the flexor carpi radialis, biceps brachii, triceps brachii, pectoralis major, upper trapezius, rectus femoris, biceps femoris and tibialis anterior muscles during the 200 m front crawl. These muscles were selected according to their main function and anatomic localisation, being considered important in front crawl swimming (Figueiredo et al., 2009). The skin of the swimmer was shaved and rubbed with an alcohol solution. Silver / silver chloride circular surface electrodes, with preamplifiers (An AD621 BN), were placed in a bipolar configuration with 2.0 cm inter-electrodes distance, in line with the muscle's fibre orientation. Electrodes were placed in the midpoint of the contracted muscle belly as suggested by Clarys and Cabri (1993), and covered with an adhesive bandage (Opsite Flexifix) to avoid contact with water (Figueiredo et al., 2009). A reference electrode was attached to the patella. The total gain of the amplifier was set at 1100, with a common mode rejection ratio of 110 dB. Additionally, the swimmer used a complete swimsuit, in order to reduce the mobility of the electrodes and to increase the comfort of the swimmer, allowing normal motion.

The EMG signals were recorded at a sampling frequency of 1000 Hz with a 16-bit resolution and then converted by an analogical/digital converter (BIOPAC

System, Inc). To synchronise EMG and video, an electronic flashlight signal / electronic trigger was marked simultaneously on the video and EMG recordings. The EMG data analysis was performed using the MATLAB 2008a software environment (MathWorks Inc., Natick, Massachusetts, USA). A new highly sensitive spectral index (FInsmk), proposed by Dimitrov et al. (2006), was calculated for one stroke cycle for each 25m. The FInsmk has been proposed to overcome the relatively low sensitivity of the median frequency and the mean frequency. The FInsmk indices were calculated as the ratio between the spectral moments of order (-1) and order, k:

$$FI_{nsmk} = \frac{\int_{f1}^{f2} f^{-1} \cdot PS(f) \cdot df}{\int_{f1}^{f2} f^{k} \cdot PS(f) \cdot df} \quad (1)$$

where k was 5, PS(f) was the spectral power for the currency frequency f and f1 = 8 Hz and f2 = 500 Hz were the high and low-pass frequencies of the amplifier filter. The relative changes in values of the spectral index, for different repetitions were calculated against the first repetition of the corresponding set: for instance, FInnsmk/FI1nsmk x 100, % (n = 1, 2, ..., 8 lap number).
Linear regression analysis method was performed on muscle EMG parameters (laps 1–8). The regression line gradients were analysed to compare rate of change and, hence, rate of fatigue development. The overall acceptable level of significance of differences for all statistical tests was set at $p < 0.05$.

Results

In fig. 1 it is possible to observe the decay of v, SL and SR through the 200m front crawl with a slightly increasing of the SR in the last length.
Values for IVV (x, y and z) and coordinative organisation parameters (IdC and stroke phases) are presented in fig. 2 (left panel and right panel, respectively) for the four laps of the 200m front crawl test.

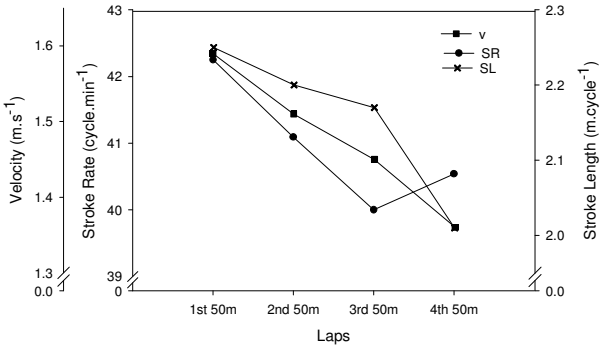


Figure 1. General biomechanical parameters (v, SL and SR) values during the 200m front crawl effort.

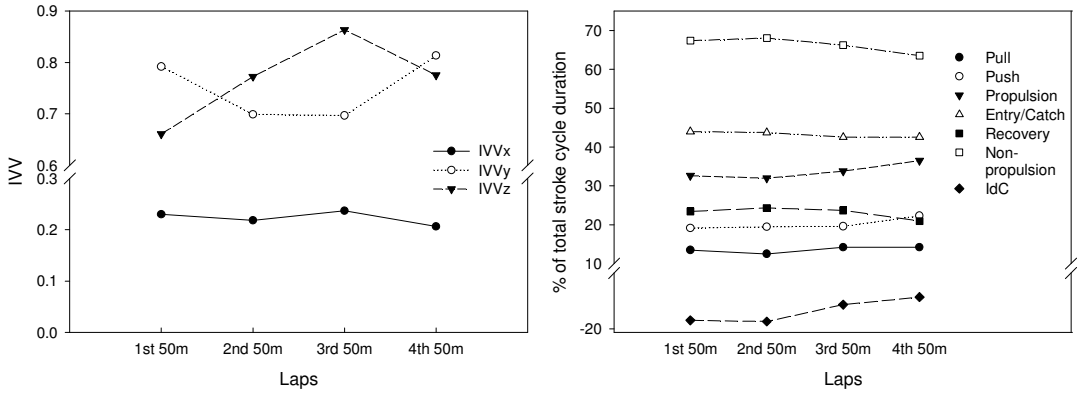


Figure 2. Values for intracyclic velocity variation (IVV) in x, y and z axes (left panel) and values of velocity (v), stroke rate (SR), stroke length (SL), index of coordination (IdC), entry/catch, pull, push, recovery, propulsive phase and non-propulsive phase in the four laps of the 200m front crawl.

The kinetics of bioenergetical parameters (Ė, VO_2 and $[La^-]$) and the spectral indices, revealing the muscular function during the 200m front crawl are shown in fig. 3 (left and right panel, respectively). For the spectral indices high relationships were observed ($r > 0.74$, $p < 0.05$), except for tibialis anterior ($r = -0.18$, $p = 0.67$).

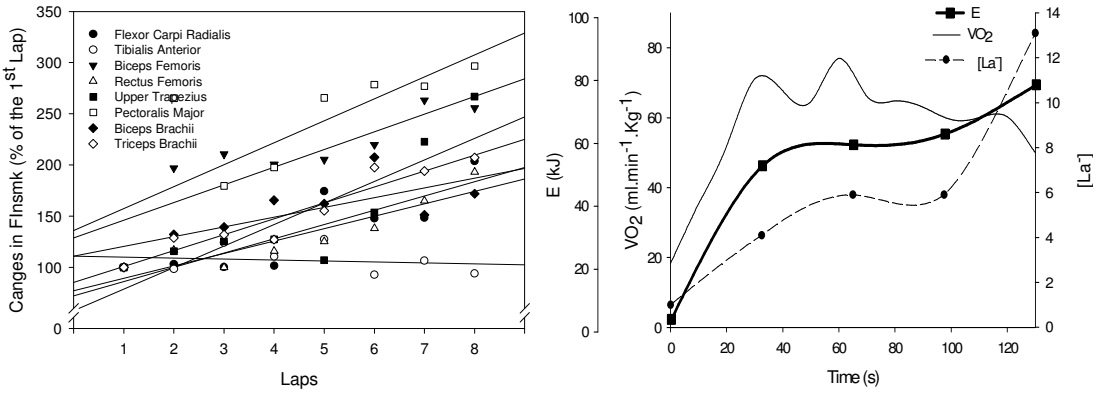


Figure 3. Ė, VO2 and [La-] kinetics during the 200m front crawl effort. The VO_2 figure was averaged every 10 s for graphical proposes (left panel) and linear regression analysis of the relative changes of spectral index FInsmk (right panel).

Discussion

The kinetics of the stroking parameters (SL and SR) along the 200 m are in agreement with the literature (Alberty et al., 2005). Moreover, the decrease of v along the test can be explained by different SR and SL combinations, as previously reported (Huot-Marchand, et al., 2005). The decrease of the SL values could be linked to the development of local muscular fatigue, reflecting a declining capacity to deliver power output. In addition, the swimmer tried to increase SR in order to compensate the SL decrease.

The observed stability of IVVx and the larger magnitudes of IVV found for y and z than in x axis, are in agreement with the literature (cf. Psycharakis et al., 2010). This IVVx stability suggests a coordinative adaptation of the upper limbs, as Figueiredo et al., (2009) reported no relationship between IVV and IdC in x, y and x axes during the 200 m front crawl effort. The coordinative adaptation pattern might be explained by the swimmer's inability to minimise the resistive force as the arm coordination change (increasing the values of IdC) manly in the last 50 m of the 200 m front crawl (Alberty et al., 2005; Figueiredo et al, in press), however IdC maintained in catch-up mode (< 0%) during the whole effort. This possibly reflects a longer duration of the stroke cycle propulsive phase and not necessarily higher force production, as the v and SL decreased in the last 50 m of the 200 m.

The Ė increased in the 1st 50 m, resulting from an exponential increase of the VO_2 kinetics at the beginning of exercise (cf. Fernandes et al., in press), reaching the VO_2 peak in the 2nd 50 m. In the 3rd lap the swimmer was not able to maintain the high VO_2 values, reducing the v, although maintaining [La^-]. Afterwards, in 4th 50 m, the glycolitic contribution was higher, which lead to high values of Ė. The inability to maintain swimming v in the last laps of the 200m effort was coincident with the increase of the fatigue indices for the muscles studied (except for the tibialis anterior). These indices (cf. Dimitrov et al., 2006) were assessed as the ratio between the signal spectral moment of order (-1), to emphasise the increase in low and ultra-low frequencies in the EMG spectrum attributable to the increase of negative after-potentials, expressing muscular fatigue. Indices were normalised to spectral moment of order (5), which emphasised the effect of decreases in the high frequencies, attributable to the increased duration of the intracellular action potentials and the decreased action potential propagation velocity.

Conclusion

This study highlights the interaction between coordinative, biomechanical, electrophysiological, and bioenergetical performance influencing parameters. Changes in some factors could imply other modifications or offer the stability needed for a better performance. The importance of observing from a biophysical point of view was shown, as the increasing of performance needs an intervention in a large number of parameters that can influence positively or negatively this process.

Acknowledgments

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Chapter 11

Interplay of Biomechanical, Energetic, Coordinative, and Muscular factors in a 200 m front crawl swim

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Abstract

The purpose of the present study was to determine the relative contribution of selected biomechanical, energetic, coordinative and muscular factors for the 200 m front crawl, and each of its four laps. Ten international swimmers performed a 200 m front crawl swim, as well as 50, 100 and 150 m at the 200 m pace. Biomechanical (stroke length, stroke rate, intracycle velocity variation of the centre of mass in x, y and z axes, propelling efficiency), energetic (total energy expenditure), coordinative (inter-arm coordination) and muscular (muscular activity and frequency) factors were assessed during the 200 m swim. Blood samples were collected before and after each swim and used in the energy expenditure calculations. Multiple linear regression analysis was used to identify the weight of the factors to the performance. For each lap the contributions to the 200 m performance were 17.6, 21.1, 18.4 and 7.6% for stroke length, 16.1, 18.7, 32.1 and 3.2% for stroke rate, 11.2, 13.2, 6.8 and 5.7% for intracycle velocity variation in x, 9.7, 7.5, 1.3 and 5.4% for intracycle velocity variation in y, 17.8, 10.5, 2.0 and 6.4% for propelling efficiency, 4.5, 5.8, 10.9 and 23.7% for total energy expenditure, 10.1, 5.1, 8.3 and 23.7% for inter-arm coordination, 9.0, 6.2, 8.5 and 5.5% for muscular activity amplitude and 3.9, 11.9, 11.8 and 18.7% for muscular frequency). The relative contribution of the factors was closely related to the task constraints, especially fatigue, as the major changes occurred from the first to the last lap.

Key words: Biophysics, Swimming, Biomechanical, Energetics, Coordination, Muscular activity

Introduction

The goal of competitive swimming is to perform the race distance as fast as possible, for that, swimmers must achieve their highest average velocity for that distance. Swimming velocity ($\bar{v}$) is the product of the stroke rate (SR) and the distance moved through the water with each complete stroke cycle (SL) (Craig et al. 1985), and can be expressed as:

$$\bar{v} = SR \times SL \quad (1)$$

For the same $\bar{v}$ several combinations of SR and SL are possible, and are a result of modifications of the time spent in different phases of the stroke cycle (inter-arm coordination), which can be measure in front crawl with the index of coordination (IdC; Chollet et al. 2000; Seifert et al. 2007; Seifert et al. 2010b). However, swimmers do not move at a constant velocity within each stroke cycle, and variations in the action of the arms, legs and trunk result in intermittent application of force and lead to variations in the swimming velocity around the mean velocity within each stroke cycle. These intermittent movements and resultant variations in velocity increase the work done by the swimmer (D'Acquisto et al. 1998), compared to swimming at a constant velocity. The average velocity attained by the swimmer, results from the average of the instantaneous velocity, resulting from intracycle velocity variations (IVV).

$$\bar{v} = v_{constant} + \Delta \mathrm{v(t)} \quad (2)$$

In addition to these factors, maximal swimming velocity ($\bar{v}_{max}$) depends on the maximal metabolic power of the swimmers ($\dot{E}_{tot\text{-}max}$) and on their energy cost of locomotion (C):

$$\bar{v}_{max} = \dot{E}_{tot-max}/C \quad (3)$$

where, $\dot{E}_{tot\text{-}max}$, can be computed based on measures / estimates of the aerobic, anaerobic lactic and anaerobic alactic energy contributions and *C* (i.e. the amount of metabolic energy spent to cover one unit of distance, $KJ.m^{-1}$). The C depends on biomechanical factors such as the mechanical efficiency (η_m), the propelling efficiency (η_p) and the mechanical work to overcome hydrodynamic resistance (W_d):

$$C = W_d/(\eta_P \times \eta_m) \quad (4)$$

To assess W_d several methods have been proposed, however there is no agreement on the most valid method (Toussaint et al. 2004; Zamparo et al. 2009; Kolmogorov and Duplishcheva 1992), and thus it remains difficult to determine active drag during a competitive event while preserving the ecology of the movement. On the other hand, propelling efficiency includes work done against drag and is defined as the ratio of useful mechanical work (W_d) to total mechanical work (W_{tot}):

$$\eta_P = W_d/W_{tot} \quad (5)$$

where in aquatic environments W_d is lower than W_{tot}, since a fraction of the work produced by the contracting muscles is used to accelerate a variable amount of water backwards (wasted work) (Toussaint et al. 1990) and for the internal work (Zamparo et al. 2002). The η_p includes W_{tot} and is dependent on the swimmers' technique and is velocity-dependent and affected by fatigue. In addition, mechanical efficiency is related to how muscles produce the mechanical work needed to sustain a given speed (Wakeling et al. 2010; Zamparo et al. 2002). Muscle efficiency arises from the range of either their force/length and/or force/speed relationships. Relations between force and iEMG have been used to estimate different efficiencies. Also, it has been suggested that the reduction in electrical efficiency with fatigue indicated that more motor units were recruited to generate the same amount of force compared with the non-fatigued muscle (Arabadzhiev et al. 2010; Deschenes et

al. 2002). However, the diagnostic value of the time domain analysis (iEMG) in muscle fatigue evaluation is considered to be more limited than that of the frequency domain analysis (Freq; Merletti et al. 2004). So, to minimize the metabolic cost of high performance activities the limbs must generate large power outputs while the muscles perform work at high efficiencies.

As described above, theoretical models have been developed that attempt to explain the influence of various factors on performance. In spite of the fact that velocity is common to the theoretical approaches, they cannot be combined due to incompatibility of terms and units. This has led to attempts at practical approaches, relating swimming performance to different anthropometrical, physiological, and biomechanical parameters (Fernandes et al. 2008; Pendergast et al. 2003; Toussaint and Hollander 1994; Zamparo et al. 2005b). This kind of research can be developed by comparing different competitive level swimmers, employing the neural network, computing cluster analysis or developing statistical models from the swimmer's profile (Barbosa et al. 2010a). However, these studies have not theorized / assessed swimming performance completely using a biophysical approach, particularly at high swimming speeds (Barbosa et al. 2010a; Pendergast et al. 2006; Vilas-Boas 2010). The 200m swim and freestyle swimming are the dominant competitive events and thus of great interest. Therefore, the purpose of this study was to examine the influence of selected biomechanical (SL, SR, horizontal IVV, vertical IVV, η_p), energetic ($\dot{E}_{tot}$), coordinative (IdC) and muscular (iEMG and Freq) factors in swimming performance. The approach used, absent an appropriate theoretical approach, was a multivariate analysis of the important factors among those listed above that would account for the average swimming velocity in a 200 m front crawl swim, and its component lengths, in well-trained swimmers. It was hypothesized that the biomechanical and energetic factors would be most important, with the coordinative and muscular factors also playing an important, but lesser, role.

Methods

Subjects

Ten well-trained swimmers (21.6 ± 2.4 yr) whom were specialists in the 200 m front crawl event participated in this study. Height, arm span, body mass and percentage of adipose tissue were 185.2 (6.8) cm, 188.7 (8.4) cm, 76.4 (6.1) kg, and 10.1 (1.8)%, respectively. The subjects had an average of 11.9 (3.5) yrs of competitive experience. Their performances in the 200 m front crawl were 109.3 (2.1) s, which correspond to a mean velocity that represents 91.6 (2.1)% of the mean velocity of the short course pool world record for men. The protocol was approved by the local ethics committee and followed the rules of the Declaration of Helsinki (2000). Swimmers were informed of the procedure, the potential risks involved, and the benefits of the study, and then gave a written consent to participate. During the testing period, subjects were asked to adapt the intensity and the total volume of training to avoid stressful training programs. Swimmers' practiced with and were accustomed to all procedures, particularly swimming with the snorkel used for measurement of VO2.

Experimental Procedures

All tests were conducted in a 25 m indoor pool and each subject swam alone in the middle lane, avoiding pacing or drafting effects. Following a warm-up that consisted of a self-selected swim of about 1000 m, including some swimming with the snorkel, swimmers performed a 200 m maximum effort front crawl swim after a push start and using open turns without a glide. They were instructed to replicate their pacing and strategy used in competition. After 90 min of active rest, swimmers performed a 50 m front crawl test and twenty-four hours later a 150 m and a 100 m tests, with 90 min active rest interval between them. Both 50, 100 and 150 m tests were at the same swimming speed as in the previous 200 m paced by a visual light pacing system placed in the bottom of the pool. The pacing lights led the swimmers as the lights progressed down the pool with a flash every 5 m (TAR 1.1, GBK-Electronics, Aveiro, Portugal).

Data Collection and Analysis

Biomechanical factors

Each swimmer's performance was recorded with a total of six stationary and synchronized video cameras (Sony, DCR-HC42E, Tokyo, Japan), four below and two above the water. The calibration setup, accuracy and reliability procedures have been previously described in detail (Figueiredo et al. 2009). The twenty-one landmarks videoed (Zatsiorsky's model adapted by de Leva 1996) that define the three-dimensional position and orientation of the head, torso, upper arms, forearms, hands, thighs, shanks and feet were manually digitized at 50 Hz using a commercial software package (Ariel Performance Analysis System, Ariel Dynamics, Inc., USA). The Direct Linear Transformation Algorithm (Abdel-Aziz and Karara 1971) was used for three-dimensional reconstruction and a digital low-pass filter at 6 Hz was used to smooth the data.

Stroking parameters

One complete stroke cycle (defined as the period between the instant of entry of one hand to the next instant of entry of the same hand) for each of the 50 m laps of the 200 m front crawl was analyzed. From these data the center of mass position as a function of time was computed. The mean velocity ($\bar{v}$) was calculated by dividing the horizontal displacement of the center of mass in one stroke cycle over its total duration. Additionally, the horizontal distance travelled by the center of mass during the stroke cycle was used to determine the stroke length (SL). The stroke rate (SR) was determined as the inverse of the time (seconds) to complete one stroke cycle, which was then multiplied by 60 to yield units of strokes per minute.

Intracycle Velocity Variation

To determine and analyze the whole body centre of mass' IVV in the x, y and z axes of motion the coefficient of variation (CV = SD / mean) was computed as previously suggested (Barbosa et al. 2010a; Barbosa et al. 2005; Figueiredo et al. 2009).

Propelling Efficiency

Propelling efficiency (η_p) was calculated from the computed 3D hand velocity as the sum of the instantaneous 3D velocity of the right and left hand combined during the underwater phase of the stroke (3Du). The η_p was calculated from the ratio of the speed of the center of mass to the 3D mean hand velocity (η_p = $\bar{v}$ / 3Du), since this ratio represents the theoretical efficiency in all fluid machines and has been used in swimming (Figueiredo et al. 2011; Zamparo et al. 2005b).

Energetic factors

Total energy expenditure and energy cost of swimming (C)

Oxygen uptake ($\dot{V}O2$) was recorded by means of the K4b² telemetric gas exchange system (Cosmed, Roma, Italy), during the 200 m front crawl test. This equipment was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system. This system was previously validated and widely used (Barbosa et al. 2005; Fernandes et al. 2008; Figueiredo et al. 2011). Expired gas concentrations were measured breath-by-breath and averaged every 5 s, to get the $\dot{V}O2$ used in subsequent calculations. Net $\dot{V}O2$ was calculated by subtracting the resting $\dot{V}O_2$ from the steady state $\dot{V}O2$ measured during swimming. Before, and after, the 50, 100, 150 and 200 m tests capillary blood samples (5µl) were collected from the ear lobe to assess rest and post exercise blood lactate (La_b) using a portable lactate analyzer (Lactate Pro, Arkray, Inc.). Lactate was measured at 1, 3, 5, and 7 min post test, and the peak value was used for further analysis.

Since the 200 m front crawl energy contribution is supplied from the three energy sources (Capelli et al. 1998; Figueiredo et al. 2011; Zamparo et al. 2011), $\dot{E}_{tot}$ was calculated for each 50 m lap (for review see Zamparo et al. 2011):

$$\dot{E}_{tot} = \dot{V}O_2 + \beta La_b + PCr\,(1 - e^{-t/\tau}) \quad (6)$$

where $\dot{E}_{tot}$ is the total energy expenditure, $\dot{V}O2$ is the aerobic contribution (calculated from the time integral of the net $\dot{V}O_2$ vs. time), $\beta \dot{L}a_b$ is the net accumulation of lactate after exercise, β is the energy equivalent for lactate accumulation in blood (2.7 ml $O_2 \cdot mM^{-1} \cdot kg^{-1}$), *PCr* is the alactic contribution, t is the time duration and τ is the time constant of PCr splitting at work onset (23.4 s). The contribution of each energy pathway was calculated for each lap and on the basis of these data, $\dot{E}_{tot}$ was computed and C was calculated as the ratio between Ė and $\bar{v}$.

Coordinative factors

Index of coordination

The calculation of the Index of coordination **(**IdC) requires the identification of key points in the stroke cycle (Chollet et al. 2000; Seifert et al. 2010b). Specifically, (A) entry and catch of the hand in the water, (B) pull in the water, (C) push in the water and (D) recovery out of the water. Each phase, within the stroke cycle, was determined from the swimmer's horizontal (x) and vertical displacement (y) of the hand noting the time corresponding to start and end of these phases for two arm stroke cycles previously digitized.

The IdC was calculated as the time gap between the propulsion (pull and push phases) of the two arms and expressed as a percentage of the duration of the complete arm-stroke cycle (sum of the propulsive and non-propulsive phases, (catch and exit phases)) (Alberty et al. 2005; Alberty et al. 2009; Seifert et al. 2007). IdC was the mean of IdC left and IdC right.

Muscular factors

The EMG signal of eight muscles (flexor carpi radialis, biceps brachii, triceps brachii, pectoralis major, upper trapezius, rectus femoris, biceps femoris and tibialis anterior), which have been shown to have high activity during front crawl swimming (Clarys and Cabri 1993; Stirn et al. 2011) were recorded simultaneously from the right side of the body using bipolar (inter-electrode distance of 2.0 cm) Ag–AgCl circular surface electrodes. The skin of the swimmer was shaved and cleaned with alcohol and the electrodes with

preamplifiers placed in line with the muscle's fibre orientation in the midpoint of the contracted muscle belly and covered with an adhesive bandage (Opsite Flexifix) (de Jesus et al. 2011; Rouard et al. 1997). A reference electrode was attached to the body's patella. All cables were fixed to the skin by adhesive tape to minimize artifacts during swimming. Additionally, swimmers wore a total body coverage swimsuit (Fastskin, Speedo) to cover the electrodes and recording wires. The total gain of the amplifier was set at 1100 times with a common mode rejection ratio of 110. The data were sampled at 1000 Hz with a 16-bit analog to digital conversion and recording system (BIOPAC System, Inc) and stored on a computer for later analysis. An electronic flashlight signal synchronized with an electronic trigger marked simultaneously the video and EMG recordings, respectively, to synchronize EMG and video recordings. The EMG data analysis was performed using the MATLAB 2008a software environment (MathWorks Inc., Natick, Massachusetts, USA).

iEMG

Raw EMG signals were band-passed (8-500 Hz), rectified to obtain the full wave signals and smoothed with a 4^{th} order Butterworth filter (10 Hz) for the linear envelope. The integration of the rectified EMG was calculated, per unit of time, to eliminate the stoke cycle duration effect (iEMG/T) and normalized to the maximum iEMG observed (signal was partitioned in 40 ms windows to identify the maximal iEMG) (Caty et al. 2007). All iEMG values from the measured muscles taken in the mid-pool section for each 50 m were averaged. In addition, the average iEMG values of all 8 muscles were added together (iEMG) and used to represent the total electrical activity of swimming

Frequency Analysis

For the frequency analysis (Freq) spectral indices were calculated (Dimitrov et al. 2006) and averaged. Spectral indices were obtained for each stroke, defined by video analysis, in the mid-section of the pool for each 50 m lap and they were averaged for each muscle. The spectral indices for each muscle were then averaged to determine the Freq factor used to represent spectral muscle

information. Spectral indices have been shown to most accurately detect changes in muscle power during dynamic contractions (Gonzalez-Izal et al. 2010), and their increases indicate fatigue (Dimitrov et al. 2006; Gonzalez-Izal et al. 2010).

Statistical Analysis

Mean (SD) computations for descriptive analysis were obtained for all variables (normal Gaussian distribution of the data was verified by the Shapiro–Wilk's test). A one-way repeated measures ANOVA was used to compare each factor along the 200 m. When a significant F-value was achieved, Bonferroni post-hoc procedures were performed to locate the pairwise differences between the means. All the statistical analysis was performed using STATA 10.1 (StataCorp, USA), with the level of significance set at 0.05. The effect size (f) for each variable was calculated in accordance with Cohen (1988) to measure the magnitude of difference.

Modeling of performance

As described in the introduction, absence of a theoretical model to combine the factors that contribute to swimming performance, a multiple linear regression was used to identify the relative contributions of factors that are associated with swimming performance. These, among the previous defined, factors are: biomechanical (SL, SR, IVVx, IVVy, ep), energetic ($\dot{E}_{tot}$), coordinative (IdC) and muscular (iEMG and Freq). This analysis was carried out for the 200 m front crawl velocity and then repeated for the velocities of each of the component 50 m laps to examine and compare the relative contribution of the factors in each segment of the swim. A common general multiple linear regression analysis was used to identify the weight of the factors identified as contributing to 200 m swim velocity and attaining 100% of the variance of the performance. The equation used for all the models tested was:

$$\bar{v} = constant + kSL + kSR + kIVVx + kIVVy + k\eta_P + k\dot{E}_{tot} + kIdC + kiEMG + kFreq \quad (7)$$

where $\bar{v}$ is the mean swimming velocity for the 200 m or the mean velocity of each 50 m lap, that equals the sum of the model' constant with the factors, stroke length, stroke rate, intracycle velocity variation (x and y), propulsive efficiency, total energy expenditure, index of coordination, muscular activation and spectral indices weighted by their specific beta coefficients (*k*). Both C and IVVz were not used in the model to limit the number of factors and they were reflected in Etot and η_p or IVVx, IVVy, respectively. To better express the relative importance of the factor the weights of the regression were converted to standardized regression coefficients (beta weights).

Results

Mean velocity for the total 200 m front crawl was 1.41 (0.04) $m.s^{-1}$. Figure 1 shows the data for the average velocity of each 50 m lap, along with the observed stroke frequency and stroke length, expressed as a percentage of their mean for the 200 m swim. The velocity in the first lap was faster than the average velocity, but decreased below the average in the second lap, after which it remained constant ($F_{3,27}$ = 24.72 P < 0.001 f = 1.27). Swimming velocity is the product of SF and SL, and they both decreased concomitantly with velocity (Figure 1). SR had a mean value for the 200 m of 38.41 (3.05) $cycles.min^{-1}$, but decreased across the swim, reaching a statistical difference after the third lap ($F_{3,27}$ = 5.08 P = 0.006 f = 0.38). SL decreased below the mean for the 200 m of 2.20 (0.14) m in lap 3, but reached significance only in the last lap ($F_{3,27}$ = 4.55 P = 0.01 f = 0.33).

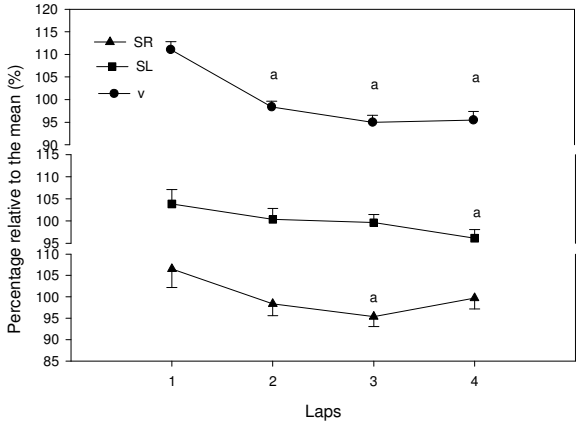


Figure 1. Mean (SE) values expressed as a percentage of the mean value for the 200 m front crawl for velocity (v), stroke length (SL) and stroke rate (SR) are plotted as a function of the 50m laps. [a] Significantly different from the 1st lap.

Figure 2 shows the four groups of factors identified as contributing to the 200 m front crawl swim (i.e., biomechanical, energetic, coordinative and muscular). Biomechanical factor IVV (x, y and z) (Figure 2 upper left) mean values for the 200 m were 0.22 (0.03), 0.76 (0.08), 0.83 (0.03), respectively. A stable pattern over the 50 m laps was observed (IVVx: $F_{3,27}$ = 1.60 P = 0.21 f = 0.18; IVVy: $F_{3,27}$ = 0.82 P = 0.49 f = 0.00; IVVz: $F_{3,27}$ = 2.18 P = 0.13 f = 0.24). Another biomechanical factor, η_p, presented a mean value over the four laps of 0.42 (0.02) (Figure 2 upper left), however, showed a significant reduction in the 4th 50 m lap ($F_{3,27}$ = 6.64 P = 0.002 f = 0.41). Energetic factors, $\dot{E}_{tot}$ ($F_{3,27}$ = 19.58 P < 0.001 f = 0.63) and C ($F_{3,27}$ = 19.77 P < 0.001 f = 0.63) (Figure 2 upper right) showed significant changes for the 50 m laps, with a mean of 80.11 (7.97) $mmlO2.kg^{-1}.min^{-1}$ and 1.60 (0.16) $KJ.m^{-1}$, respectively. The coordinative factor, IdC presented a mean value of -14.94 (2.15)% (Figure 2 lower right) and showed a significant increase in the 4th 50 m lap ($F_{3,27}$ = 4.09 P = 0.02 f = 0.34). The two muscular factors, Freq ($F_{3,27}$ = 30.40 P < 0.001 f = 0.89) and iEMG (Figure 2 lower right) showed a significant increase ($F_{3,27}$ = 4.22 P = 0.01 f = 0.22), in the last 50 m lap and the mean was $1.97e^{-14}$ ($0.22e^{-14}$) and 1.76 (0.37), respectively.

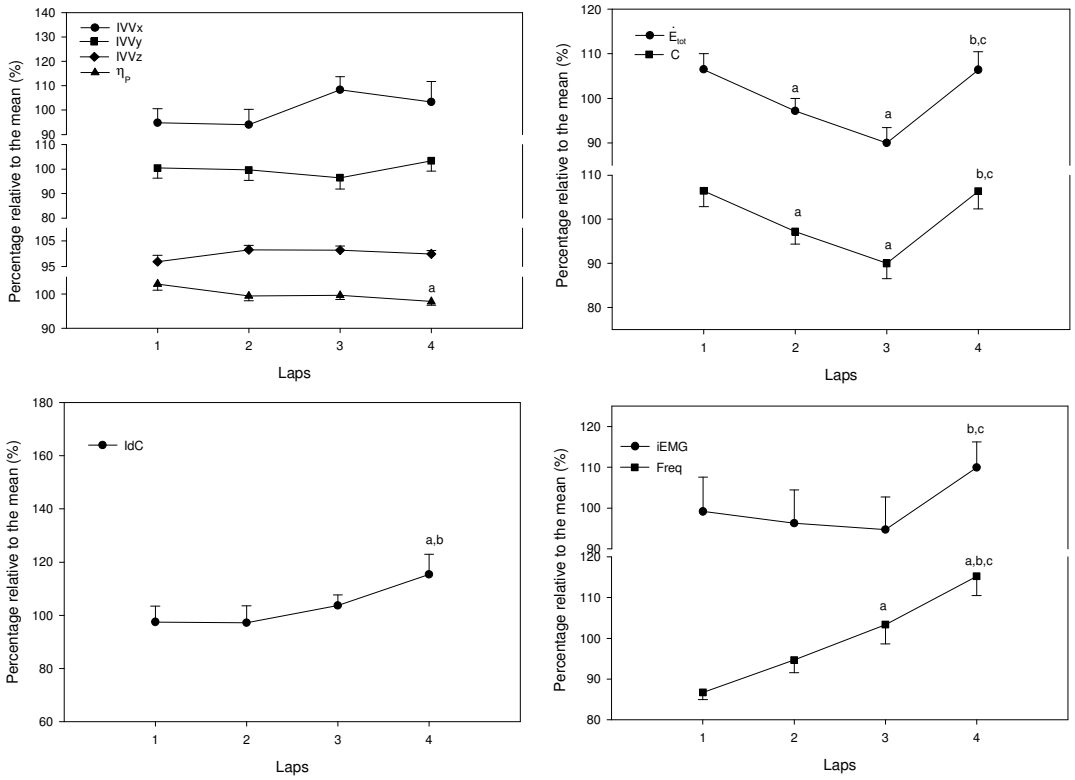


Figure 2. Mean (SE) values for the percentage of the 200 m front crawl mean value for the: i) biomechanical factors: IVV for x, y and z axes η_p (upper left panel); ii) energetic factors $\dot{E}_{tot}$ C (upper right panel); iii) coordinative factor: IdC (lower left panel); and, iv) muscular factors: iEMG and Freq (lower right panel) for the 200 m Front crawl event. [a, b, c] Significantly different from the 1st, 2nd and 3rd lap, respectively.

The beta coefficients for all factors are presented in Table 1, for their contribution in the four laps to the 200 m velocity (upper half) and to the average velocity in each 50 m lap (lower half). Standardized coefficients from the multiple linear regression model showed that the contribution of the first and last 50 m laps velocity to the mean 200 m velocity were higher (26.1 and 30.8%, respectively) than the contributions of the second and third laps (21.7 and 21.4%, respectively) of the 200 m front crawl. The model had an $F_{4,5}$ = 339.159, $P < 0.001$, $R^2 = 0.996$, Adjusted $R^2 = 0.993$ for these factors. These data are consistent with the changes in velocity shown in Figure 1.

Table 1. The Beta coefficients (k) determined to identify the importance of the factors included in the multiple linear regression models computed for the mean for the overall 200m performance, as well as for each individual performance lap.

		SL	SF	IVVx	IVVy	η_p	$\dot{E}_{tot}$	IdC	iEMG	Freq	Constant
A	Lap 1	-1.10	-0.04	4.04	-1.40	11.55	0.01	0.05	-0.32	0.01	0.89
	Lap 2	5.90	0.26	-14.15	-3.52	-28.08	0.04	-0.08	-0.64	-0.04	-2.12
	Lap 3	0.20	0.02	0.25	-0.02	-0.16	0.002	-0.006	0.03	0.001	0.05
	Lap 4	-0.13	-0.002	0.21	0.12	-0.97	0.005	-0.02	-0.04	0.002	1.04
B	Lap 1	-6.52	-0.25	19.87	-8.02	62.06	0.03	0.26	-1.44	0.02	4.29
	Lap 2	1.32	0.07	-1.65	-0.52	-2.72	0.004	-0.01	-0.08	-0.01	-1.75
	Lap 3	0.63	0.05	0.35	-0.18	-0.49	-0.002	-0.01	0.05	-0.001	-1.59
	Lap 4	0.50	0.03	-0.15	-0.03	-0.12	0.001	-0.004	-0.01	-0.0001	-0.92

A: 200 m performance; B: each 50 m performance.

The biomechanical factors showed a great importance, manly the SL and SR (Figure 3) to the overall performance of the 200 m front crawl (16.2% and 17.5%, respectively). However, their contribution decreased in the final lap (from 17.6% and 16.1% to 7.6% and 3.2%, respectively). The SR had a very high contribution in the third 50 m lap (32.1%), concomitant with this, there was a great decrease in the contribution of the other biomechanical factors (6.7% for IVVx, 1.3% for IVVy and 2.0% for η_p), with the IVVy and η_p factors increasing afterwards (5.4% and 6.4%, respectively). The $\dot{E}_{tot}$ contribution increases continually during the four laps (4.5%, 5.8%, 10.9% and 23.7%), while the IdC factor shows a “U” pattern with a large contribution at the beginning (10.1%), a decrease in the middle (5.1%) and then increase at the end of the swim (23.7% for the fourth lap). Relative to the muscular parameters (iEMG and Freq), iEMG appears to be quite stable (ranging from 5.5 - 9.0%), with only small oscillations, while the contribution of Freq increased over the length of the swim (from 3.9% in the first lap to 18.7% in the last lap).

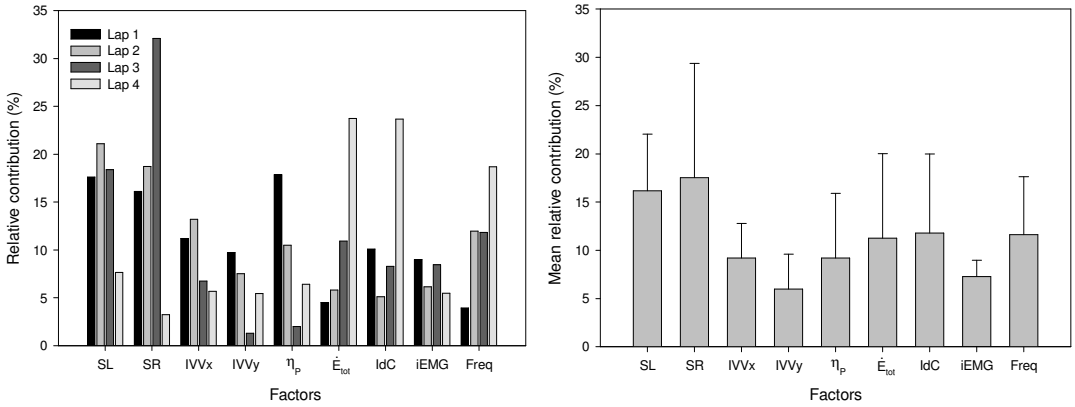


Figure 3. The percentage of the contributions of each factor in each lap for the 200 m swim performance (left panel) and mean percentages for all laps (right panel).

In Figure 4 the contribution of the relative importance of the factors used in the analysis for the average velocity in each lap individually are showed. The biomechanical factors (SL, SR, IVVx, IVVy and η_p) had a higher contribution (81.1%) than the energetic ($\dot{E}_{tot}$, 3.9%), coordinative (IdC, 5.5%) and muscular (iEMG and Freq, 9.5%) factors. Within all the analyzed factors SL and SR showed the highest contribution (26.4% and 34.6%, respectively), the remaining ones (IVVx, IVVy, η_p, $\dot{E}_{tot}$, IdC, iEMG and Freq) had a similar contributions (ranging from 3.8 to 6.9%). It should be noted that SL and SR are related mathematically with the v. However, the contribution of each of these two factors for each 50 m lap performances showed that SL contribution decreased in the third lap (from 27.9% to 24.8%), in spite of its increase tendency over the four laps (from 20.0% in the first lap to 33.1% in the last lap), while the SR increased throughout the entire 200 m swim (from 17.6% to 49.4%). All the other factors used in the model showed a tendency to decrease their contribution from the beginning until the end of the swim, as the contributions of SL and SR increase.

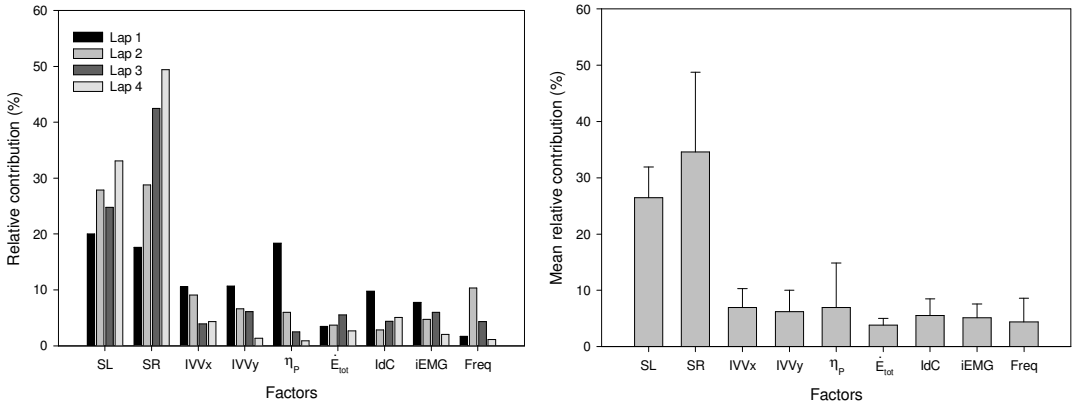


Figure 4. The percentage contributions of the factors for the 50 m laps performances (left panel) and mean percentages for all laps (right panel) of the 200 m front crawl.

Discussion

Although previous studies have evaluated the role of biomechanical (Craig et al. 1985; Psycharakis et al. 2010; Toussaint et al. 2006), energetic (Capelli et al. 1998; Fernandes et al. 2006; Figueiredo et al. 2011), muscular (Aujouannet et al. 2006; Rouard et al. 1997; Stirn et al. 2011) or coordinative (Alberty et al. 2005; Chollet et al. 2000; Seifert et al. 2010b) factors on the performance and others developed models to predict performance combining several factors (Barbosa et al. 2010b), we are unaware of a study that examined their combined interactive effects as was performed in this study. The regression analysis performed was not intended to predict performance, but to determine the contribution of the important factors to it. For the mean velocity of 1.41 $m.s^{-1}$ the biomechanical, energetic, coordinative, and muscular factors were 58.1%, 11.2%, 18.9% and 11.8%, respectively, with SL and SR factors explaining 33.7 % of the 200 m mean velocity. A decrease in velocity during the second 50 m lap was observed, and then velocity was constant. Although the patterns were different, SL and SR decreased from the first 50 m and together accounted for the decrease in velocity. These changes in SL and SR are in agreement with previous studies (Alberty et al. 2005; Craig et al. 1985). Also, the velocities that account for the major contribution more to the overall performance of the 200m front crawl were the first and last lap velocities, suggesting two important stages during this particular event. On the first lap, the highest velocities are achieved

and on the last lap the consequences of fatigue were felt, and although velocity was constant, the contribution of the factors determining it changed. Among the 50 m laps the contribution of biomechanical, energetic, coordinative, and muscular factors was on average 81.1%, 3.9%, 9.5% and 5.5%, respectively, and 61% of the biomechanical contribution was attributed to the SL and SR.

Biomechanical Factors

Stability in the IVV (x, y and z) was observed over the four laps, as previously reported by Psycharakis et al. (2010). IVV (x, y) accounted for 15.2% of the variability of the 200 m swim and 13.2% for the 50 m laps. In spite of the stability of IVVx, the η_p decreased in the last lap likely due to fatigue, as fatigue has been shown to evolve during the 200 m front crawl (Alberty et al. 2005; Figueiredo et al. 2011). As a result, η_p accounted for 9.2% of the variability of the 200m swim and on average 6.9% for the 50 m laps individual performance.

Energetic Factors

$\dot{E}_{tot}$ and C decreased over the second and third 50 m laps, concomitant with the velocity decrease. However, due to the development of fatigue and decrease in η_p, C, and thus $\dot{E}_{tot}$, increased in the last lap, which is in agreement with previous studies (Figueiredo et al. 2011; Zamparo et al. 2005a). $\dot{E}_{tot}$ accounted for 11.2% of the variability of the 200m swim and on average 3.9% for the 50m laps.

Muscular Factors

The assessed muscular factors revealed a submaximal fatigue in swimming, as amplitude increased and frequency decreased (i.e., increase in the spectral indices), as previously reported for amplitude (Aujouannet et al. 2006) and frequency (Caty et al. 2006) for a 4x50m test simulating the 200 m front crawl, and also shown for the 100 m swim (Stirn et al. 2011). The iEMG and Freq factors contributed 7.3% and 11.6%, respectively, to the variance of the 200 m swim and on average 5.1% and 4.4% respectively, to the 50 m laps.

Coordinative Factors

As velocity and the SL-SR ratio changed, inter-arm coordination adapted, with an increase in IdC in the final stages of the 200 m event. This observation is consistent with the development of fatigue as reported previously (Alberty et al. 2005; Alberty et al. 2009). This factor (IdC) accounted for 18.9% of the variance of the 200 m swim performance and on average 5.5% of the 50 m laps.

Interplay among factors

A theoretical framework for the interaction of the biomechanical, energetic, coordinative and muscular factors is presented in Figure 5 and used in the subsequent discussion.

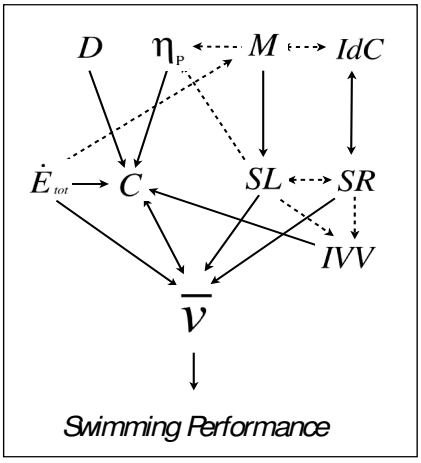


Figure 5. The relationship between biomechanical, energetic, coordinative and muscular factors with performance in competitive swimming. $\bar{v}$: mean swimming velocity; *SF*: stroke frequency; *SL*: stroke length; *IVV*: intracycle velocity variation of the center of mass; η_p: propelling efficiency; *C*: energy cost; $\dot{E}_{tot}$: energy expenditure; *IdC*: index of coordination; *M*: muscular activity; *D*: hydrodynamic drag.

The biomechanical factors had the highest contribution to the 200 m front crawl and also to each 50 m lap mean velocities, where together they accounted for up to 33.7% and 61.0%, respectively. These contributions are understandable, as the product of two of these factors (SL and SR) determines swimming velocity (Craig et al. 1985). The contribution of SL and SR to the total performance are very important to achieve high velocities, however their

contributions decreased during the swim, which suggested that several other factors had increased importance in determining the last 50 m lap velocity (see Figure 5). The contribution of SL showed a higher contribution than SR in the last 50 m. This observation is supported by a study of Craig et al. (1985), where the best swimmers' in the 200 m front crawl could maintain higher SL distances at the end of the event, in spite of having similar SRs.

Changes in SL and SR are associated with IVVx and IVVy (see Figure 5), however, the latter showed a stable pattern over the 200 m. In spite of its stability, IVVx showed a decrease contribution over the length of the swim. IVVy's contribution decreased even more than IVVx in the third lap, and then it increased in the fourth lap. Relative to the individual lap performances, η_p had similar mean contributions to velocity as IVVx, IVVy, and all of them decrease from the beginning to the end of the swim. IVVx's and SL contributions to the 200m performance showed a similar pattern, which could be explained by the increased time between propulsive phases as SL decreases, and SR increases (Chollet et al. 2000; Seifert et al. 2007; Seifert et al. 2010b). This change is also associated with a decrease in η_p (see Figure 5) (Figueiredo et al. 2011; Toussaint et al. 1990; Zamparo et al. 2005b) and, increase in the IVVx and $\dot{E}_{tot}$ (Barbosa et al. 2006). This can be explained as a smaller IVV will lead to a lower energy cost, for example if two swimmers swim at equal mean velocity, but the IVV = 0 in swimmer 1 and in swimmer 2 IVV>0 than mean power of swimmer 1 will be v^3 but in swimmer 2 it will be $>v^3$, as $\dot{E}_{tot}$ has the same relation with v (Capelli et al. 1998; Toussaint and Hollander 1994). Supporting this concept, it was found that swimming with hand paddles, which increase η_p and SL (Toussaint et al. 1991), results in decrease IVVx and increase IdC (Sidney et al. 2001). On the other hand, IVVy and η_p showed a contribution pattern that was inverse of that of SR.

IVVy can be linked to the medial-lateral hand movements that account for vertical displacement changes suggesting great importance of the sideways movements during the stroke's propulsive actions, which have been highlighted by previous studies (for review see Toussaint and Beek 1992), and are decreased with higher SRs. In addition, as η_p is SL-related (Figueiredo et al.

2011; Zamparo et al. 2005b) its contribution to the variance in performance decrease when the SR contribution increase. The similar pattern observed for IVVy and η_p seem to confirm the possible link between IVVy and the sideways hand pattern motion, which resulted in a high η_p. This may also account for the larger contribution of η_p than IVVy. Propelling efficiency's decreasing contribution to the laps performance might be linked to reduced muscles force production during the stroke due to fatigue. It is likely that a reduced muscle force production occurs, as indicated by the changes in EMG factors, and the swimmers became unable to sustain the initial SL (Craig et al. 1985; Keskinen and Komi 1993), as observed in this study. The spectral indices (Freq) has been suggested as one of the first indicators of fatigue (Dimitrov et al. 2006; Gonzalez-Izal et al. 2010). The SL and η_p decreases shown in this study are likely the result of fatigue developing toward the end of the 200m swim.

As the biomechanical factors show a decrease contribution to the variance of the 200 m in each 50 m swim performance between the first and the last lap, other factor's contributions must increase (see Figure 5). This was the case for the energetic and coordinative factors. Over the 50 m laps the contribution of $\dot{E}_{tot}$ to the overall performance increased, thus the swimmer's capacity to deliver higher energy expenditure became more important over the 200m. Swimmers can have the same time splits for the 50, 100 and 150 m, but if $\dot{E}_{tot}$ cannot be increased to match the increase in C in the last 50 m velocity cannot be sustained. The contribution of $\dot{E}_{tot}$ in the three final laps is similar to that of IdC, which could be explained by the swimmer naturally adopting a movement pattern to minimize his metabolic energy expenditure (Seifert et al. 2010a; Sparrow and Newell 1998).

The reduction in C, and thus $\dot{E}_{tot}$, in laps 2 and 3 may involve the process of self-optimization (Sparrow and Newell 1998), which occurs to overcome the constraints imposed, in this case by the fatigue task constraint (Seifert et al. 2007). The IdC factor had the inverse pattern of contribution to performance in the first three laps compared to that of SL. As indicated by previous studies, based on the dynamical theories of motor organization, stroke rate is the first determinant of motor organization in swimming (Seifert et al. 2007) and it has

an inverse relation with SL (Keskinen and Komi 1993; Seifert et al. 2010b). As SR and IdC are associated with each other (see Figure 5), IdC had a higher contribution to first 50 m lap, as was the case in overall performance analysis. This is likely due to the direct relationship between IdC and velocity that has been suggested (Chollet et al. 2000; Seifert et al. 2010b). After the first 50 m, the contribution of IdC starts to decrease, as a result of the decrease in velocity and SL, until the development of fatigue, which resulted in an increase in the contribution of the SR to a greater extent than SL. When strokes are closer together, or overlap, this has the effect of increasing the average propulsive force while the mean force per stroke is maintained (Alberty et al. 2009). These changes in stroke patterns increase the contribution of IdC in the latter stages of the 200 m swim, which also has previously been shown (Alberty et al. 2005).
The increased $\dot{E}_{tot}$ contribution to overall performance reported in this study is related to the changes in the balance of the three energy pathways (aerobic, anaerobic lactic and anaerobic alactic) as a function of time as previously reported (Capelli et al. 1998; Figueiredo et al. 2011; Zamparo et al. 2011). The increase contribution of the anaerobic lactate contribution, and resultant lactate accumulation, by the end of the effort (Figueiredo et al. 2011) contribute to the explanation of the decrease in SL and η_p. These changes are consistent with the deterioration of stroke mechanics observed by other authors (Keskinen and Komi 1993; Zamparo et al. 2005a). The reduced SL and increased Freq are associated with muscle fatigue most likely brought about by high-lactate levels and reduced muscle glycogen (Costill et al. 1988). This conclusion is supported by the suggestion that the increase in blood lactate concentration may change the stroking strategy significantly (Keskinen and Komi 1993) and thus IVVy and η_p. These deviations from the optimal combination of SL and SR result in a significant increase in energetic demand (see Figure 5), suggesting that minimizing energy cost may be an important factor contributing to cadence determination in cyclical forms of locomotion (Sparrow and Newell 1998). Supporting this, swimmers preferred to swim front crawl at the lowest SR (or the longest SL) that does not require an increase in oxygen uptake (McLean et al. 2010), as a significant decrease in the preferred SR, for example, determines

the decline in time limit exercise duration (Alberty et al. 2011), which might be caused by an unusual muscular recruitment.

The increase in $\dot{E}_{tot}$, particularly of anaerobic lactic contribution, in the final lap due to muscle fatigue is generally (although not exclusively) attributed to the reduced muscular fibre conduction velocity, which is causally related to a decrease in the pH (Allen et al. 2008). Although pH was not directly measured, high values of blood lactate concentration collected after the 200 m swim (Capelli et al. 1998; Figueiredo et al. 2011; Pelayo et al. 1996) implied a significant pH decrease during swimming. As muscles fatigue, power output is reduced during the swim (Toussaint et al. 2006), as is the case for SL. Since the SL is an index of propelling efficiency (Toussaint and Beek 1992; Zamparo et al. 2005b), η_p should decrease, as was observed in this study. The resultant deterioration of stroke mechanics in fatigued subjects is expected to lead to a progressive increase in the energy cost of swimming (see Figure 5), as was observed in this study. However, to maintain the total mechanical power output as Craig et al. (1985) have shown for races of 200 m and longer, the distance per stroke tends to decrease as fatigue develops and SR has to increase to compensate to maintain the speed constant, or if SR and $\dot{E}_{tot}$ can not be increased velocity decreases, which happen in this study in the second lap. In addition, increases in muscle activity can lead to decreases in efficiency (see Figure 5) with no increase in power output if the muscle coordination is inappropriate (Wakeling et al. 2010). Muscle coordination changes due to fatigue in swimming have been shown (Rouard et al. 1997).

In the first lap, the contribution of the SL is higher than the SR, but in the last lap SR is greater suggesting fatigue in the last lap, which is supported by the EMG data (see Figure 5). The muscular factor iEMG (amplitude analysis) has a tendency to decrease its contribution to the overall performance of the 200 m during subsequent 50 m laps. In the first 50 m lap the highest contribution of the iEMG over the 200m could be associated with the high velocity and also a higher contribution of the SL, that is linked to higher force production (see Figure 5) (Keskinen et al. 1989). This would also be associated with a higher power output and velocity, as was the case for the first lap, and concomitant

with the high contribution observed. On the third lap, the iEMG contribution increases after its decrease in the second lap, which might explain the decrease in the absolute value of SR in this particular lap. This is supported by the higher SR in this lap that was associated with higher EMG activity (Cabri et al. 1988), and its increase in contribution. Also, additional recruitment or increased synchronization of muscle fibers as a result of submaximal fatigue (Gandevia 2001) most likely explains the reduced contribution in the last 50 m. If the velocity is an indicator of the power output and it was stable in the last three laps, mechanical efficiency and concomitant efficiency of the electrical activity (SL vs. increased iEMG and Feq) was decreased.

In spite of these associations described above, the relationship between iEMG and force is not linear and the diagnostic value of the time domain analysis (iEMG) in muscle fatigue evaluation is considered to be more limited than that of the frequency domain analysis (Freq) (Merletti et al. 2004). Freq showed a higher contribution to the 200 m swim than iEMG in the mean values and for the second, third and fourth lap. These higher contributions might be explained by the $\dot{E}_{tot}$ absolute values and contributions, as $\dot{E}_{tot}$ absolute value is higher on the first lap, because of the higher velocity when swimmers are not fatigued. However, after the first lap velocity starts to decline, as did $\dot{E}_{tot}$, maintaining a statistical stability during the second and third laps. Freq's contribution increases during these two laps. As swimmers reach the fourth lap Freq increases and SL decreases suggesting the presence of fatigue, $\dot{E}_{tot}$ increase in both absolute value and contribution to velocity in spite of the constant velocity. The contribution of the increased Freq over the swim distance attained a similar contribution to the overall performance as did the energetic and coordinative factors.

For the mean velocity in each lap, both iEMG and Freq, present a similar mean contribution, however their pattern of change over the laps is different. The iEMG has its highest contribution on the first lap, whereas Freq has a small contribution. However, Freq is higher, and iEMG lower, in the last lap. This can suggest that at the beginning of the effort higher muscular activation is needed to recruit more fast-twitch muscle fibers and achieve the higher SR at this

stage. In the second lap the contribution of Freq surpass that of iEMG, and after this it decreases constantly until the end of the 200 m effort. The decreased contribution of iEMG is contrarily to the increase in absolute values relative to the mean value for 200 m. This pattern of changes is similar to the decrease in spectral parameters that indicate the evolvement of fatigue. As higher η_p requires higher effective application of propulsive force, the decrease of the contribution of iEMG might be associated with a decrease in the contribution of η_p and be associated with muscle fatigue.

Conclusion

The swimmers in this study had the highest velocity in the first lap of the 200 m swim. The factors contributing to this were a balance of SL, SR, η_p, IVVx, IdC and iEMG, denoting particular importance for the biomechanical factors (SL, SR and η_p), as this first lap is done confortable enough, without fatigue constraints. From the second through the fourth lap, although the velocity was similar, dynamical changes occurred in the importance of the contributing factors, especially in the fourth lap. In this last, the contribution of Freq and IdC were high and suggest fatigue of the muscles used in swimming, resulting in a high contribution of $\dot{E}_{tot}$ and lower contribution of η_p. These data may suggest swimming at a uniform velocity to avoid the effects of fatigue, and / or training to increase $\dot{E}_{tot}$ and muscular endurance.

Acknowledgments

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Chapter 12. General Discussion

The overall purpose of this Thesis was to conduct a biomechanical, energetic, coordinative and muscular characterization of the 200 m front crawl event, aiming to understand the interplay among these four domains. The used approach was that swimming performance is influenced by several major factors, which interplay with each other, and are changed by the swimmer to face the constraints imposed by the environment and race distances (Figure 1). Of particular interest was the study of the effect of the evolvement of fatigue along the effort on the performance determinant factors. Results identified three components of a 200 m front crawl swim: the first 50 m lap, the second and third 50 m laps, and the fourth 50 m lap.

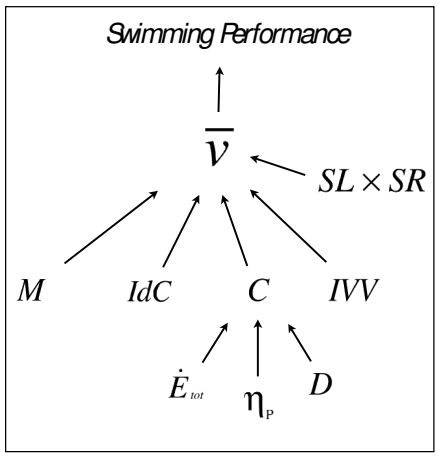


Figure 1. Swimming performance influencing factors. $\bar{v}$: mean swimming velocity; *SF*: stroke frequency; *SL*: stroke length; *IVV*: intracycle velocity variation of the centre of mass; η_p: propelling efficiency; *C*: energy cost; $\dot{E}_{tot}$: energy expenditure; *IdC*: index of coordination; *M*: muscular activity; *D*: hydrodynamic drag.

Swimming performance is measured by the time required to cover a specific distance or by the overall velocity (resultant from the ratio of distance to time, or by the product of the SL by the SR) (Craig & Pendergast, 1979; Craig et al., 1985). As the SL and SR, and their relationship, is changed along a swimming event, velocity may be constant, increased or decreased, depending on the

goal of the task and it constraints. Craig et al. (1985) compared race distances, ranging from 100 m to 1500 m, and found that all stroke parameters had a tendency to decrease along each event. Specifically in the 200 m freestyle event, where swimmers adopt the front crawl (the faster swimming technique), decreases in velocity occur, concomitant with the SL and SR decreases. However, due to the development of fatigue in the last 50 m, SR can be increased to compensate the SL decrease, attempting to maintain the velocity as high as possible (Craig et al., 1985). Recent studies (Alberty et al., 2005; Chatard et al., 2001; Huot-Marchand et al., 2005; Psycharakis & Sanders, 2008) focused specifically on the 200 m front crawl, and supported the findings of Craig et al. (1985).

As SL and SR are primary velocity contributors, they were the first factors analysed in the current Thesis, and are shown across all chapters. Its study showed that the ten international level male swimmers evaluated performed in accordance with the above-referred literature. The velocities that accounted for the major contribution to the 200 m front crawl overall performance were those obtained in the first and last lap (**Chapter 11**). In addition, the positive relationship between velocity and SF (**Chapter 9**) is in agreement with the SF-velocity relation proposed by Termin and Pendergast (2000), as well as with the suggestion that SF is the first swimming motor organization determinant (Alberty et al., 2008; Potdevin et al., 2006; Seifert, Chollet, & Rouard, 2007). These changes in SF seem also to be linked to modifications in shoulder roll (**Chapter 3**), as observed previously (Cappaert, 1999; Psycharakis & Sanders, 2010; Yanai, 2003).

Front crawl is considered the most economic competitive swimming technique, (Barbosa, Fernandes, et al., 2006; Holmer, 1974; Karpovich & Millman, 1944; Lavoie & Montpetit, 1986; Pendergast et al., 1978; Troup, 1991), due to its biomechanical characteristics (Barbosa, Fernandes, Keskinen, et al., 2008; Costill et al., 1987; Costill et al., 1985; Kornecki, & Bober, 1978; Nigg, 1983; Wakayoshi et al., 1996). It presents a low intracycle velocity variation (Alves et al., 1996; Barbosa et al., 2010; Craig & Pendergast, 1979; Holmer, 1983;

Keskinen & Keskinen, 1997; Miyashita, 1971; Vilas-Boas et al., 2010), which may account for its lower C comparing to the other swimming techniques, particularly the simultaneous ones (butterfly and breaststroke). However, the data concerning the relationship between velocity and IVV previously reported are conflicting, as some researchers reported no relationship between them (Schnitzler et al., 2010; Schnitzler et al., 2008; Seifert, Leblanc et al., 2010), a decrease in velocity associated with increase in IVV (Barbosa et al., 2005; Manley & Atha, 1992; Takagi et al., 2004; Togashi, 1992; Vilas-Boas, 1996), an increase in velocity associated with increases in IVV (Alves et al., 1996; Craig & Pendergast, 1979), or even a polynomial relationship between them (Barbosa, Lima, et al., 2006). An explanation for the disagreeing results could be the different protocols and velocities employed, and the different swimming techniques studied.

Most of the studies about IVV in front crawl have been conducted in the direction of swimming (IVVx) (e.g. Alberty et al., 2005; Alves et al., 1996; Barbosa, Lima, et al., 2006; Craig, & Pendergast, 1979; Schnitzler et al., 2010; Schnitzler et al., 2008; Seifert, Leblanc et al., 2010), as it reflects the horizontal changes in velocity due to the interaction of propulsion and drag. However, it has been recently suggested that changes in velocity in the three axes of motion are important to better understand the overall front crawl swimming performance (Psycharakis et al., 2010). In addition, most of the IVV related studies used a fixed point on the body (normally the hip) instead of the CM (Alberty et al., 2005; Alves et al., 1996; Schnitzler et al., 2010; Schnitzler et al., 2008), due to the complex and time consuming procedures of the digitizing method needed for the assessment of the CM kinematics.

Acknowledging these methodological issues, a study was conducted to verify the validity of the hip assessment to accurately reflect the kinematics of the CM (**Appendix I**) by monitoring eight high level male competitive swimmers during a 25 m front crawl swim near maximum velocity. It was found that the hip accurately reflects the displacement of the CM in the x and z axes, presenting

high and moderate correlation values, respectively. However, differences were found between hip and CM values displacement in the y axis, velocity and acceleration in the x, y and z axes, and for IVVx and IVVy. These findings justified the use of the CM instead of the hip in the following chapters of this Thesis. In addition, the number and distribution of calibration points in a matrix that allow three-dimensional reconstruction were studied, to have reliable and accurate kinematic results (**Appendix II**). So, to maximise the accuracy of three-dimensional coordinate reconstruction, 12 markers were digitised in the calibrated space over 50 frames for each of the four underwater and two above water camera views. Seven series of digitising were performed for this set of 12 markers, using 8, 12, 16, 20, 24, 28 and 30 control points, both above and below water. The number and distribution of the calibration points, chose to be used in the biomechanical analysis of the 200 m front crawl, showed low resultant RMS error for under and above water environments. Considering the volume of the calibrated space, the errors were similar or lower than those reported previously (Chen et al., 1994; Gourgoulis et al., 2008; Kwon et al., 1995; Lauder et al., 1996; Payton et al., 2002; Payton & Bartlett, 1995; Psycharakis et al., 2005), which allowed a suitable 3D swimming kinematic analysis.

The study of **Chapter 2** characterized the IVV in x, y and z axes during the 200 m front crawl, and aimed to evaluate its behaviour during the course of the event, as well as their relationships with velocity. This study also examined the hand kinematics related parameters that influence IVV, as it was reported to have decisive importance for butterfly swimming (Barbosa, Fernandes, Mouroço, et al., 2008; Martins-Silva & Alves, 2000). It was observed that IVV in x, y and z axes was stable across the 200 m as previously described (Psycharakis et al., 2010). The differences between maximal and minimum velocities in the x axis were similar to the ones presented before using a speedometer (Alberty et al., 2005; Craig & Pendergast, 1979). As in butterfly technique (Barbosa, Fernandes, Morouço, et al., 2008; Martins-Silva & Alves, 2000), hand kinematics influenced the IVV in all the axes of motion along the

200 m, allowing changing it (e.g. IVVx was directly related to the backward horizontal amplitude normalized to SL, whereas IVVy and IVVz were inversely related with hand angular velocity and with the elbow angle range in the pull phase, respectively.

Resulting from the findings between hand kinematics and IVV (x, y and z), kinematic changes were deeply investigated in **Chapter 3**, as well as the activation of the movement producers (muscles) over the 200 m front crawl swimming event. The suggestion advanced in this chapter regarding the decrease in propelling efficiency due to the decrease of the hand angular velocity combined with a higher relative duration of the pull phase and a backward amplitude normalised to SL increase, was confirmed afterwards in **Chapter 4**. Also, kinematic changes occurred in the depths of the finger, wrist, and elbow, being observed a decrease from the first to the last lap. In the push phase, the elbow angle end back values decreased across the effort imposed by changes in triceps brachii muscle that showed evidences of fatigue (**Chapter 9**), in agreement with the results of Aujouannet et al. (2006). Muscle activation was in agreement with studies reviewed by Clarys and Cabri (1993), showing a selective activation according to the stroke and kick phases, and showing higher activation at the end of the effort for the upper limb muscles (Monteil et al., 1993; Rouard et al., 1997; Stirn et al., 2011; Wakayoshi et al., 1994). The lower limbs KF decreased in the third 50 m, as the SF did, suggesting the same arm-leg coordination throughout the effort. The lower limbs did not show changes in the depth variables and their level of activation of biceps femoris and rectus femoris, only changing from downbeat to upbeat phase working as kick agonistic/antagonistic muscles. Consistent antagonist activity during both extension and flexion phases was observed, as previously described in this kind of movement (Kellis & Kellis, 2001).

As stated before, the font crawl is the most economic conventional swimming technique, but during the course of the 200 m event, changes in C were observed and reflected modifications in $\dot{E}_{tot}$, as well as in the contribution of the energy sources (**Chapter 4**). C showed to be higher in the beginning and at the

end of the 200 m, due to a higher velocity in the beginning of the effort, and to fatigue development at the end. These phenomena have an influence of both energetic and biomechanics factors (Barbosa et al., 2010; Pendergast et al., 2006; Toussaint & Hollander, 1994; Zamparo et al., 2011). From the energetic point of view, the first 50 m accounted for the fact that C is directly related to velocity (Capelli et al., 1998; di Prampero, 1986; Fernandes et al., 2005; Fernandes et al., 2006; Wakayoshi et al., 1995), and at the last lap the anaerobic lactate contribution has increased greatly. The anaerobic lactate contribution increase could have influenced the decrease in the pH, as observed in the 200 m front crawl (Strumbelj et al., 2003), compromising muscle function. Regarding biomechanics, the major influence was observed at the end of the effort where propelling efficiency showed to decrease, as previously described (Toussaint et al., 2006; Zamparo, Bonifazi, et al., 2005), and the possibility of an increase of the internal mechanical work, trough the SR increase (Pendergast et al., 2003; Zamparo, Pendergast, et al., 2005). Although no relationship was found between the decrease in velocity, SL and SF with the increase in blood lactate concentrations, it was possible to observe the evolvement of muscular fatigue of the primer muscles involved in propulsion at the end of the effort (**Chapter 9**), explaining some kinematic and efficiency changes.

The major contribution (65.9%) of the aerobic pathway in the 200 m swim than the anaerobic one (**Chapter 4**), established the importance of the study of the $\dot{V}O_2$ kinetics by modeling the bio-signal (**Appendix III**). The On-$\dot{V}O_2$ kinetics started by a sudden exponential increase at the onset of the effort. It was observed a direct relationship between the mean velocity of the 200 m (and the first 50 m lap) with the $\dot{V}O_{2peak}$. The amplitude of the $\dot{V}O_2$ kinetics and the blood lactate at the end of the effort confirmed that the aerobic power developed during the swim plays a central role among the energy yielding mechanisms in middle distance swimming.

In swimming, the biophysical approach has examined the relationship between C and IVV in the four conventional swimming techniques. Alves et al. (1996) observed a significant relationship between the hip's IVVx and C of backstroke swimming at submaximal velocities, but did not report any relationship between C and IVVx in front crawl; this last fact is in agreement with Kjendlie et al. (2004) that compared children and adults during 4 x 25 m front crawl at submaximal velocities. For the breaststroke, Vilas-Boas (1996) found a correlation (although non-significant) between C and hip's IVVx for the pooled data, however when individual analysis was conducted, both variables were highly correlated. Barbosa et al. (2005) concluded for butterfly, that high IVV was related with lower swimming efficiency inducing an increase in the C. In addition, Barbosa, Lima, et al. (2006) found that increases in C were strongly related to IVVx for all swim techniques, even when partial correlations controlling for the effect of velocity were computed. Nevertheless, during competitive events, the above-referred relationship has not been assessed.

In **Chapter 5,** the analysis between the IVV and C was undertaken, showing a negative **"**within subject" correlation coefficients for the IVVx and IVVz, which is not in agreement with the results found in the literature for large ranges of velocities. In addition, the negative relationship found between IVV (x and z) and velocity in horizontal axis, SL and SR (**Chapter 3**), determine a lower IVV (x and z) with higher velocities. Consequently, as velocity is mostly determined by the vminx than vmaxx, a higher mean velocity in turn gives a lower coefficient of variation (lower IVV) and a higher C, as this one is directly related with velocity. Also, higher velocities or fatigue stages suggest that less time is spent between propulsive phases (higher IdC) (Alberty et al., 2005; Alberty et al., 2009; Chollet et al., 2000; Schnitzler et al., 2010; Seifert, Leblanc, et al., 2010), explaining the positive "between subjects" correlation between IdC and C (**Chapter 8**).

The changes occurred in SR (and SL) showed to be closely related to the coordination mode used (Alberty et al., 2008; Potdevin et al., 2006; Seifert,

Chollet, & Rouard, 2007). Coordination emerges as a consequence of the constraints imposed on swimming action (Newell, 1986), and is characterized by qualitative reorganizations of the movement in the course of practice (Newell, 1991). The patterns of inter-limb coordination during adult locomotion have been quantitatively described for numerous vertebrate and invertebrate species (e.g. Bekoff & Trainer, 1979; Burns, 1973). In humans, arm to leg coordination has mostly been investigated during walking, i.e., in a situation where the arms do not contribute to propulsion, but to the stabilisation of the trunk (Wannier et al., 2001). To examine meaningful coordinative information in front crawl swimming, a study was undertaken (**Chapter 6**) to understand the individual coordination profiling during a 200 m maximal front crawl effort using a continuous spatial-temporal analysis, providing information on the type of relationship (in-phase or anti-phase), and the relative amount of coupling between arms. A strong preservation of anti-phase coordination in front crawl was observed, as previously described (Nikodelis et al., 2005) in spite of the changes occurred in the kinematic and eletromyographic parameters (**Chapter 3**). Different coordinative solutions were identified, in accordance with Glazier et al. (2006) and Seifert (2010), which stated that an effective front crawl technique must be sufficiently flexible and adaptable to enable emerging patterns of coordination to be modified according to constraints. This is more evident bellow 0.75 Hz, a critical value below which swimmers have several motor solutions when the SF is increased (Potdevin et al., 2006; Potdevin et al., 2003; Seifert, Chollet, & Rouard, 2007). Above this value, the number of motor solutions is reduced; however, maximum SF values were 0.68 Hz in the first lap. This suggests, in agreement with Barbosa et al. (2010), that coordination is one of the primer factors in the “cascade” to performance.

As the only observed changes in coordination were temporal, a further coordinative analysis was developed using the IdC (**Chapter 7**). Six national level swimmers performed a 200 m swim for inter-arm coordination assessment purposes. A catch-up mode was observed for the entire effort (IdC < 0%), with an increase in the fourth lap; in fact, in this fatigued stage, swimmers tend to

increase their propulsive continuity, as observed elsewhere (Alberty et al., 2008; Alberty et al., 2005; Alberty et al., 2009), as well as to increase the relative duration of propulsive phases, and decrease the non-propulsive phases (manly the catch phase). These results are supported by the observed decrease in hand angular velocity (**Chapter 6**), reflecting more time spent during the propulsive phase than greater force generation, particularly due to the development of upper limb muscle fatigue (**Chapter 9**).

Inter-arm coordination, assessed by IdC, has been largely used in front crawl swimming, comparing different genders (Seifert et al., 2004), different skill levels (Lerda & Cardelli, 2003; Seifert, Leblanc et al., 2010), different paces (Chollet et al., 2000; Seifert et al., 2004), different specialty (Seifert, Komar, et al., 2010), different breathing conditions (Lerda & Cardelli, 2003; Seifert et al., 2008; Seifert et al., 2005), and using different equipment (Hue et al., 2003; Sidney et al., 2001; Telles et al., 2011). IdC has also been related to oxygen consumption (Fernandes et al., 2010; Komar et al., 2010; Seifert, Komar, et al., 2010), intracycle velocity variations (Figueiredo et al., 2008; Schnitzler et al., 2010; Schnitzler et al., 2008), fatigue (Alberty et al., 2005; Tella et al., 2008), time to exhaustion (Alberty et al., 2008; Alberty et al., 2009; Alberty et al., 2011), SR (Potdevin et al., 2006; Potdevin et al., 2003; Seifert, Chollet, & Rouard, 2007), and competitive events (Alberty et al., 2005; Schnitzler et al., 2011; Seifert, Chollet, & Chatard, 2007). Moreover, in triathlon athletes (Hue et al., 2003; Millet et al., 2002), and disability populations (Querido et al., 2010; Satkunskiene et al., 2005) were also assessed. However, a lot remains to understand during competitive events, and its relationship with other factors, as efficiency parameters (IVV and propelling efficiency) and C (**Chapter 8**).

As the above-mentioned coordinative changes occurred during the 200 m swim (**Chapter 7**), inter-limb coordination adapted, as an optimization mechanism to obtain as much velocity as possible, by increasing the inter-arm continuity. The inexistence of a relationship between IVV (x, y and z) and IdC is in accordance with previous results for high-level swimmers (Schnitzler et al., 2010; Schnitzler

et al., 2008; Seifert, Leblanc, et al., 2010), suggesting an adaption of inter-limb coordination to attain lower energy expenditure that, in the short term, organisms adopt as a process of self-optimization (Seifert, Komar, et al., 2010; Sparrow & Newell, 1998). As an example, the self-regulated SF seemed to be more economical than imposed frequencies (Alberty et al., 2011; McLean et al., 2010). In addition, the IdC showed to be inversely related to η_p, in agreement with the findings that η_p is directly related to SL (**Chapter 4**), and that IdC directly relates with SR (Alberty et al., 2009; Chollet et al., 2000; Potdevin et al., 2006; Seifert, Chollet, & Rouard, 2007). The observed positive "between subject" correlation between IdC and C supports the late findings (as C is inversely influenced by η_p), and also reflect that the preferred coordination mode of each swimmer is influenced by several constraints (Newell, 1986; Seifert, Chollet, & Rouard, 2007; Sparrow & Newell, 1998). As an example, the type of training (with implications in coordination) was suggested as primarily responsible for these results, in agreement with the cluster analysis presented in **Chapter 6.** Clusters were mostly defined by coordination parameters.

The absence of a significant relationship between IdC and IVVx suggests that swimmers may optimize the IVVx, since it is directly coupled to variations in the optic flow, as is the case in humans during terrestrial locomotion where they use not only the egocentric direction but also the optic flow to achieve their goal (Bruggeman et al., 2007; Fajen, 2008; Sun et al., 1992; Warren et al., 2001). Optic flow is the pattern of visual motion at the moving eye (Gibson, 1950), i.e., the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and the environment. Hence, using visual information, the propulsive and resistive actions of the swimmer could be improved to enhanced coordination with the benefit of reducing energy loss due to excessive intracycle velocity variations of the CM. The possibility that swimmers in this study optimized their stroke coordination by using IVV' optic flow is reasonable, as humans have been shown to acquire numerous perceptual-motor skills over the lifetime, and this could have happened during their daily training. These skills may involve a tight coupling

between continuously available information in sensory arrays and continuously controlled movements of the body (Fajen, 2008). It is widely recognized that adaptation to changes in the dynamics of the body and environment plays a crucial role in the acquisition and execution of skills such as reaching (Lackner & Dizio, 1994; Shadmehr & Mussa-Ivaldi, 1994), and throwing (Bruggeman et al., 2005), and walking (Bruggeman et al., 2007; Choi & Bastian, 2007). Factors such as growth and fatigue can significantly alter the limb movements that result from a particular pattern of muscle forces. The ability to adapt to such changes, which has been thoroughly investigated by imposing forces on the body during execution of the task, provides the means by which flexible, robust control is achieved (Fajen, 2008). As optic flow plays a central role in control of walking and adaptation of the visuo-locomotor mapping (Bruggeman et al., 2007), it is highly likely that it can also influence aquatic locomotion.

As shown, coordination seems to have a great importance on performance (Barbosa et al., 2010). However, coordination as specified combination of joint moments (Prilutsky, 2000), is produced by the distribution of muscle activation or force among each muscle (Hug, 2011; Wakeling et al., 2010; Wakeling et al., 2011; Wakeling & Horn, 2009). This way, in **Chapter 9** the study of upper and lower limbs muscle fatigue was included. The observed suggestion of muscular fatigue (**Chapter 3**) was confirmed by the increases of iEMG and of FI (decrease of the frequency spectrum) observed for the upper limb muscles. No evidence of fatigue for the lower limbs muscles, confirming the greater involvement of the upper limbs regarding the lower limb, as observed in **Chapter 3**. These results suggested that, in spite of performing at maximal intensity, the muscles under observation were involved at a sub-maximum level, as observed by Stirn et al. (2011) in the all-out 100 m front crawl. As it was discussed in this chapter (**Chapter 9**), changes in amplitude and frequency parameters cannot be attributed solely to the fatigue process, since EMG parameters can also be affected by alterations in motor control. In fact, significant relations were observed between EMG and kinematic variables that could influence them (Potvin, 1997), and should be analysed more profoundly.

Nevertheless, several kinematic, physiological and coordinative variables, assessed in this Thesis, confirmed the state of fatigue. In addition, the only relationships found between kinematic parameter and EMG amplitude were with the muscles that did not presented evidence of fatigue.

At high-level performance, individual modifications/adaptations are determinant. In **Chapter 10,** the Portuguese National record holder of the 200 m freestyle was evaluated during this competitive distance, regarding the velocity, SL, SR, IVV (x, y and z), IdC, $\dot{E}_{tot}$, and EMG. The results were in accordance with the findings of the chapters that investigated each one of those variables separately. However, for the first time, it was possible to observe the biomechanical, energetic, coordinative and muscular factors in an evident interplay during the 200 m event, as fatigue was evolving towards the end. Stroking parameters (SL and SR) decreased along the 200 m and, as a result, velocity decreased. The decrease of the SL values were linked to the development of muscular fatigue, and, as a consequence, SR increased in the last 50 m to attempt to maintain velocity. This was attained by an IdC increase, through a higher relative duration of the propulsive phases, in contrast with decrease of the non-propulsive phases. All these changes converged to IVVx stability. The $\dot{E}_{tot}$ was higher in the first 50 m, resulting from an exponential increase of the $\dot{V}O2$ kinetics, and in the fourth 50 m due to the anaerobic lactic contribution. The high anaerobic lactic contribution, evidenced from the capillary blood lactate concentration, implied a pH decrease, possibly inducing muscle fatigue, observed in the spectral content of the EMG signal.

Linking the factors' contribution to dynamic changes in demand, face to the constraints imposed during the effort, is necessary to understand the mechanisms underlying swimming locomotion. With the increased understanding of the 200 m front crawl performance influencing factors, it became important to analyse factors contribution to this biophysical phenomenon. In **Chapter 11** the specific contribution of the biomechanical, energetic, coordinative, and muscular factors to the performance of a 200 m

front crawl, and its partial laps were assessed, as well as a deep discussion of the relationship between the parameters assessed in each factor was undertaken.

A framework for the interaction of the biomechanical, energetic, coordinative, and muscular factors is presented in Figure 2, resulting from the reorganization of the Figure 1 of this chapter, and based on the theoretical background and the chapters of this Thesis.

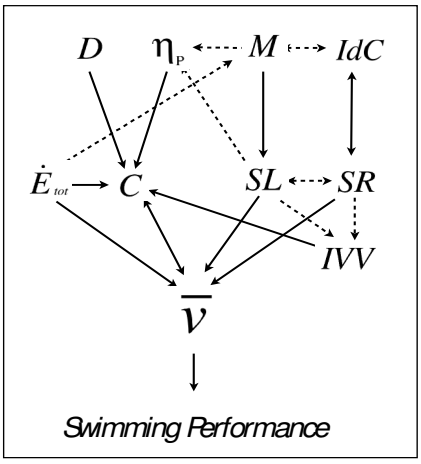


Figure 2. The relationship between biomechanical, energetic, coordinative and muscular factors with performance in competitive swimming. $\bar{v}$: mean swimming velocity; *SF*: stroke frequency; *SL*: stroke length; *IVV*: intracycle velocity variation of the centre of mass; η_p: propelling efficiency; *C*: energy cost; $\dot{E}_{tot}$: energy expenditure; *IdC*: index of coordination; *M*: muscular activity; *D*: hydrodynamic drag.

In a macroscopic view, the contribution of each factor (biomechanical, energetic, coordinative or muscular) changed over the 200 m front crawl event in accordance to the interplay and relationships discussed along this Thesis, and expressed in Figure 2. The biomechanical, energetic, coordinative, and muscular factors contributed, in average, 58.1%, 11.2%, 18.9% and 11.8%, respectively to the mean velocity, with SL and SR parameters by themselves explaining 33.7% of the 200 m mean velocity. It was a continuous decrease of the biomechanical factor, continuous increases of the energetic and muscular factors, and a “U” shape (with a higher increase at the end of the effort) of the coordinative factor. These changes, and interplay of contributions, seem to

reinforce the three stages found: the first lap, the second and third lap, and the fourth lap.

The relative contribution of each factor changed over the effort, due to their interdependence. Muscle activation in general, and in swimming in particular, depends on the mechanics of the movement, but in turn, the mechanics of the limbs depend on muscles that actively develop force to drive movement. This emphasizes that the muscle limits the maximal performance of a limb in terms of both power output and efficiency (Wakeling et al., 2010); however, the movement mechanics also determines muscle recruitment (Wakeling et al., 2006). The movement mechanics can deviate muscle recruitment from the optimal shortening velocities for a muscle fibre to generate maximum power (typically 0.25–0.36 of the maximum intrinsic speed of the fibres shorten velocities; He et al., 2000; Swoap et al., 1997), and operate at maximum efficiency (0.15–0.29 of the maximum intrinsic speed of the fibres shorten velocities; He et al., 2000; Hill, 1964). Muscles are related to the mechanical demands of each movement with the appropriate timing and level of activation, being related to the velocity and load of the movement (Wakeling & Horn, 2009).

Movement coordination allows the best power production in face of the imposed constraints (organismic, environmental, and task). The power output (and propelling efficiency) from a limb should thus be expected to depend on the coordination pattern. Coordination relates to the mechanics, as motor control refers to the absolute magnitude of the limb or limb segment movement, expressed as a property of the kinetics or kinematics (Sparrow & Newell, 1998). Optimal coordination is required for high power outputs and high mechanical efficiencies from the limb. Subsequently, the metabolic cost of generating a given power is changed as well.

The energy expenditure is the result of the metabolic equivalent of all the forces generated by the muscles (Minetti, 2011). However, mechanisms behind the effects of various factors (e.g. velocity, fatigue) on energy consumption, and thereby into the function of the metabolic processes involved in work

production, are not only directly associated with the work conversion process (muscle contraction), but also, for example, ventilation and circulation (Ettema & Loras, 2009), and in swimming energy expended in pushing away masses of water changing its kinetic energy (Barbosa et al., 2010; Toussaint & Hollander, 1994; Zamparo et al., 2011).

To achieve the best swimming performance, and to attain a more effective movement, sensory feedback is integrated and alters the motor output that controls movement of the body and limbs. The 200 m front crawl swimming suites the constraints and attributes that dictate the underlying mechanisms of movement, accompany by different energetic demands, patterns of coordination, and muscle activation and efficiency. It seems that knowledge of the precise factors that limit performance is essential, supporting its understanding. It is improbable that the factors explaining performance are restricted to only one scientific discipline (e.g. physiological system) (Abbiss & Laursen, 2005; Noakes, 2000). The models (e.g. cardiovascular/anaerobic, muscle recruitment, biomechanical, psychological) by themselves fail to totally explain performance, as the changes can or cannot be causally linked, i.e., they do influence performance or they occur with other adaptations that are in fact linked with performance.

Chapter 13. Conclusions

The findings obtained in the collection of studies presented in this Thesis emphasize the importance of the biophysical approach to evaluate swimming performance. It can be concluded that:

(i) the 200 m front crawl event was shown to be comprised of three different components, the first lap, the two middle laps and the last lap. The first and last seem to have a higher influence in performance than the second and third laps;

(ii) the 200 front crawl performance is achieved through a balance of several factors denoting particular importance for the biomechanical factors (SL, SR and η_p), which stress the importance of the technical training. However, dynamical changes occurred in the relative importance of the contributing factors, especially in the fourth lap with the energetic, coordinative and muscular factors becoming predominant.

(iii) IVV in x, y and x axes are stable over the 200 m front crawl;

(iv) horizontal velocity is directly influenced by vmax and vmin in the direction of swimming and inversely influenced by IVVx and IVVz;

(v) IVV in all the axes of the motion is influenced by hand kinematics (e.g. IVVx was positively related to the backward horizontal amplitude normalized to stroke length, IVVy negatively related with hand angular velocity, and IVVz negatively related with the elbow angle range in the pull phase);

(vi) fatigue develops during the 200 m swim, as shown by the increased iEMG, Freq, C and the reduction in both SL, SF, and propelling efficiency;

(vii) underwater upper limb kinematics is influenced by fatigue, provoking changes in swimming technique (e.g. hand angular velocity, maximal depths of finger, wrist and elbow, and elbow angle at the end back significantly diminished along the 200 m);

(viii) the contribution of aerobic, anaerobic lactic and anaerobic alactic energy sources for the 200 m front crawl are of 65.9, 13.6, and 20.4%,

respectively. The three energy sources available for exercise change their contribution along the effort;

(ix) the rises in IVV (x and z) determine a lower C during the 200 m, reflecting mainly the changes on velocity and coordination;

(x) although changes in the factors that influence 200 m performance are common among swimmers, individual coordinative adaptations occur;

(xi) swimmers maintain a “catch-up” coordination mode during the 200, presenting a more continuous inter-arm coordination visible at the end of the effort (this change is attained mainly by the decrease of the catch and glide phases);

(xii) IdC showed a negative relation with propelling efficiency;

(xiii) EMG parameters (amplitude and frequency) for the upper limb muscles were in accordance with the development of fatigue, resulting from the sub-maximal application of forces during the arm-stroke cycle.

The findings of the studies presented in this work may contribute to a better understanding of the relationships between the factors that contribute to the swimming performance. In addition, the data stress the great specificity of the 200 m front crawl and changes in the factors that influence performance during the event. These results highlight the importance for research and training of coupling biomechanical, energetic, coordinative and muscular information for a better understanding of performance.

Chapter 14. Suggestions for future research

Despite of the importance of a holistic approach of the sports phenomena, there is still a lack of research in the swimming Biophysical domain. In this sense, and acknowledging the main findings of this Thesis, it seems important to continue researching in this field, following some ideas and unanswered questions:

(i) how do these factors (biomechanical, energetic, coordinative, and muscular) interplay in other swimming events?;

(ii) combine the analysis of the assessed factors (biomechanical, energetic, coordinative, and muscular) with a measure of active drag, propulsive force, and muscle power;

(iii) how do these factors (biomechanical, energetic, coordinative, and muscular) actually influence/change the propulsion mechanics? Which are in fact the human swimming propelling mechanisms?;

(iv) which is the role of optic flow in the IVV?;

(v) a performance swimming model that combine the studied factors (biomechanical, energetic, coordinative, and muscular) needs to be developed;

(vi) which is the brain role in the adaptation to the constraints?;

(vii) which is the influence of training in the interplay between these factors?

(viii) what does exactly limit swimming performance? Which factors are really influencing performance and which ones are only linked to these factors?

Appendix I

Does the hip reflect the centre of mass swimming kinematics?

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Abstract

The purpose of this study was to determine the relationship between the hip point and the centre of mass for kinematical parameters (displacement, velocity and acceleration) in the three axes of motion. One complete stroke cycle was analysed in eight swimmers performing a 25 m front crawl swim test at high intensity. Within-subject correlation coefficients were computed between the centre of mass and both hips, as well as mean of the errors, RMS error and a paired sample t-test. High correlation coefficients were found for the displacement in the horizontal direction ($r = 1.00$ for both hips) and low to moderate correlation coefficients ($r = -0.01$ to $r = 0.54$) were found for all other studied variables. Moreover, moderate to large RMS differences were observed: (i) between 0.05 and 0.15 for the displacement; (ii) between 0.16 and 0.30 for the velocity and (iii) between 5.28 and 7.86 for the acceleration. Complementarily, RMS differences for the intracyclic velocity variation were between 0.07 and 0.18. Considering the centre of mass and hips values it were found statistical differences in velocity in x, acceleration in x and y, and intracyclic velocity variation in y axes. Therefore, results suggest that the hip point does not represent most kinematical parameters of the estimated centre of mass in front crawl swimming.

Key words: Biomechanics, Digitization, Three-dimensional, Front crawl

Introduction

Achieving higher velocities in competitive swimming lead researchers and coaches to assess and analyse swimmers' performance determinant factors. The intracyclic velocity variation (IVV) characteristic of a stroke cycle has been considered as an indicator of effective technique [6]. It is common to assess the IVV profile of the hip through digitizing or mechanical methods [12,13], due to the complex and time consuming procedures of the digitizing method needed for the assessment of the centre of mass (CM) kinematics. Since the CM and the hip have high proximity when subjects stand in anatomical position, it is usually accepted that the hip might provide an accurate estimate of variations in the swimming CM kinematical parameters. However, some authors (eg. [11]) suggested that it is more accurate to analyse the IVV of the CM, based on the fact that intersegment actions during the stroke cycle constantly change the CM position. Additionally, the typical body rotation in front crawl technique may affect hip motion. These facts justify the comparison between these parameters.

When comparing the kinematics of the CM and of the hip in front crawl, it is common to assess only the IVV in the swimming direction (i.e. in the horizontal axis). Generally, significant differences in IVV from hip point to CM is observed, despite some conflicting results [7,11]. Moreover, considered the multi-planar nature of swimming, a three-dimensional approach is required. It should also be considered that, although hips may move in opposite directions in the vertical and lateral axes of motion, quantifying the differences between CM and hip may allow a better understanding of the swimming movement.

The purpose of this study was to analyse, for the horizontal (x), vertical (y) and lateral (z) axes of motion, the validity of the hip point to properly represent the kinematical parameters of the CM in front crawl. In this sense, the relationship between the hips (right and left points) and the CM velocities was analysed. In addition, and according to Barbosa et al. [2] for butterfly stroke, displacement and acceleration were also assessed and compared.

Methods

Experimental Procedure

Eight male high level competitive swimmers volunteered to participate in this study (20.3 ± 2.8 years old, 69.4 ± 4.8 kg, 177.2 ± 5.9 cm, 183.3 ± 7.0 cm of arm span, 10.0 ± 2.6% of fat mass and a training experience of more than 10 years). All subjects signed a written informed consent in which the experimental protocol was described.

Swimmers were monitored in a 25 m a near maximum front crawl test, when passing through a specific pre-calibrated space. A cubic calibration frame with dimensions of 3 x 3 x 3 m for the x, y and z directions was used, placed 16 m from the starting wall of the pool. Thirty points of calibration were used, and the synchronisation of the images was obtained using a pair of lights visible in the field of each video camera. Six stationary video cameras (*Sony® DCR-HC42E)* were used: two located on the surface and four underwater. The angle between the axes of the two surface cameras was approximately 120º, while the angles between axes of adjacent underwater cameras varied from 75º to 110º. One complete arm stroke cycle, without breathing, was analysed (a six-beat kick per arm stroke cycle synchronization was assumed). Test session took place in a 25 m indoor pool. In-water pushing starts were used in order to minimize the starting effect.

Data analysis

The video images were digitized with Ariel Performance Analysis System *(Ariel Dynamics, USA)* at a frequency of 50 Hz, manually and frame by frame. Zatsiorsky and Seluyanov's model adapted by de Leva [5] was used, being the following 21 anatomical reference points marked with black tape: vertex, 7th cervical, mandible (mental protuberance), humeral heads, ulnohumeral joints, radiocarpal joints, 3rd dactylions, trochanter major of femurs, tibiofemoral joints, talocrural joints, calcanei and acropodion. Image coordinates were transformed to 3D object-space coordinates using the Direct Linear Transformation algorithm [1]. After residual analysis for a wide range of cut-off frequencies, 6

Hz was selected as the optimal cut-off frequency for the smoothing of the data using a low pass digital filter. Root Mean Square (RMS) reconstruction errors of eight validation points on the calibration frame, which were not served as control points, were, respectively for x, y and z axes: (i) 3.4, 2.5 and 5.6 mm for above the water and (ii) 7.5, 1.9 and 3.2 mm for underwater.

Displacement (d), velocity (v) and acceleration (a), from right and left hip points (trochanter major) and the CM in x, y and z axes were the selected parameters for analysis. The reliability of the digitizing procedure was established by performing two repeated digitizations of a randomly selected trial. As proposed before [3], the coefficient of repeatability, that involved calculating the 95% limits of agreement (± 1.96 standard deviations of the differences) for each variable of interest, was obtained, being: (i) 0.01 m for dx, dy and dz; (ii) 0.09, 0.04 and 0.07 $m.s^{-1}$ for vx, vy and vz, respectively and (iii) 3.00, 1.73, 3.98 $m.s^{-2}$ for ax, ay and az, respectively.

Statistical analysis

All data were checked for distribution normality with the Shapiro-Wilk test. The within-subject correlation coefficients between variables were tested [4] and a paired sample t-test was used to investigate the relationship between the hip point and the CM. Significance level was set at 5%. IVV was calculated through the coefficient of variation of the v(t) mean values. The mean value of differences between hip point and CM, as well as the RMS errors, were also computed.

Results

Within-subject correlation coefficients in x, y, and z axes, between right hip and the CM, and between left hip and the CM, for displacement, velocity and acceleration parameters are presented in Table 1.

Table 1. Within-subject correlation coefficients between right hip and CM and between left hip and CM for the intracyclic displacement (d), velocity (v) and acceleration (a) in x, y, z axes.

	dx(r)	dy (r)	dz (r)	vx (r)	vy (r)	vz (r)	ax (r)	ay (r)	az (r)
Right hip point	1.00	0.02	0.54	0.08	-0.01	0.04	0.09	0.19	0.19
Left hip point	1.00	0.01	0.51	0.33	-0.01	0.05	0.44	0.08	0.20

High and moderate correlation coefficients values were observed for dx and dz, respectively. For all the other studied variables, it were found low correlation values. In addition, negative values were found, suggesting a conflict between the control method (CM values) and the hip assessment protocol.

Differences between CM and hip values of relevant parameters are presented in Table 2.

Table 2. Validity of the right and left hip values (using the centre of mass as criterion measurements) for displacement (d), velocity (v), acceleration (a) and, intracyclic velocity variation (IVV) for the x, y and, z motion axes.

Variable	Mean errors		RMS errors		Paired samples t-test (p value)	
	Right hip	Left hip	Right hip	Left hip	Right hip	Left hip
dx (m)	-0.05	-0.07	0.05	0.06	<0.001	<0.001
dy (m)	-0.03	-0.03	0.06	0.06	<0.001	<0.001
dz (m)	0.15	-0.14	0.15	0.14	<0.001	<0.001
vx ($m.s^{-1}$)	0.01	0.00	0.26	0.27	0.202	0.898
vy ($m.s^{-1}$)	-0.18	-0.17	0.30	0.27	<0.001	<0.001
vz ($m.s^{-1}$)	-0.07	-0.08	0.16	0.17	0.002	<0.001
ax ($m.s^{-2}$)	-0.08	0.28	7.07	7.86	0.690	0.364
ay ($m.s^{-2}$)	-0.17	0.15	5.90	5.61	0.211	0.232
az ($m.s^{-2}$)	0.21	-0.12	5.28	5.31	0.020	0.296
IVVx	-0.06	-0.11	0.07	0.12	0.006	<0.001
IVVy	-0.01	-0.02	0.07	0.12	0.655	0.709
IVVz	-0.05	-0.13	0.11	0.18	0.186	0.036

Discussion

The main aim of this study was to verify the validity of the hip point assessment to accurately reflect the kinematics of the CM. It seems to accurately reflect the displacement in the x and z axes, presenting high and moderate correlation values, respectively. However, differences were found between CM and both hips mean values.

The observed correlation values between the two above-referred parameters suggest the low validity of the hip point as a representative landmark of the velocity and acceleration profiles of the body CM, since correlation values ranged from -0.01 to 0.19, and from -0.01 to 0.44 for the right and left hips, respectively. In a previous study conducted in butterfly [6], the referred relationships were only accepted for very high correlations values ($r>0.95$), in spite of their statistical significance. Furthermore, it was observed that the correlation of vy, for both hips, was negative, indicating opposition in velocity profiles in the y axis. Despite the low correlation values for the forward velocity, no differences were observed for both hips and the CM for vx (cf. Table 2) as previously suggested by Maglischo et al. [7]. However, both hip points tend to underestimate IVVx as was suggested before by Psycharakis and Sanders [11].
Regarding the acceleration parameter, differences were found only for the right hip point in az. Nevertheless, profiles do not seem to match, presenting low correlation and high RMS values, in tendency.
Differences between the results obtained for both hips might be explained by somewhat asymmetrical rotations along the longitudinal axis and also some asymmetrical lateral inclinations of the trunk out of the most convenient horizontal alignment of the body.
Notwithstanding the relevancy of the data, it is important to mention the errors associated to image distortion as a result of filming through three media (air, perspex and water), to the digitization and to the three-dimensional reconstruction [9], which are likely to affect data acquisition. Also, the anatomical model adopted may influence in the estimation of the CM [14], being a daunting task to conduct this kind of studies during human movement. As Plagenhoef [10] referred, when shoulder movement is involved in any motion, the trunk CM estimation is less accurate. In summary, it can be concluded that the hip, in the majority of the assessed parameters, does not accurately represent the CM in front crawl swimming. Moreover, the difficulties in the CM assessment methodology should be taken into account.

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Appendix II

Reconstruction Error of Calibration Volume's Coordinates for 3D Swimming Kinematics

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Abstract

The aim of this study was to investigate the accuracy and reliability of above and underwater 3D reconstruction of three calibration volumes with different control points disposal (#1 - on vertical and horizontal rods; #2 - on vertical and horizontal rods and facets; #3 - on crossed horizontal rods). Each calibration volume (3 x 2 x 3 m) was positioned in a 25 m swimming pool (half above and half below the water surface) and recorded with four underwater and two above water synchronised cameras (50 Hz). Reconstruction accuracy was determined calculating the RMS error of twelve validation points. The standard deviation across all digitisation of the same marker was used for assessing the reliability estimation. Comparison among different number of control points showed that the set of 24 points produced the most accurate results. The volume #2 presented higher accuracy (RMS errors: 5.86 and 3.59 mm for x axis, 3.45 and 3.11 mm for y axis and 4.38 and 4.00 mm for z axis, considering under and above water, respectively) and reliability (SD: underwater cameras ± [0.2; 0.6] mm; above water cameras ± [0.2; 0.3] mm) that may be considered suitable for 3D swimming kinematic analysis. Results revealed that RMS error was greater during underwater analysis, possibly due to refraction.

Key words**:** Accuracy, Reliability**,** Digitisation, Swimming, Kinematics

Introduction

When analysing human movement, it is a common practice to measure the position of significant body landmarks to determine the movement kinematics (Challis, 1995). This approach has been applied to a wide variety of problems (Chen et al., 1994), particularly to evaluate the above and underwater swimming stroke (Figueiredo et al., 2009).

Analysis of multi-planar activities engage three-dimensional (3D) reconstruction, frequently using the direct linear transformation algorithm by transforming two-dimensional image coordinates – DLT (Chen et al., 1994; Allard et al., 1995; Challis, 1995), as proposed by Abdel-Aziz and Karara (1971). With the DLT technique, an appropriate number of points with known 3D coordinates on a calibration volume are used as control points for the calibration of the recording space. In this procedure, the number and distribution of the control points, as well as the size of calibration volume, affect the reconstruction accuracy (Lam et al., 1992; Chen et al., 1994).

For aquatic propelling purposes, swimmers must constantly interact with water. However, since it is a complex and highly integrated form of movement, all the immersed and emerged body parts play a key role in this sport. The kinematic analysis of the swimming locomotion impose obstacles to data acquisition, particularly by the existence of errors associated to image distortion, digitisation and 3D reconstruction (Payton and Bartlett, 1995; Kwon and Casebolt, 2006); thus, it seems important to observe its influence on the final results, analysing validity, reliability, and accuracy (Scheirman et al., 1998; Hopkins, 2000). When referring to underwater 3D kinematic analysis, regardless of the equipment used (underwater housing, underwater windows or periscope systems), refraction implies higher reconstruction error (Yanai et al., 1996; Lauder et al., 1998; Kwon, 1999; Kwon and Lindley, 2000).

Three-dimensional reconstruction has been frequently used in swimming studies (Cappaert et al., 1995; Payton and Bartelett, 1995; Berger et al., 1999; Figueiredo et al., 2009). However, the study of its accuracy has been scarce (Psycharakis et al., 2005; Gourgoulis et al., 2008). The purpose of this study

was to assess the influence of the number of control points in the accuracy of the under and above water 3D reconstruction. In addition, the influence of the control location was also assessed, and both environments were compared.

Material and Methods

Recordings of the different control points distribution in a calibration volume (Figure 1) were carried out simultaneously by four under and two above water cameras (Sony® DCR-HC42E). The volumes were positioned half above and half below water surface, in a 25 m swimming pool. The cameras were mounted at an equal distance from the centre of the calibration volume, and their optical axes formed an angle of ~100° between the axes of the two above water cameras; the angle between below water cameras varied from ~75°to 110°. A LED system visible in the field of view of each camera was used for its temporal synchronisation. Cameras were placed at 1.0 to 1.5 m depths to avoid errors due to its axes being in the same reference planes of the volume. The above water cameras were placed at height of 3.0 to 3.5 m.

All calibration volumes were made-up from 1 cm diameter aluminium tubing, being 3 × 2 × 3 m in the horizontal (x), vertical (y) and lateral (z) directions, respectively. The size of the calibration frame was established to allow a complete stroke cycle of front crawl swimming.

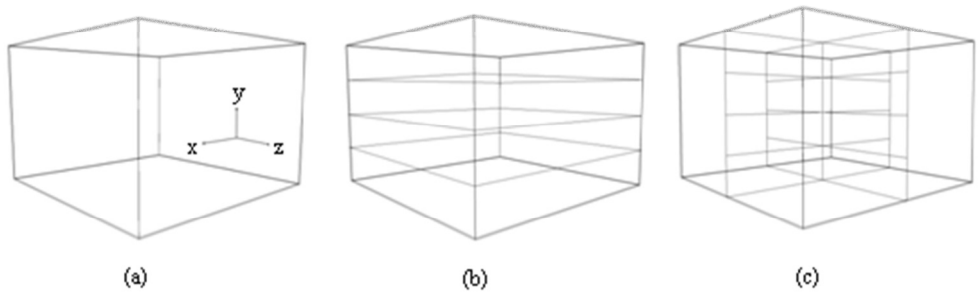


Figure 1. Calibration volumes: (a) calibration volume #1 where the control points are distributed on vertical and horizontal rods; (b) calibration volume #2 where the control points are distributed on vertical and horizontal rods and facets; (c) calibration volume #3 where the control points are distributed on crossed horizontal rods.

To assess the number of control points required to maximise the accuracy of 3D coordinate reconstruction, 12 markers in the calibrated space were digitised over 50 frames for each underwater and above water camera views. Seven series of digitising were performed for this set of 12 markers, using 8, 12, 16, 20, 24, 28 and 30 control points, both for above and below water. In addition, the used validation points did not serve as control since the DLT algorithm is optimised for its reconstruction (Challis and Kerwin, 1992; Chen et al., 1994; Kwon, 1999).

All reconstruction errors were calculated from the raw coordinate data without any smoothing procedure (Scheirman et al., 1998), and determined by the Root Mean Square (RMS) error of the 12 validation points (for each calibration volume) using the following equations:

$$Ex_r = \sqrt{\frac{\sum_{i=1}^{N}(x_{ni} - x_i)^2}{N}} \quad (1)$$

$$Ey_r = \sqrt{\frac{\sum_{i=1}^{N}(y_{ni} - y_i)^2}{N}} \quad (2)$$

$$Ez_r = \sqrt{\frac{\sum_{i=1}^{N}(z_{ni} - z_i)^2}{N}} \quad (3)$$

$$E_r = \sqrt{\frac{\sum_{i=1}^{N}(x_{ni} - x_i)^2 + (y_{ni} - y)^2 + (z_{ni} - z_i)^2}{N}} \quad (4)$$

where E_{Xr}, E_{Yr}, E_{Zr} and E_r were the RMS errors for each axis and for the resultant error, respectively; x_{ni}, y_{ni} and z_{ni} were the real coordinates; x_i, y_i and z_i were the reconstructed coordinates; and N was the number of points used. To obtain reliability estimation, one operator (to avoid any inter-operator errors) repeated the procedure 10 times, being considered as the standard deviation value across all digitisation of same the marker.

Results

Figure 2 presents the RMS errors for the x (left panel), y (centre panel) and z (right panel) coordinates, for different numbers of underwater control points in the three studied calibration volumes.

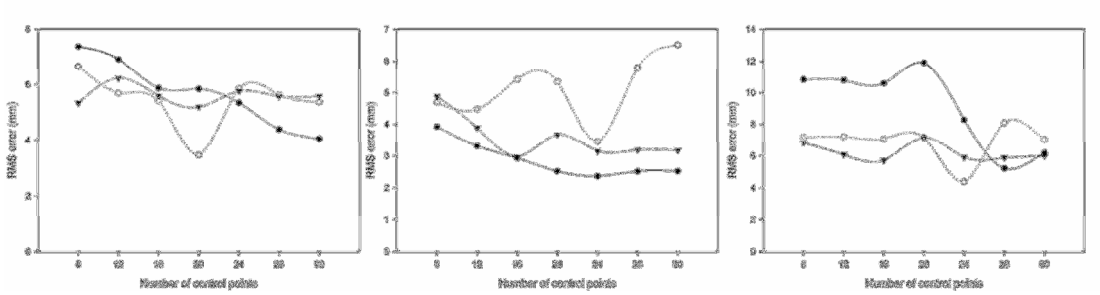


Figure 2. Underwater RMS errors for the x (left panel), y (centre panel) and z (right panel) axes for the different calibration volumes (#1 - solid line, #2 - dotted line and #3 - dashed line).

Figure 3 shows the RMS errors for the x (left panel), y (centre panel) and z (right panel) coordinates, for different numbers of control points above water in the three studied calibration volumes.

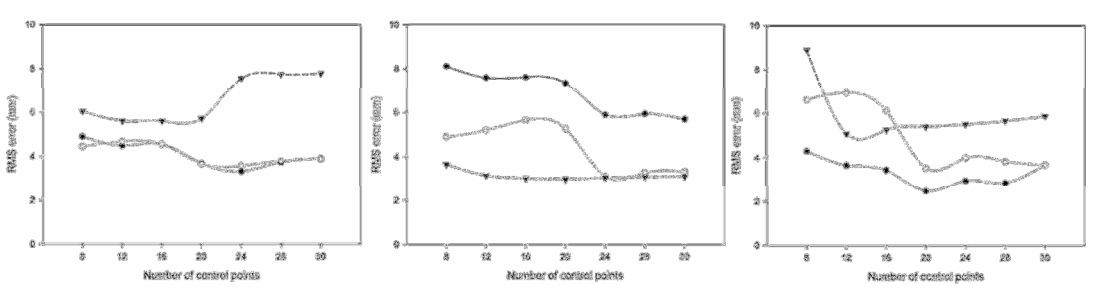


Figure 3. Above water RMS errors for the x (left panel), y (centre panel) and z (right panel) axes for the different calibration volumes (#1 - solid line, #2 - dotted line and #3 - dashed line).

The resultant RMS errors are presented in Table 1, being possible to observe higher underwater values comparing to the above water values.

The reliabilities of one marker varied between ± [0.2; 0.6] mm for the underwater cameras, and between ± [0.2; 0.3] mm for the above water cameras.

Table 1. Resultant RMS errors for underwater and above water recordings for the #1, #2 and #3 calibration volumes

Number of control points	Underwater			Above water		
	#1	#2	#3	#1	#2	#3
8	7.38	6.19	5.69	5.17	5.32	6.19
12	7.01	5.80	5.40	5.25	5.60	4.61
16	6.47	5.97	4.76	5.21	5.44	4.62
20	6.76	5.33	5.34	4.51	4.16	4.69
24	5.34	4.56	4.94	4.06	3.57	5.37
28	4.04	6.51	4.88	4.18	3.64	5.49
30	4.25	6.30	4.92	4.43	3.64	5.58

Discussion

The results of the present study revealed that for the underwater recordings accuracy increased as the number of control points augmented (until 20-24, depending of the studied volume), as reported before (Lauder et al., 1998; Psycharakis et al., 2005). Regarding the above water recordings, accuracy also increased with the number of the control points (8 to 20-24), as reported by Chen et al. (1994) and Shapiro (1978). A further increase until 30 points did not improve the accuracy of both measurements.

The calibration volume #2 showed lower resultant RMS error for under and above water environments, representing 0.2 % of the calibrated space for each underwater axes, and 0.1, 0.2 and 0.1 % of the calibrated space for the x, y and z above water axes.

Considering the volume of the calibrated space, the errors were similar or lower than those reported previously. For the underwater environment Payton and Bartlett (1995) reported values of 2.3, 3.3 and 2.9 mm, while Lauder et al. (1996) observed RMS values ranging from 1.86 to 2.82 mm (lateral axis), from 4.53 to 7.32 mm (horizontal axis) and from 3.51 to 7.76 mm (vertical axis). Psycharakis et al. (2005) presented RMS error values of 3.9, 3.8 and 4.8 mm for the x, y and z axes respectively, representing 0.1, 0.2 and 0.5 % of the calibrated space. Payton et al. (2002) reported mean errors of 1.5 to 3.1 mm for a 1.1 m^3 volume (representing 0.2 % of the calibrated space for each direction). Kwon et al. (1995), for a calibration volume of 3 x 1 x 1 m, referred RMS values

of 6.4, 6.6, 4.2 mm for x, y and z axes, respectively. Gourgoulis et al. (2008), presented for a small (1 x 1 x 1 m) and large (1 x 3 x 1 m) calibration volume, RMS values of 1.61 and 2.35 mm (lateral axis), 2.99 and 4.64 mm (horizontal axis) and 2.83 and 2.59 mm (vertical axis), respectively.

For above water reconstruction, Coleman and Rankin (2005) studied the golf swing and reported RMS errors of 5.1 to 9.8 mm (representing 0.4, 0.5 and 0.3 % of the calibrated space, for the x, y and z axes, respectively). Challis (1995) presented values ranging from 6.1 to 23.0 mm (calibration volume with 1 x 1 x 0.6 m of dimensions), while Chen et al. (1994), for a calibration volume of 2.10 x 1.35 x 1.00 m, found a mean error ranging from 1.8 to 3.6 mm for x, 1.9 to 2.7 mm for y, 5.4 to 12.8 mm for z, and a resultant from 6.6 to 1.6 mm, depending on the number of control points used. In addition, Yanai et al. (1996) reported mean resultant errors ranging from 8.34 to 16.44 mm for the above and from 9.93 to 16.22 mm for the below water control volumes (1.5 x 8.4 x 2 m).

The higher RMS errors observed in the horizontal axis, independently of the recording environment, are in agreement with the literature (Lauder et al., 1996; Yanai et al., 1996). According to Chen et al. (1994), the greater reconstruction error in the horizontal axis could be attributed to the cameras' set-up regarding to the calibration volume, i.e. when the angle between the optical axes of the cameras is low, the resolution of a given distance on the image plane is different in the horizontal than in the other two axes. Consequently, random errors during the digitisation cause higher reconstruction errors in the longitudinal axis. However, the angles used in the present study ranged between 75 and 110º, which are higher than those used by Chen et al. (1994) and Gourgoulis et al. (2008): 35 and 41º, respectively. These higher RMS values in x axis occurred only for some of the control points series (Figure 2).

The present results revealed that during underwater recordings the RMS reconstruction errors were greater comparing to those obtained above the water, independently of the calibration volume used, which is in accordance with the literature (Yanai et al., 1996; Lauder et al., 1998; Gourgoulis et al., 2008). These increased reconstruction errors, when underwater recordings were analysed, were probably due to light refraction (Lauder et al., 1996;

Lauder et al., 1998; Kwon and Lindley, 2000; Kwon and Casebolt, 2006). Furthermore, according to Kwon and Lindley (2000), during the calibration of the underwater space, the real 3D coordinates of the control points are forced to fit to the deformed image-plane coordinates. Although this mismatch error could be evenly distributed through the control volume, its maximum values (calibration error) normally occur at the boundary of the control volume, due to the non-linear distortion caused by refraction (Kwon and Lindley, 2000). In addition, the observed results pointed out a good reliability, since small errors were found in our study. In fact, the reliability of the coordinate reconstruction was similar (or even better) than the values reported by Psycharakis et al. (2005): ± 0.4, ± 0.5 and ± 0.4 mm, for the x, y and z axes, respectively.

The results of this study indicated that the reconstruction errors were higher in underwater than above water environment. However, in both conditions, the magnitude of the reconstruction errors may be considered suitable for 3D swimming kinematic analysis. Complementarily, in spite of a lower resultant RMS error of the calibration volume #2, the choice of the number of control points and corresponding location should consider the specificity of the aquatic activity; for instance, calibration volume #3 could be used for synchronised swimming since its actions are mostly in y and z axes, in which the volume #3 presented low RMS error values.

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Appendix III

$\dot{V}O_2$ kinetics in 200-m race-pace front crawl swimming

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Abstract

Studies that aim to characterize oxygen uptake kinetics in efforts above maximal oxygen consumption intensity are scarce. Our purpose was to analyze the oxygen kinetics in a maximal 200-m front crawl, being all measurements conducted in swimming pool conditions. Ten high level male swimmers performed a maximal 200-m bout being oxygen uptake directly measured through breath-by-breath gas analysis. Mean (SD) peak oxygen uptake was 68.58 (5.79) $ml.kg^{-1}.min^{-1}$, evidencing a fast component phase. As expected, peak oxygen uptake presented a direct relationship with mean swimming speed of the first 50-m lap and with the 200-m effort, also being correlated with the amplitude of the fast component ($r = 0.75$, $r= 0.72$, $r = 0.73$, $p < 0.05$, respectively). The observed mean amplitude value was higher than those observed in the literature for other exercise intensity domains. However, the time for its onset, as well as the duration for attaining the steady state, was shorter, being the peak oxygen uptake not correlated with these two components. Moreover, as previously described for swimming at high intensities, the slow component phenomenon was not observed. Aerobic metabolic pathway accounted for 78.6%, confirming the high aerobic contribution in middle distance swimming events.

Key words: Swimming, $\dot{V}O_2$ response, Extreme intensity exercise

Introduction

Conventionally, the oxygen uptake ($\dot{V}O_2$) kinetic response to exercise has been studied in the moderate, heavy and severe intensity domains (21), being its nature and magnitude also dependent on changes within each exercise intensity domain (16). In moderate exercise, i.e., at intensities below the anaerobic threshold, the transition from rest to constant load exercise is characterized by an increase in $\dot{V}O_2$ as a three-phase response (34): following an early delay-like phase at exercise onset, lasting approximately 15-20 s (phase I), $\dot{V}O_2$ increases monoexponentially with a time constant of 30-45 s (phase II), to achieve a steady state within 3 min (phase III). In the heavy intensity domain, at exercise intensities higher than the anaerobic threshold, after a first fast rise of the $\dot{V}O_2$ kinetics, it does not achieve an early steady state but continues to rise - $\dot{V}O_2$ slow component phenomenon - until delayed steady state is achieved, exhaustion ensues, or exercise ends (4, 33). In severe exercise, in which the exercise intensity is specifically above the anaerobic threshold, and neither $\dot{V}O_2$ nor blood lactate levels can be stabilized (33), $\dot{V}O_2$ continues to increase until the point of exhaustion (21). In this domain, $\dot{V}O_2$ slow component is much more developed than that during heavy exercise, being its magnitude dependent on the duration and type of exercise (49).

More recently, a fourth exercise intensity domain - extreme exercise - has been proposed for power outputs that lead to exhaustion before maximal oxygen uptake ($\dot{V}O_{2\,max}$) is attained (24). According to Burnley and Jones (9), in this intensity domain, $\dot{V}O_2$ kinetics is characterized by the development of an evident fast component, not being observed the slow component phenomenon. In fact, extreme exercise is so intense that there is not enough time to reach $\dot{V}O_{2max}$ or for a slow component to appear. Complementarily, due to the short duration of exercise before the appearance of exhaustion, blood lactate at the end of the effort main not reach such high values as those recorded at the end of severe intensity exercise.

The characteristics of $\dot{V}O_2$ kinetics in moderate and heavy exercise intensities are well documented in the literature, namely in treadmill running and cycle ergometer exercise. In addition, evaluations carried out in the severe and extreme exercise domains are almost inexistent. Specifically in swimming, $\dot{V}O_{2\,max}$ is considered to be a standard of maximal aerobic power, being one of the primary areas of interest in training and performance diagnosis in swimming (14, 36, 43). Indeed, since Liljestrand and Stenstrom, high values of $\dot{V}O_{2\,max}$ have been commonly associated with excellence in competitive swimming, and, to the best of our knowledge, only Rodríguez et al. (40) and Rodríguez et al. (39) studied $\dot{V}O_2$ kinetics in real swimming pool conditions, not in simulated conditions (i.e. in swimming-flume), but for the 100-m and 400-m front crawl events in a pilot study.

Knowing that studies that aim to characterize the specific $\dot{V}O_2$ kinetics in extreme intensity exercises are scarce, the purpose of this study was to characterize the $\dot{V}O_2$ kinetics during a maximal 200-m front crawl effort, being all gas measurements directly obtained in habitual training and competition swimming pool conditions.

Material and Methods

Subjects

Ten front crawl elite male swimmers volunteered to participate in this study. The subjects provided informed written consent before data collection, which was performed in accordance with the ethical standards proposed by Harriss and Atkinson (23). The inclusion criterion was a personal best time less than 115 s in the 200-m front crawl long course event. Individual and mean (SD) values for subjects' main physical and performance characteristics are described in Table 1. Body mass, fat mass and lean body mass were assessed through the bioelectric impedance analysis method (Tanita TBF 305, Tokyo, Japan). All swimmers were involved in more than eight training units per week. The tests

were carried out in a recovery microcycle at the end of the second macrocycle of the season.

Table 1. Individual and mean (SD) values for the swimmers' main physical and performance characteristics.

Swimmer	Age (years)	Height (cm)	Body mass (kg)	Fat mass (%)	Lean body mass (kg)	200-m personal best (s)
#1	23.9	180.5	74.5	11.0	60.8	106.3
#2	25.9	184.0	80.9	11.9	59.9	110.2
#3	20.6	178.5	67.9	11.9	60.2	109.3
#4	23.8	191.5	81.2	12.1	58.8	107.4
#5	22.8	195.5	84.6	11.3	59.2	110.9
#6	21.9	180.0	70.6	8.8	62.7	106.4
#7	20.9	182.0	69.4	9.7	61.5	107.7
#8	18.1	178.5	72.8	10.2	72.3	112.3
#9	18.9	196.0	81.4	7.2	63.0	111.1
#10	20.1	186.0	81.2	7.3	64.9	110.8
Mean	21.6	185.2	76.4	10.1	62.3	109.3
(SD)	(2.4)	(6.8)	(6.1)	(1.8)	(3.9)	(2.1)

Data Collection

The test sessions took place in a 25-m indoor swimming pool with a water temperature of 27.5ºC. In-water starts and open turns, without underwater gliding, were used. After a standard competition warm-up, all subjects rested outside the water while the equipment was set up and calibrated for the experiments. Each subject performed a 200-m front crawl effort at maximal speed, being encouraged to swim at his best effort. The mean swimming speed values corresponding to the 200-m (200_{speed}), and each 50-m lap (50_{speed}) were calculated by the ratio between exercise distances and corresponding times. $\dot{V}O_2$ kinetics was directly measured using a telemetric portable gas analyzer (K4 b^2, Cosmed, Italy) that was suspended over the water (at a 2-m height) in a steel cable, following the swimmer along the pool, and minimizing disturbances of the normal swimming movements. This equipment was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (25). Expired gas concentrations were measured breath-by-breath and averaged every 0.2 Hz (50). Using this sampling interval, the highest $\dot{V}O_2$ value

during the 200-m swim was considered as the peak oxygen uptake ($\dot{V}O_{2peak}$). The $\dot{V}O_2$ value just before the beginning of the exercise was also measured ($\dot{V}_b$). After the end of the 200-m maximal bout, expired air was continuously measured until the swimmers $\dot{V}_b$ values were achieved. Capillary blood samples for lactate concentrations ($[La^-]$) were also assessed (Lactate Pro analyzer, Arkay, Inc) from the earlobe in the final of the warm-up ($[La^-]_b$), immediately after the test, and during the recovery period (1, 3, 5 and 7 min), until maximal values were reached ($[La^-]_{max}$). $\Delta[La^-]$ was considered as the difference between the $[La^-]_{max}$ and $[La^-]_b$, being used to estimate the partial contribution of both aerobic and anaerobic pathways (as described in the Metabolic pathways assessment section).

VO_2 Kinetic Parameters

The $\dot{V}O_2$ kinetics was fitted by the following model, in which the exponential term started after a certain time delay (TD in the equation):

$$\dot{V}O_2(t) = V_b + A \times (1 - e^{-(1-TD/\tau)}) \quad (1)$$

where t is the time, $\dot{V}_b$ is the oxygen uptake at the start of the maximal event ($ml.kg^{-1}.min^{-1}$), A is the amplitude of the fast component ($ml.kg^{-1}.min^{-1}$), TD is the time for the onset of the fast component (s) and τ stands for the time constant of the fast component, i.e., the time to reach 63% of the plateau of this phase (during which physiological adaptations adjust to meet the increased metabolic demand). A nonlinear least squares method was implemented in MatLab environment for the adjustment of this function to $\dot{V}O_2$ data. The inexistence of a slow component was also confirmed by the fixed intervals method, consisting in the difference between the last $\dot{V}O_2$ measurement of the exercise and the value measured in the final 5 s of the 200-m event (26, 18). An example of the $\dot{V}O_2$ uptake kinetics during the maximum 200-m front crawl protocol is shown in Figure 1.

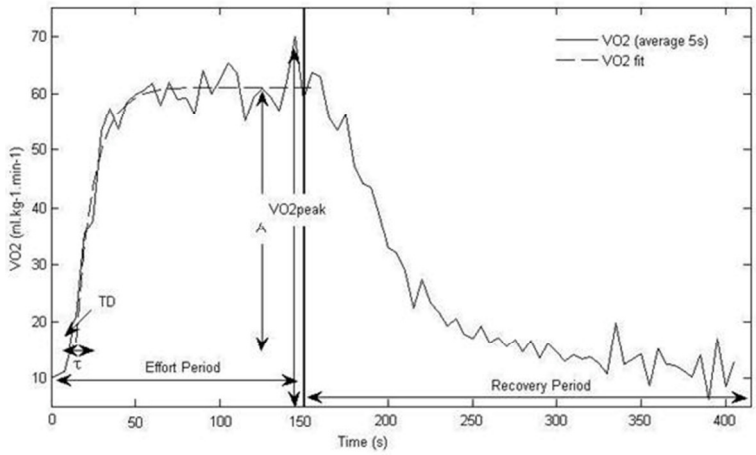


Figure1. Example of an oxygen consumption to time curve, being the time of the onset of the fast component (TD), the time constant of the fast component (τ) and the amplitude of the fast component (A) identified.

Metabolic Pathways Assessment

The partial contribution of the aerobic (Aer%) and anaerobic (Anaer%) energy systems during the maximal 200-m effort were assessed as described in equation 2 (adapted from 14, 27):

(2)

where $O_2Eq\left[La^-\right]$ is obtained by the product of the Δ[La$^-$] by the 2.7 mlO2·kg^{-1}·mM^{-1} proportionality constant, $\dot{V}O_2$ and $\dot{V}O_{2b}$ are considered as the average between three consecutive values just after and before the 200-m maximal bout (respectively), t is time (min), $\tau$is the time constant (s). The Aer% was obtained by subtracting 100 by the Anaer% value.

Statistical Analysis

Mean (SD) computations for descriptive analysis were obtained for all variables and for the entire group of subjects (all data where checked for distribution normality with the Shapiro-Wilk test). Simple linear regression and Pearson's correlation coefficient were also used. All statistical procedures were conducted with SPSS 10.05 and the significance level was set at 5%.

Results

200-m self-imposed maximal pace test

Table 2 shows the 200_{speed}, 50_{speed}, VO_{2peak}, $\dot{V}O_{2b}$, $[La^-]_{max}$, A, TD and τ values reached during the 200-m front crawl maximal effort. $\dot{V}O_2$ kinetics response in the 200-m front crawl maximal effort started by a sudden and exponential increase in $\dot{V}O_2$ close to the beginning of the effort, as shown by the TD and τ mean values, respectively (cf. Figure 1 and Table 2). The A mean value indicates that swimmers were able to attained high values of oxygen consumption, maintaining these during the 200-m all-out event. Afterwards, it was observed a fast transition period needed to attain a steady state (τ), followed by a steady state period, in which a $\dot{V}O_2$ slow component phenomenon was not evident.

Table 2. Individual and mean (SD) values for 200_{speed}, 50_{speed}, $\dot{V}O_{2peak}$ (absolute and relative), $\dot{V}O_{2b}$, $[La^-]_{max}$, A, TD and τ in the 200-m maximal effort.

Sw	200_{speed} ($m\ s^{-1}$)	50_{speed} ($m\ s^{-1}$)	$\dot{V}O_{2peak}$ ($l\ min^{-1}$)	$\dot{V}O_{2peak}$ ($ml.kg^{-1}.min^{-1}$)	$\dot{V}O_{2b}$ ($ml.kg^{-1}.min^{-1}$)	$[La^-]_{max}$ ($mmol.l^{-1}$)	A ($ml\ kg^{-1}min^{-1}$)	TD (s)	τ (s)
#1	1.38	1.47	5.24	69.88	13.18	9.3	49.03	19.67	10.83
#2	1.40	1.60	5.51	68.04	14.37	13.4	49.60	10.00	6.21
#3	1.36	1.44	4.70	60.19	13.51	9.9	38.56	4.99	12.04
#4	1.44	1.49	5.46	67.37	14.01	12.7	44.93	3.98	13.28
#5	1.42	1.60	5.67	66.67	12.53	11.6	44.50	4.99	9.31
#6	1.49	1.71	6.30	81.79	9.73	13.1	52.00	5.00	12.43
#7	1.42	1.50	4.56	66.10	16.77	11.5	45.40	4.99	11.56
#8	1.42	1.52	4.59	63.73	10.4	11.0	46.88	4.99	9.17
#9	1.42	1.57	5.92	73.07	10.51	11.0	45.63	5.15	7.05
#10	1.47	1.63	5.60	69.03	10.04	13.0	50.18	4.99	13.41
Mean	1.42	1.55	5.41	68.58	12.50	11.71	46.67	6.88	10.53
(SD)	(0.03)	(0.08)	(0.61)	(5.79)	(2.29)	(1.41)	(4.78)	(4.78)	(2.51)

Sw = swimmer; 200_{speed} = mean swimming speed of the 200-m; 50_{speed} = mean swimming speed of the first 50-m; $\dot{V}O_{2peak}$ = peak oxygen uptake; $\dot{V}O_{2b}$ value = $\dot{V}O_2$ just before the beginning of the exercise; $[La^-]_{max}$ = maximal lactate concentrations after the maximal swim; A = amplitude of the fast component; TD = time of the onset of the fast component; τ = time constant of the fast component.

Metabolic pathway percentage

The mean estimated contributions of aerobic and anaerobic metabolisms during the 200-m effort were 78.6% (2.9) and 21.3% (2.9), respectively.

Relationships between the studied variables

Complementarily to the above referred data, direct relationships between 200_{speed} and $\dot{V}O_{2peak}$ (r = 0.69, p = 0.03), $[La^-]_{max}$ (r = 0.73, p = 0.02) and A (r = 0.64, p = 0.04) were observed (Figure 2, panel A). The same trend is reported for 50_{speed} and $\dot{V}O_{2peak}$ (r = 0.75, p = 0.01), $[La^-]_{max}$ (r = 0.72, p = 0.02) and A (r = 0.70, p = 0.02) (Figure 2, panel B). Other direct relationship was obtained between $\dot{V}O_{2peak}$ and A (r = 0.73, p = 0.01) (Figure 2, panel C). No significant correlations were found between $\dot{V}O_{2\,peak}$ (expressed in absolute and relative values) and others $\dot{V}O_2$ kinetic parameters, particularly TD (r = 0.07) and τ (r = 0.03), both for p>0.05. The absence of significant relationships was also observed between the swimming performance and the $\dot{V}O_2$ kinetic parameters: (i) 200_{speed} with TD (r = 0.14) and τ (r = 0.01), both for p>0.05, and (ii) 50_{speed} with TD (r = -0.25) and τ (r = -0.09), both for p>0.05.

Discussion

The aim of this study was to describe and analyze the specific $\dot{V}O_2$ kinetics of extreme intensity swimming effort: the 200-m maximal front crawl effort. After the pilot study of Rodriguez et al. (40), this is, to the best of our knowledge, the first attempt to monitor the $\dot{V}O_2$ uptake kinetics during this specific middle-distance swimming event. This is novel and extremely important since the testing was conducted in normal swimming pool conditions, overlapping the standard laboratory conditions that may not perfectly reflect the real-world performances (8). $\dot{V}O_2$ kinetics was assessed using up-to-date procedures for collecting and measuring breath-by-breath expired gas, disposing the data in real time. The modified snorkel and valve system, specific for breath-by-breath

gas analysis, was already considered suitable for measurements during swimming (25).

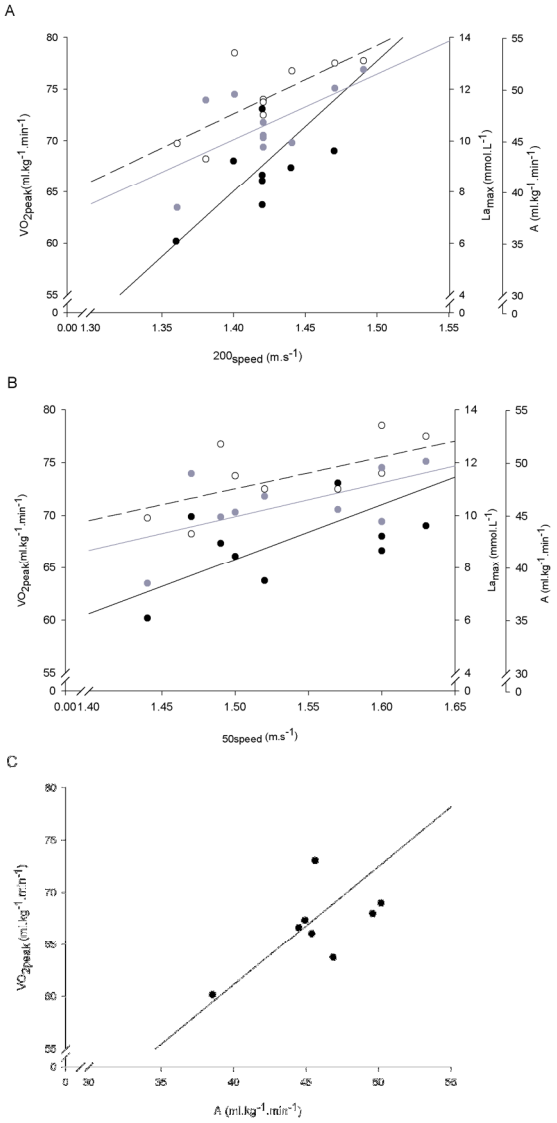


Figure 2. Panel A: Relationship between mean swimming speed of the 200-m (200_{speed}) and peak oxygen uptake ($\dot{V}O_{2peak}$) (y= 103.67 - 78.835x, n=10, r = 0.7, p<0.05) (full line), between 200_{speed} and lactate concentrations at the final of the maximal swim ($[La^-]_{max}$) (y= 26.49 - 26.02x, n=10, r = 0.7, p<0.05) (dotted line) and between 200_{speed} and amplitude of the fast component (A) (y= 63.42 - 43.52x, n=10, r = 0.6, p<0.05) (grey line). Panel B: Relationships between mean swimming speed of the first 50-m (50_{speed}) and $\dot{V}O_{2peak}$ (y= 52.18 - 12.45x, n=10, r = 0.8, p<0.05) (full line), between 50_{speed} and $[La^-]_{max}$ (y= 12.04 - 7.05x, n=10, r = 0.7, p<0.05)(dotted line) and between 50_{speed} and A (y= 32.09 - 3.16x, n=10, r = 0.7, p<0.05) (grey line). Panel C: Relationship between A and $\dot{V}O_{2peak}$ (y= 1.108 + 16.89x, n=10, r = 0.7, p<0.05).

For the $\dot{V}O_2$ kinetics analysis, it was used a sampling frequency of 0.2 Hz, since the breath-by-breath gas acquisition could induce a significant variability of the acquired $\dot{V}O_2$ values, overestimating them. Following several studies (2, 8, 29, 44), the 0.2 Hz sampling frequency has a good temporal resolution, being more appropriated than other less frequent sampling frequency for this kind of studies. Additionally, accepting that the concept of $\dot{V}O_{2max}$ is more related with constant load exercise testing (9), $\dot{V}O_{2peak}$ was used as a measure of aerobic power.

$\dot{V}O_{2peak}$

In the swimming related literature, few attempts were conducted in order to assess $\dot{V}O_2$ kinetics parameters using direct oxymetry protocols in real swimming pool conditions. Moreover, studies that aimed to characterize the specific $\dot{V}O_2$ kinetics in extreme intensity exercises are almost inexistent. Once the 200-m was performed at maximal effort, swimmers began at a very high swimming intensity. Thus, since the very beginning of exercise that the need of oxygen in muscles triggered an instantaneous and sudden increase in the $\dot{V}O_2$ uptake. Indeed, the $\dot{V}O_2$ values were very high just after the first 50-m lap, being most of the subjects able to maintain these high $\dot{V}O_2$ values for almost all the 200-m effort. Considering the total sample, $\dot{V}O_{2peak}$ ranged from 60.19 to 81.79 ml min^{-1} kg^{-1}, which is in accordance with previously obtained data in national and elite male competitive swimmers (17, 19, 36, 38, 43, 49). However, among these studies, only Reis et al. (36) implemented a swimming effort at intensities similar to our protocol, i.e., in the extreme intensity domain. In the specialized literature, other studies were also conducted in real swimming pool conditions, but involved swimmers with lower performance level (18, 28) and used different test distances (39-40), which seems to explain the reported lower $\dot{V}O_{2max}$ mean values comparing to the present study. This fact seems to be explained by the higher performance level and training background of the present tested swimmers, and by the specificity of the testing protocol.

$\dot{V}O_2$ kinetics related parameters

In moderate constant speed exercise bouts, the cardiodynamic phase of the $\dot{V}O_2$ kinetics, representing the early fast increase in $\dot{V}O_2$, is usually completed within the first 15-25 s of exercise (49), while the fast component increases monoexponentially with a □ of 30-45 s (32). However, in the extreme intensity exercise domain, the $\dot{V}O_2$ kinetics assumes an exponential rise that is cut off at $\dot{V}O_{2max}$ before the $\dot{V}O_2$ slow component has time to develop, not occurring a $\dot{V}O_2$ steady state (9, 48). In fact, in the present study, the $\dot{V}O_2$ slow component was not observed, although it was previously described in swimming for slower intensities (13, 18, 39-40). During the analyzed effort, it was observed only two distinct components: the cardiodynamic phase, which was not taken into consideration (due to its insignificant value in terms of amplitude), and the fast component, which started a few seconds later than the effort onset.

During the fast component, the increasing in Amplitude is described to be linearly related to the increase in exercise intensity (5, 7, 11-12, 34, 42). In fact, the mean Amplitude value observed is higher than the previously described for elite swimmers (1, 35). High values of this parameter are directly related to best performances in the 400-m front crawl event (20), which seems to corroborate that the aerobic contribution to the total 200-m front crawl energy supply is also very important. The fact that subjects with higher percentage of type I muscle fibres have a lower Amplitude value in the fast component phase (cf. 4), indicates that future swimming related studies should consider analyzing the relationship between phenotypic expression of muscle fibres and the Amplitude value of the fast component of $\dot{V}O_2$ kinetics.

Several studies conducted in treadmill running and cycling ergometer showed that τ remains remarkably constant as exercise intensity increases, despite increasing lactic acidosis (3, 5-7, 11, 34, 42, 49) However, the observed τ mean value is lower than those reported previously for higher effort distances (1, 35, 40), which means that a faster attainment of the $\dot{V}O_2$ steady state occurred in the 200-m effort. This seems to be physiologically useful since the existence of

a shorter lag in the unbalance of $\dot{V}O_2$ demand and supply implies a reduced requirement for anaerobic energy provision during the transition from rest to exercise (9), which helps conserving intramuscular glycogen reserves (32). It was described before that aerobic elite trained athletes have remarkably faster fast component $\dot{V}O_2$ kinetics that enables them to minimize the magnitude of the oxygen deficit, which could reduce the perturbation of homeostasis, typical of a transition from a lower to a higher metabolic rate (3). Additionally, Alves et al. (1) proposed that shorter τ mean value is related to higher aerobic fitness and performance level in aerobic swimming events, which reflects an enhanced potential for oxidative metabolism. Nevertheless, in the present study it was not found a significant relationship between $\dot{V}O_{2peak}$ and τ, corroborating the findings of Rodríguez et al. (39), Rodríguez et al. (40) and Fernandes et al. (20), suggesting that $\tau$is not a good predictor of performance in this middle-distance swims (namely due to its high variability among swimmers). Complementarily, Pringle et al. (34) previously observed a negative correlation between the τ of the fast component and the percentage of type I fibers for heavy exercise ($r = -0.68$, $p \leq 0.01$), meaning that subjects with a low percentage of type I fibers tended to have longer τ than subjects with a high percentage of type I fibers. From this perspective, it might be hypothesized that, due to genetic predisposition and/or to the type of training, the swimmers of our sample may have a high Type I phenotypic expression of muscle fibres that leaded to shorter τ values. According to Barstow (3), a simple monoexponential description of $\dot{V}O_2$ kinetics shows that the τ magnitude rises as the exercise intensity increases, especially when accompanied by sustained elevations in blood lactate (i.e., above the lactate threshold). In fact, Rodríguez et al. (40) and Rodríguez et al. (39) used monoexponential descriptions of $\dot{V}O_2$ kinetics and showed higher mean τ values for the 100- and 400-m swimming efforts.

According to literature, significant differences in the TD values associated with the fast component are observed only between heavy and severe exercise (34). In fact, in the present study, the fast component of the $\dot{V}O_2$ kinetics started almost at the beginning of the effort, contrarily to the results reported before (1,

35). It should be highlighted that the present study was conducted in the extreme intensity exercise domain, and the referred studies were conducted in heavy intensity, not being evident the selection of very high swimming velocities in the beginning of the exercise.

Relationship between $\dot{V}O_{2peak}$ and swimming performance

The observed relationship between $\dot{V}O_{2\,peak}$ and 200_{speed} (and 50_{speed}) is in accordance with studies conducted in different swimming distances: Rodríguez et al. (40) (r=0.787 and r=0.752, for the 100-m and 400-m, respectively), Rodríguez et al. (39) (r=0.84 and r=0.78, for the 100-m and 400-m, respectively) and Fernandes et al. (20) (r=0.93, for the 400-m). In fact, although $\dot{V}O_{2max}$ is a major influence of the 400-m distance, the results of the present study evidence that $\dot{V}O_2$ is also a good predictor of 200-m distance, confirming the relevance of the aerobic contribution to energy demands in other events than the long-distance ones (20, 37-38, 40, 43). However, the determination coefficient value obtained between $\dot{V}O_{2\,peak}$ and 200_{speed} indicates that other factors (like anaerobic capacity) might help to explain the performance in this specific distance. The observed direct relationship between Amplitude and 200_{speed} (and 50_{speed}), as well as between this kinetic parameter and $\dot{V}O_{2peak}$, emphasis the importance of this kinetic parameter as a good predictor of the 200-m event performance.

In the studies 200-m front crawl it was observed a 78.6% of aerobic energy contribution, which reflects the significant role of the aerobic metabolism pathway even in high intensity exercise (22). Although different approaches have been used to assess anaerobic energy pathway (transformation of the net blood lactate concentration into O_2 equivalents or through the accumulated oxygen deficit), the aerobic contribution is slightly higher than those proposed by Ogita (31) and Capelli et al. (10) for 2-3 m bouts and 182.9 m distances (65% and 61.5%, respectively), by Troup (46-47) (71.7%, 60% and 61%, respectively) and Zamparo et al. (50) (71.7%), both for the 200-m swim. However, it is lower than the results presented by Silva et al. (43) (85%) and

Reis et al. (36) (87%), both for the 200-m swim. Complementarily, Rodríguez & Mader (38), through computer simulation, proposed aerobic contributions for the 400-m (83.2%) and 100-m (54.1%) events. Nonetheless, the method by which energy release is determined can have a significant influence on the calculated relative contribution of the energy systems during periods of maximal exercise (22), which can explain this variability. The competitive level of the subjects tested may also help to explain the differences obtained.

The used protocol allowed to characterize $\dot{V}O_2$ kinetics in a 200-m maximal effort, carried out in normal swimming pool conditions. The $\dot{V}O_{2peak}$ mean value is in accordance with the literature for elite male competitive swimmers. Also, direct relationships between swimming speed and $\dot{V}O_{2peak}$, Amplitude and $[La^-]_{max}$ were found, confirming that developed aerobic capacity plays a central role among the energy-yielding mechanisms in middle distance swimming. However, the Amplitude, τ and TD mean values were different from those observed in the literature (presenting high inter-subjects variability), which seems to be explained by the intensity domain in which the event was carried out. It was also confirmed that $\dot{V}O_2$ slow component was not observed in swimming extreme efforts (as previously reported for laboratory running and cycling), in opposition to what occurs at slower swimming paces.

However, since swimmers performed 200-m at race pace different pacing strategies was adopted, which may explain distinct $\dot{V}O_2$ kinetics. In addition, the fact that no starting from block and the use of open turns, without underwater gliding, could limited the swimmers performance, and consequently influenced $\dot{V}O_2$ kinetics.

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Chapter 15. References

Chapter 1

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Appendix I

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