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Bioenergetical and biomechanical characterisation of butterfly stroke

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Symbols index

(1dwn)	First downbeat
(2dwn)	Second downbeat
(1upb)	First upbeat
(2upb)	Second upbeat
(APAS)	Ariel Performance Analysis System
(ARI)	Average resultant impulse per phase
(BxB)	Breath-by-breath
(dV)	Intra-cycle variation of the horizontal velocity of displacement
(EC)	Energy cost
(ent)	Hand's entry
(Eq)	Equation
($\dot{E}_{tot}$)	Total energy expenditure
(ins)	Hand's insweep
(max)	Maximal value
(min)	Minimal value
(N.S.)	Not significant.
(out)	Hand's outsweep
(r)	Coefficient of correlation
(S.D.)	Standard desviation
(SF)	Stroke frequency
(SI)	Stroke index
(SL)	Stroke length
(ups)	Hand's upsweep
(V)	Mean swimming velocity
(VO_2)	Oxygen consumption
(Vx)	Horizontal component of the segmental velocity
(Vy)	Vertical component of the segmental velocity
(Vz)	Lateral component of the segmental velocity

Resumo

O estudo da Biofísica da natação é uma das áreas de maior interesse para os investigadores em Ciências do Desporto. No entanto, existe um défice de entendimento sobre as relações que se estabelecem entre as variáveis bioenergéticas e biomecânicas, especialmente na técnica de Mariposa. Assim, foi objectivo desta tese efectuar uma caracterização bioenergética e biomecânica da técnica de Mariposa, compreendendo as relações que se estabelecem entre estes dois domínios. Na presente tese são apresentados 6 estudos independentes que foram levados a cabo no sentido de atingir o objectivo geral definido previamente. Os dois primeiros estudos tiveram como objectivo efectuar uma caracterização geral da técnica de Mariposa. Num primeiro estudo efectuou-se a comparação do dispêndio energético total ($\dot{E}_{tot}$) nas quarto técnicas de nado formal, mas com especial referência à técnica de Mariposa. A técnica de Crol foi a mais económica, seguida das técnicas de Costas, de Mariposa e por fim de Bruços. Num segundo estudo, o propósito foi o de estimar o impulso médio resultante (ARI) por fase propulsiva do ciclo gestual. A técnica de Mariposa caracteriza-se pelas elevadas variações intracíclicas do ARI. Este facto parece dever-se às significativas reduções da ARI ocorridas durante a recuperação dos membros superiores e a entrada destes na água. De seguida foram desenvolvidos estudos no sentido de compreender as relações que se estabelecem entre as variáveis bionergéticas e biomecânicas. Aumentos do $\dot{E}_{tot}$ foram significativamente relacionados com o aumento da velocidade de nado (V). O custo energético (EC) aumentou significativamente com o aumento da frequência gestual (SF) e do índice de nado (SI). O EC diminui com o aumento da distância de ciclo (SL). O aumento do EC também foi significativamente associado ao aumento da variação intracíclica da velocidade horizontal do deslocamento do centro de massa (dV). Os últimos estudos procuraram identificar as relações que se estabelecem entre as diversas variáveis biomecânicas com a dV. As relações entre a SF e a V, assim como, entre a SI e a V foram positivas e significativas. No caso da relação entre a V e a SL, verificou-se uma ligeira tendência para a diminuição da SL com o aumento da V. Observou-se uma relação significativa e negativa entre a dV e a V, entre a dV e a SL e entre a dV e a SI. A uma dada V, verificou-se uma relação positiva e significativa entre a dV e a SF. Elevadas velocidade segmentares, nas fases mais propulsivas do ciclo gestual, foram significativamente associadas com a diminuição da dV. Em conclusão, o comportamento de diversas variáveis biomecânicas, tais como os parâmetros gerais do ciclo gestual, a velocidade segmentar dos pés e das mãos, influenciam significativamente a V e o perfil da dV. Em consequência, estes parâmetros irão influenciar significativamente o $\dot{E}_{tot}$ e o EC. Logo, os treinadores e os mariposistas devem efectuar uma avaliação exaustiva e frequente da técnica de nado, por forma a reduzir o EC associado a uma determinada velocidade de deslocamento.

PALAVRAS-CHAVE: natação, mariposa, custo energético, mecânica gestual, velocidade segmentar, flutuação da velocidade

Abstract

The Biophysical study of swimming is one of the major interests of the sport sciences investigators. However, there is a lack of investigation trying to understand the relationships established between the bioenergetical and biomechanical variables, especially in butterfly stroke. Therefore, the purpose of this thesis was to conduct a bioenergetical and biomechanical characterizations of the butterfly stroke, understanding the relationships established between those two domains. In this thesis 6 independent studies are presented in order to achieve the purpose defined. The first two investigations had the purpose to obtain a general characterisation of butterfly stroke. The purpose of the first study was to compare the total energy expenditure ($\dot{E}_{tot}$) of the four competitive swimming techniques, with special reference to butterfly stroke. The freestyle was the most economic swimming technique, followed by the backstroke, the butterfly and the breaststroke. The purpose of a second study was to estimate the average resultant impulse (ARI) per stroke phase. Butterfly stroke is a swimming technique where it is possible to observe high intra-cycle variations of the ARI, due to significant reductions of this parameter during the arm's recovery and hand's entry. The following papers had the aim of understand the relationships established between the biomechanical and bioenergetical variables. Increases in the $\dot{E}_{tot}$ were significantly related to the increase of swimming velocity (V). The energy cost (EC) increased significantly along with the increasing stroke frequency (SF) and stroke index (SI). The EC decreases with increasing stroke length (SL). The increase of the EC is significantly associated with the increase of the intra-cyclic variations of the horizontal velocity of the centre of mass (dV), in Butterfly stroke. The last papers had the aim to identify the relationships established between the biomechanical variables and the dV. The relationships between SF and V, as well as, between SI and V were positive and significant. For the relationship between V and SL, there was a slight tendency to decrease SL with the increase in V. There was a negative and significant relationship between dV and V, between dV and SL and between dV and SI. For a given swimming velocity, it is observed a positive and significant relationship between dV and SF. High segmental velocities, in the most propulsive phases of the stroke cycle, were significantly associated to decreases of dV. As a conclusion, the behavior of biomechanical variables, such as the stroke determinant, the hand's and feet's velocities, influence the V and the dV profile. Consequently, these parameters will affect the $\dot{E}_{tot}$ and the EC of swimming. Therefore, coaches and butterfliers should conduct an exhaustive and frequent evaluation of their technique in order to reduce the EC associated to a given swimming velocity.

KEYWORDS: swimming, butterfly stroke, energy cost, stroke mechanics, segmental velocity, speed fluctuation

Resumé

L'étude de la Biophysique de la nage est un des secteurs les plus intéressants pour les chercheurs des Sciences du Sport. Il y a cependant, un déficit, de compréhension sur les relations qui s'établissent entre les variables bio-énergétiques et bio-méchaniques, spécialement en ce qui concerne la technique Papillon. Ce fut donc l'objectif de cette thèse d'entreprendre une caractérisation bio-énergétique et bio-méchanique de la technique Papillon, en comprenant les relations qui s'établissent entre ces deus domaines. Nous présentons dans cette thèse 6 études indépendantes qui ont été entreprises dans le but d'atteindre l'objectif général préalablement défini. Les deux premières études ont eu pour but de réaliser une caractérisation générale de la technique Papillon. Dans une première étude nous avons entrepris la comparaison de la dépense énergétique totale ($\dot{E}_{tot}$) dans les quatre techniques de nage formelles, mais avec une référence particulière à la technique Papillon. La technique du Crawl fut la plus économique, suivie des techniques du Dos, Papillon et enfin Brasse. Dans une deuxième étude, le but fut celui d'estimer l'impulsion moyenne résultante (ARI) par phase propulsive du cycle gestuel. La technique Papillon se caractérise par d'élevées variations intra-cycliques de l'ARI. Ce fait semble être causé par de significatives variations de l'ARI lors de la récupération des membres supérieurs et leur entrée dans l'eau. Nous avons ensuite développé des études allant dans le sens de comprendre les relations qui s'établissent entre les variables bio-énergétiques et bio-méchaniques. Des augmentations de la $\dot{E}_{tot}$ ont été significativement mises en rapport avec l'augmentation de la vitesse de la nage (V). Le coût énergétique (EC) a augmenté de façon significative avec l'augmentation de fréquence gestuelle (SF) et de l'indice de la nage (SI). La EC diminue avec l'augmentation de la distance de cycle (SL). L'augmentation de la EC a aussi été significativement associée à l'augmentation de variation intra cyclique de la vitesse horizontale du déplacement du centre de masse (dV). Les dernières études ont cherché à identifier les relations qui s'établissent les différentes variables bio-méchaniques et la dV. Les relations ente la SF et la V, bien que celles entre le SI et la V ont été positives et significatives. Dans le cas de la relation entre la V et la SL nous avons remarqué une légère diminution de la SL avec l'augmentation de la V. Nous avons remarqué une relation significative et négative entre la dV et la V. Pour une V donnée, nous avons remarqué une relation positive et significative entre la dV et la SF. Des vitesses segmentaires élevées dans les phases les plus propulsives du cycle gestuel ont été significativement associées avec la diminution de la dV. En conclusion, le comportement des différentes variables bio-méchaniques telles que les paramètres généraux du cycle gestuel, la vitesse segmentaire des pieds et des mains, influencent de façon significative et a V et le profil de la dV. Conséquemment, ces paramètres iront influencer significativement et la $\dot{E}_{tot}$ et la EC. Donc. Les entraîneurs et les nageurs Papillon devront entreprendre une évaluation exhaustive et fréquente de la technique de la nage de façon à réduire la EC associée à une vitesse déterminée de déplacement.

MOTS CLES: nage, papillon, coût énergétique, mécanique gestuelle, vitesse segmentaire, fluctuation de la vitesse

Chapter 1: Introduction

Swimming performance is influenced by several factors. The kineanthropometric characteristics (e.g., van Tilborgh et al., 1983; Zhu et al., 1997; Saavedra et al., 2002), the psychological factors (e.g., Stallman et al., 1992; Zientek, 2003), the genetic background (e.g., Bouchard, 1986), the environment, as for example, the pool length, the pool depth or the water temperature (e.g., Keskinen et al., 1996; Lyttle et al., 1998; Srámek et al., 2000), the energetics and technical characteristics of the swimmers (e.g., Holmér, 1974; 1983: Miyashita, 1975; 1996; Troup, 1996) are some of those factors.

The Biophysical study of swimming is one of the major interests of the sport scientists Clarys (1996) analysed 685 papers related to swimming and distinguish them according to the area of knowledge applied for its study: Physiology, Biochemistry, Termoregulation, Psychology, Medicine/Clinic, Biomechanics, Hydrodynamics, Electromyography, Kineantropometry, Methodology/Instrumentarium, Evaluation/Education and other interdisciplinary areas. The category with the highest number of studies was Biomechanics with 20%, followed by Physiology with 18%, Medicine/Clinic with 16%, Hydrodynamics with 9% and Electromyography with 8%. It seems that the Biophysical principals related to swimming performance are one of the more attractive areas of investigation. This might be related to the fact that performance, in this sport, is strongly affected by the swimming technique, the swimmer’s physiological profile and the training procedures.

Butterfly stroke is one of the least studied strokes, especially when compared with front crawl or breaststroke. A major focus in front crawl might be associated to the fact of being the swimming technique with the higher number of events in the official competitions. Front crawl is the stroke that promotes the highest swimming velocity and represent the most important swimming event: the 100-m freestyle. Probably the strong interest in breaststroke is justified because it is one of the earliest swimming techniques and due to the restrictions imposed by swimming rules, witch limits the development of more efficient patterns of displacement.

There are some classic studies comparing the swimming economy of several swimming techniques (Karpovich, 1930; Karpovich and Pestrecov, 1939; Karpovich and Le Maistre, 1940; Holmér, 1974; 1983; Holmér and Haglund, 1978; Pendergast et al., 1978). Based on these studies, it is common to assume that, for a given velocity, butterfly is the less economical swimming technique, followed by the breaststroke, the backstroke and the front crawl. Since the publication of these papers, major changes in the training procedures and in the swimming techniques occurred. For example, the ondulatory breaststroke is used on a regular base by several swimmers. Different breathing models are adopted in butterfly. There was an increment in the number of kicks per stroke cycle (from 2 to 6) in front crawl. Therefore, it is important to conduct a re-evaluation of the swimming economy of the four strokes and to re-establish a new comparative profile of all of them. It is also interesting to know if there was an evolution of the butterfly stroke, in the last few years, in what concerns to improvements in its relative economy profile.

Some studies about the relationship between speed fluctuation and energy cost were done in breaststroke (Vilas-Boas, 1996), front crawl and backstroke (Alves et al., 1996). In breaststroke, the correlation coefficients and the determination coefficients between the intra-cyclic variation of the horizontal velocity of the hip and the energy cost presented significant values, when analysed intra-individually. For the front crawl, there were not observed significant relationships between the same variables, at any swimming velocity studied (Alves et al., 1996). According to Alves et al. (1996), in backstroke, the relationship was significant at low velocities, such as, $1.1 m.s^{-1}$ (r=0.78) and $1.2 m.s^{-1}$ (r=0.66). Apparently there is an increment of the energy cost with the increment of the intra-cyclic variations in breaststroke and in backstroke at low velocities. The relationship between speed fluctuation and energy cost seems to be more consistent, or at lest, easier to be observed, in the simultaneous techniques (breaststroke and butterfly) than in the alternated techniques (front crawl and backstroke). Probably this is justified due to the higher intra-cyclic variations of the horizontal velocity of the swimmer in breaststroke and butterfly (Mason et al., 1989; 1992; Vilas-Boas, 1996; Barbosa et al., 2003). It is known that, in breaststroke, the high speed fluctuation promotes also a higher average resultant impulse of the swimmer's body (van Tilborgh et al., 1988; Vilas-Boas, 1994). It is the needs of re-accelerate the body mass after each resistive phase that induces an increase of the energy cost (Vilas-Boas, 1996). However, there is no study published about the average resultant impulse per phase and the relationship between the speed fluctuation and the energy cost, in butterfly stroke.

Still in the edge areas of Biomechanics and Physiology, Wakayoshi et al. (1995; 1996) and Nomura and Shimoyana (2003) studied the relationships between stroke determinants (stroke length and stroke frequency) and the bioenergetical profile at various swim speeds. Only one study (Wakayoshi et al., 1995) analyzed butterfly stroke. But, evaluating a single butterflier, in a sample of ten swimmers. Despite Nomura and Shimoyana (2003) described the evaluation of one butterflier, they did not presented its results. According to the authors, the butterflier's results were quite different from all the other swimmers evaluated. In the study of Wakayoshi et al. (1995), it was observed significant correlation coefficients between energy cost and swimming velocity, as well as, between energy cost and stroke frequency. However, the reduce number of subjects evaluated in butterfly should lead investigators to consider to perform a similar study, but with a larger number of butterfliers.

Martins-Silva and Alves (2000) studied the components of the hand's velocity and how they affected the intra-cyclic variation of the horizontal velocity of the centre of mass, in butterfly stroke. Using a stepwise regression, Martins-Silva and Alves (2000) verified that all 3D components of the hand's velocity were important to the intra-cyclic variations of the horizontal velocity, especially during the most propulsive phases (upsweep and insweep). The first variable to be included in the model was the 3D resultant of the hand's velocity during the insweep (r^2=-0.98), followed by the lateral component of the hand's velocity during the insweep (r^2=0.99) and the vertical component of the hand's velocity during the insweep (r^2=1).

Butterfly stroke is a swimming technique characterised by the body waving action (Sanders et al., 1995); phenomena associated to the leg's actions from the neuromuscular (Barthels and Adrian, 1971) and kinematical (Sanders et al., 1995; Barbosa et al., 1999) point of views. In fact, Sanders et al. (1995) observed a significant association between the body wave and the swimming velocity (r=0.88 for males and r=0.96 for females). Therefore, it might be interesting to understand not only the contribution of the hand's velocity to the intra-cyclic variations of the horizontal velocity of the centre of mass, but also the influence of the feet's to the speed fluctuation.

Despite the studies referred above, there is a lack of research trying to understand the relationships established between the bioenergetical and biomechanical variables in swimming, especially in butterfly stroke. The study of efficiency, in the water, becomes more complex due to difficulties in quantifying, with accuracy, the energetic exchanges between the swimmer and the environment. In our days, one of the most active groups studding the efficiency of the aquatic locomotion, as for example, kayaking, rowing or swimming, is from the Udine University (Zamparo et al., 2002; Pendergast et al., 2003). There are also other important groups working in this area of knowledge, as for example the Vrije University Amsterdam (Hollander et al., 1986; Toussaint, 1988; Berger, 1996) or the International Center for Aquatic Research in Colorado Spring (Cappaert et al., 1992). However, it should be developed an increasing quantity and quality of studies about the efficiency of different aquatic locomotion activities. Including the study of butterflier efficiency.

Butterfly stroke is an aquatic locomotion technique where much investigation is to be done. What is the bionergetical profile of butterfly stroke? What is the intra-cyclic variation profile of the swimmer's velocity? Are there any relationships between bioenergetical and biomechanical variables? An overall perspective of the steps to be taken for a biophysical evaluation of butterfly stroke is presented in figure 1. In one first approach, it would be interesting to understand how biomechanical variables (e.g., intra-cycle variation of the horizontal velocity of the centre of mass) influences the bioenergetical profile of butterfly stroke. In a second moment, understand how the segmental velocities and the stroke determinants influence the intra-cyclic variations of the horizontal displacement of the centre of mass and/or the swimming velocity. Achieving this goal, it might be possible to identify biomechanical variables that have significant influence in the butterfly bioenergetical profile. Therefore, coaches can modify the swimming technique of butterfliers, in order to reduce energy cost, and consequently, improve swimming performance.

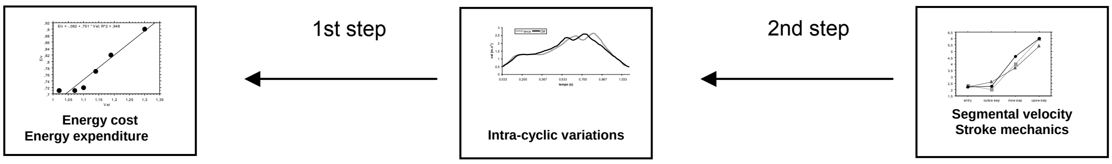


Figure 1. An overall perspective of the steps to be taken, for a biophysical evaluation, of butterfly stroke.

Therefore, the purpose of this thesis was to conduct a bioenergetical and biomechanical characterizations of the butterfly stroke, understanding the relationships established between those two domains.

In Chapter 2 is presented the research problem from this investigation and the research purposes (including the general purpose and the specific purposes).

In Chapter 3 is presented an experimental study, with the purpose to compare the total energy expenditure of the four competitive swimming techniques, with special reference to butterfly stroke.

In Chapter 4 is presented another experimental study, with the aim of estimate the average resultant impulse per stroke phase in Butterfly stroke.

In Chapter 5 is presented a study identifying the relationships between the stroke determinants (stroke frequency, stroke length and stroke index) and the velocity in Butterfly stroke; as well as, identifying the relationships established between the energy cost and the stroke determinants through a range of swimming velocities.

In Chapter 6 is presented an investigation investigating the relationship between the intra-cycle variation of the horizontal velocity of the center of mass and the energy cost in butterfly stroke.

In Chapter 7 is presented an investigation investigating the relationships between the intra-cyclic variations of the horizontal velocity of the center of mass, the stroke determinants (stroke length, stroke frequency and stroke index) and the swimming velocity in butterfly stroke.

In Chapter 8 is presented an investigation investigating the relationships between the intra-cycle variation of the horizontal velocity of the center of mass, the hand's and feet's velocities, as well as, to identify the variables that most predict the intra-cyclic variations of swimming velocity, in butterfly stroke.

In Chapter 9 a general discussion from the results obtained in the 6 independent studies is performed and the main conclusion from the thesis is presented.

Chapter 2: Purpose of the study

1. RESEARCH PROBLEM

With the present study, it was tried to answer to the following research problems:

- What is it the bioenergetical profile of the butterfly stroke?
- What is the intra-cyclic variation profile of the horizontal velocity of the centre of mass of the butterfly stroke?
- What biomechanical factors do affect the intra-cyclic variations of the horizontal velocity of the centre of mass and the swimming velocity in butterfly stroke?
- Is there any relationship between the bioenergetical profile and the biomechanical variables in butterfly stroke?

2. RESEARCH PURPOSES

2.1. GENERAL PURPOSE

The general purpose of this thesis was to perform a bioenergetical and biomechanical characterization of the butterfly stroke. Moreover, the aim was also to understand the relationships between the bioenergetical and the biomechanical domains in this swimming technique.

2.2. SPECIFIC PURPOSES

Based on the major goal of the research, the purposes have been decomposed in the form of the following specific purposes:

- To compare the total energy expenditure of the four competitive swimming techniques, with special reference to butterfly stroke (chapter 3);
- To estimate the average resultant impulse per stroke phase in Butterfly stroke (chapter 4);
- To identify the relationships between the stroke determinants (stroke frequency, stroke length and stroke index) and the velocity in Butterfly stroke (chapter 5);

- To identify the relationships established between the energy cost and the stroke determinants through a range of swimming velocities (chapter 5);

- To examine the relationship between the intra-cycle variation of the horizontal velocity of the center of mass and the energy cost in butterfly stroke (chapter 6);

- To examine the relationships between the intra-cyclic variations of the horizontal velocity of the center of mass, the stroke determinants (stroke length, stroke frequency and stroke index) and the swimming velocity in butterfly stroke (chapter 7);

- To examine the relationships between the intra-cycle variation of the horizontal velocity of the center of mass, the hand’s and feet’s velocities (chapter 8) and;

- To identify the variables that most predict the intra-cyclic variations of swimming velocity, in butterfly stroke (chapter 8).

Chapter 3: Total energy expenditure in butterfly stroke

The purpose of this study was to measure and compare the total energy expenditure of the four competitive swimming strokes. 26 swimmers of international level were submitted to an incremental set of 200-m swims (5 swimmers at Breaststroke, 5 swimmers at Backstroke, 4 swimmers at Butterfly and 12 swimmers at Front Crawl). The velocity was increased by 0.05 $m \cdot s^{-1}$ after each swim until exhaustion. Cardio-pulmonary and gas exchange parameters were measured breath-by-breath (BxB) for each swim to analyse oxygen consumption (VO_2) and other energetic parameters by portable metabolic cart ($K4b^2$, Cosmed, Italy). A respiratory snorkel and valve system with low hydrodynamic resistance was used to measure pulmonary ventilation and to collect breathing air samples. Blood samples from the ear lobe were collected before and after each swim to analyze blood lactate concentration (YSI 1500L, Yellow Springs, US). Total energy expenditure ($\dot{E}_{tot}$), was calculated for each 200-m stage. $\dot{E}_{tot}$ differed significantly between the strokes at all selected velocities. At the velocity of 1.0 $m.s^{-1}$ and of 1.2 $m.s^{-1}$ the $\dot{E}_{tot}$ was significantly higher in Breaststroke than in Backstroke, in Breaststroke than in Freestyle and in Butterfly than in Freestyle. At the velocity of 1.4 $m.s^{-1}$, the $\dot{E}_{tot}$ was significantly higher in Breaststroke than in Backstroke, in Backstroke than in Freestyle, in Breaststroke than in Freestyle and in Butterfly than in Freestyle. At the velocity of 1.6 $m.s^{-1}$, the $\dot{E}_{tot}$ was significantly higher in Breaststroke and in Butterfly that in Freestyle. As a conclusion, $\dot{E}_{tot}$ of well-trained competitive swimmers was measured over a large range of velocities utilising a new BxB technique. Freestyle was shown to be the most economic among the competitive swimming strokes, followed by the Backstroke, the Butterfly and the Breaststroke.

KEYWORDS: total energy expenditure, aerobic contribution, anaerobic contribution, swimming strokes

1. INTRODUCTION

It was in the 1960's that physiological data about swimming began to be published regularly. However, one landmark in this area of knowledge it was the investigation developed Holmér (1974).

Holmér (1974) compared the swimming economy of several competitive swimming strokes in a flume. An obvious dichotomy was observed between the alternated (Freestyle and Backstroke) and the simultaneous (Breaststroke and Butterfly) techniques, later on confirmed by other authors (Pendergast et al., 1978; Lavoie and Montpetit, 1986). For a given velocity, and by this order, the Butterfly and the Breaststroke were the least economical strokes, the Backstroke and the Freestyle being the most economical ones.

More recently, Troup (1991) observed that the Breaststroke was less economical than the Butterfly, for a range of swimming velocities. The researcher explained this finding by the higher velocities chosen for his study, when compared with the previously published ones. In fact, Karpovich and Millman (1944) verified the same occurrence. At velocities higher than 2.5 feets.s^{-1} (equivalent to 0.76 m.s^{-1}), the "side stroke" variant at breaststroke presented a higher cost than the Butterfly.

Since the study of Holmér (1974) three decades have passed. In this period of time, major changes in the training procedures and in the swimming strokes have occurred. Obviously, this can't be disconnected from the evolution of research regarding swimming.

Several studies have only analyzed the aerobic contribution to the swimming economy (e.g., Holmér, 1974; Pendergast et al., 1978; van Handel et al., 1988; Chatard et al., 1990). Presently, however, the analysis of the energy expenditure should also allow understanding the role of the anaerobic contribution (di Prampero et al., 1978; Camus et al., 1984; Thevelein et al., 1984; Camus and Thys, 1991). In fact, the perceptual contribution of the anaerobic system to the overall energy expenditure must not be disregarded.

Most studies about cardiorespiratory profiles in swimming have used Douglas bags or mixing chamber gas analyzers (e.g., Holmér, 1974; Lavoie and Montpetit, 1986; Chatard et al., 1990; Wakayoshi et al., 1995; 1996). The recent development of improved instrumentation and technology in breath-by-breath (BxB) analysis has resulted in new approaches to study cardiorespiratory variables. Several studies verified that these equipments recorded with acceptable accuracy, reliability and validity oxygen consumption and other metabolic parameters, in different exercise conditions (e.g., Hausswirth et al., 1997; McLaughlin et al., 2001; Keskinen et al., 2003; Maiolo et al., 2003). The last version of miniaturized metabolic carts has been developed for BxB gas analysis, allowing direct measurement of cardiorespiratory parameters during free swimming in an easiest way. Moreover, this apparatus allows the characterization of oxygen uptake kinetics in a more feasible and detailed manner, during direct measurement. Nevertheless, there is a lack of studies around this topic, using BxB technology, in swimming.

The purpose of this study was to compare the total energy expenditure of the four competitive swimming strokes in high-level swimmers of both genders.

2. METHODS

Subjects. 26 swimmers (8 females and 18 males) of international level volunteered to serve as subjects. 5 swimmers were evaluated performing Breaststroke (including one female swimmer), 4 swimmers performing Butterfly (including one female swimmer), 5 swimmers performing Backstroke and 12 swimmers performing Freestyle (including 6 female swimmer). The fat mass for Breaststroke swimmers was 6,4 ± 2.9%, for Butterfly 6.1 ± 3.0%, for Backstroke 6.8 ± 2.4% and for Freestyle was 7.6 ± 2.3%.

Design. The subjects were submitted to an incremental set of 200-m swims. The velocities and increments were chosen in agreement with swimmers so that they would make their best performance on the 7^{th} trial. The starting velocity was set at a speed, which represented a low training pace. The last trial should represent the swimmers best performance, in competitive context, at that time. After each successive 200-m swim, the velocity was increased by 0.05 $m \cdot s^{-1}$ until exhaustion and/or until the swimmer could not swim at the predetermined pace. The resting period between swims was 30s to collect blood samples. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Portugal), on the bottom of the 25-m pool, were used to control the swimming speed and to help the swimmers keep an even pace along each step.

Data Collection. The swimmers breathed through a respiratory snorkel and valve system (Keskinen et al., 2003; Rodríguez et al., 2003) connected to a telemetric portable gas analyzer (K4 b^2, Cosmed, Italy). Cardio-respiratory and gas exchange parameters were measured BxB for each swim to analyze oxygen consumption (VO_2) and other energetic parameters.

Blood samples (25 µl) from the ear lobe were collected to analyze blood lactate concentration (YSI 1500 L, Yellow Springs, US) before and after each swim as well as 1, 3, 5 and 7 minutes after the last swim.

The total energy expenditure ($\dot{E}_{tot}$) was calculated using the VO_2 net (difference between the value measured in the end of the stage and the rest value) and the blood lactate net (difference between the value measured in two consecutive stages), transformed into VO_2 equivalents using a 2.7 $mlO_2.Kg^{-1}.mmol^{-1}$ constant (di Prampero et al., 1978; Thevelein et al., 1984).

Individual regression equations were computed between the $\dot{E}_{tot}$ and the V, for all the swimmers. Figure 1 presents, as an example, the relationship between $\dot{E}_{tot}$ and V obtained with two swimmers. $\dot{E}_{tot}$ was extrapolated or interpolated for the velocities of 1.0 $m.s^{-1}$, 1.2 $m.s^{-1}$, 1.4 $m.s^{-1}$ and 1.6 $m.s^{-1}$, using the individual regression equations computed. These velocities were selected from the range of velocities swum during the incremental protocol and are similar to the ones previously used by Troup [33]. The maximal swimming velocity achieved in Freestyle was 1.57 $m.s^{-1}$, in Backstroke was 1.46 $m.s^{-1}$, in Breaststroke was 1.18 $m.s^{-1}$ and in Butterfly was 1.30 $m.s^{-1}$.

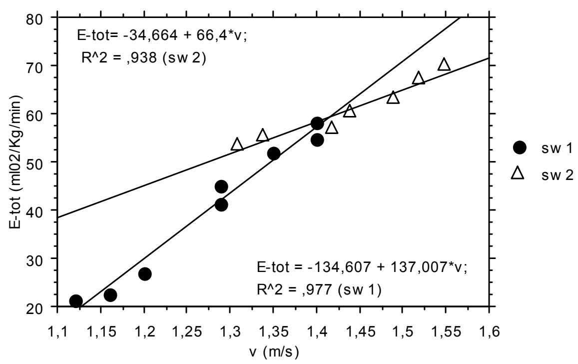


Figure 1. Relationship between the total energy expenditure (E-tot) and the swimming velocity (v) from two of the studied swimmers (sw). From the individual regression equations computed, $\dot{E}_{tot}$ was extrapolated or interpolated for 1.0 $m.s^{-1}$, 1.2 $m.s^{-1}$, 1.4 $m.s^{-1}$ and 1.6 $m.s^{-1}$, for both swimmers.

Statistical procedures. Individual regression equations, describing the relation between the $\dot{E}_{tot}$ and the velocity were computed, as well as, its coefficients of determination and correlation. The analysis of variance (ANOVA 1 factor) was used to detect statistically significant differences between the bioenergetical parameters of the swimming strokes for a given velocity ($\dot{E}_{tot}$ x swimming technique) with Fisher's PLSD as post-hoc test. The level of statistical significance was set at $p \leq 0.05$.

3. RESULTS

Figure 2 presents the overall energy expenditure profile of the four swimming techniques. For all of the selected velocities, the Freestyle was the most economic one (lowest $\dot{E}_{tot}$ at all velocities), followed by the Backstroke, the Butterfly and the Breaststroke. In this way it was observed that the alternated techniques (Freestyle and Backstroke) were more economical then the simultaneous ones (Butterfly and Breaststroke).

Significant variations were observed on the $\dot{E}_{tot}$ of the four strokes at the velocity of 1.0 m.s^{-1} [$F(3;22)=5.48$, $p<0.01$], at the velocity of 1.2 m.s^{-1} [$F(3;22)=12.41$, $p<0.01$], at the velocity of 1.4 m.s^{-1} [$F(3;22)=12.04$, $p<0.01$] and at the velocity of 1.6 m.s^{-1} [$F(3;22)=5.19$, $p=0.01$].

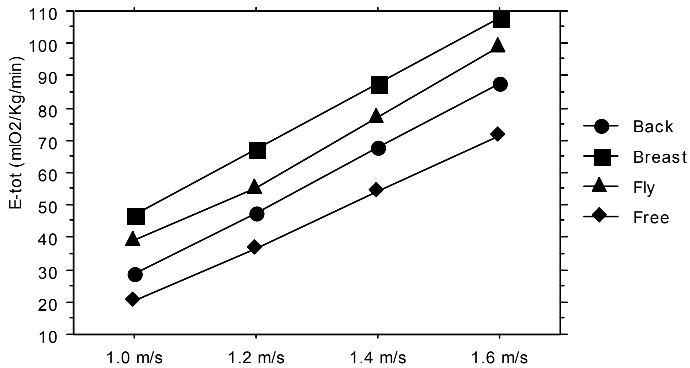


Figure 2. Energy expenditure (E-tot) profile, of the four swimming techniques, for the selected velocities.

Figure 3 presents the post-hoc comparison of $\dot{E}_{tot}$ at a given velocity. At the velocity of 1.0 m.s^{-1} it was verified that the $\dot{E}_{tot}$ was significantly higher in Breaststroke than in Backstroke ($p=0.03$), in Breaststroke than in Freestyle ($p<0.01$) and in Butterfly than in Freestyle ($p=0.02$). At the velocity of 1.2 m.s^{-1} the same profile was found. The $\dot{E}_{tot}$ was significantly higher in Breaststroke than in Backstroke ($p<0.01$), in Breaststroke than in Freestyle ($p<0.01$) and in Butterfly than in Freestyle ($p<0.01$). Therefore, Breaststroke was the less economical swimming stroke and the Freestyle the most economical one. In the next selected velocity, 1.4 m.s^{-1}, the $\dot{E}_{tot}$ was significantly higher in Breaststroke than in Backstroke ($p=0.01$), in Backstroke than in Freestyle ($p=0.03$), in Breaststroke than in Freestyle ($p<0.01$) and in Butterfly than in Freestyle ($p<0.01$). This result confirmed the assumption that, at least at 1.4 m.s^{-1}, the Freestyle was significantly more economical than any other competitive swimming stroke. Finally, at the selected velocity of 1.6 m.s^{-1}, the $\dot{E}_{tot}$ was significantly higher in Breaststroke ($p<0.01$) and in Butterfly ($p=0.02$) than in Freestyle. Not-significant differences were found between Freestyle and Backstroke.

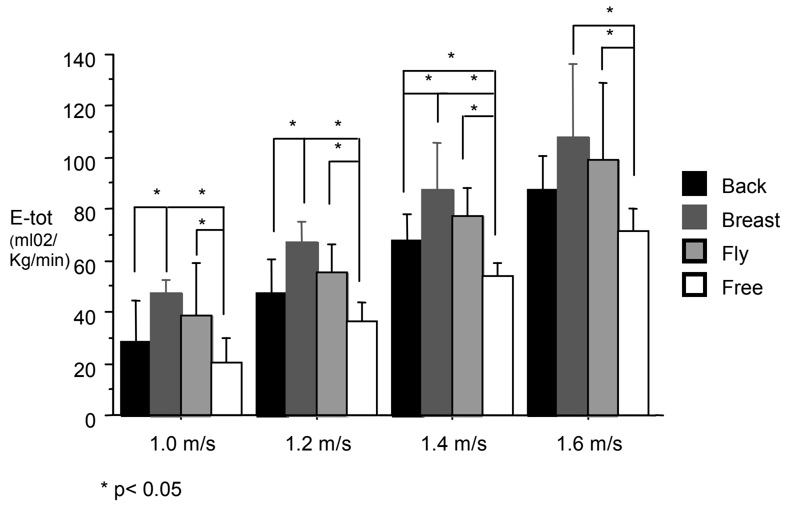


Figure 3. Comparison of total energy expenditure (E-tot) between the swimming stroke according to the Fisher's Post-hoc test, in each selected velocity.

4. DISCUSSION

The purpose of this study was to compare the total energy expenditure of the four competitive swimming strokes. The main finding of the study was that for all the selected velocities, the Freestyle was the most economic stroke, followed by the Backstroke, the Butterfly and the Breaststroke.

From the 23 swimmers evaluated, 8 were female swimmers. It is reported that swimming economy is influenced by the swimmer's gender. Female swimmers are more economical then male swimmers (Onodera et al., 1999). Those differences are related to anthropometrical characteristics, such as body density and hydrodynamic torque (Onodera et al., 1999). Female swimmers can adopt a better horizontal body alignment and are affected by a lower hydrodynamic torque (Zamparo et al., 1996; Yanai, 2001). In the present investigation, once the sample was a convenience one, the effect of gender was only controlled later on. In Breaststroke and Butterfly it was evaluated only one female swimmer in each stroke. In Backstroke, there was no female swimmer evaluated. Therefore, in these strokes, the influence of gender was minimal or non-existent. Only Freestyle an expressive number of female swimmers were studied. In this swimming technique, 6 female swimmers were evaluates, but this was also the swimming technique with the higher number of subjects studied. The absolute number of female swimmers can under-estimate the $\dot{E}_{tot}$ in Freestyle. However, comparing the $\dot{E}_{tot}$ in Freestyle according to gender, there were no significant differences in any swimming velocity selected. For example, at the velocity of 1.6 $m.s^{-1}$, the mean $\dot{E}_{tot}$ for males swimmers was 70.9±7.4 $ml.kg^{-1}.min^{-1}$ and for female swimmers was 71.8±9.8 $ml.kg^{-1}.min^{-1}$. Moreover, comparing the mean body fat of the swimmers, according to swimming technique and gender, there was no significant difference. Probably, elite female swimmers are becoming more androgenous, with anthropometrical characteristics even more close to the ones observed in elite male swimmers. Therefore, the comparison of the $\dot{E}_{tot}$ of the several strokes seems not to be significantly influenced by gender.

There are some studies in the literature concerned with the economy of the competitive swimming techniques (e.g., Holmér, 1974; Pendergast et al., 1978; van Handel et al., 1988; Chatard et al., 1990; Wakayoshi et al., 1995; 1996). However, the role of the anaerobic system to the total energy expenditure is not always taken in account. The few exceptions are the investigations developed by Vilas-Boas and Santos (1994), Vilas-Boas (1996) or Rodriguez (1999). The percentual contribution of this bioenergetical system to the overall energy expenditure should not be disregarded (di Prampero et al., 1978; Camus et al., 1984; Thevelein et al., 1984; Camus and Thys, 1991). For example, Troup (1991) in a 200-m swim observed a contribution of proximally 35% of the anaerobic system in freestyle, 30% in Backstroke, 39% in Butterfly and 37% in Breaststroke. Nevertheless, well-trained swimmers use a greater percentage of energy from the aerobic source (Troup et al., 1992). Therefore, the study of the energy expenditure based exclusively on the oxygen consumption might both underestimate the values and reduce the validity and utility of the measurements.

Most studies about cardiorespiratory parameters in swimming used Douglas bags or mixing chamber gas analyses (e.g., Holmér, 1974; Lavoie and Montpetit, 1986; Chatard et al., 1990; Wakayoshi et al., 1996). However, BxB analysis provides new insights into this field (Keskinen et al., 2003). The feasibility of this system to measure the oxygen uptake of incremental free swimming has been proved (Rodríguez et al., 2003). In this way, the BxB technology offers a more feasible and convenient tool to explore cardiorespiratory adaptations during swimming and in a more detailed manner (Keskinen et al., 2003; Rodríguez et al., 2003).

For all selected velocities, the Breaststroke and the Butterfly strokes were the swimming techniques with higher $\dot{E}_{tot}$. These results are in agreement with data from other authors (Holmér, 1974; Lavoie and Montpetit, 1986; Pendergast et al., 1978) who observed an obvious distinction between the alternated and the simultaneous techniques. This might be related with the higher variation of the swimmer's impulse along the stroke cycle in both techniques (van Tilborgh et al., 1988; Vilas-Boas, 1994; Barbosa et al., 2002). The high amplitude of the swimmer's impulse is explained by the extreme intracyclic variations of the swimming velocity (Kornecki and Bober, 1978; Mason et al., 1992; Togashi and Nomura, 1992; Sanders, 1996; Vilas-Boas, 1996; Barbosa et al., 2003). This phenomenon promotes high peaks of accelerations and/or high peaks of deceleration. In the butterfly stroke, great intracyclic variations of the impulse are due to a greater reduction of this variable during the arm recovery

(Barbosa et al., 2002). In breaststroke, great intracyclic variations are due to a great and positive peak during the leg spreading and a negative peak during the leg's recovery (van Tilborgh et al., 1988; Vilas-Boas, 1994). Higher intracyclic variations of the impulse, such as the ones described above, induce an additional mechanical work done by the swimmers and, consequently, higher energy expenditure (Nigg, 1983).

Holmér (1974) presented a higher VO_2, for a given velocity, for Butterfly stroke than for the Breaststroke. Karpovich and Millman (1944) observed the same up to velocities of 2.5 feets.s^{-1}. At higher velocities, the Butterfly was more economical than the Breaststroke. Troup (1991) confirmed that the Breaststroke was the least economical technique. The data from the present study also revealed higher $\dot{E}_{tot}$ for the Breaststroke than for the Butterfly stroke for all selected velocities. The lower values observed by Holmér (1974) in butterfly, than in breaststroke, might be related to the lower range of velocities studied. Whenever these two strokes were evaluated at higher velocities, Breaststroke was the less economical. Probably, and even though the energy expenditure changes with the change in swimming velocity due to the increasing drag, the Breaststroke is the most affected (Kolmogorov et al., 1997). As the velocities increase, the breaststrokers have less possibility to reduce the drag, especially during the non-propulsive phase of the leg's action. At low velocities, swimmers can have higher durations of the legs actions, expending less energy (Takagi et al., 2003). But at higher velocities the swimmer pushes both legs forward through the water more quickly (Chollet et al., 1999) leading to significant increases of the speed fluctuation (Manley and Atha, 1992) and therefore in the energy cost (Vilas-Boas, 1996).

The freestyle was the most economic competitive technique, followed by the backstroke, at all selected velocities. This is a consensual result over several studies (Karpovich and Millman, 1944; Holmér, 1974; Lavoie and Montpetit, 1986; Pendergast et al., 1978; Troup, 1991). These strokes are characterized by the lower intracyclic variations of the swimming velocity (Keskinen and Komi, 1993; Cappaert et al., 1996; Alves et al., 1998). Consequently one other important biomechanical repercussion is the low value of the swimmer's impulses during the stroke cycle to overcome inertial forces, in comparison to Breaststroke or to Butterfly stroke. Interestingly, in Backstroke, Alves (1996) verified that the impulse in the final downsweep differed significantly between a more economical and a less economical group of swimmers and correlated significantly with the best time in a 100-m event.

One major question is how was the swimming economy evolution over the past decades. Are the swimmers from 2000 more economical that the swimmers evaluated by Holmér [13] in the 70's? First of all, it is important to emphasis that the evaluation procedures used by Holmér [13] and in the present study are quite different. This author used Douglas bags and a flume; in the present study it was used a BxB apparatus, a swimming pool and under-water pace-lights. Secondly, the parameters evaluated were not the same. Holmér (1974) measured the absolute VO_2; in the present study the parameter evaluated was the $\dot{E}_{tot}$. Nevertheless, it was attempted a comparison between the absolute VO_2 reported by Holmér (1974) and the absolute $\dot{E}_{tot}$ from the present investigation, at the swimming velocity of 1.0 $m.s^{-1}$. This swimming velocity was chosen, since it is the only common velocity selected by Holmér (1974) and the present study, for all strokes. It was verified that, for all strokes, the swimming economy has increased in the past decades. For Freestyle, the swimming economy increased 45.9%, for Backstroke 27.0%, for Breaststroke 18.0% and for Butterfly 46.7%. Freestyle, Backstroke and Butterfly presented a high increase over the past decades. In comparison to these swimming techniques, Breaststroke was the one with lower increase. The phenomenon can be related to the strong restrictions imposed in the rules of this swimming technique, in what concerns to its biomechanical evolution.

The values of $\dot{E}_{tot}$ in swimming seem to be a consequence of the specific mechanical limitations of each swimming stroke. In other words, probably the $\dot{E}_{tot}$ profile of each swimming technique is related with its biomechanical characteristics (Kornecki and Bober, 1978; Nigg, 1983; Costill et al., 1985; Smith et al., 1988; Wakayoshi et al., 1995; 1996). Nevertheless, few studies focused on the relationship between swimming economy and swimming mechanics, as it was the cases of Wakayoshi et al. (1995; 1996), Alves et al. (1996) or Vilas-Boas (1996).

5. CONCLUSIONS

As a conclusion, $\dot{E}_{tot}$ of well-trained competitive swimmers was measured over a large range of velocities utilizing a new BxB technique. Freestyle was shown to be the most economic among the competitive swimming strokes, followed by the Backstroke, the Butterfly and the Breaststroke.

Chapter 4: Average resultant impulses per phase in butterfly stroke

The aim of this study was to measure the average resultant impulse (ARI) per phase of the stroke cycle in butterfly and to analyse the variability of ARI according to the adopted breathing technique. The sample was composed of 6 male Portuguese swimmers at national and international level. 6 cameras were set, obtaining non-coplanar images (2 “dual media” images included). The study comprised the kinematical analysis of stroke cycles of the butterfly stroke (Ariel Performance Analysis System, Ariel Dynamics Inc., US) and a VCR (Panasonic, AG7355, Japan) at a frequency of 50 Hz. The ARI was calculated using the mean horizontal acceleration of the center of mass in each phase, the absolute duration of each phase and the body mass of the swimmer. Comparing the ARI according to the breathing technique adopted in each phase of the stroke cycle, we only observed significant differences in the outsweep. Comparing the intra-cyclic variations of the ARI in the different breathing techniques adopted, the arm’s recovery when compared with the remained phases presented a significantly lower ARI.

KEYWORDS: swimming, butterfly stroke, kinematics, impulse

1. INTRODUCTION

The average resultant impulse (ARI) can provide us with useful information about the technical proficiency of the swimmer (Alves, 1996). This is possible due to the ARI result from the differences between propulsion and resistance (van Tilborgh et al., 1988).

One method to estimate the horizontal resultant impulse is through the swimming speed profiles, knowing the time values and the swimmers body mass (Vilas-Boas, 1994). This method has the benefit of allowing the calculation of the ARI per stroke phase (van Tilborgh et al., 1988). In that way, knowing the strongest and the weakest points of the stroke cycle it is possible to promote an improvement on the mechanics of the swimming technique in study. In other words, the measurement of the ARI per phase can be a useful diagnostic tool helping the optimisation of the co-ordination movement, the body position and the stroke mechanics of a swimmer.

In fact, this approach has been used in several swimming techniques, such as the front crawl (Alves, 1996), the backstroke (Alves, 1996) and the breaststroke (Persyn et al., 1986; van Tilborgh et al., 1988; Vilas-Boas and Fernandes, 1993; Vilas-Boas, 1994). However, there seems to be no investigation regarding the butterfly stroke.

Therefore the aim of this study was to estimate the ARI per stroke phase in Butterfly and to analyse the variability of these parameter according to the breathing technique adopted by the swimmers.

2. METHODS

Subjects. The sample was composed of 6 male Portuguese swimmers at national and international level (19.0±2.0 years old; 67.367±6.571 Kg of body mass; 173.9±4.0 cm of height).

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

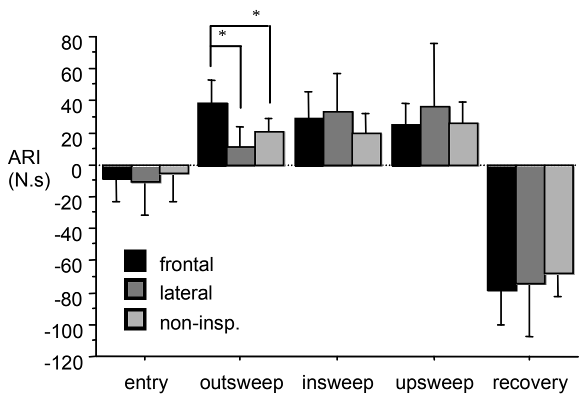
DP 200 SVHS) was set 4.50m above the surface water. In these two last cases, the optical axis was oriented in the direction of the displacement of the swimmers. In all the situations, all cameras or pair of cameras recorded images of the swimmer in non-coplanar planes, different from all the other cameras or pair of cameras. Synchronization of the images was obtained using LED's placed on the recording field of every camera or pair of cameras, which were turned on regularly and simultaneously to initiate the synchronization every time the swimmer entered the performance volume. This it was assume to be delimited by the calibration volume, which was defined by a 3x3x3 meters cube. The calibration cube was marked with 32 calibration points. Each swimmer started in water and performed 3 sets of 3x25 meters in Butterfly stroke at a constant velocity as close as possible from the maximal, using exclusively frontal inspiration cycles, lateral inspiration cycles and non-inspiratory cycles in each set. The study comprised the kinematical analysis of the different stroke cycles at the Butterfly stroke using the "Ariel Performance Analysis System" from Ariel Dynamics Inc. (APAS) and a VCR (Panasonic AG 7355) at a frequency of 50 Hz. It was used the Zatsiorsky's model adapted by de Leva (1996) which is composed by 22 anatomical points of reference. The 3D reconstruction of the digitized images was performed using the "Direct Linear Transformation" procedure (Abdel-Aziz and Karara, 1971). It was used a filter with a cut-off frequency of 5Hz, as suggested by Winter (1990) for the analysis of the velocity and the acceleration of the center of mass. The ARI was calculated using the mean horizontal acceleration of the center of mass per stroke phase, the absolute duration of each phase and the swimmers body mass. The acceleration and the duration values were obtained from the APAS. The mean horizontal velocity of the center of mass did not presented significant differences between the 3 breathing styles.

Statistical Methods. Differences on ARI between the breathing techniques and in each technique between phases were tested using the "ANOVA for repeated measures" ($p \leq 0.05$).

3. RESULTS AND DISCUSSION

Figure 1 presents the comparison of the ARI in each swim phase between the three breathing techniques. Comparing the ARI according to the adopted breathing technique in each phase of the stroke cycle, we only observed significant differences in the outsweep. In this phase, the ARI was significantly higher using the frontal inspiration cycles rather than the lateral inspiration cycles [$F(1;5)= 82.688$, $p=0.0003$] or the non-inspiratory cycles [$F(1;5)= 12.944$, $p=0.0156$]. There was no significant differences between the three breathing techniques in the hands path or in the relative duration of the outsweep, factors that could explain this results. However, the absolute duration of the outsweep was higher using the frontal inspiration technique than the others two, but without statistical significance. However, this is probably one explanation for the higher values of the ARI during the outsweep adopting the frontal breathing.

In other way, the inspiration act might also have a little influence in the ARI. Doing the inspiration through a cervical extension, it will promote an increase of the maximal body cross-section area; and therefore, an increase of the Drag Force (Clarys, 1979). Therefore, the swimmer needs a higher horizontal impulse in the subsequent phases, specially the outsweep, to achieve mean horizontal velocities in the most propulsive phases of the stroke cycle, similar to the ones observed in the other breathing techniques.

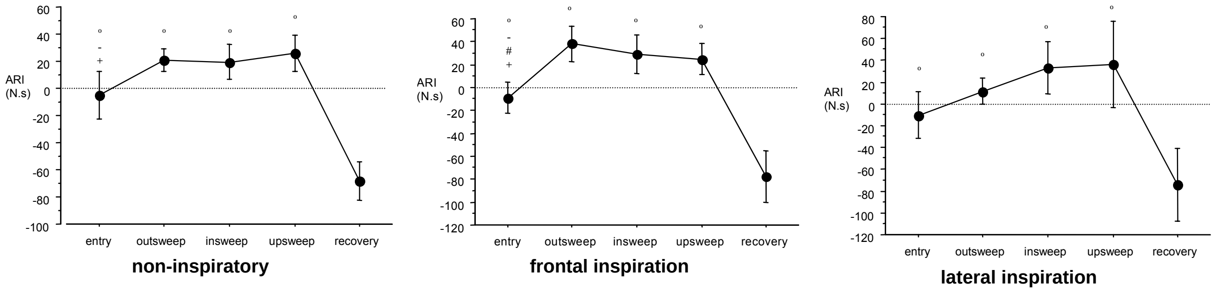


* p≤0.05 between breathing technique

Figure 1. Comparison of the average resultant impulse (ARI), in each swim phase, between the breathing techniques.

Figure 2 presents the intra-cyclic variations of the ARI using the different breathing techniques. Comparing the intra-cyclic variations of the ARI in the different breathing techniques, they were quite similar. In all models, the recovery phase when compared with the remained phases presented a significantly lower ARI. In fact, this is in agreement with the findings of Schleihauf (1979), Schleihauf et al. (1988) and Mason et al. (1992). This might be explained due to the body position in that phase, which is characterised by an increase of the maximal body cross-section area and consequently a decrease of the mean horizontal acceleration of the center of mass of the swimmer.

In the non-inspiratory cycles the ARI during the entry was significantly lower than in the outsweep [$F(1;5)=18.095$, $p=0.0081$] and in the upsweep [$F(1;5)= 8.370$, $p=0.0341$]. In the frontal inspiration cycles the ARI was significantly lower in the entry than in the outsweep [$F(1;5)= 22.458$, $p= 0.0052$], in the insweep [$F(1;5)= 33.349$, $p=0.0029$] and in the upsweep [$F(1;5)=14.706$, $p=0.0129$]. In other word, the entry was the second less propulsive phase of the stroke cycle as reported previously by Schleihauf (1979), Schleihauf et al. (1988) and Mason et al. (1992). This might be a result of the entry of the hands in the water as well as of the previously entry from part of the body, increasing the wave drag and, therefore, promoting a decrease of the mean horizontal acceleration of the center of mass. The ARI in the frontal inspiration cycles in the outsweep was higher than in the insweep [F(1;5)= 0.568, p=0.4853] and the upsweep [F(1;5)=1.547, p=0.2687]. Although this values did not present significant differences, the higher ARI in the outsweep might be due to a higher absolute duration of this phase in the frontal technique.



*** p≤0.05 between one phase and the entry**
+ p≤0.05 between one phase and the outsweep
 # p≤0.05 between one phase and the insweep
- p≤0.05 between one phase and the upsweep
° p≤0.05 between one phase and the recovery

*** p≤0.05 between one phase and the entry**
+ p≤0.05 between one phase and the outsweep
 # p≤0.05 between one phase and the insweep
- p≤0.05 between one phase and the upsweep
° p≤0.05 between one phase and the recovery

*** p≤0.05 between one phase and the entry**
+ p≤0.05 between one phase and the outsweep
 # p≤0.05 between one phase and the insweep
- p≤0.05 between one phase and the upsweep
° p≤0.05 between one phase and the recovery

Figure 2. Comparison of the intra-cyclic variations of the average resultant impulse (ARI) using the different breathing techniques.

4. CONCLUSIONS

The butterfly stroke is a swimming technique where it is possible to observe some specific intra-cyclic variations of the ARI due to greater reductions of this parameter during the arm's recovery. So swimmers must learn to reduce the drop of the ARI during the arm's recovery by increasing the propulsive force produced by the legs actions and adopting a more streamline position of the body during this phase.

It seems that there is no significant differences in the ARI during almost every phases of the stroke cycle, except for the outsweep, according to the breathing technique. So, the breathing style used it is not decisive for the adoption of a more fluent swimming in butterfly.

Chapter 5: Energetics and stroke determinants in butterfly stroke

The purpose of this study was to identify the relationship between the bioenergetical and the biomechanical variables (stroke determinants), through a range of swimming velocities, in butterfly stroke. Three male and one female butterflier of international level were submitted to an incremental set of 200-m butterfly swims. The starting velocity was 1.18 $m \cdot s^{-1}$ for the males and 1.03 $m \cdot s^{-1}$ for the female swimmer. Thereafter, the velocity was increased by 0.05 $m \cdot s^{-1}$ after each swim until exhaustion. Cardio-pulmonary and gas exchange parameters were measured breath by breath for each swim to analyze oxygen consumption and other energetic parameters by portable metabolic cart ($K4b^2$, Cosmed, Rome, Italy). A respiratory snorkel and valve system with low hydrodynamic resistance was used to measure pulmonary ventilation and to collect breathing air samples. Blood samples from the ear lobe were collected before and after each swim to analyze blood lactate concentration (YSI 1500L, Yellow Springs, US). Total energy expenditure ($\dot{E}_{tot}$), energy cost (EC), stroke frequency (SF), stroke length (SL), mean swimming velocity (V) and stroke index (SI) were calculated for each lap and average for each 200-m stage. Correlation coefficients between $\dot{E}_{tot}$ and V, EC and SF, as well as between EC and SI were statistically significant. For the relation between EC and SL, only one regression equation presented a correlation coefficient with statistical significance. Relations between SF and V, as well as between SI and V were significant in all of the swimmers. Only two individual regression equations presented statistically significant correlation coefficient values for the relation established between V and the SL. As a conclusion, the present sample of swims demonstrated large inter individual variations concerning the relationships between bioenergetic and biomechanical variables in butterfly stroke. Practitioners should be encouraged to analyze the relationships between V, SF and SL individually to detect the deflection point in SL in function of swimming velocity to further determine appropriate training intensities when trying to improve EC.

KEYWORDS: swimming, energetic, stroke length, stroke rate, stroke index, velocity

1. INTRODUCTION

Holmér (1974) was one of the pioneers in the study of the energetic swimming cost at different velocities. Since then, several studies have been published about this topic (e.g. Pendergast et al., 1978; Nomura, 1983; Costill et al., 1985; Montpetit et al., 1988; van Handel et al., 1988; Vilas-Boas and Santos, 1994; Vilas-Boas, 1996). However, most of these investigations centered their attention in freestyle swimming (e.g. D'Aquisto et al., 1992; Keskinen and Komi, 1993; Rodriguez et al., 2003) butterfly being the least studied stroke. Comparing the four competitive swimming techniques, for a given velocity, the butterfly stroke presented the higher energetic cost, followed by the breaststroke, the backstroke and the freestyle (Holmér, 1974).

The analysis of the stroke determinants is one of the major points of interests in the biomechanical investigation of swimming techniques, being studied for the first time by East (1970). The purpose of the study was to understand the behavior of variables such as the stroke frequency (SF), the stroke length (SL) and the mean swimming velocity (V). While V it is a product of SF and SL (Craig and Pendergast, 1979). Increases or decreases in V are due to a combined increase or decrease in SF and SL, respectively (Craig and Pendergast, 1979; Craig et al., 1979; 1985). One other parameter often used is the stroke index (SI), considered as a valid indicator for swimming efficiency (Costill et al., 1985). This index assumes that, at a given velocity, the swimmer that moves the greatest distance per stroke has the most efficient swimming technique. Butterfly presents higher V than breaststroke and backstroke. The SF is also higher in this technique than in breaststroke and the SL is higher than in the freestyle (Craig and Pendergast, 1979; Craig et al., 1979).

On the other hand, there are a small number of investigations concerned to study the relationships between the energy cost (EC) and the stroke determinants (e.g. Costill et al., 1985; Lavoie et al., 1987; Smith et al. 1988; Wakayoshi et al., 1995; 1996). Only one study (Wakayoshi et al., 1995) analyzed butterfly stroke, evaluating a single butterflier, in a sample of ten swimmers. At least in freestyle, there were significant correlations between energy cost and V, energy cost and SF, SF and V (Wakayoshi et al., 1995). Thus, there is a lack of scientific approaches around the relationships between the bioenergetic and biomechanical characteristics, in butterfly stroke. Especially between the EC and the determinants of the stroke performance (SF, SL and SI).

The purpose of this study was to identify the relationships established between the EC and the stroke determinants (SF, SL and SI) through a range of swimming velocities, as well as, the relationship between the stroke determinants and the velocity, in Butterfly stroke.

2. METHODS

Subjects. Three male and one female butterflier of international level volunteered to serve as subjects. Anthropometrical and the performance characteristics of the swimmers in 25-m pool (short course) were presented in table 1. At the time of the experiments, one of the male swimmers was the Portuguese record holder in the 200-m Butterfly in short course and the female swimmer was the Portuguese record holder of the 200-m Butterfly in 50-m pool (long course).

Table 1. Anthropometrical and performance characteristics in short course of the butterfliers studied.

Swimmer	Age (Years old)	Height (cm)	Body mass (Kg)	Fat mass (%)	50-m (s)	100-m (s)	200-m (s)
#1 (m)	24	184	80.2	12	24.76	54.13	118.94
#2 (f)	17	165	54.2	13	28.09	60.87	133.52
#3 (m)	20	174	64.2	7	26.05	56.89	121.92
#4 (m)	17	180	67.2	5	27.30	58.40	119.76
mean ± S.D.	19.5 ± 3.3	175.7 ± 8.3	66.5 ± 10.7	9.3 ± 3.8	26.55 ± 1.46	57.57 ± 2.82	123.53 ± 6.78

Design. The swimmers were submitted to an incremental set of 200-m butterfly swims. The starting velocity was 1.18 $m \cdot s^{-1}$ for the males and 1.03 $m \cdot s^{-1}$ for the female swimmer. After each swim, the velocity was increased by 0.05 $m \cdot s^{-1}$ until exhaustion and/or until the swimmer could not swim at the predetermined pace. The velocities and increments in V were chosen in agreement with the swimmers so that they would make their best performance on the 7^{th} trial. The resting period between swims was 30 s to collect blood samples. Two swimmers made 5 trials, another swimmer made 6 trials and a last one made 7 trials. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Portugal) were placed on the bottom of the 25-m pool, used to control the swimming speed and to help the swimmers keep an even pace along each step. In addition, elapsed time for each swim was measured with a chronometer to control the swimmer's velocity.

Data Collection. The swimmers breathed through a respiratory snorkel and valve system (Toussaint et al., 1987; Keskinen et al., 2003), connected to a telemetric portable gas analyzer (K4 b^2, Cosmed, Italy). Cardio-respiratory and gas exchange parameters were measured breath by breath (BxB), during the whole 200-m, to analyze oxygen consumption (VO_2) and other energetic parameters.

Blood samples (25 µl) from the hyperemisized ear lobe were collected to analyze blood lactate concentration (YSI 1500 L, Yellow Springs, US) before and after each swim as well as 1, 3, 5 and 7 minutes after the last swim.

The total energy expenditure ($\dot{E}_{tot}$) was calculated using the VO_2 net (difference between the value measured in the end of the stage and the rest value), and the blood lactate net (difference between the value measured in two consecutive stages), transformed into VO_2 equivalents using a 2.7 $mlO_2.Kg^{-1}.mmol^{-1}$ constant (di Prampero et al., 1978). The EC it was calculated dividing the $\dot{E}_{tot}$ by V (di Prampero et al., 1986; Zamparo et al., 2002).

Stroke determinants were measured for each 25-m lap and averaged for each 200-m stage. V was obtained from the distance and the 25-m split times. The swimmers were advised to reduce gliding during the start and the turning in order to keep the V as constant as possible in relation to the pace maker lights. The SF was measured with a cronofrequency meter from 3 consecutive strokes, in the middle of each pool length. The SL it was then calculated by dividing V with SF (Craig and Pendergast, 1979). The SI was obtained as the product of the SL and V (Costill et al., 1985).

Statistical procedures. Mean values for the stroke determinants in all 200-m were calculated from each 25-m. Individual regression equations describing the relation between the bioenergetic ($\dot{E}_{tot}$ and EC) and biomechanical (SF, SL, SI and V) variables were computed, as well as, its coefficients of determination and Spearman correlation coefficients. Individual regression equations as well as coefficients of determination and correlation were also calculated to describe the relationships between V and the stroke determinants. Mean values and standard deviation of the correlation coefficients were computed. The level of statistical significance was set at $p \leq 0.05$.

3. RESULTS

Individual regression equations between $\dot{E}_{tot}$ and V, between $\dot{E}$ and V^2 and between $\dot{E}$ and V^3 were calculated. Individual regression line together with the plots between the $\dot{E}_{tot}$ and V for one swimmer was presented in figure 1. The correlation coefficients between $\dot{E}$ and V ranged from r=0.90 (p=0.04) to r=0.95 (p=0.05), having a mean value of 0.92±0.03. In the case of the relation between $\dot{E}_{tot}$ and V^2, the correlation coefficients were between r=0.85 (p=0.07) and r=0.96 (p=0.04) with a mean value of 0.91±0.05. Finally, the correlation coefficient between $\dot{E}_{tot}$ and V^3, ranged from r=0.87 (p=0.05) to r=0.95 (p<0.01) with a mean value of 0.91±0.04. The linear approach presented mean values of the regression coefficients higher than the exponential ones. When the quadratic approach was applied, the coefficient of determination was non-significant for one swimmer. When the cubic approach was applied the coefficient of determination was non-significant in two of the swimmers.

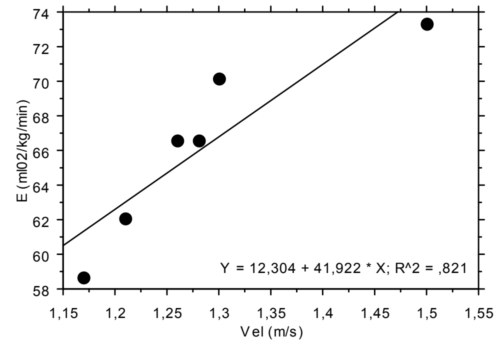


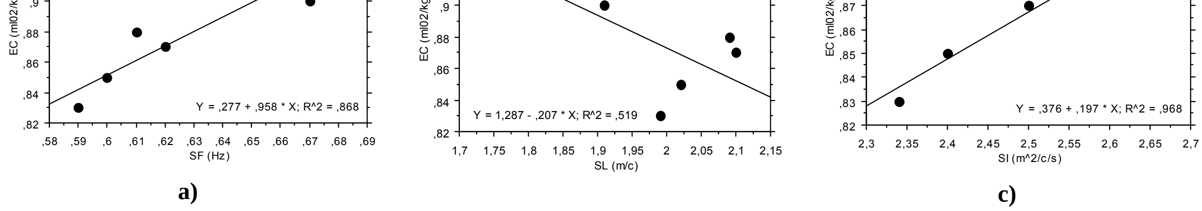
Figure 1. Relationship between the total energy expenditure ($\dot{E}_{tot}$) and the mean swimming velocity (V) for one swimmer.

Individual regression equations and the respective correlation coefficients, between $\dot{E}_{tot}$ and V, for all swimmers were presented in table 2. All correlation coefficients were statistically significant, ranging from r=0.90 (p=0.04) to r=0.95 (p=0.05). So, increases in the energy expenditure through the set of swims were related to the increase in the V, from stage to stage.

Individual regression line together with the plots computed between the EC and the SF, the SL and the SI for one swimmer were presented in figure 2. Individual regression equations and the respective correlation coefficients between EC and SF, and between SL and SI were listed in table 2.

All correlation coefficients between EC and SF and between EC and SI were statistically significant. For the relationship between EC and SF, the coefficients ranged from r=0.93 (p<0.01) to r=0.98 (p=0.02). In the case of EC versus SI, the coefficients ranged from r=0.77 (p=0.04) to r=0.98 (p<0.01). Thus, there was a significant positive relationship between EC and both the SF and SI throughout the set of swims.

For the relationship between EC and SL, only one regression equation presented a correlation coefficient with a statistical significant value. The correlation coefficients ranged between r=0.15 (p=0.81) to r=0.93 (p=0.01).



a) c)

b)

Figure 2. Relation between: a) energy cost (EC) and the stroke frequency (SF); b) EC and stroke length (SL); c) EC and stroke index (SI) of one of the analyzed swimmers.

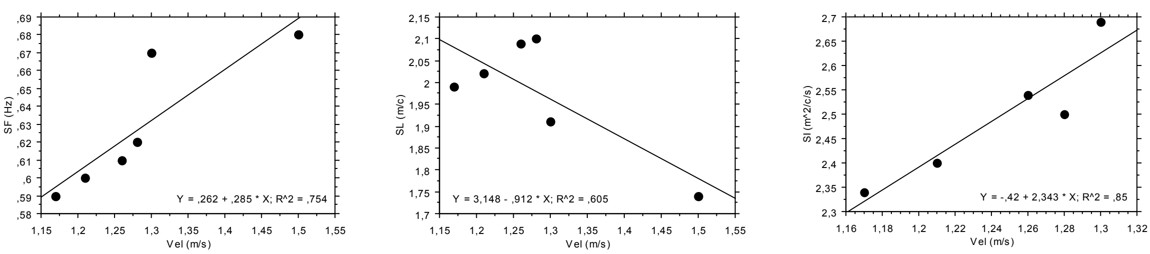
Table 2. Individual regression equations (Eq) and correlation coefficients (r) between total energy expenditure ($\dot{E}_{tot}$) and velocity (V), energy cost (EC) and stroke frequency (SF), EC and stroke length (SL) and EC and stroke index (SI).

Swimmer		Equation $\dot{E}_{tot}$ (y) vs V (x)	Equation EC(y) vs SF (x)	Equation EC(y) vs SL (x)	Equation EC(y) vs SI (x)
#1 (m)	Eq	Y=-257.719+247.111x	Y=2.274+4.79x	Y=2.984-1.247x	Y=-0.686+0.606x
	r	r=0.95, p=0.05	r=0.98, p=0.02	r=0.51, p=0.50 (NS)	r=0.96, p=0.04
#2 (f)	Eq	Y=-77.066+115.567x	Y=-0.016+1.303x	Y=3,22-1.349x	Y=-0.473+0.58x
	r	r=0.90, p<0.01	r=0.94, p<0.01	r=0.93, p<0.01	r=0.77, p=0.04
#3 (m)	Eq	Y=20.344+32.125x	Y=-3.247+6.254x	Y=0.359+0.264x	Y=-0.133+0.417x
	r	r=0.90, p=0.04	r=0.97, p=0.03	r=0.15, p=0.81 (NS)	r=0.89, p=0.05
#4 (m)	Eq	Y=12.304+41.922x	Y=0.277+0.958x	Y=1.287-0.207x	Y=0.376+0.197x
	r	r=0.91, p=0.01	r=0.93, p=0.01	r=0.72, p=0.11 (NS)	r=0.98, p<0.01
Mean r		0.92	0.96	0.58	0.90
± S.D.		± 0.03	± 0.02	± 0.33	± 0.10

Individual regression lines together with the plots between the V and the SF, the SL and the SI for one of the studied swimmers were presented in figure 3. Individual regression equations and the correlation coefficients computed between the strokes parameters were presented in table 3.

Relationships between SF and V, as well as, between SI and V were significant in all the swimmers. In the first case, the coefficients ranged from r=0.87 (p=0.03) to r=0.99 (p<0.01). In the second case, the coefficients ranged between r=0.86 (p=0.01) and r=0.98 (p=0.02). It seems that the increment of velocity, from stage to stage, are explained by the increases of SF and of SI, observed through the triangular protocol.

For the relationship between V and SL, only two individual regression equations presented correlation coefficients with significant values. In the case of 3 swimmers, there was a light tendency, with no statistical significance, for the decrease of the SL with the increasing V.



a) b) c)

Figure 3. Relation between: a) stroke frequency (SF) and mean velocity (V); b) stroke length (SL) and V; c) stroke index and V for one of the evaluated swimmers.

Table 3. Individual regression equations (Eq) and correlation coefficients (r) between the mean velocity (V) and the stroke frequency (SF), the stroke length (SL) and the stroke index (SI).

Swimmer		Equation SF (y) vs V (x)	Equation SL (y) vs V (x)	Equation SI (y) vs V (x)
#1 (m)	Eq	Y=-0.165+0.63x	Y=3.085-1x	Y=0.423+2.29x
	r	r=0.97, p=0.03	r=0.78, p=0.22 (NS)	r=0.98, p=0.02
#2 (f)	Eq	Y=-0.272+0.782x	Y=2.6-0.636x	Y=0.755+1.257x
	R	r=0.99, p<0.01	r=0.85, p=0.02	r=0.86, p=0.01
#3 (m)	Eq	Y=0.387+0.23x	Y=1.645+0.117x	Y=0.598+1.407x
	R	r=0.92, p=0.03	r=0.30, p=0.62 (NS)	r=0.94, p=0.02
#4 (m)	Eq	Y=0.262+285x	Y=3.148-0.912x	Y=-0.42+2.343x
	r	r=0.87, p=0.03	r=0.78, p=0.07 (NS)	r=0.92, p=0.03
Mean r		0.94	0.68	0.93
± S.D.		± 0.05	± 0.25	± 0.05

4. DISCUSSION

The purpose of this study was to identify the relationships established between the EC and the stroke determinants (SF, SL and SI) through a range of swimming velocities, as well as, the relationship between the stroke determinants and the velocity, in Butterfly stroke. Irrespective to the small sample of subjects, the present study supports the theory, that there is a close connection between the bioenergetic parameters ($\dot{E}_{tot}$ and EC) and biomechanical determinants of stroke performance (SF, SL, V, SI).

Several authors have used the exponential model for the study of the relation between $\dot{E}_{tot}$ and V (Hollander et al., 1990; Wakayoshi et al., 1995; 1996). According to these authors, the establishment of relations between $\dot{E}_{tot}$ and V^3 will be more fit than the linear model. The main argument presented concerns with the identification of external power with energy expenditure, and with the assumption that the first one is the product of swimming velocity and drag (related to the velocity squared). However, it is also a common notion in the literature that the linear approach makes the best match (di Prampero et al., 1978; Montpetit, 1981; Montpetit et al., 1983; 1988; van Handel et al., 1988; Vilas-Boas and Santos, 1994; Vilas-Boas, 1996). The higher correlation values obtained for the linear approach may be related with an increased efficiency associated with mean velocity values, and with a concomitant reduction of the intra-cyclic speed fluctuation of the center of mass of the swimmers. Assuming an exponential relationship, doing an infinitesimal analysis from a reduced interval of velocities, the linear approach might present a better adjustment. So, one other hypothetical explanation is that for a reduced range of velocities, such as in the present data, the linear approach might be more fit. However, for a higher spectrum of velocities, the exponential approach might be the most appropriate model.

For the study between $\dot{E}_{tot}$ and V, comparing the linear approach with the exponential ones, the linear model presented higher mean values for the correlation coefficient. In fact, the correlation coefficients of the present data were close or higher to the ones observed by other authors adopting the linear approach (Montpetit et al., 1983; 1988; Vilas-Boas and Santos, 1994; Vilas-Boas, 1996). Moreover, in the quadratic approach, there was a correlation without significant value, while in the case of the cubic approach, the same occurred for two swimmers. When the pooled data was analyzed, the linear relation was still stronger (r^2=0.48, p<0.01) than the exponential relation (r^2=0.31, p=0.01) possibly due to the small sample of swimmers and because all swimmers swam the same range of velocities. In addition, the 4 swimmers represented equal competitive level. Therefore, in the present study, the linear approach was adopted to compute the regressions between $\dot{E}_{tot}$ and V.

All the equations between $\dot{E}_{tot}$ and V presented correlation coefficients with significant values. This means that increases in the energy expenditure through the protocol were related to the increase of V, from stage to stage. In fact, there is an agreement in the literature that with the increase in swimming velocity there is an increase in the energy expenditure (Holmér, 1974; Vilas-Boas and Santos, 1994; Wakayoshi et al., 1995; 1996; Vilas-Boas, 1996). The increase of $\dot{E}_{tot}$ is due to the necessity to overcome water resistance, which is related to the increase of V. Furthermore, the increment of $\dot{E}_{tot}$ seems to be due not only to an increase of the VO_2, but also from the blood lactate concentrations (di Prampero, 1986; Wakayoshi et al., 1995).

Concerning the relationship between EC and SF and between EC and SI, the results of the present study are in agreement with investigations conducted in other swimming strokes (Costill et al., 1985; Smith et al., 1988; Klentrou and Montpetit, 1992; Tourny, 1992; Wakayoshi et al., 1995). EC increased significantly along with the increasing SF and SI, throughout the set of swims. This factor seems to be more consistent in stages above the anaerobic threshold pace, according to Wakayoshi et al. (1996). Especially in the breaststroke and in the butterfly stroke, there is a high intra-cycle variation in the average resultant impulse (van Tilborgh et al., 1988; Barbosa et al., 2002). This variation results from large acceleration and deceleration phases within the stroke cycle, which consumes energy. So, if the swimmer performs a higher number of strokes in a given distance, the total energy requirement for the acceleration of the body will increase. Consequently, there was a significant relationship between the SF and the EC. The significant increase of the EC associated with the increase of the SI is explained by the fact that the index is the product of V and SL. So, the increment of the EC might be justified, primarily, due to the increment of the V and not from the behavior of the SL. Thus, it would be more appropriate to study the relationship between the EC and the SI at a given V.

For the relationship between EC and SL, only one regression equation presented a correlation coefficient with a significant value. The tendency however, was that EC decreased with increasing SL. In the backstroke, an inverse and significant relationship between the SL and the EC was found (Smith et al., 1988). Wakayoshi et al. (1996), observed a decrease of the SL in the stages above the anaerobic threshold. But in the aerobic stages, the SL was constant. The most obvious explanation for the present result is the muscular fatigue along with the increasing velocity (Keskinen and Komi, 1993). The decrease in the SL, apparently, might be associated with the accumulation of blood lactates and other anaerobic metabolites, as it was previously observed by Keskinen and Komi (1993).

Relationships between SF and V, as well as, between SI and V were significant in all cases. Several studies have observed that increases in V were related to increases of SF (Craig and Pendergast, 1979; Craig et al., 1979; 1985; Wakayoshi et al., 1995). So, the observed increase in SF with the increment of swimming velocity follows the biomechanical pattern described by Keskinen (1993). The relationship between SI and V were also significant. In fact, increments of the SI being strongly associated to increases of V aren't a new. Costill et al. (1985) proposed, that SI it is calculated as the product of V by SL. Consequently from the statistical point of view these two variables are multicolinear. This is the reason for the high correlation values found.

For the relation between V and SL, there was a slight tendency to decrease SL with the increase in V. Craig et al. (1985) reported that increments of V were explained fundamentally by an increase of the SF with a slight decrease of the SL. So, with an incremental protocol, butterfliers also increase V, from stage to stage, through increments of SF, trying to maintain SL with a constant pattern. Weiss et al. (1988) also shared this idea, as they found a similar phenomenon, analyzing specialists in breaststroke, backstroke and freestyle.

5. CONCLUSIONS

As a conclusion: (i) EC increased significantly along with increasing SF and SI; (ii) the present sample demonstrated large inter-individual variations concerning the relationships between EC and SL. However, the tendency was to a decrease of EC with increasing SL; (iii) Through the trials, there was an increase of V, mainly due to increases of the SF and maintaining SL constant. Therefore, practitioners should be encouraged to analyze the relationships between V, SF and SL individually to detect the deflection point in SL in function of swimming velocity to further determine appropriate training intensities when trying to improve EC.

Chapter 6: Energetics and speed fluctuation in butterfly stroke

The purpose of this study was to examine the relationship between the intra-cycle variation of the horizontal velocity of displacement (dV) and the energy cost (EC), in butterfly stroke. Five Portuguese swimmers of national level performed one maximal and two sub-maximal 200-m butterfly swims. The oxygen consumption was measured breath-by-breath by portable metabolic cart ($K4b^2$, Cosmed, Rome, Italy). A respiratory snorkel and valve system with low hydrodynamic resistance was used to measure pulmonary ventilation and to collect breathing air samples. Blood samples from the ear lobe were collected before and after each swim to analyze blood lactate concentration (YSI 1500L, Yellow Springs, US). Total energy expenditure ($\dot{E}_{tot}$) and EC were calculated for each swim. The swims were videotaped in sagital plane with a set of two cameras providing dual projection from both underwater and above the water surface. APAS (Ariel Dynamics Inc, USA) was used to analyse dV for the centre of mass. The $\dot{E}_{tot}$ increased linearly with the increasing V, presenting a significant correlation coefficient between the parameters ($r=0.827$, $p<0.001$). The increase in EC was significantly associated with the increase in the dV ($r=0.807$, $p<0.001$). It is concluded that high intra-cycle variation of the velocity of the centre of mass was related to less efficient swimming and vice versa in butterfly.

KEYWORDS: butterfly, energy cost, velocity fluctuation, centre of mass

1. INTRODUCTION

Fluctuating velocity while swimming as compared to swimming with constant velocity leads to an increase in the amount of work done by the swimmer (Nigg, 1983). This increase is related to the need of overcoming the inertia, as well as, the hydrodynamic drag. However, the swimmer does not move at a constant velocity. The variations in the arms, in the legs and in the trunk actions lead to variations on the swimming velocity, in every stroke cycle. Whereas these movements are necessary to move the swimmer forward, they include elements, which add up to the necessary work done by the swimmer (Nigg, 1983; D'Acquisto et al., 1998). However, less energy might be consumed with lower intra-cyclic variations of the velocity. Thus, velocity fluctuations within a stroke cycle should give an indication of swimming efficiency (Barthels and Adrian, 1975; Kornecki and Bober, 1978).

Although numerous papers around biomechanical (kinematical) and bioenergetic (energy cost) characteristics of different swimming techniques have been published, only a few approaches combine these two domains. Alves et al. (1996) explored an attempt to explore the links between the intra-cycle variation of the horizontal velocity of displacement (dV) and the energy cost (EC) of swimming in front crawl and in backstroke. In backstroke, the correlation between dV of the hip and the EC presented significant values at low velocities (r=0.78 at 1.1 $m.s^{-1}$ and r=0.66 at 1.2 $m.s^{-1}$). In front crawl the relationship was non-existent at all studied velocities (Alves et al., 1996).

Vilas-Boas (1996) made a similar study in breaststroke. Overall correlation coefficient, from all the swimmers evaluated, between the EC and an index of dV from the hip were statistically non-significant. However, when individual correlations were computed, the two variables were highly correlated. It was suggested that an increase in dV would induce an increase of the EC, whenever an individual approach would be done, but not adopting an overall approach.

In what concerns to the butterfly stroke, there are no scientific approaches between the EC and variables of technique performance. Moreover, when compared with other swimming techniques, the dV (Kornecki and Bober, 1978; Mason et al., 1992; Barbosa et al., 2003) and the bioenergetical profile (Holmér, 1974; Troup, 1991) of butterfly stroke presents higher values. Therefore, it was the purpose of this study to examine the relationships between the dV of the centre of mass and the EC, in butterfly stroke.

2. METHODS

Subjects. Five Portuguese national level swimmers, 2 females and 3 males, volunteered to serve as subjects. Table 1 presents the anthropometrical data and the performance times in 25-m distances (short course).

Table 1. Anthropometrical data and performance characteristics of the subjects in short course.

Swimmer	Age (Years old)	Height (cm)	Body mass (Kg)	Fat mass (%)	200-m (s)
#1 (m)	21	171	67.8	8	129.89
#2 (f)	14	147	47.4	25	154.99
#3 (m)	16	170	59.8	5	135.52
#4 (f)	16	159	55.6	21	149.86
#5 (m)	16	183	75.2	4	131.13
Mean ± S.D.	16.6 ± 2.6	166.0 ± 13.6	61.2 ± 10.8	12.6 ± 9.7	140.28 ± 11.43

Design. The swimmers performed 3x200-m trials in butterfly, two sub-maximal (75% and 85%) and one maximal stage. At least 30 minutes of rest was allowed between each trial. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Portugal), on the bottom of the 25-m pool, were used to control the swimming speed and to help the swimmers to keep an even pace along the two sub-maximal trials.

Data Collection.

The swimmers breathed through a respiratory snorkel and valve system (Toussaint et al. 1987; Keskinen et al., 2003), connected to a telemetric portable gas analyzer (K4 b^2, Cosmed, Italy). The oxygen consumption (VO_2) was measured for each swim breath-by-breath (BxB). Figure 1 presents the example of the VO_2 kinetics from one of the studied swimmers during a 200-m stage.

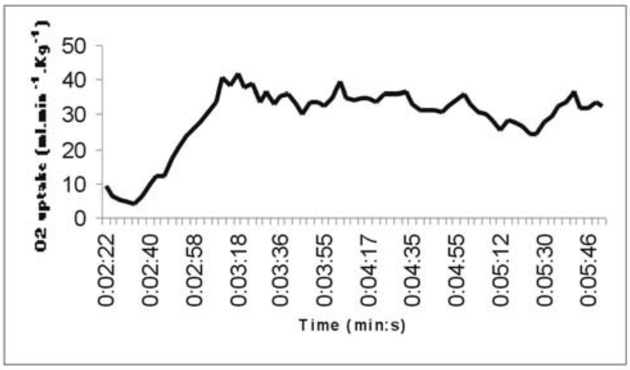


Figure 1. The VO_2 kinetics from one of the studied swimmers during a 200-m stage.

Blood samples (25 µl) from the hyperemisized ear lobe were collected to analyze blood lactate concentration (YSI 1500 L, Yellow Springs, US) before and 1, 3, 5 and 7 minutes after each swim.

The total energy expenditure ($\dot{E}_{tot}$) was calculated using the VO_2 net and the blood lactate net (difference between the highest value measured in the end of the stage and the rest value), transformed into VO_2 equivalents using a 2.7 $mlO_2.Kg^{-1}.l^{-1}$ constant and the procedures described by di Prampero et al. (1978). The energy cost (EC) was calculated dividing the $\dot{E}_{tot}$ by the velocity of displacement (V).

The swims were videotaped (50 Hz) in sagittal plane with a pair of cameras (JVC GR-SX1 SVHS and JVC GR-SXM 25 SVHS), providing a dual projection from both underwater and above the water surface. The cameras were placed stationary on the opposite lateral wall of the pool, perpendicular to the line of motion and 10.2 m away from the object. The images of the two cameras were real time synchronized and edited on a mixing table (Panasonic Digital Mixer WJ-AVE55 VHS) to create one single image of dual projection as described previously by Vilas-Boas et al. (1997).

APAS (Ariel Dynamics Inc, USA) and a VCR (Panasonic AG 7355) at a frequency of 50 Hz were used to analyze dV of the centre of mass and a kinematical analysis of the stroke cycles. Zatsiorsky's model with an adaptation by de Leva (1996) was used with the division of the trunk in 3 articulated parts. A filter with a cut-off frequency of 5Hz, as suggested by Winter (1990) was used for the analysis of the horizontal velocity curve of the centre of mass. Figure 2 illustrates the typical intra-cyclic fluctuation of the velocity of the center of mass of one of the swimmers.

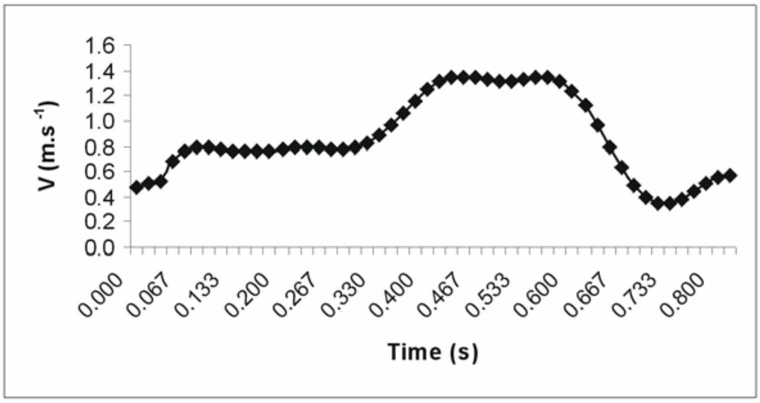


Figure 2. The intra-cyclic fluctuation of the velocity of the center of mass for one of the swimmers.

Statistical procedures. Means and standard deviations of all variables were calculated. Coefficients of variation for the horizontal velocity of the centre of mass along with the stroke cycle were calculated. Linear regressions between the bioenergetic and biomechanical variables were computed, as well as, its Coefficients of determination and correlation. The level of statistical significance was set at $p \leq 0.05$.

3. RESULTS

Figure 3 presents the economy profile of butterfly stroke, for all the swimmers. The $\dot{E}_{tot}$ increased with V following the equation $\dot{E}_{tot}$=-97.29+140.339*V (r=0.827, p<0.001). So, the energy expenditure increased linearly with the velocity of displacement. The coefficient of determination assumed an association of 68.3% between the increase of the $\dot{E}_{tot}$ with the increase of the V.

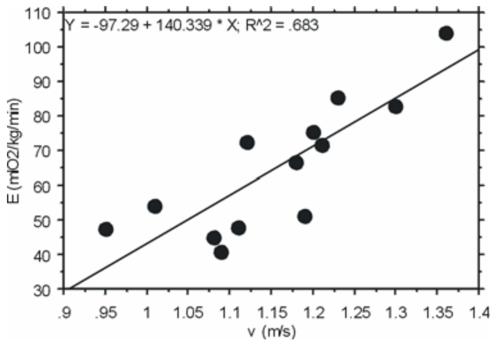


Figure 3. Economy profile established between the total energy expenditure (E_{tot}) and the velocity of displacement (V) for all the swimmers.

Figure 4 presents the overall regression between the EC and the dV of the centre of mass. The EC increased with dV following the equation EC=0.077+0.019*dV (r=0.807, p<0.001). It was found a coefficient of determination of r^2=0.651. This means that the associate variance of both variables was 65.1%, where the increase in the EC was strongly associated with the increase in the dV.

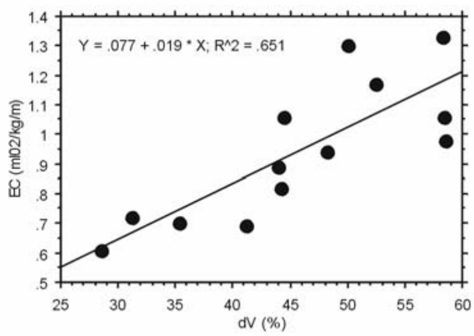


Figure 4. Overall regression between the energy cost (EC) and the intracyclic variation of the horizontal displacement of the centre of mass (dV).

4. DISCUSSION

The purpose of this study was to examine the relationships between the dV of the centre of mass and the EC, in butterfly stroke. It is observed that high intra-cycle variation in centre of mass displacement was associated to less efficient swimming, in butterfly.

The $\dot{E}_{tot}$ increased linearly with the V, and presented a significant correlation coefficient. Since the water resistance is related to the V ($D=k.v^2$) obviously, the increase of $\dot{E}_{tot}$ is due to the necessity to overcome a higher water resistance, as the velocity increases (Holmér, 1974; 1983; Chatard et al., 1990; Vilas-Boas and Santos, 1994; Alves et al., 1996; Vilas-Boas, 1996). Moreover, propelling efficiency seems to decrease with V, at least in freestyle (Toussaint et al., 1988). The relationship theoretically expected should be cubic, once energy output run in parallel with power, and power is a function of the velocity cubed. Interestingly, the relationship that we found was linear. We assume that probably this was due to an increased efficiency with speed or to the small range of velocities analysed. If it would be possible to do an evaluation with a higher range of velocities, probably an exponential relation might be observed. Nevertheless, the better adjustment of the linear approach, for the present data, might be the limited number of subjects studied.

In the breaststroke and in the butterfly stroke, especially in the undulating style variants, the body movement will promote higher changes in the position of the centre of mass due to higher inter-segmental variations (Mason et al., 1992). Consequently, the hip does not represent properly the intra-cycle variations of the kinematical variables of the centre of mass (Barbosa et al., 2003). In accordance to the previous arguments, the analysis of the dV for the centre of mass was adopted instead of the dV of the hip.

The increase of the EC was significantly associated with the increase of the dV, in butterfly stroke. High variations in dV also impose a high EC, since energy should be delivered to overcome inertial forces (Costill et al., 1987; Nigg, 1983). In fact, the associate variance between the EC and the dV was 65.1%. However, in other swimming techniques, the association between the dV and the EC were not so clear (Alves et al., 1996; Vilas-Boas, 1996). The explanation might be that, in butterfly stroke, the speed fluctuation is higher than in the other swimming techniques – namely in the front crawl and in the backstroke – so that such a relationship was easier to establish. Moreover, in the present study, the swimmers were videotaped simultaneously with the bioenergetic protocol. In this way, we are confident that the $\dot{E}_{tot}$ was measured correctly when the whole stroke cycle was digitised. In previous investigations (Alves et al., 1996; Vilas-Boas, 1996) the biomechanical and the bioenergetical protocols were applied separately, in different moments. Furthermore, in those investigations the relationship was established between the EC and the dV of the hip and not with the dV of the centre of mass.

Sih and Stuhmiller (2003) showed that energy cost is proportional to the force applied and the number of repetitive application of the force over a wide range of species (Humans and Quadruped species) and repetitive movements (cycling, running and arm movements).

However, the authors did not evaluate any aquatic species or any locomotion activity in aquatic environment. In butterfly stroke, the increase of the dV might lead to a proportional increase of external forces submitted to the swimmer, such as the Drag force or Inertial forces, inducing an increase of the EC. Therefore, apparently, swimming might be added to the activities reported by Sih and Stuhmiller (2003).

The water resistance, which a swimmer should overcome at a given V, is widely variable and dependent on individual morphology and technique (Clarys, 1979; Chatard et al., 1990). With the number of trials made by each swimmer, it was not possible to run individual regression equations. From the statistical point of view it does not seems to be reasonable to do such analysis with only three plots. However, Vilas-Boas (1996) made an intra-individual analysis for the correlation between the dV and the EC, at breaststroke. The author observed that individual correlation coefficients were higher than the overall correlations. So, it seems that EC is highly dependent of anthropometrical and technical characteristics of the swimmer.

5. CONCLUSIONS

It is concluded that high intra-cycle variation in the displacement of the centre of mass was connected to less efficient swimming in butterfly. We suggest that the swimmers should strive to improve their technique performances to avoid large variations in the dV, while high dV will induce increments of the EC, which may be detrimental especially in 200-m butterfly.

Chapter 7: Speed fluctuation and stroke determinants in butterfly stroke

The purpose of this study was to understand the relationships established between the intra-cyclic variations of the horizontal velocity of the center of mass (dV), the stroke determinants and the swimming velocity in butterfly stroke. The study was divided in two parts. 3 male Portuguese swimmers and 1 female swimmer, of international level were studied in Part I. The swimmers were submitted to an incremental set of 200-m butterfly swims, with a start in water. The starting velocity was 1.18 $m.s^{-1}$ for the males and 1.03 $m.s^{-1}$ for the female swimmer. After each swim, the velocity was increased by 0.05 $m.s^{-1}$ until exhaustion or until the swimmer could not keep the predetermined pace. In the Part II, 10 male swimmers and 4 female swimmer of national and international level were studied. Each swimmer performed two 25-m butterfly swims with a start in water, at a constant velocity and as close as possible to their maximal capability. Several cameras recorded both protocols, including 2 images of “dual media” system, allowing a 3D analysis. It was calculated the intra-cyclic variation of the horizontal velocity of the centre of mass (dV), the stroke length (SL), the stroke frequency (SF), the mean horizontal velocity of displacement of the centre of mass (V) and the stroke index (SI) of the stroke cycles digitised. For Part I, there was a significant and negative relationship between dV and V (r=-0.49, p=0.04), between dV and SL (r=-0.64, p=0.03) and between dV and SI (r=-0.56, p=0.01), as well as, a significant and positive relationship between dV and SF (r=0.57, p<0.01). For Part II, there was a significant and negative relationship between dV and V (r=-0.44, p=0.04), between dV and SL (r=-0.56, p<0.01) and between dV and SI (r=-0.41, p=0.04). A significant and positive relationship was observed between dV and SF (r=0.47, p=0.03). For overall analysis, all the coefficients of correlation of the regression equation presented significant and negative relationships. The main conclusion is that stroke determinants and the V influence the dV observed in butterfly stroke.

KEYWORDS: swimming, velocity fluctuation, swimming velocity, stroke frequency, stroke length, stroke index

1. INTRODUCTION

A discriminator factor of the technical ability in swimming is the intra-cyclic variation of the horizontal velocity of the centre of mass (dV) at a given velocity (Nigg, 1983). Some studies, with different swimming techniques, observed significant relationships between dV and the energy cost (Alves et al., 1996; Vilas-Boas, 1996; Barbosa et al., 2005a). A high dV is a determining factor for the increase of energy cost, especially in breaststroke (Vilas-Boas, 1996) and butterfly stroke (Barbosa et al., 2005a).

Since the consistent observations about the influence of dV in the energy cost, the next step in this field of investigation is to know which factors are related to the dV. Therefore, it is important to identify what biomechanical variables, and how, influence the behaviour of the dV.

It is known that a high stroke frequency is related to a higher energy cost in several swimming techniques (Costill et al., 1985; Klentour and Montpetit, 1992; Smith et al., 1988; Tourny, 1992; Wakayoshi et al., 1996; Barbosa et al., 2005b). When swimmers increase the number of strokes, in a given period of time, they will be submitted to higher forces associated to body accelerations and decelerations. This is particularly relevant in the simultaneous techniques (Breaststroke and Butterfly) where the impulses produced – positive and negative - are extremely high (van Tilborgh et al., 1988; Vilas-Boas, 1994; Barbosa et al., 2002). Nevertheless, there is no study in the literature about the relationship between dV and the stroke frequency, at least, in butterfly stroke.

Higher values of stroke length are assumed to be indicators of high levels of swimming efficiency, at a given velocity (Costil et al., 1985; Smith et al., 1988; Tourny, 1992). It was described significant relationships between bioenergetical variables (e.g. energy cost) and the dV (e.g., Vilas-Boas, 1996; Barbosa et al., 2005a). It is suggested that decreases of energy cost are associated to decreases in the dV. Therefore, it is also possible to exist an influence of the stroke length in the dV.

Some investigators suggested the existence of an association between the mean horizontal velocity of displacement of the swimmer and the dV (Vilas-Boas, 1996; Barbosa et al., 2005a). They assume the possibility of high dV being related with lower swimming velocities. In fact, Togashi and Nomura (1992) observed a significant and negative relationship between the mean horizontal velocity and the speed fluctuation ($r=-0.51$, $p<0.03$) in butterfly stroke. Swimming at slow velocities can promote a lower propulsive efficiency, due to an increasing transfer of energy to the water, instead of its use for overcome drag force (de Groot and van Ingen Schenau, 1988; Toussaint, 1990).

Costill et al. (1985) referred that high stroke index values were strongly associated with a low energy cost in swimming. Since, the energy cost in swimming is related to the dV, it is possible to exist an association between the stroke index and the dV. However, the understanding of this relationship was never explored.

Apparently, some biomechanical parameters (e.g., stroke frequency, stroke length, mean horizontal velocity of displacement and stroke index) might influence the behavior of the dV. The butterfly stroke is one of the swimming techniques presenting the higher dV (Kornecki and Bober, 1978; Hahn and Krug, 1992; Mason et al., 1992; Togashi and Nomura, 1992; Sanders, 1996). So, the butterfly stroke is an optimal technique for the identification and comprehension of hypothetical relationships between dV and other biomechanical variables.

The purpose of this study was to understand the relationships between the dV, the stroke determinants and the swimming velocity in butterfly stroke.

2. METHODS

The study was divided in two parts. Within Part I the aim was to investigate the behaviour of variables in study at slow swimming velocities. The Part II allowed the same study at high swimming velocities. In the results and discussion sections it was defined the overall sample as the plot and analysis of all data from Part I and Part II together.

Part I

Subjects. Three male Portuguese swimmers (20.3±3.5 years old; 179.3±5.0 cm of height; 70.5.5±8.5 Kg of body mass) and one female Portuguese swimmer (17 years old; 165 cm of height; 54.2 Kg of body mass) of international level were studied.

Protocol. The swimmers were submitted to an incremental set of 200-m butterfly swims, with a start in water. The starting velocity was 1.18 $m \cdot s^{-1}$ for the males and 1.03 $m \cdot s^{-1}$ for the female swimmer. After each swim, the velocity was increased by 0.05 $m \cdot s^{-1}$ until exhaustion or until the swimmer could not keep the predetermined pace. The velocities and increments in velocity were chosen in agreement with the swimmers, so that they would make their best performance on the 7th trial. The resting period between swims was 30 seconds. Two swimmers completed 5 trials, one swimmer made 6 trials and one last swimmer made 7 trials. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Portugal) were placed on the bottom of the 25-m pool, to control the swimming speed and to help the swimmers keep an even pace along each step.

Part II

Subjects. Ten male Portuguese swimmers (17.8±2.3 years old; 172.7±10.9 cm of height; 64.4±8.1 Kg of body mass) and four female Portuguese swimmer (17.5±1.3 years old; 177.6±7.5 cm of height; 69.7±9.0 Kg of body mass) of national and international level were studied.

Protocol. Each swimmer performed two 25-m butterfly swims with a start in water, at a constant velocity and as close as possible to their maximal capability. Between trials, swimmers had a rest period of at least 30 minutes.

Data Collection. Several cameras recorded both protocols, as described elsewhere (Barbosa et al., 2002; 2003), including 2 “dual media” systems, allowing a 3D analysis. Two pairs of video cameras (JVC GR-SX1 SVHS and JVC GR-SXM 25 SVHS) were used for dual media videotape recording in non-coplanar planes. Both pairs of cameras were synchronized in real time and edited on a mixing table (Panasonic Digital Mixer WJ-AVE55 VHS and Panasonic Digital AV Mixer WJ-AVE5) creating one single image of “dual media” as previously described by Vilas-Boas et al. (1997). One of the two supports was set in one end walls, 8.10m away from the trajectory of the swimmer. The second structure was set in one of the lateral walls at 9.30m from the forehead wall where the first structure was installed and at 10.20m from the trajectory of the swimmer. Another camera (Panasonic DP 200 SVHS) was set in an underwater window in the end wall, at 0.90m deep. One last camera (Panasonic DP 200 SVHS) was set 4.50m above the surface water. In these two last cases, the optical axis was oriented in the direction of the displacement of the swimmers. In all the situations, all cameras or pair of cameras recorded images of the swimmer in non-coplanar planes, different from all the other cameras or pair of cameras. Synchronization of the images was obtained using LED’s placed on the recording field of every camera or pair of cameras, which were turned on regularly and simultaneously to initiate the synchronization every time the swimmer entered the performance volume. It was used a calibration cube (3x3x3 meters) marked with 32 calibration points. The study comprised the kinematical analysis of stroke cycles (Ariel Performance Analysis System, Ariel Dynamics Inc., USA) through a VCR (Panasonic, AG 7355, Japan) operating at a frequency of 50 Hz. It was used the Zatsiorsky’s model adapted by de Leva (1996) which included the division of the trunk in 3 articulated parts. The 3D reconstruction of the digitized images was performed using the “Direct Linear Transformation” procedure (Abdel-Aziz and Karara, 1971). For the analysis of the curve of the velocity of the centre of mass in order to time, it was used a filter with a cut-off frequency of 5Hz, as suggested by Winter (1990). It was calculated the stroke length (SL), the stroke frequency (SF=1.absolute duration of the stroke cycle^{-1}), the mean horizontal velocity of displacement of the centre of mass (V) and the stroke index (SI=SL.V) of the stroke cycles digitised.

Statistical procedures. Included the calculation of the coefficients of variation of the horizontal velocity of displacement of the centre of mass along the stroke cycle, for the analysis of the dV. Linear regression equations, coefficients of determination and coefficients of correlation were computed to describe the relationships between dV and all the biomechanical variables studied, for each group and for overall sample. The level of statistical significance was set at $p \leq 0.05$.

3. RESULTS

Figure 1 presents the regression plots between the dV and the stroke determinants analyzed at slow (Part I) and high (Part II) swimming velocities.

At slow swimming velocities, all the equations between the dV and the stroke determinants studied present significant coefficients of correlation. There was a significant relationship between the dV and the V, where dV=224.591-148.18V (r=-0.49, p=0.04). In the case of the relationship between dV and the SF, the equation established was dV=-30.976+112.704SF (r=0.57, p<0.01). So, at slow swimming velocities, it seems that increases in the dV are due to decreases in the V and increases in the SF. The relationship between dV and SL and between dV and SI also presented significant coefficients of correlation, where the equations computed were dV=136.802-51.67SL (r=-0.64, p=0.03) and dV=94.366-24.771SI (r=-0.56, p=0.01). This means that increases in the SL and in the SI were related to decreases in the dV, at slow swimming velocities.

When studying the relationship between dV and the stroke determinants at high swimming velocities, the behaviour was similar. As in Part I, the higher dV was significantly related to the lower V and higher SF, where dV=41.658-15.217V (r=-0.44, p=0.04) and dV=-25.816+45.489SF (r=0.47, p=0.03). In the same way, the regressions between dV and SL and between dV and SI presented significant coefficients of correlation. For the first case, the equation established was dV=48.086-16.434SL (r=-0.56, p<0.01) and for the second, dV=31.043-4.781SI (r=-0.41, p=0.04). Therefore, these results point out that increases in the SL and in the SI produce decreases in the dV, at high swimming velocities.

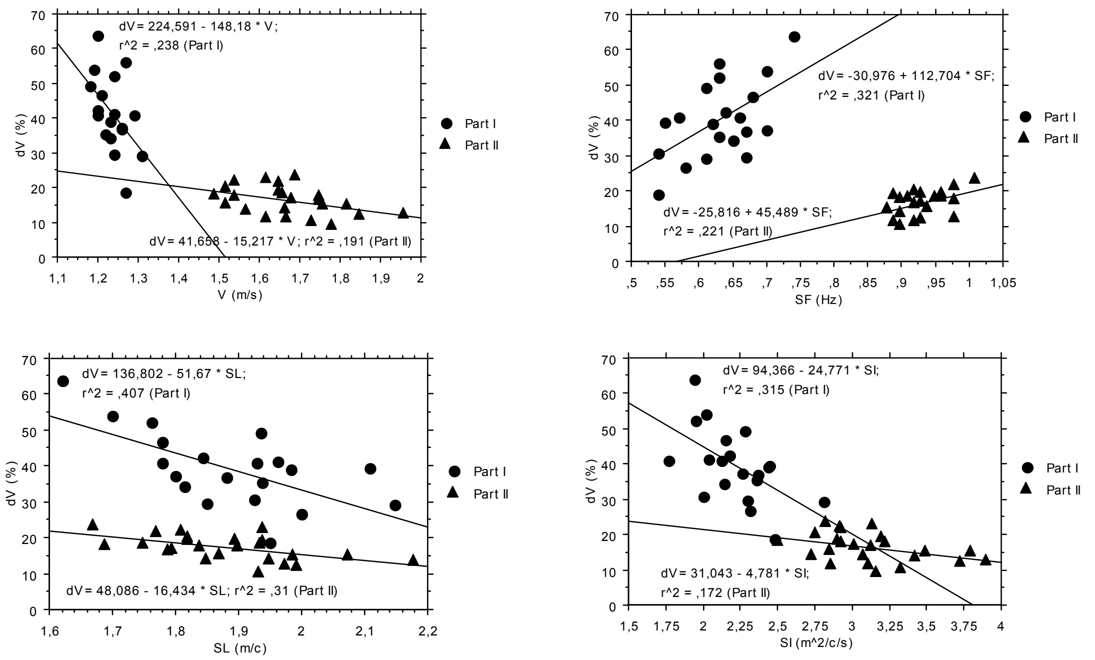


Figure 1. Regression plots between the intra-cyclic variation of the horizontal velocity of the centre of mass (dV) and the mean horizontal velocity of displacement (V), the stroke length (SL), the stroke frequency (SF) and the stroke index (SI) at slow (Part I) and high (Part II) swimming velocity.

Figure 2 presents the overall regression plots between the dV and the stroke determinants analysed. The regression equation between dV and V presented significant coefficients of correlation, where dV=105.791-52.99V ($r=-0.85$, $p<0.01$). The regression equation between dV and SF also presented values statistically significant and computed as dV=78.735-64.732SF ($r=-0.71$, $p<0.01$). This means that, in a large spectrum of velocities, increases of dV can be associated to decreases of SF. In the case of the relationship between the dV and the SL, the equation was established as dV=89.158-32.861SL ($r=-0.30$, $p=0.05$). The regression between dV and SI was computed as dV=83.827-21.06SI ($r=-0.82$, $p<0.01$), suggesting a decrease of the dV with increasing SI. It seems that when the overall regressions were computed, the results were much more consistent, specially the relationships between V, SL and SI with dV, then conducting partial analysis of data at different swimming velocities.

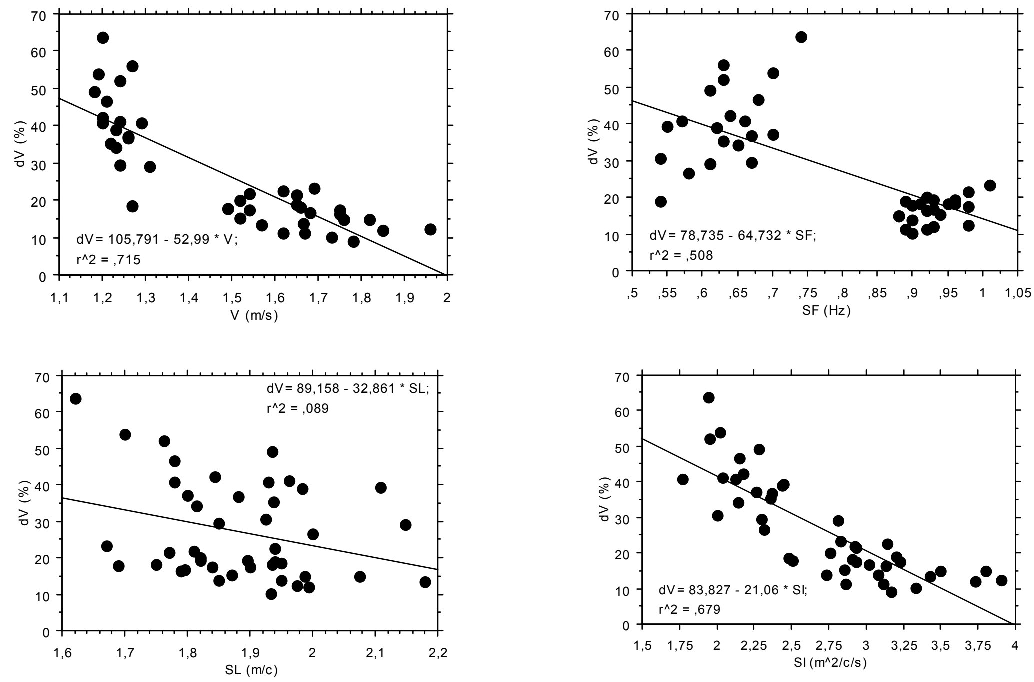


Figure 2. Overall regression plots between the intra-cyclic variation of the horizontal velocity of the centre of mass (dV) and the mean horizontal velocity of displacement (V), the stroke length (SL), the stroke frequency (SF) and the stroke index (SI).

4. DISCUSSION

The purpose of this study was to understand the relationships established between the dV, the stroke determinants and the swimming velocity, in butterfly stroke. The main conclusion was that stroke determinants and the swimming velocity influence the dV profile observed in butterfly stroke.

25-m and 200-m sets were selected for the analysis of dV and stroke determinant. Those distances were adopted since they promote significantly different behaviours in the parameters analysed (e.g., V, SF, SL). It is well described in the literature that with increasing distances, the V, the SF and the SL decreases (Craig et al., 1979; 1985). With these two extreme distances (25-m and 200-m), it was easier to establish different profile patterns of the parameters evaluated. If we had selected other distances, much closer one from the other, probably, it could be more difficult to draw the relationship between dV, the stroke determinants and the swimming velocity.

When overall results were analysed, the profiles were similar to the ones verified in each group, but much more consistent, except for the relationship between dV and SF. These similar findings, between V, SI and SL with dV have two reasons. First, there was an increase of the observations inputted in the regression plots. From a statistical point of view, an increase of the observations will allow a much more consistent analysis. Second, the spectrum of values analysed also increased. Therefore, it was possible to understand the behaviour of the variables analysed in higher amplitude of values.

Increases of V promoted decreases of dV, allowing a much more continuous butterfly stroke. Therefore, the expeculations of Nigg (1983), Vilas-Boas (1996) and Barbosa et al. (2005a), as well as, the observations of Togashi and Nomura (1992) or Manley and Atha (1992) were confirmed. Higher swimming velocities revealed to be more stable in what concerns to dV. On the other hand, lower swimming velocities can promote high negative impulses, due to increasing time decelerating the swimmer's body. This might also promote a percentual increase of the kinematical energy transferred to the water, instead of its use for propulsion. Consequently, it will induce a lower propulsive efficiency. Toussaint (1990) comparing competitive and triathlon swimmers, at front crawl, verified that propulsive efficiency was significantly lower in the triathletes. Probably, as it was observed with present data, triathlon swimmers could present a higher dV. Takagi et al. (2004) compared the dV of the hip of a group of breaststrokers eliminated in the preliminaries of the 9^{th} FINA World Swimming Championships with another who advanced to the semi-finals. The authors verified that the dV was significantly higher in the group of eliminated breaststrokers. Apparently, these results justified the assumptions that lower dV is an important biomechanical characteristic to achieve high swimming velocities and, therefore, high performances. The higher dV observed in slow swimming velocities are not related to maximal values of the intra-cyclic velocity obtained, but to a lower minimal intra-cyclic velocity adopted (Takagi et al., 2004). So, swimmers should give a major attention to actions leading to strong body decelerations.

Through a stroke cycle, swimmers are submitted to forces associated with body accelerations and decelerations (van Tilborgh et al., 1988; Vilas-Boas, 1994; Barbosa et al., 2002). It is the magnitude of those positive and negative accelerations that imposes different dV profiles. When swimmers increase the SF, increasing the number of strokes in a given period of time, they probably will be submitted to an increasing acceleration and/or deceleration peaks, in order to overcame inertial forces (van Tilborgh et al., 1988). Those inertial forces are especially high in butterfly stroke (Barbosa et al., 2002). The consequence will be an increase of the dV, for a given swimming velocity. Some studies reported, in different swimming techniques, that SF is significantly related to energy cost (Costill et al., 1985; Klentour and Montpetit, 1992; Smith et al., 1988; Tourny, 1992; Wakayoshi et al., 1996; Barbosa et al., 2005b). High SF promotes increases in energy cost. Those increases in energy cost can be due to increases of dV, by influence of the SF.

Increasing the SL, the swimmer will be submitted to lower inertial forces, presenting a more continuous swimming. Consequently, swimmers can reduce the characteristics of critical events associated to resistance phenomena's, such as, the arm's recovery or the breathing action. However, for this assumption to be valid, increasing SL should not be a result of increasing glide phase. A higher glide phase can imposes a higher discontinuity of the stroke, leading to increments of total energy expenditure or energy cost. Probably swimmers of higher competitive level can swim, at a given velocity, simultaneously with high SL and reduce dV than swimmers of lower competitive level. The relationships establish between SL and dV is similar to the one between SI and dV. It is known that SI is dependent of SL and V (Costill et all, 1985). If the relationships between SI and dV, as well as, between V and dV were negative; so, the relationship between SL and dV should also be negative or slight negative. If the relationship between SL and dV, for a group of swimmers, would be positive, the probability of a negative relationship between SI and dV might be reduce. However, when in individual bases these relationships are studied, it is possible to detect swimmers increasing dV with increasing SL.

The dV was described as being positively associated with energy cost (Nigg, 1983; Vilas-Boas, 1996; Barbosa et al., 2005a). Therefore, for a given velocity, increasing SI should promote decreases of dV, leading to decreases of energy cost. In the present study, increases of the SI were significantly associated with decreases in the dV. Previously, Barbosa et al. (2005b) observed a significant relationship between energy cost and SI, as well as, between V and SI, in butterfly stroke. Therefore, the present data confirms the concept of SI as a valid swimming efficiency index.

From the overall plotting data between dV and SF, the regression equation presented a significant correlation coefficient, but with a different pattern from the one verified in each group. It was observed that increasing SF leaded to lower dV. Higher swimming velocities seem to be achieved as a result of increasing SF and decreasing the SL (Craig and Pendergast, 1979; Craig et al., 1979; Hay and Guimarães, 1983; Keskinen and Komi, 1993). The increase of the V up to 80% of the maximal velocity in female swimmers and up to 94% in male swimmers was described as a result of the increase of SF and a constant SL (Craig and Pendergast, 1979). It can be suggest that higher SF imposes a lower absolute duration of each stroke phase, promoting a lower intra-cyclic resultant impulse and, therefore a lower dV.

5. CONCLUSIONS

In conclusion, stroke determinants and swimming velocity influence the dV profile in butterfly stroke. The dV decreases with increasing swimming velocity. Swimmers should be encouraged to increase the swimming velocity as a result of the increase of the SL instead of the increase of the SF. In this way, they might achieve the same swimming velocity but with a lower dV and therefore with a lower energy cost.

Chapter 8: Contributions of segmental velocities to speed fluctuation in butterfly stroke

The purpose of this study was to analyze the relationship between the intra-cycle variation of the horizontal velocity of displacement of the center of mass (dV), the hand's and feet's velocity, as well as, to identify the variables that most predict the dV's, in butterfly stroke. The study was divided in two parts. The aim of Part I was to investigate the behaviour of variables in study at slow swimming velocities and the purpose of Part II was the same but at high swimming velocities. 3 male Portuguese swimmers and 1 female swimmer, of international level were studied in Part I. The swimmers were submitted to an incremental set of 200 m butterfly swims. In the Part II, 7 Portuguese male swimmers of national and international level were studied. Each swimmer performed two maximal 25 m butterfly swims. Several cameras recorded both protocols, allowing a 3D analysis. It was calculated the dV, the 3D components (Vx, Vy, Vz) of the hand's velocity and the 2D components (Vx, Vy) of the feet's velocity. Several variables presented significant correlation coefficients with dV at all selected velocities. For high velocity, the variables that best predict dV were Vy during first downbeat, Vx and Vy during insweep (r^2= 0.93). At slow velocity, the variables included in the forward step-by-step regression model were Vx during upsweep, Vy and Vx during insweep (r^2= 0.69). For overall velocity, the variables that most fit the regression model were Vx during upsweep, Vy during second downbeat and Vz during entry (r^2= 0.94). In order to reduce dV, butterfliers should increase hand's velocity in all orthogonal components at the end of the underwater path, should increase the vertical velocity during the downbeats and decrease the velocity during the hand's entry.

KEYWORDS: body's velocity fluctuation, feet's velocity, hand's velocity, swimming

1. INTRODUCTION

The intra-cyclic variation of the horizontal velocity of the centre of mass (dV) is a widely accepted criterion for the biomechanical study of a swimming technique. Considerable variations of the dV submit the swimmer to higher hydrodynamic forces during the stroke cycle, due to high positive and/or negative body impulses.

Some studies showed that less energy cost is associated to lower dV, in several swimming techniques (Kornecki and Bober, 1978; Barthels and Adrian, 1979; Nigg, 1983; Alves et al., 1996; Vilas-Boas, 1996; Barbosa et al., 2005a). It is concluded also that low dV was connected to high swimming efficiency. This relationship is especially evident in the simultaneous strokes (Vilas-Boas, 1996; Barbosa et al., 2005a); probably because of their higher dV in comparison with remain swimming techniques.

However, swimmers do not swim at a constant velocity, in order to reduce the energy cost. The variations in the upper limbs, in the lower limbs and in the trunk actions lead to variations in the instantaneous swimming velocity, along the stroke cycle. These movements include elements, which add up to necessary work done by the swimmer (Nigg, 1983; D'Acquisto et al., 1998).

For the study of the behaviour of dV, the analysis of simultaneous swimming techniques, such as butterfly stroke, are quite useful, since they present a pronounced variation. Persyn et al. (1983) showed that the amplitude of variation of dV, during some phases of the stroke cycle was significantly related to swimmer's skill and that they were more critical in the breaststroke and in the butterfly stroke, compared to alternated techniques.

Martins-Silva and Alves (2000) evaluated the importance of the hand's velocity in a 200 m butterfly event, as related to dV. The results showed significant correlations between all directional components of the hand's velocity during the most propulsive phases (insweep and upsweep) and the dV. Authors computed a prediction equation for dV using a step-by-step regression model. The equation included the horizontal velocity of the hand during the insweep (r^2= -0.98), the lateral velocity of the hand during the insweep (r^2= 0.99) and the vertical velocity of the hand during the insweep (r^2= 1). In fact, previous studies had demonstrated the importance of the last phases of the underwater stroke cycle for propulsion (Schleihauf, 1979; Schleihauf et al., 1988). One limitation of Martins-Silva and Alves (2000) study is that they only studied 200 m sets. Consequently, it is only possible to predict the dV for relative slow swimming velocities. The development of the same kind of investigation, but at higher swimming velocities, apparently was never explored.

Some investigation groups dedicate their attention to the role of the lower limbs, as well as, the role of the dynamic movement of the body on the propulsion in swimming (e.g., Bucher, 1975; Colman and Persyn, 1993; Ungerechts, 1985; Hollander et al., 1988; Sanders et al., 1995; Deschodt, 1999; Colman et al., 1999; Ungerechts et al., 1999; 2000; Arellano et al., 2003). Sanders et al. (1995) suggested that body waving velocity within a cefalo-caudal direction, in butterfly stroke, is significantly related to the centre of mass velocity (r= 0.88 for males and r= 0.96 for females). Arellano et al. (2003) attempted to identify the independent variables that most predict the swimmer's velocity, using underwater butterfly kick. The reduction of the kick amplitude plus the increase of kick frequency, combined with the increase of the knee's angle during the downbeat, seems to be the best way to increase the swimmer's velocity.

It is common to assume the importance of the downbeats, in butterfly stroke, to reduce the swimmer's deceleration during the arm's recovery and entry, increasing the mean swimming velocity (Barthel and Adrian, 1971; Jensen and McIlwain, 1979). Therefore, it seems that the lower limb's velocity might be also a determinant factor for the dV's behavior, in butterfly stroke. Nevertheless, it is not known any investigation about this relationship.

The purpose of this study was to analyze the relationship between the dV, the hand's and feet's velocity, as well as, to identify the segmental velocities that most predict the dV, in butterfly stroke.

2. METHODS

The study was divided in two parts. Within Part I the aim was to investigate the behaviour of variables in study at slow swimming velocities. The Part II allowed the same study at high swimming velocities. In the results and discussion sections it was defined the overall velocity as the plot and analysis of all data from Part I and Part II together.

Part I

Subjects. Three male Portuguese swimmers (20.3±3.5 years old; 179.3±5.0 cm of height; 70.5.5±8.5 Kg of body mass) and one female Portuguese swimmer (17 years old; 165 cm of height; 54.2 Kg of body mass) of international level were studied.

Protocol. The swimmers were submitted to an incremental set of 200 m butterfly swims, with a start in water. The starting velocity was 1.18 $m.s^{-1}$ for the males and 1.03 $m.s^{-1}$ for the female swimmer. After each swim, the velocity was increased by 0.05 $m.s^{-1}$ until exhaustion or until the swimmer could not keep the predetermined pace. The velocities and increments in velocity were chosen in agreement with the swimmers, so that they would achieve the best performance, of the protocol, on the 7th trial. The resting period between swims was 30 seconds. Two swimmers completed 5 trials, one swimmer 6 trials and one last swimmer 7 trials. Therefore, it was possible to obtain a total number of 23 trials. Two swimmers achieved the maximal swimming velocity of 1.43 $m.s^{-1}$, one swimmers 1.48 $m.s^{-1}$ and a last swimmers 1.38 $m.s^{-1}$. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Portugal) were placed on the bottom of the 25 m pool, to control the swimming speed and to help the swimmers keep an even pace along each step.

Part II

Subjects. Seven male Portuguese swimmers of national and international level were studied (18.4±1.9 years old; 175.8±6.2 cm of height; 68.6±6.8 Kg of body mass).

Protocol. Each swimmer performed two 25 m butterfly swims with a start in water, at a constant velocity and as close as possible to their maximal capability. Therefore, it was possible to obtain a total number of 14 trials. Between trials, swimmers had a rest period of at least 30 minutes. The mean swimming velocity was 1.75±0.09 $m.s^{-1}$.

Data Collection. Several cameras recorded both protocols, as described elsewhere (Barbosa et al., 2002; 2003), including 2 “dual media” systems, allowing a 3D analysis. Two pairs of video cameras (JVC GR-SX1 SVHS and JVC GR-SXM 25 SVHS) were used for dual media videotape recording in non-coplanar planes. Both pairs of cameras were synchronized in real time and edited on a mixing table (Panasonic Digital Mixer WJ-AVE55 VHS and Panasonic Digital AV Mixer WJ-AVE5) creating one single image of “dual media” as previously described by Vilas-Boas et al. (1997). It was used the procedure described by Vilas-Boas et al. (1997) to correct the distortion and refraction when underwater cameras are used. One of the two supports was set in one end walls 8.10 m away from the trajectory of the swimmer. The second structure was set in one of the lateral walls at 9.30 m from the forehead wall where the first structure was installed and at 10.20 m from the trajectory of the swimmer. Another camera (Panasonic DP 200 SVHS) was set in an underwater window in the end wall, at 0.90 m deep. One last camera (Panasonic DP 200 SVHS) was set 4.50 m above the surface water. In these two last cases, the optical axis was oriented in the direction of the displacement of the swimmers. In all the situations, all cameras or pair of cameras recorded images of the swimmer in non-coplanar planes, different from all the other cameras or pair of cameras. Synchronization of the images was obtained using LED’s placed on the recording field of every camera or pair of cameras, which were turned on regularly and simultaneously to initiate the synchronization every time the swimmer entered the performance volume. This it was assume to be delimited by the calibration volume, which was defined by a 3x3x3 meters cube. The calibration cube was marked with 32 calibration points. The study comprised the kinematical analysis of stroke cycles

(Ariel Performance Analysis System, Ariel Dynamics Inc., USA) through a VCR (Panasonic, AG 7355, Japan) operating at a frequency of 50 Hz. It was analyzed one stroke cycle, during the 150-m distance from each 200-m trial, and from each 25-m trial. It was used the Zatsiorsky's model adapted by de Leva (1996) which included the division of the trunk in 3 articulated parts. The 3D reconstruction of the digitized images was performed using the "Direct Linear Transformation" procedure (Abdel-Aziz and Karara, 1971). For the analysis of the curve of the velocity of the centre of mass in order to time, it was used a filter with a cut-off frequency of 5 Hz, as suggested by Winter (1990). For the analysis of the curve of the velocity of the hands and feet's in order to time, it was used a filter with a cut-off frequency of 9 Hz, near to the value proposed by Winter (1990). The digitise-redigitise reliability was $r = 0.97 \pm 0.01$. It was calculated the 3D components (horizontal, vertical and lateral) of the hand's velocity during: (i) the entry – period from visualization of hand in water till its full extension and forward gliding; (ii) the outsweep – period from the end of hand's entry till achieves the most deep vertical position of its trajectory, after lateral movement; (iii) the insweep – period from the end of outsweep till the hand's come together under the swimmers body, after a circular trajectory and; (iv) the upsweep – period from the end of insweep till achieve the legs level, after backward extension of the arms. It was also calculated the 2D components (horizontal and vertical) of the feet's velocity during: (i) the downbeats – period from the highest vertical position of the feet's trajectory till its lowest vertical position and; (ii) the upbeats – period from the final of the downbeat till the highest vertical position from the feet's trajectory.

Statistical procedures. Included the calculation of the descriptive statistics of all the variables studied (mean, standard deviation, minimum and maximum) at slow and high swimming velocities. Coefficients of variation for the horizontal velocity of the centre of mass along the stroke cycle were calculated for the assessment of dV. It was calculated the Pearson correlation coefficient between dV and all the hands and feet's velocities at slow swimming velocity, high swimming velocity and overall velocity. Forward step-by-step regression models were computed, for prediction of dV, at slow swimming velocity, high swimming velocity and overall velocity. For the determination of the independent variables that most predict the dV, were included the hands and feet's velocities with significant correlation coefficient with the dependent variable and that, at the same time, correspond the necessary procedures to enter in the model. For overall velocity, the swimming velocity (sw-vel) it was used as a "dummy" variable (nominal variable describing high velocity vs slow velocity). In this way, the between-treatment (high velocity= 1;slow velocity= 0) can be analysed and, therefore, identify only the effects on dV attributable to the differences in swimming technique. The variables entered the equation if $F \geq 4.0$ and removed if $F \leq 3.96$. The level of statistical significance was set at $p \leq 0.05$.

3. RESULTS

Table 1 presents the mean, standard deviation, minimum and maximum values from the intra-cyclic variation of the horizontal velocity of the centre of mass (dV), the horizontal (Vx), vertical (Vy) and lateral (Vz) velocity from the hands in the entry (ent), in the outsweep (out), in the insweep (ins), in the upsweep (ups) and from the feet's in the first downbeat (1dwn), in the first upbeat (1upb), in the second downbeat (2dwn) and in the second upbeat (2upb) at slow and high swimming velocities. It was possible to verified large variations in the velocity of the hands and feet's for both swimming velocities. The ranges of variation of several parameters were quite high. For example, Vz-ent ranged from –2.1 $m.s^{-1}$ to 0.1 $m.s^{-1}$ and Vx-ins ranged from –4,5 $m.s^{-1}$ to -2.0 $m.s^{-1}$, at high velocity. At slow velocity, Vx-ups ranged from –3.5 $m.s^{-1}$ to –0.7 $m.s^{-1}$ and Vy-1dwn ranged from -1.8 $m.s^{-1}$ to –0.2 $m.s^{-1}$. In both swimming groups (high and slow swimming velocities) the mean velocities of the hands presented the highest values at the end of the underwater path. The highest mean horizontal velocity of the hands was identified during the upsweep at slow velocity (Vx-up= -2.0±0.7 $m.s^{-1}$) and at high velocity (Vx-up= -6.0±1.1 $m.s^{-1}$). For the feet's vertical velocity, different kinematical behaviours were found for the lower limbs, at different swimming velocities. At high velocity, the higher mean vertical velocity occurred during the second downbeat (Vy-2dwn= -1.8±0.31 $m.s^{-1}$). At slow velocity, the mean vertical velocity of the feet's during both downbeats was non-different (Vy-1dwn= -1.01±0.5 $m.s^{-1}$ vs Vy-2dwn= -0.9±0.6 $m.s^{-1}$).

Table 2 presents the Pearson product correlation coefficient calculated between dV, the hands and feet's velocities at slow velocity, high velocity and overall velocity. At high velocity, several variables presented significant correlation with dV. The highest correlation coefficients were obtained between dV and Vy-1dwn (r= 0.82, p< 0.01) and between dV and Vz-ups (r= 0.81, p< 0.01). This means that high negative vertical velocities from the feet's during the first downbeat and lateral movements from the hands during the upsweep were significantly associated with a decrease in the dV. At slow velocity, the correlation coefficients with the highest values were found between dV and Vx-ups (r= 0.73, p< 0.01) and between dV and Vz-ins (r= -0.69, p= 0.01). Increases in the lateral movements of the hands in the insweep and increases of horizontal velocity during upsweep were significantly associated with decreases in the dV. For overall velocity, the highest correlations coefficients were verified between dV and Vx-ups (r= 0.88, p< 0.01), between dV and Vx-ins (r= 0.82, p< 0.01) and between dV and Vy-2dwn (r= 0,79, p< 0.01). Therefore, it was observed significant associations between the highest horizontal velocity of the hands during the insweep and upsweep with the decrease of the dV. In the same way, it was verified significant association between increase of the vertical velocity of the feet's in the second downbeat and decreases of the dV. It was particularly interesting to detect some significant correlations coefficients between dV and the horizontal velocity of the feet's, such as in the case of the Vx-1dwn for slow velocity (r= -0.45, p= 0.05) and overall velocity (r= -0.78, p< 0.01), for the Vx-1upb (r= -0.48, p< 0.01), Vx-2dwn (r= -0.79, p< 0.01) and Vx-2upb (r= -0.56, p< 0.01) for overall velocity. In all the cases, increases in the horizontal velocity of the feet's were significantly associated with decreases in the dV.

Table 1. Descriptive statistics of the intra-cyclic variation of the horizontal velocity of the centre of mass, the hands and feet's velocity at slow and high velocity.

	High velocity				Slow velocity			
	mean	sd	min	max	mean	sd	min	max
dV (%)	14.8	4.1	9.1	23.4	39.2	11.5	18.5	63.8
Vx-ent ($m.s^{-1}$)	1.5	0.3	1.1	1.9	1.4	0.6	0.5	2.4
Vy-ent ($m.s^{-1}$)	-1.2	0.5	-1.9	-0.5	-1.0	0.5	-2.4	-0.4
Vz-ent ($m.s^{-1}$)	-0.9	0.7	-2.1	0.1	-0.3	0.6	-1.5	1.0
Vx-out ($m.s^{-1}$)	-1.4	0.3	-1.8	-1.0	-0.9	0.3	-1.5	-0.5
Vy-out ($m.s^{-1}$)	-0.7	0.5	-1.5	0.0	-0.6	0.1	-0.8	-0.4
Vz-out ($m.s^{-1}$)	-1.0	0.4	-1.4	-0.3	-1,1	0.4	-1.6	-0.3
Vx-ins ($m.s^{-1}$)	-3.4	0.8	-4.5	-2.0	-1.5	0.5	-2.5	-0.9
Vy-ins ($m.s^{-1}$)	2.0	1.0	0.3	3.3	1.1	0.5	0.4	2.3
Vz-ins ($m.s^{-1}$)	1.5	0.8	0.2	2.9	1.3	0.6	0.4	2.5
Vx-ups ($m.s^{-1}$)	-6.0	1.1	-7.4	-3.9	-2.0	0.7	-3.5	-0.7
Vy-ups ($m.s^{-1}$)	1.2	0.6	0.3	2.4	1.8	0.6	0.9	3.1
Vz-ups ($m.s^{-1}$)	-1.8	1.2	-3.3	-0.2	-0.6	0.4	-1.2	0.0
Vx-1dwn ($m.s^{-1}$)	1.3	0.4	0.6	2.1	0.5	0.2	0.1	1.0
Vy-1dwn ($m.s^{-1}$)	-1.2	0.4	-1.7	-0.6	-1.0	0.5	-1.8	-0.2
Vx-1upb ($m.s^{-1}$)	1.6	0.2	1.3	2.0	1.1	0.4	0.5	1.7
Vy-1upb ($m.s^{-1}$)	0.9	0.2	0.7	1.3	0.5	0.2	0.2	1.0
Vx-2dwn ($m.s^{-1}$)	2.2	0.2	1.8	2.5	1.1	0.4	0.4	2.0
Vy-2dwn ($m.s^{-1}$)	-1.8	0.3	-2.2	-1,4	-0.9	0.6	-1.7	-0.2
Vx-2upb ($m.s^{-1}$)	1.7	0.3	0.9	1.9	1.2	0.4	0.7	1.9
Vy-2upb ($m.s^{-1}$)	1.0	0.3	0.5	1.8	0.4	0.2	0.2	0.8

Table 3 presents the predictors of dV included in the forward step-by-step regression model at slow velocity, high velocity and overall velocity. For high velocity, the variables that best predict (or that have the highest influence in the behaviour of dV) by order of entry in the model were Vy-1dwn, Vx-ins and Vy-ins. The combination of these 3 variables explained with statistically significance 93 % of the behaviour of dV [F(3; 9)= 45.91, p< 0.01]. So, it seems that to achieve high swimming velocities, butterfliers imposes high vertical velocities in the first downbeat, high vertical and horizontal hand's velocities during the insweep. At slow velocity, the variables included in the forward step-by-step regression model were Vx-ups, Vy-ins and Vx-ins, once again. The final model explains, with significant value, 69 % of the variance of dV [F(3; 13)= 6.68, p= 0.01] for slow swimming velocity. This means that for swimming butterfly stroke at slow velocities, the insweep phase and the horizontal velocity of the hand at the end of the underwater path were decisive in the prediction of dV. For overall velocity, the independent variables that most fit the regression model were, by order of entering, the Vx-ups, the Vy-2dwn, the Vz-ent and the sw-vel. The sw-vel was included as a "dummy" variable. It was verified that the swimming velocity did not had a significant influence in the regression model

(Beta= -0.01, p= 0.92). The model computed explains 94 % of the variation of dV [F(4; 29)= 43.31, p< 0.01] with statistical significance. So, when data from a large range of swimming velocities are included for determination of the regression model, the final phase of the stroke cycle, the second downbeat and the entry in the beginning of the stroke cycle were the most important segmental actions for the prediction of dV.

Table 2. Pearson product correlation coefficient between dV, the hands and feet's velocities at slow velocity, high velocity and overall velocity. N.S. – not significant.

	High velocity		Slow velocity		Overall velocity	
	r	p	r	p	r	p
dV vs Vx-ent	0.61	0.02	0.21	N.S.	0.05	N.S.
dV vs Vy-ent	-0.59	0.03	-0.11	N.S.	0.04	N.S.
dV vs Vz-ent	-0.70	0.01	0.59	0.02	0.34	0.04
dV vs Vx-out	0.58	0.03	0.28	N.S.	0.63	<0.01
dV vs Vy-out	-0.25	N.S.	-0.27	N.S.	-0.12	N.S.
dV vs Vz-out	-0.60	0.02	0.58	0.01	0.13	N.S.
dV vs Vx-ins	0.69	<0.01	0.58	0.03	0.82	<0.01
dV vs Vy-ins	-0.66	0.01	-0.47	0.03	-0.40	0.02
dV vs Vz-ins	-0.67	0.01	-0.69	0.01	-0.40	0.02
dV vs Vx-ups	0.57	0.03	0.73	<0.01	0.88	<0.01
dV vs Vy-ups	0.61	0.02	-0.20	N.S.	0.39	0.02
dV vs Vz-ups	0.81	<0.01	0.32	N.S.	0.62	<0.01
dV vs Vx-1dwn	-0.24	N.S.	-0.45	0.05	-0.78	<0.01
dV vs Vy-1dwn	0.82	<0.01	0.58	<0.01	0.48	<0.01
dV vs Vx-1upb	0.23	N.S.	0.07	N.S.	-0.48	<0.01
dV vs Vy-1upb	-0.17	N.S.	-0.44	N.S.	-0.68	<0.01
dV vs Vx-2dwn	-0.03	N.S.	-0.24	N.S.	-0.79	<0.01
dV vs Vy-2dwn	0.67	0.01	0.63	0.01	0.79	<0.01
dV vs Vx-2upb	-0,10	N.S.	-0.08	N.S.	-0.56	<0.01
dV vs Vy-2upb	-0.15	N.S.	0.13	N.S.	-0.62	<0.01

Table 3. Summary of the model, included in the forward step-by-step regression equation, for predictors of dV, at slow velocity, high velocity and for overall velocity.

	Variable	r^2	r^2 adjusted	T	p	Beta	F	p
High velocity	Vy-1dwn	0.67	0.64	5.08	<0.01	0.522		
	Vx-ins	0.88	0.86	5.42	<0.01	0.470		
	Vy-ins	0.93	0.91	-2.70	0.02	-0.269	(3; 9) = 45.91	<0.01
Slow velocity	Vx-ups	0.35	0.29	3.91	<0.01	1.745		
	Vy-ins	0.54	0.45	2.84	0.02	0.726		
	Vx-ins	0.69	0.59	-2.07	<0.01	-0.785	(3;13) = 6.68	0.01
Overall velocity	Vx-ups	0.89	0.79	3.11	<0.01	0.62		
	Vy-2dwn	0.92	0.84	2.94	0.01	0.29		
	Vz-ent	0.93	0.85	1.62	0.04	0.13		
	Sw-vel	0.94	0.86	-0.09	0.92	-0.01	(4; 29) = 43.31	<0.01

4. DISCUSSION

The purpose of this study was to examine the relationship between the dV, the hand's and feet's velocity, as well as, to identify the variables that most predict dV, in butterfly stroke. The main conclusion is that several segmental velocities are significantly related to speed fluctuation and predict the behavior of dV.

There are a small number of investigations analysing the 3D components of hand's velocity. Comparing the results from present study with data available from other investigations, the hands mean velocities were similar for slow swimming velocity and a beat higher for high swimming velocity. Martins-Silva and Alves (2000) analysed the 3D components of hand's velocity, in 200 m sets, in butterfly stroke. Alves et al. (1999) compared the horizontal and vertical components of hand's velocity, using different breathing models, in butterfly stroke during 50 m swims. For slow velocity, the distances adopted in the study of Martins-Silva and Alves (2000) were similar to the present investigation. But for higher speeds, Alves et al. (1999) selected 50 m sets, instead of 25 m. This difference in the distance adopted between the actual study and from other authors, might lead to higher hand's velocity in the present research. Moreover, Alves et al. (1999) conducted a 2D analysis. The utilization of different methodologies for the kinematical analysis can also be a reason for the differences between the results of both investigations.

The hand's mean horizontal velocity increased along the underwater path, in all swimming velocities studied. The highest mean values were obtained at the end of the underwater path, as previously described by Schleihauf (1979) and Schleihauf et al. (1988). The slowest hand's mean horizontal velocity occurred during the entry. In fact, this result was already published in the literature by the same authors (Schleihauf, 1979; Schleihauf et al., 1988).

Downbeat actions are clearly connected to propulsion through lower limbs actions, in butterfly stroke (Barthels and Adrian, 1971; Jensen and McIlwain, 1979). In order to keep an even pace, swimmers have to do a strong first downbeat to reduce body deceleration due to hand's entry. The second downbeat has to be as strong as possible to keep the hip near to surface, but not to powerful, avoiding that this anatomical landmark emerges from water. At high swimming velocity, the Vy-2dwn presented a higher mean value than Vy-1dwn. This is in accordance to general feedbacks sent from coaches to butterfliers. At slow swimming velocity, Vy-1dwn and Vy-2dwn mean values were close one to the other. This can be explain by the small importance that butterfliers give to lower limbs propulsion, specially to the second downbeat, when swimming at slow velocities.

It was possible to verify large variations in hand and feet's velocities, within every swimming velocity. For a given swimming velocity, the range of variations and the standard deviation values from several parameters were very high. In other studies, this phenomenon had already occurred (Alves et al., 1999; Martins-Silva and Alves, 2000). The large range of variations can result from different interpretations of the swimming model by butterfliers. It is possible to find out in the technical literature, suggestions of several underwater paths, for butterfly stroke (e.g., Crist, 1979; Bachman, 1983; Maglischo, 2003). Some swimmers probably privilege a more anterior-posterior trajectory, and therefore the propulsive drag force generation (Schleihauf et al., 1988); others a more lateral-medial trajectory, and there by the propulsion with origin in the lift force (Schleihauf et al., 1988). For slow swimming velocity, high standard deviations can also be explained by the experimental protocol used. It was chosen an incremental protocol, with gradual increases in swimming velocity from set to set, until exhaustion, which can promote different hand's velocities profiles at different swimming paces.

Some investigations reported that swimming parameters presented different behaviors between males and female swimmers (e.g., Kennedy et al, 1990; Chengalur and Brown, 1992; Boulesteix et al., 2003). However, a previous study (Barbosa et al., 2005b) with the same subjects used in the present investigation, did not verified significant differences in the swimming parameters along the incremental protocol between the males and the female butterfliers. Therefore, it seems that in this particular case, it could be presented together the results from the males and the female butterfliers.

At high swimming velocity, several variables presented significant correlations coefficients with dV. For example, Vx-ent and Vy-ent presented significant coefficients, where increases in both variables were associated to increases of dV. This can be explained because hand's entry should be a smooth action; other wise it will increase the wave drag and therefore the dV. The highest correlation coefficients were observed between dV and Vy-1dwn and between dV and Vz-ups. The increase of vertical velocity during the first downbeat has the role to decrease the deceleration and negative body impulse due to hand's entry (Barbosa et al., 2002). Increases of lateral hand's velocity during upsweep were significantly associated to decreases of dV. The need to achieve high swimming velocities, lead to increases in the hand's velocity at the end of the most propulsive phases of the stroke cycle. In fact, all variables analyzed during the insweep and upsweep presented significant associations with dV, as previously described by Martins-Silva and Alves (2000).

At slow swimming velocity, Vx-ups and Vz-ins were the velocity components with higher and significant correlation coefficients with dV. As for high swimming velocity, increases in the hand's velocity during the most propulsive phases of the underwater path were significantly associated to decreases of dV. This was especially true for the horizontal and lateral components. From a 400-m pace to a 50-m pace, Chollet et al. (2005) verified an increase in the relative duration of the pull phase, enabled the application of high propulsive forces. Probably butterfliers swimming at slow pace, try to adopt a more lateral-medial trajectory, in order to promote higher propulsion from lift force. In fact, some authors relate this propulsive force to a more efficient swimming action, since the transfer of kinetic energy to water is 5 to 6 times lower then using anterior-posterior trajectories (de Groot and van Ingen Schenau, 1988).

For overall velocity, correlation coefficients between all components of hand's velocity during insweep and upsweep and dV were significant. Moreover, Vy-1dwn and Vy-2dwn were also significantly associated to the behavior of dV. The higher and significant correlation coefficients were observed between dV and Vx-ups, Vx-ins and Vy-2dwn. These results confirm the hypothesis of strong association, in butterfly stroke, between the last phases of the underwater path and the most propulsive phases of the feet's actions with dV. In fact, Chollet et al. (2005) suggested that high relative duration of upper limb actions were associated with great relative durations of downward undulation, as pace increased.

It was interesting to detect significant associations between dV and segmental actions that usually are not considered as determinants for propulsion, such as the cases of the horizontal and vertical velocities during the upbeat. The results suggested that increases in those variables were associated to decreases in dV. It is possible that this relationship results from the need of butterfliers increase slightly the velocity of the upbeat in order to not affect the global segmental coordination and therefore the propulsion (Barthels and Adrian, 1971).

Several segmental velocities were identified as predicting or as being the independent variables with most influence in the behavior of dV. For high swimming velocity, the variables that entered in the final model for prediction of dV were Vy-1dwn, Vx-ins and Vy-ins. These variables explained significantly 93 % of dV's behavior. For slow swimming velocity, the variables included in the final forward step-by-step regression model were Vx-ups, Vy-ins and Vx-ins, explaining significantly 69 % of the dependent variable behavior. For overall velocity, the variables included in the final regression model were Vx-ups, Vy-2dwn, Vz-ent and sw-vel explaining with significance 94 % of dV's behavior.

The hand's velocity in the most propulsive phases of the stroke cycle seems to be a determinant variable for the behavior of dV, at different swimming velocities. The horizontal and vertical components of hands velocity during the insweep were determinant variables for dV behavior, at slow and high swimming velocity. Those variables had already been included in the final model computed by Martins-Silva and Alves (2000). Increases in the hand's velocity in the most propulsive phases of the underwater path can increase the instant and mean body horizontal velocity (Mason et al., 1992; Maglischo, 2003). Some studies reported significant relationships between increases in mean swimming velocity and decreases of dV (Togashi and Nomura, 1992). In the same way, increases of the vertical velocity of the first downbeat have importance to reduce the swimmers deceleration at the beginning of the stroke cycle, maintaining a low dV.

At slow swimming velocity, only hand's variables entered in the final regression model. This can be interpreted as a consequence of butterfliers only promotes high vertical velocity from the feet's to achieve high swimming velocities. To swim at slow paces, butterfliers give more importance to upper limbs actions than to lower limbs. At this paces, probably butterfliers imposes leg actions mostly to maintain a convenient body alignment in the most propulsive phases of the stroke cycle.

Butterfly stroke requires a high degree of arm-to-leg coordination (Chollet et al., 2005). High degrees of synchronisation between key motor points of segmental actions are critical. Butterfliers should develop strategies to minimize segmental actions that impose increases of dV, such as the case of increases of Vz-ent, included in the final model for overall velocity. High lateral movements during entry increase the wave drag, decelerating the swimmer's body. Simultaneously, they should chose the most propulsive phases of the stroke cycle to increase the velocity of propulsive segments, to maintain high mean swimming velocity and therefore, decrease dV. With that purpose, at overall swimming velocity, the best predicting variables of dV were Vx-ups and Vy-2dwn.

5. CONCLUSIONS

In conclusion, high segmental velocities in the most propulsive phases of the stroke cycle are significantly associated to decreases of dV. In order to reduce dV, butterfliers should increase all orthogonal components of hand's velocity at the end of the underwater path, should also increase the vertical velocity during the downbeats and decrease the hand's velocity during the entry.

Chapter 9: General discussion and conclusions

1. GENERAL DISCUSSION

The general purpose of this thesis was to conduct a bioenergetical and biomechanical characterization of the butterfly stroke, as well as, to understand the relationships established between the bioenergetical and the biomechanical domains in this specific swimming technique. The main conclusion was that butterfly stroke is one of the competitive swimming techniques that elicit higher energy expenditure and energy cost. These high values are due to high intra-cycle variations of the horizontal velocity of the center of mass. This high speed fluctuation profile is related to biomechanical factors, such as, the stroke determinants behavior, the feet's and hand's velocities profiles.

Comparing the energy expenditure of the four competitive swimming techniques, for all the selected velocities, the Freestyle was the most economic swimming technique, followed by the Backstroke, the Butterfly and the Breaststroke (chapter 3). The Breaststroke and the Butterfly stroke were the swimming techniques with higher $\dot{E}_{tot}$. These results are in agreement with data from other authors (Holmér, 1972; 1974; Pendergast et al., 1978; Lavoie and Montpetit, 1986) who observed an obvious distinction between alternated (Freestyle and Backstroke) and simultaneous (Breaststroke and Butterfly) techniques. This might be related with the higher variation of the swimmer's impulse along the stroke cycle in both techniques. Troup (1991) confirmed that Breaststroke was the less economical technique. The data from the present study also revealed higher $\dot{E}_{tot}$ for the Breaststroke than for the Butterfly stroke. The higher values observed by Holmér (1974) in Butterfly, in comparison with Breaststroke, can be related to the lower range of velocities studied. Whenever both techniques were evaluated at higher velocities, the Breaststroke was the less economical (Karpovich and Millman, 1944; Troup, 1991). Probably, and even though the total energy expenditure changes with the change in swimming velocity due to the increasing drag, the Breaststroke is the most affected (Kolmogorov et al., 1997). Consequently, the range of variation of the ARI per phase, in Breaststroke is one of the highest (cf. table 1).

The Freestyle was the most economic competitive technique, followed by the Backstroke. This is a consensual result over several studies (Karpovich and Millman, 1944; Holmér, 1974; Pendergast et al., 1978; Lavoie and Montpetit, 1986; Troup, 1991). The values of $\dot{E}_{tot}$ in swimming seem to be consequence of the specific mechanical limitations of each swimming technique. Probably the $\dot{E}_{tot}$ profile of each swimming technique is related with its biomechanical characteristics (Kornecki and Bober, 1978; Nigg, 1983; Costill et al., 1985; 1987; Lavoie et al., 1985; Smith et al., 1988; Wakayoshy et al., 1995; 1996). Figure 1 presents a comparison of swimming economy from the present investigation with data from literature. The values presented for the swimming economy of different authors were calculated using the regression equations presented by themselves. The values of swimming economy were extrapolated or interpolated for the same swimming velocities adopted in the present study (1.0 $m.s^{-1}$, 1.2 $m.s^{-1}$, 1.4 $m.s^{-1}$ and 1.6 $m.s^{-1}$). The only exception was the comparison of the swimming economy in Breaststroke and Butterfly stroke. To be possible the comparison of data from the present investigation with the results from by Holmér (1974) the swimming velocities really used by the author in the original study were also plotted. It should be noted that some authors used procedures different from the ones we used (direct oximetry vs recto-extrapolation; swimming pool vs Hydro-flume; oxygen up-take vs total energy expenditure; exponential vs linear approaches). For example, some investigator only measured the oxygen up-take (e.g, Holmér, 1974; Lavoie and Montpetit, 1986; Montpetit et al., 1988). In those cases, the energy expenditure might be underestimated, because they do not take in account the role of anaerobic system.

To be possible the comparison from the present results with other authors, it was necessary to calculate the absolute swimming economy instead of the relative swimming economy (cf. chapter 3). Especially in Backstroke and Butterfly stroke there is a lack of investigations analyzing the relative swimming economy. Therefore, it is only possible to compare the present results with a significant number of investigations if absolute swimming economy is considered. The swimming economy of Freestyle was the highest in the present investigation, when compared with remain literature. At swimming velocities of 1.6 $m.s^{-1}$, Freestyle was less economical than the results presented by Montpetit et al. (1988). At those velocities, probably the anaerobic contribution increases; consequently, the total energy expenditure also increases. In the study of Montpetit et al. (1988) only the oxygen up-take was considered. Therefore, the swimming economy presented by these authors might be underestimated. The lowest swimming economy was observed in Alves et al. (1996). Possibly, this can explain because the authors used different procedures (e.g., the exponential regression technique and a rectroextrapolation method). In Backstroke, only Alves et al. (1996) presented a more economical swim for the velocities adopted. The results from the present investigation suggest a more economical Backstroke than data from Smith et al. (1988) and Holmér (1974). Once more, the use of different approaches by Alves et al. (1996) can explain the obvious difference in the results. Breaststroke and Butterfly were also more economical in the present investigation that the results presented by Holmer (1974) and Vilas-Boas (1993) for flat Breaststroke. In fact, Butterfly stroke is one of the swimming techniques with a better improvement of its economy, comparing data from the 70’s and 2000. Generally, it can be concluded that, in all competitive strokes, swimmers from 2000 are more economical that the swimmers evaluated in previous decades.

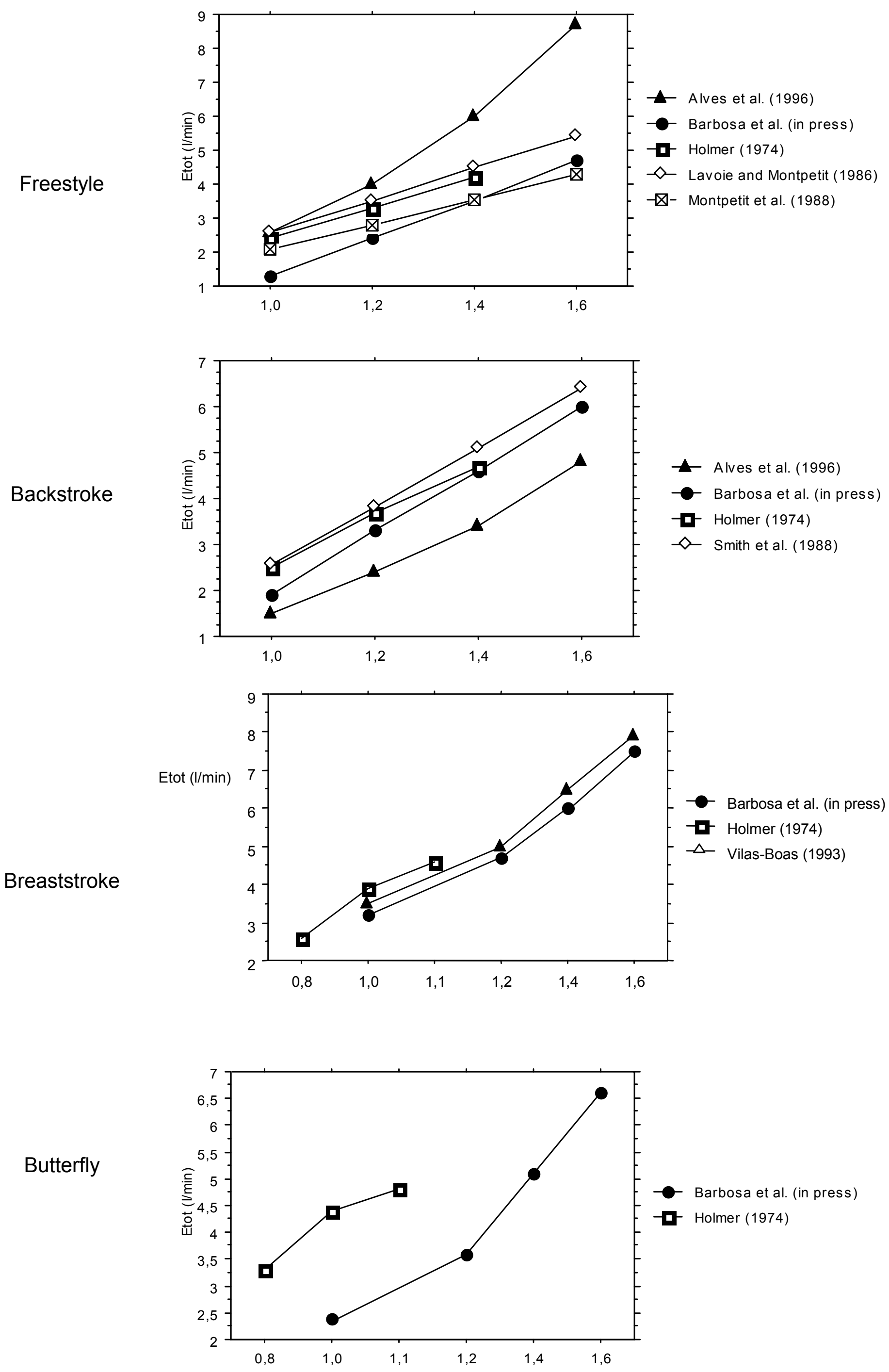


Figure 1. Comparison between data from literature and present results, of swimming economy.

Since the expeculation about the influence of the intra-cycle variations of the swimmers impulse for the $\dot{E}_{tot}$ in butterfly, a study about the profile of ARI, was taken in account (chapter 4). The ARI, during the arm's recovery phase, when compared with the remained propulsive phases, presented a significantly lower value. In fact, this is in agreement with the findings of Schleihauf (1979), Schleihauf et al. (1988) and Mason et al. (1992). These results can be explained due to the particular body position and actions during that phase, which are characterised by an increase of the maximal body cross-section area. Consequently, it was observed a decrease of the mean horizontal acceleration of the center of mass of the swimmer. The hand's entry was the second less propulsive phase of the stroke cycle, as reported previously by Schleihauf (1979), Schleihauf et al. (1988) and Mason et al. (1992). This can be the result of the hand's entry, as well as, of the previous entry from a relevant part of the swimmer's body. Those actions will increase the wave drag, promoting a decrease of the mean horizontal acceleration of the center of mass. In conclusion, the butterfly stroke is a swimming technique where it is possible to observe high intra-cycle variations of the ARI due to significant reductions of this variable during the arm's recovery. Moreover, the adoption of different breathing techniques seems to do not affect the behaviour of the ARI.

Table 1 presents a review of the most important studies about ARI, in several swimming techniques. As it is observed, Butterfly stroke is one swimming techniques with high intra-cycle variations of the ARI. Analysing the range of variation of the ARI, according to the competitive swimming techniques, the stroke with higher ARI is Breaststroke, followed very closely by the Butterfly stroke and then by the Backstroke and the Freestyle. Interestingly, this is the same order found for the study of the $\dot{E}_{tot}$ in the four competitive swimming techniques. Moreover, Kolmogorov et al. (1997) found the same sequence comparing active drag, at different swimming velocities. The swimming technique with higher active drag was the Breaststroke, followed by the Butterfly, the Backstroke and the Freestyle. These findings create some clues about the hypothetical existence of relationships between bioenergetical (in this case, the $\dot{E}_{tot}$) and biomechanical variables (such as the ARI per phase) in swimming.

Table 1. Revision of the most important studies about average resultant impulses per phase (ARI) in competitive swimming techniques.

Author(s)	Swimming technique	Lower mean ARI for the all sample (N.s)	Higher mean ARI for the all sample (N.s)
van Tilborgh et al. (1988)	Breaststroke (flat variant)	-50	46
Vilas-Boas (1994)	Breaststroke (flat variant)	-60	55
Alves (1996)	Freestyle	-11	17
	Backstroke	-5	16
Barbosa et al. (2002)	Butterfly (frontal inspiration)	-78	38

At this moment of our study development, it was clear that butterfly stroke is characterized by a high energy expenditure and a high intra-cycle variation of the ARI. Therefore, emerged the need to identify what biomechanical factors, and how, affect the bioenergetical outputs assessed in butterfliers. Some authors already suggested or speculated about the existence of significant relationships between biomechanical and bioenergetical variables in butterfly stroke. However, only few attempts were conducted to understand those hypothetical relationships (e.g., Wakayoshi et al., 1995).

In one first study (chapter 5), the purpose was to identify the relationships established between $\dot{E}_{tot}$ and V, and between EC and stroke determinants (i.e. SF, SL and SI) through out a range of swimming velocities. This study supported the hypothesis, that there is a close connection between the bioenergetic parameters and biomechanical determinants of stroke performance.

All the equations computed between $\dot{E}_{tot}$ and V presented coefficients of correlation with significant values. This means that increases in the $\dot{E}_{tot}$ were related to increases of V. The increase of $\dot{E}_{tot}$ is due to the need of overcoming drag force, which is related to the increase of V, from stage to stage. EC increased significantly along with the increasing SF and SI, throughout the set of swims. Concerning the relationship between EC and SF and between EC and SI, the results of the study were in agreement with investigations conducted in other swimming strokes (Costill et al., 1985; Smith et al., 1988; Klentrou and Montpetit, 1992; Tourny, 1992; Wakayoshi et al., 1995). For the relationship between EC and SL, only one swimmer presented a correlation coefficient with a significant value. The tendency was to EC decrease with increasing SL. The most obvious explanation for this result is the muscular fatigue along with the increasing velocity (Keskinen and Komi, 1993). The decrease in the SL, apparently, might also be associated with the accumulation of blood lactate and other anaerobic metabolites, as it was previously observed (Keskinen and Komi, 1993). Several causes are attributed to fatigue. The depletion of the energy systems, the accumulation of metabolic products, phenomena's in the nervous system and the failure of the fiber's contractile mechanism (Wilmore and Costill, 1994). It should be noted that it is not the lactate that promotes the fatigue. In the blood, the lactic acid dissociates, converting to lactate and causing an accumulation of Hydrogen ions. That increase in Hydrogen ions causes acidosis, which affects the energy production and the muscle contraction mechanisms.

In a second study (chapter 6), the aim was to examine the relationship between dV and EC, in Butterfly stroke. It is observed that high dV is associated to less economical swimming, in butterfly stroke. The increase of the EC was significantly associated with the increase of the dV. High variations in dV also impose a high EC, since energy should be delivered to overcome inertial forces (Costill et al., 1987; Nigg, 1983). In butterfly stroke, the increase of the dV might lead to a proportional increase of external forces submitted to the swimmer, such as the drag force or inertial forces, inducing an increase of the EC. Therefore, apparently, swimming might be added to the activities reported by Sih and Stuhmiller (2003), where EC is proportional to the force applied and the number of repetitive application of the force over a wide range of species (Humans and Quadruped species) and repetitive movements (cycling, running and arm movements).

Vilas-Boas (1996) has found a similar result, comparing the speed fluctuation in Breaststroke with EC. On the other hand, Alves et al. (1996) only detected significant relationships between these variables in Backstroke at low swimming velocities. The assumptions of a more pronounced variation of the dV in the simultaneous techniques (Breaststroke and Butterfly) make it easier to observe significant relationships, with EC, that in the alternated strokes (Freestyle and Backstroke).

From both studies discussed above, became clear the existence of significant relationships between bioenergetical variables (i.e., EC and $\dot{E}_{tot}$) and biomechanical variables (dV, V, SF and SI). For example, increases in V and dV, respectively, lead to increments in $\dot{E}_{tot}$ and EC. The following question to be raised was what biomechanical variables influence the behaviours of dV and V. If we recognize the biomechanical variables that influence, or predict, dV and V behaviours, it would be possible to reduce the EC, improving swimming performance.

In one study (chapter 5), the purpose was to identify the relationships between the stroke determinants and V, in butterfly stroke. The relationships between SF and V, as well as, between SI and V were significant in all swimmers analyzed. Several studies observed that increases in V were related to increases of SF (Craig and Pendergast, 1979; Craig et al., 1979; 1985; Wakayoshi et al., 1995). The relationships between SI and V were also significant. In fact, increments of the SI being strongly associated to increases of V aren't new. Costill et al. (1985) proposed that SI is the product of V by SL. Therefore, the relationship between V and SI should be interpreted with some precaution. For the relationship between V and SL, there was a slight tendency to decrease SL with the increase in V. So, with an incremental protocol, butterfliers also increase V, from stage to stage, through increments of SF, trying to maintain SL within constant values. In fact, previously other authors suggested that increases in V are related to increases of SF trying to maintain SL as constant as possible (Craig and Pendergast, 1979; Craig et al., 1979; Hay and Guimarães, 1983).

The purpose of another study (chapter 7) was to understand the relationships established between the dV, the stroke determinants and the swimming velocity, in butterfly stroke. The main conclusion was that both stroke determinants and swimming velocity influence the dV profile. Slow swimming velocities revealed to be less stable in what concerns dV. Swimming at slow paces might promote an increase of the kinematical energy transferred to water, instead of its use for propulsion. Consequently, it will induce a lower propulsive efficiency and a high dV. Moreover, when high velocity is considered, the absolute duration of each propulsive phase is reduced. Consequently, the ARI per phase is also reduced and, a lower dV is imposed.

It was observed an increase of the dV with the increase of the SF, for a given swimming velocity or distance swam. However, whenever the overall sample was analysed, the results were different. It was observed that increasing SF leaded to lower dV. The increase of the V up to 80% of the maximal velocity in female swimmers and up to 94% in male swimmers was described as a result of the increase of SF and a constant SL (Craig and Pendergast, 1979). In fact this same results are observed in the present investigation (cf. chapter 5). When an incremental protocol was applied, the increase of V was significantly related to the increase of SF, but without statistical relationship with SL. It can be suggest that higher SF imposes a lower absolute duration of each stroke phase, promoting a lower intra-cyclic resultant impulse and, therefore a lower dV.

In the same study, it was found that increasing SL, for a given V, will reduce the dV. Toussaint et al. (1983) compared a group of female olympic swimmers with other group of female swimmers but, from lower competitive level. The elite female swimmers presented significantly higher SL. Takagi et al. (2004) compared the dV of the hip of a group of swimmers eliminated in the preliminaries of the 9th World Swimming Championships with another who qualified to the semi-finals. The authors observed that the dV was significantly higher in the group of eliminated breaststrokers. Probably swimmers of higher competitive level can swim, simultaneously, with high SL and reduce dV, than swimmers of lower competitive level. However, when these relationships are studied in individual bases, it is possible to detect swimmers increasing dV with increasing SL. Increases of the SI were significantly associated with decreases in the dV. So, these results confirm the concept of SI as being a valid swimming efficiency index.

It seems that stroke determinants have a significant influence in dV and in V. So, it can be assumed that dV and V are "indirect mediators" for the influence of the stroke determinants in the EC and in the $\dot{E}_{tot}$. Therefore, butterfliers should be encouraged to analyze the relationships between V, SF and SL individually. They should detect the deflection or inflection points of stroke determinants as a function of swimming velocity to further determine appropriate training intensities to reduce EC.

The purpose of the last study (chapter 8) was to examine the relationships between the dV, the hand's and feet's velocities, as well as, to identify the segmental velocities that most predict the dV, in butterfly stroke. Several segmental velocities were significantly related to speed fluctuation and predicted the behavior of dV, at different swimming velocities. These results confirm the evidence of the strong association between the last phases of the underwater path with dV, as previously described by Martins-Silva and Alves (2000). But not only the hands actions were determinants for the dV's behavior. The most propulsive phases of the feet's actions also revealed to be strongly and significantly associated to the dV's profile. For example, at high swimming velocity, the highest correlation coefficients were observed between dV and Vy-1dwn and between dV and Vz-ups. At slow swimming velocity, Vz-ups and Vz-ins were the velocity components with higher and significant correlation coefficients with dV. For overall velocity, correlation coefficients between all components of hand's velocity during insweep and upsweep with dV were significant, as well as, between dV, Vy-1dwn and Vy-2dwn.

Several segmental velocities were identified as predicting (or as being the variables with most influence in the behavior of) dV. For high swimming velocity, the variables that entered in the final model for prediction of dV were Vy-1dwn, Vx-ins and Vy-ins. For slow swimming velocity, the variables included in the final model were Vx-ups, Vy-ins and Vx-ins. For overall velocity, the variables included in the final regression model were Vx-ups, Vy-2dwn, Vz-ent and Sw-vel. The hand's velocity in the most propulsive phases of the stroke cycle seems to be important variables for dV's behavior, at different swimming velocities. To swim at slow paces, butterfliers give more importance to upper limbs actions than to lower limbs. Swimmers should chose the most propulsive phases of the stroke cycle to increase segmental velocity, increasing mean swimming velocity and therefore, decreasing dV. Probably, swimmers of high competitive level can simultaneously increase the hand's velocity during the upsweep and decrease the dV, since they present high degree of arm-to-leg coordination, as described by Chollet et al. (2005). This mean that, presumably, elite swimmers can present high segmental accelerations in the most propulsive phases of the stroke cycle; but, can develop strategies to also reduce the desacelerations in the less propulsive phases. In this perspective, they present a lower variation of the instantaneous velocity along the stroke cycle.

Wakayoshi et al. (1995) suggest that there is a significant relationship between swimming performance and the slope of the swimming economy regression equation. According to these authors, at the same range of swimming velocities, swimmers with reduce slopes are more economical and can obtain better performances, that swimmers with increased slopes. For all the butterfliers evaluated in the bioenergetical protocol, it was attempted the study of the relationship between the slopes of the $\dot{E}_{tot}$ and EC regression equations, with the their best swimming performances in the 200-m butterfly events. Significant relationships were observed in both situations. The coefficient of correlation between the $\dot{E}_{tot}$ slope and the 200-m performance was r= 0.79 (p=0.03). So, 63% of the performance in the 200-m events, for these swimmers, can be explained by the $\dot{E}_{tot}$ profile (r^2= 0.63). The coefficient of correlation computed between the EC slope and the 200-m performance was r= 0.81 (p=0.02). Therefore, 65% of the performance in the 200-m events, for these swimmers, was explained by the EC (r^2= 0.65). In conclusion, these results suggest the relevance of the bionergetical variables to the performance in butterfly swimming. Swimming performance is the major point of interests for coaches and sport scientists. All work done by both groups has the aim to access swimmers to higher levels of performance. From what was discussed previously, it seems that, presumably, to improve swimming performance coaches and investigators must analyze and have a strong intervention in what concerns to the biophysical profile of the swimmer. It seems to be reasonable to say that more that 50% of swimming performance can be explained by biophysical phenomena's. Nevertheless, the relative importance of other variables, such as the psychological ones, the environment, genetic background, etc. should not be disregard (cf. chapter 1).

Hay and Reid (1982) presented the procedures to develop a model, where it is possible to sinteticly describe all biophysical factors that influence the performance in a sports technique. The authors called this as "deterministic model". With the model it is possible to identify, by hierarchical order, the variables that are determinants of performance.

Figure 1 presents the deterministic model of the relationships studied between performance, bioenergetical and biomechanical variables, in Butterfly stroke. With the last studies conducted, became obvious significant influences of several biomechanical variables in dV and V. The stroke determinants presented significant relationships with both variables. The segmental velocities can also predict dV. V has a significant influence in dV. The dV and V explain, with statistic significance, the EC and $\dot{E}_{tot}$ values. Finally, EC and $\dot{E}_{tot}$ presumably have a relevant influence in the swimming performance.

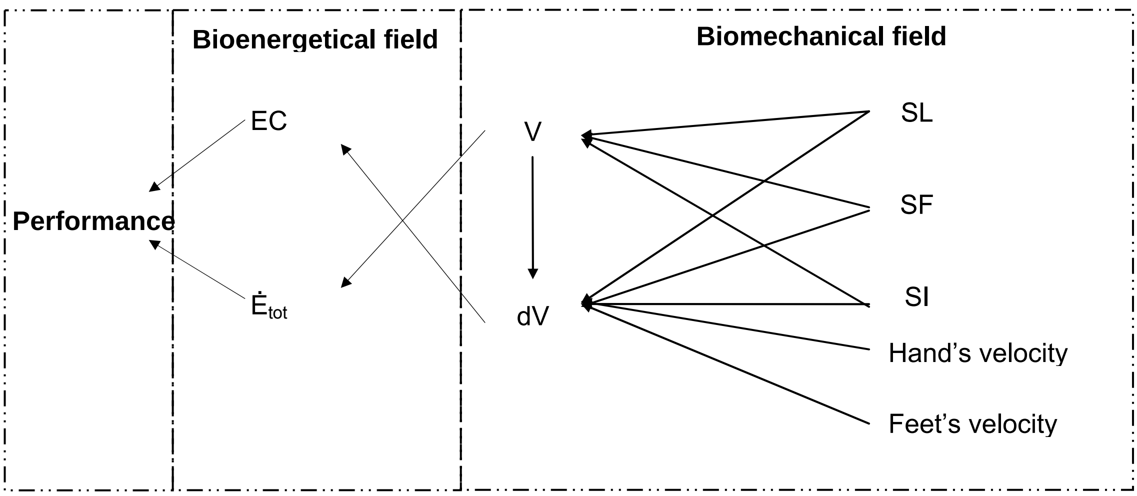


Figure 2. Deterministic model for the relationships between bioenergetical and biomechanical variables, in Butterfly stroke.

Despite the progresses allowed, some lines of investigation were open with these results. In a near future it would be interesting to understand if the hand's and feet's velocities influence the stroke mechanics, especially V, SF and SL. Speculating, if that's so, it is possible to exist a 4^{th} level in the deterministic model presented in Figure 2. The segmental action will influence the stroke determinants (4th level); the stroke determinants will influence the dV and V (3rd level); dV and V will determine the bioenergetical profile (2nd level); and those bioenergetical parameters influence the swimming performance (1st level). Nevertheless, apparently, this approach never has been developed in swimming.

Some studies previously published (e.g. Mason et al., 1992; Sanders et al., 1995) suggested the relevance of the waving velocity for the mean swimming velocity in butterfly stroke. It could be interesting to study the role of body waving for the prediction of dV and V. Apparently was never explored the possible relationship or prediction of dV and V according to the dynamic movement, in butterfly stroke.

Other line of investigation can be the development of studies with these characteristics, but in other competitive swimming techniques. It will be interesting to know if the relationships described in the present study are similar or different in the other swimming techniques. A major attention should be given to Freestyle and Backstroke. Both swimming techniques present bioenergetical and biomechanical profiles different from the simultaneous strokes. It is possible to admit different relationships, or different degrees of relationship, between all the parameters evaluated.

2. CONCLUSIONS

Based on the specific purposes of this research it can be concluded that:

- Comparing the $\dot{E}_{tot}$ of the four competitive swimming techniques, for all the selected velocities, the Freestyle is the most economic swimming technique, followed by the Backstroke, the Butterfly and the Breaststroke;

- Butterfly stroke is a swimming technique where it is possible to observe high intra-cycle variations of the ARI, due to significant reductions of this parameter during the arm's recovery and hand's entry;

- Increases in the $\dot{E}_{tot}$ are significantly related to increases of V. The EC increases significantly along with the increasing SF and SI. The EC decreases with increasing SL;

- The increase of the EC is significantly associated with the increase of the dV, in Butterfly stroke;

- The relationships between SF and V, as well as, between SI and V are positive and significant;

- There is a negative and significant relationship between dV and V, between dV and SL and between dV and SI. For overall data, it is observed a negative and significant relationship between dV and SF;

- High segmental velocities, in the most propulsive phases of the stroke cycle, are significantly associated to decreases in dV;

- To reduce dV, butterfliers must increase all components of hand's velocity at the end of the underwater path, should increase the vertical velocity during the downbeats of the feet's and decrease the hand's velocity during the entry.

As a general conclusion, butterfly stroke is one of the competitive swimming techniques with higher energy expenditure. The intra-cycle variations of the average resultant impulses per phase and the intra-cycle variations of the swimming velocity are also high, compared to data of other competitive swimming techniques, analysed from literature. The high values of bioenergetical outputs are related to biomechanical factors. The behavior of biomechanical variables, such as the stroke determinants, the hand's and feet's velocities, influence the swimming velocity and the speed fluctuation profile. Consequently, these parameters will affect the total energy expenditure, the energy cost of swimming and, presumably, performance. Therefore, coaches and butterfliers should conduct an exhaustive and frequent evaluation of their technique in order to reduce the energy cost associated to a given swimming velocity.

Chapter 10: References

Chapter 1: Introduction

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Chapter 8: Contributions of segmental velocities to speed fluctuation in butterfly stroke

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Chapter 9: General discussion and conclusions

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