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Research article

Predicting the intra-cyclic variation of the velocity of the centre of mass from segmental velocities in butterfly stroke: A pilot study

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Abstract
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 behavior 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. Both protocols were recorded from four different plans, 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 (high velocity ranged from r = 0.58 for Vx-out to r = 0.82 for Vy-1dwn; slow velocity ranged from r = -0.45 for Vx-1dwn to r=0.73 for Vx-ups; overall velocity ranged from r= 0.34 for Vz-ent to r = 0.82 for Vx-ins). It was also computed a regression model to predict dV. For high velocity (up to 1.75 ± 0.09 m.s^{-1}), the variables that best predict dV were Vy during the first downbeat, Vx and Vy during the arm's insweep ($r^2 = 0.93$). At slow velocity (up to 1.48 m.s^{-1}), 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.

Key words: Swimming, body's velocity fluctuation, feet's velocity, hand's velocity.

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 swimming strokes. 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. Positive impulses are related to propulsion and negative ones to drag force. This experimental approach tries to understand the relationship between both hydrodynamic forces. The main problem related to this approach might be the errors derived from digitizing procedures, the errors derived from distortion and underwater video techniques. On the other hand, experimental approach allows a specific characterization of the swimmers technique. In this way, it becomes useful for coaches and swimmers analyze and improve their technique. Another approach is to analyze such relationship using the computer model simulations, such as, the computer fluid dynamics (e.g., Rouboa et al. 2006). The numerical technique presents some limitations, such as, the ecological validity of the data, at least in this stage of the research development using computer fluid dynamics in swimming. Most of the studies were performed with objects of geometries different from human bodies or human segments and most of the research was based in 2D calculations. However, if an appropriate computer cluster is used, numerical approach can be less time consuming and less costly.

Some studies showed or suggested that less energy cost is associated to lower dV, in several swimming strokes, such as, Freestyle (Alves et al., 1996; Barbosa et al., 2006a; Nigg, 1983), Backstroke (Alves et al., 1996; Barbosa et al., 2006a), Breaststroke (Barbosa et al., 2006a; Vilas-Boas, 1996) and Butterfly stroke (Barthels and Adrian, 1971; Barbosa et al., 2005a; 2006a; Kornecki and Bober, 1978). It is described that low dV is related to high swimming efficiency. This relationship is especially evident in the simultaneous strokes (Barbosa et al., 2005a; 2006a; Vilas-Boas, 1996); probably because of their higher dV in comparison with remaining ones.

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, within the stroke cycle. These movements include elements, which add up to necessary work done by the swimmer (D'Acquisto et al., 1998; Nigg, 1983). Some studies reported a relationship between dV and swimming velocity and/or performance. Some investigators suggested the possibility of high dV being related with lower swimming velocities (e.g., Barbosa et al., 2005a; Vilas-Boas, 1996). It was observed a significant and negative relationship between the mean horizontal velocity and the speed fluctuation in Butterfly stroke (Togashi and Namura, 1992) and Breaststroke (Takagi et al., 2004). It was described a polynomial relationship between dV and velocity in the four competitive swimming strokes (Barbosa et al., 2006a). At relatively slow velocity, increasing speed promoted an increasing dV up to a given value. Achieving such velocity, dV started to decrease. So, at high swimming velocities, dV decreased. However, Leblanc et al. (2007) showed that high dV reflected the capacity of acceleration of elite swimmers. This acceleration capacity was calculated by an index of dV and the acceleration-deceleration time ratio.

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For the study of dV's behavior, 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 range of dV, during some phases of the stroke cycle was significantly related to swimmer's skill and that they were more critical in Breaststroke and in Butterfly stroke, compared to Front Crawl or Backstroke.

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 relatively 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., Arellano et al., 2003; Bucher, 1975; Colman et al., 1999; Colman and Persyn, 1993; Deschodt, 1999; Hollander et al., 1988; Sanders et al., 1995; Ungerechts, 1985; Ungerechts et al., 1999; 2000). 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. So, it could be interesting to understand the role of the lower limbs kinematics in the dV's behavior in Butterfly stroke.

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 could account for the dV, in Butterfly stroke. It was hypothesized that: i) high segmental velocity of the arms during the final part of the underwater path will decrease the dV and; ii) high segmental velocity of the legs during the downbeats will decrease the dV.

Methods

The study was divided in two parts. Within Part I the aim was to investigate the behavior 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 butterfliers (20.3 ± 3.5 years old; 1.79 ± 0.05 m of height; 70.5.5 ± 8.5 kg of body mass; 121.1 ± 2.1 s of personal record for the 200 m Butterfly event in short course) and one female Portuguese butterfliers (17 years old; 1.65 m of height; 54.2 kg of body mass; 133.52 s of personal record for the 200 m Butterfly event in short course) of international level were studied.

Protocol

The swimmers were submitted to an incremental set of 200 m butterfly swims, with a start in water, similar to the one previously described in the literature (e.g., Barbosa et al. 2006a; 2006b; Fernandes et al. 2003). The starting velocity was 1.18 $m \cdot s^{-1}$ for the males and 1.03 $m \cdot s^{-1}$ for the female swimmer. The stroke rate started at 0.61 ± 0.05 Hz and the stroke length at 1.94 ± 0.14 m for males. The stroke rate started at 0.54 Hz and the stroke length at 1.89 m 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 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 $m \cdot s^{-1}$, one swimmers 1.48 $m \cdot s^{-1}$ and a last swimmers 1.38 $m \cdot s^{-1}$. 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. Although it have been shown that pace-maker light are an effective method to adjust velocity for experient and less experient swimmers (Keskinen and Keskinen, 1999); all butterfliers had previous experiences with the apparatus.

Part II

Subjects

Seven male Portuguese butterfliers of national or international level were studied (18.4 ± 1.9 years old; 1.76 ± 0.06 m of height; 68.6 ± 6.8 kg of body mass; 122.6 ± 2.6 s of personal record for the 200 m Butterfly event in short course).

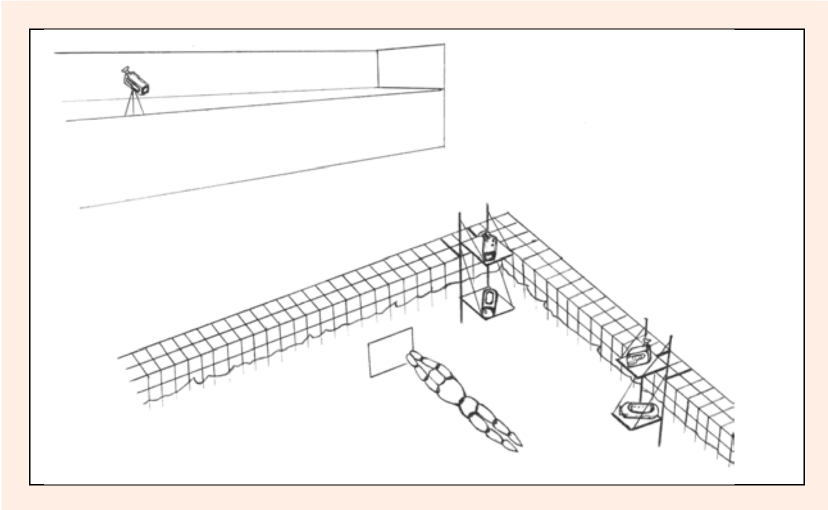

Figure 1. Experimental setup.

Protocol

Each swimmer performed two 25 m Butterfly swims with a start in water, as close as possible to their maximal capability, as described elsewhere (e.g., Barbosa et al. 2002; 2003). 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 $m \cdot s^{-1}$, the stroke rate 0.90 ± 0.05 Hz and the stroke length 1.82 ± 0.09m.

Data collection

Figure 1 presents the experimental setup. 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, for a better 3D reconstruction according to the algorithm adopted. 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 27 m^3 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) 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, in the central part of the pool. 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). It was used a double-passage filtering for the signal processing. The digitise-redigitise reliability was r = 0.97 ± 0.01. It was calculated the 3D components (horizontal, vertical and lateral) of the hand's velocity during: (i) the entry – period from touch of hand in water till its full extension and forward gliding; (ii) the outsweep – period from the full hand's extension till achieves the most deep vertical position of its trajectory, after lateral movement, when the hand is in the vertical projection of the shoulder; (iii) the insweep – period from the most deep vertical position of the hand, in the vertical projection of the shoulder 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.

Table 1. 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

	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 ($m \cdot s^{-1}$)	1.5	.3	1.1	1.9	1.4	.6	.5	2.4
Vy-ent ($m \cdot s^{-1}$)	-1.2	.5	-1.9	-.5	-1.0	.5	-2.4	-.4
Vz-ent ($m \cdot s^{-1}$)	-.9	.7	-2.1	.1	-.3	.6	-1.5	1.0
Vx-out ($m \cdot s^{-1}$)	-1.4	.3	-1.8	-1.0	-.9	.3	-1.5	-.5
Vy-out ($m \cdot s^{-1}$)	-.7	.5	-1.5	.0	-.6	.1	-.8	-.4
Vz-out ($m \cdot s^{-1}$)	-1.0	.4	-1.4	-.3	-1,1	.4	-1.6	-.3
Vx-ins ($m \cdot s^{-1}$)	-3.4	.8	-4.5	-2.0	-1.5	.5	-2.5	-.9
Vy-ins ($m \cdot s^{-1}$)	2.0	1.0	.3	3.3	1.1	.5	.4	2.3
Vz-ins ($m \cdot s^{-1}$)	1.5	.8	.2	2.9	1.3	.6	.4	2.5
Vx-ups ($m \cdot s^{-1}$)	-6.0	1.1	-7.4	-3.9	-2.0	.7	-3.5	-.7
Vy-ups ($m \cdot s^{-1}$)	1.2	.6	.3	2.4	1.8	.6	.9	3.1
Vz-ups ($m \cdot s^{-1}$)	-1.8	1.2	-3.3	-.2	-.6	.4	-1.2	.0
Vx-1dwn ($m \cdot s^{-1}$)	1.3	.4	.6	2.1	.5	.2	.1	1.0
Vy-1dwn ($m \cdot s^{-1}$)	-1.2	.4	-1.7	-.6	-1.0	.5	-1.8	-.2
Vx-1upb ($m \cdot s^{-1}$)	1.6	.2	1.3	2.0	1.1	.4	.5	1.7
Vy-1upb ($m \cdot s^{-1}$)	.9	.2	.7	1.3	.5	.2	.2	1.0
Vx-2dwn ($m \cdot s^{-1}$)	2.2	.2	1.8	2.5	1.1	.4	.4	2.0
Vy-2dwn ($m \cdot s^{-1}$)	-1.8	.3	-2.2	-1,4	-.9	.6	-1.7	-.2
Vx-2upb ($m \cdot s^{-1}$)	1.7	.3	.9	1.9	1.2	.4	.7	1.9
Vy-2upb ($m \cdot s^{-1}$)	1.0	.3	.5	1.8	.4	.2	.2	.8

Statistical analyses

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 hand's and feet's velocities with significant correlations 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 (Swvel) it was used as a "dummy" variable (nominal variable describing high velocity versus slow velocity). In this way, the between-treatment (high velocity = 1; slow velocity = 0) can be analyzed and, therefore, identify only the effects on dV due 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 $p \leq 0.05$.

Results

Table 1 presents the 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. Vx was defined as positive when the hand's or feet displaced forward. Vy was assumed as positive when the hands or feet displaced upwards. Vz was considered as positive when the hand's displaced inwards. It was possible to verified large variations in the velocity of the hands and feet for both swimming velocities. The ranges of variation of several parameters were quite high. For example, Vz-ent ranged from –2.1 $m \cdot s^{-1}$ to 0.1 $m \cdot s^{-1}$ and Vx-ins ranged from –4.5 $m \cdot s^{-1}$ to -2.0 $m \cdot s^{-1}$, at high velocity. At slow velocity, Vx-ups ranged from –3.5 $m \cdot s^{-1}$ to –0.7 $m \cdot s^{-1}$ and Vy-1dwn ranged from -1.8 $m \cdot s^{-1}$ to –0.2 $m \cdot s^{-1}$. 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, specially the Vx. The highest mean horizontal velocity of the hands was identified during the upsweep at slow velocity (Vx-up = -2.0 ± 0.7 $m \cdot s^{-1}$) and at high velocity (Vx-up = -6.0 ± 1.1 $m \cdot s^{-1}$). For the feet's vertical velocity, different kinematical behaviors 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 $m \cdot s^{-1}$). At slow velocity, the mean vertical velocity of the feet's during both downbeats was non-different (Vy-1dwn = -1.01 ± 0.5 $m \cdot s^{-1}$ vs Vy-2dwn = -0.9 ± 0.6 $m \cdot s^{-1}$).

Table 2 presents the Pearson product correlation coefficient 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 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

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	.61	.02	.21	N.S.	.05	N.S.
dV vs Vy-ent	-.59	.03	-.11	N.S.	.04	N.S.
dV vs Vz-ent	-.70	.01	.59	.02	.34	.04
dV vs Vx-out	.58	.03	.28	N.S.	.63	<.01
dV vs Vy-out	-.25	N.S.	-.27	N.S.	-.12	N.S.
dV vs Vz-out	-.60	.02	.58	.01	.13	N.S.
dV vs Vx-ins	.69	<.01	.58	.03	.82	<.01
dV vs Vy-ins	-.66	.01	-.47	.03	-.40	.02
dV vs Vz-ins	-.67	.01	-.69	.01	-.40	.02
dV vs Vx-ups	.57	.03	.73	<.01	.88	<.01
dV vs Vy-ups	.61	.02	-.20	N.S.	.39	.02
dV vs Vz-ups	.81	<.01	.32	N.S.	.62	<.01
dV vs Vx-1dwn	-.24	N.S.	-.45	.05	-.78	<.01
dV vs Vy-1dwn	.82	<.01	.58	<.01	.48	<.01
dV vs Vx-1upb	.23	N.S.	.07	N.S.	-.48	<.01
dV vs Vy-1upb	-.17	N.S.	-.44	N.S.	-.68	<.01
dV vs Vx-2dwn	-.03	N.S.	-.24	N.S.	-.79	<.01
dV vs Vy-2dwn	.67	.01	.63	.01	.79	<.01
dV vs Vx-2upb	-,10	N.S.	-.08	N.S.	-.56	<.01
dV vs Vy-2upb	-.15	N.S.	.13	N.S.	-.62	<.01

the 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 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, 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 were significantly associated with decreases in the dV.

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 behavior of dV) by order of entry in the model were Vy-1dwn, Vx-ins and Vy-ins. The combination of these three variables explained with statistically significance 93 % of the behavior 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

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	.67	.64	5.08	<.01	.522		
	Vx-ins	.88	.86	5.42	<.01	.470		
	Vy-ins	.93	.91	-2.70	.02	-.269	(3 ;9) = 45.91	<.01
Slow velocity	Vx-ups	.35	.29	3.91	<.01	1.745		
	Vy-ins	.54	.45	2.84	.02	.726		
	Vx-ins	.69	.59	-2.07	<.01	-.785	(3;13) = 6.68	.01
Overall velocity	Vx-ups	.89	.79	3.11	<.01	.62		
	Vy-2dwn	.92	.84	2.94	.01	.29		
	Vz-ent	.93	.85	1.62	.04	.13		
	Sw-vel	.94	.86	-0.09	.92	-.01	(4;29) = 43.31	<.01

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.

Homocedasticity was computed with the Weighted Least Square model. For the three regression models, the residuals did not presented an increasing or decreasing tendency. In fact, the standardized residuals were around zero values (slow swimming velocity: $-5.75 \cdot 10^{-15} \pm 5.43$; high swimming velocity: $3.55 \cdot 10^{-15} \pm 4.23$; overall swimming velocity: $-7.75 \cdot 10^{-15} \pm 2.64$). The normality was assessed by the K-S test and the Durbin-Watson test. For all regression models, the distribution of data was normal.

Discussion

The goal 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 results were that several segmental velocities from upper and lower limbs were related to dV for slow, fast and overall velocity. Therefore, the hypothesis that: i) high segmental velocity of the arms during the final part of the underwater path will decrease the dV and; ii) high segmental velocity of the legs during the downbeats will decrease the dV were partially confirmed.

In comparison to literature, this research presents new highlights about the Butterfly stroke kinematics. It seems that our study presents some innovations: i) Butterfly stroke is one of the less studied strokes, especially when compared with Front Crawl or Breaststroke; ii) most kinematical studies about swimming strokes are 2D approaches and we developed a 3D analysis; iii) the swimmers are all butterfliers and not specialists in other techniques evaluated at Butterfly stroke. Moreover, some of them are international level butterfliers and; iv) the dV's behavior was evaluated inputting the feet kinematics in the regression model and not only the arms, as done in previous papers.

There are a small number of investigations analyzing the 3D components of hand's velocity. Comparing the results from present study with data available in the literature, the hand's mean velocities were similar for slow swimming velocity and slightly higher for high swimming velocity. Martins-Silva and Alves (2000) analyzed 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 Martins-Silva and Alves (2000) research was similar to the present one. But for higher speeds, Alves et al. (1999) selected 50 m sets, instead of 25 m. This difference in the distance adopted between studies, might lead to higher hand's velocity in our research. Moreover, Alves et al. (1999) conducted a 2D analysis. The implementation of different methodologies for the kinematical analysis can also be a reason for the differences between both investigations.

The hand's mean horizontal velocity increased along the underwater path, in all swimming velocities. The highest mean values were obtained at the end of the underwater path, as previously described by Schleihauf (1979) and Schleihauf et al. (1988) for the propulsive forces produced. 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) describing the entry as one of the stroke cycles phase with lower propulsive force produced.

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 given from coaches to butterfliers. It is usual that coaches stress the importance of a strong second downbeat during Butterfly stroke. This is especially evident in butterfliers with a strong first downbeat and a weak or no-existent second downbeat. At slow swimming velocity, Vy-1dwn and Vy-2dwn mean values were close one to the other. This can be explain by the little 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's 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 (e.g., at high swimming velocity: Vz-ups, Vy-out, Vx-ins; at slow swimming velocity: Vy-ent, Vz-ent, Vy-ups, Vy-1dwn). In other studies, heterogeneous spatial motor patterns for arms and legs had been described (e.g., 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 spatial underwater paths, for Butterfly stroke (e.g., Crist, 1979; Bachman, 1983; Maglischo, 2003) as well as, different temporal organizations (Seifert et al., 2008). 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 set used. It was chosen an intermittent and incremental protocol, 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., Boulesteix et al., 2003; Chengalur and Brown, 1992; Kennedy et al., 1990). However, a previous study (Barbosa et al., 2005b; 2006b) 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. Moreover, Chollet et al. (1996) compared the four swimming strokes between 100 and 200 m events, as well as, between males and females. The authors stated that no differences occurred according to gender for stroke rate in each style and distance event. 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 probably 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, might 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 reported by Martins-Silva and Alves (2000).

At slow swimming velocity, Vx-ups and Vz-ins were the variables with dV's higher association. 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. (2006) verified an increase in the relative time spend in propulsive phases. 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 five to six 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 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. (2006) suggested that the synchronization of key points that determine the start and the end of arm and leg phases of upper limbs with those of the down limbs is determinant.

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 dV's behavior. 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 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 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 94 % of dV's behavior. Probably we can speculate that: i) at high swimming velocity, a strong first downbeat and the arm's insweep are determinants for decreasing the dV; ii) at slow swimming velocity, arm's insweep and the full extension of the arms with high velocity during the upsweep are important to decrease dV and; iii) at overall velocity, the full extension of the arms with high velocity during the upsweep, a strong second downbeat and a reduced velocity during the hand's entry will promote a decrease of dV.

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 hand's velocity during the insweep were determinant for dV behavior, at slow and high swimming velocity. Those variables had been already 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 (Barbosa et al., 2006a; Takagi et al., 2004; 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 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.

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 might 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.

Conclusion

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. They should also increase the vertical velocity during the downbeats and decrease the hand's velocity during the entry.

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Key points

- Segmental velocities are a determinant phenomenon for swimming performance and should be carefully analyzed by coaches and butterfliers.
- Butterfliers must finish the last phase of the underwater path with a high hand's velocity in order to reduce the speed fluctuation and increase the swimming velocity.
- Butterfliers should also pay more attention to downbeats, since they are important to reduce the speed fluctuation during the hand's entry, as well as, the arm's recovery.

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