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Relationships Between Energetic, Stroke Determinants, and Velocity in Butterfly

Abstract

The purpose of this study was to identify the relationship between the bioenergetical and the biomechanical variables (stroke parameters), 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 1500 L, Yellow Springs, US). Total energy expenditure ($\dot{E}_{tot}$), energetic 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.

Key words
Swimming · energetic · stroke length · stroke rate · stroke index · velocity

Introduction

Holmér [11] 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. [2,19–21,26,28,29]). However, most of these investigations centered their attention in freestyle swimming (e.g. [6,14,22]) butterfly being the least studied stroke. Comparing the four competitive swimming techniques, for a given velocity, the butterfly stroke presented the

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

Swimmer	*Age (years)*	*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 ± SD	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

higher energetic cost, followed by the breaststroke, the backstroke, and the freestyle [11].

The analysis of the stroke parameters is one of the major points of interests in the biomechanical investigation of swimming techniques, being studied for the first time by East [9]. The purpose of the study was to understand the behaviour of variables such as the stroke frequency (SF), the stroke length (SL), and the mean swimming velocity (V). While the V is a product of SF and SL [3]. Increases or decreases in V are due to a combined increase or decrease in SF and SL, respectively [3 – 5]. One other parameter often used is the stroke index (SI), considered as a valid indicator for swimming efficiency [2]. 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 [3, 4].

On the other hand, there is a small number of investigations concerned to study the relationships between the energetic cost and the stroke parameters (e.g. [2, 16, 23, 30, 31]). Only one study [30] analyzed butterfly stroke, evaluating a single butterflier, in a sample of ten swimmers. At least in freestyle, there were significant correlations between energetic cost and V, energetic cost and SF, SF and V [30]. 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.

Material and 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 a 25-m pool (short course) are 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 a 50-m pool (long course).

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 at the 7th trial. The resting period between swims was 30 s to collect blood samples. Two swimmers completed 5 trials, another swimmer completed 6 trials and a last one completed 7 trials. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Portugal) were placed at 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 [14, 25], connected to a telemetric portable gas analyzer ($K4b^2$, Cosmed, Italy). Cardio-respiratory and gas exchange parameters were measured breath by breath (B·B), during the whole 200-m, to analyze oxygen consumption ($\dot{V}O_2$) 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 min after the last swim.

The total energy expenditure ($\dot{E}_{tot}$) was calculated using the $\dot{V}O_2$ 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 $\dot{V}O_2$ equivalents using a 2.7 $ml\ O_2 \cdot kg^{-1} \cdot mmol^{-1}$ constant [7]. The energetic cost (EC) was calculated dividing the $\dot{E}_{tot}$ by V [8, 33].

Stroke parameters 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

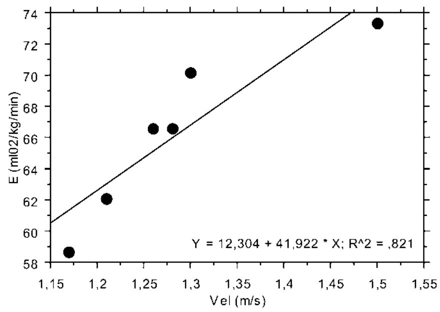

Fig. 1 Relationship between the total energy expenditure ($\dot{E}_{tot}$) and the mean swimming velocity (V) for one swimmer.

was measured with a cronofrequency meter from 3 consecutive strokes, in the middle of each pool length. The SL was then calculated by dividing V with SF [3]. The SI was obtained as the product of the SL and V [2].

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 $p \leq 0.05$.

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 are presented in Fig. **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.

Individual regression equations and the respective correlation coefficients, between $\dot{E}_{tot}$ and V, for all swimmers are 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 are presented in Fig. **2**. Individual regression equations and the respective correlation coefficients between EC and SF, and between SL and SI are 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 relation 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 $r = 0.93$ ($p = 0.01$).

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

Table **2** Individual regression equations (Eq) and correlation coefficients (r) between total energy expenditure ($\dot{E}_{tot}$) and velocity (V), energetic 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 ± SD		0.92 ± 0.03	0.96 ± 0.02	0.58 ± 0.33	0.90 ± 0.10

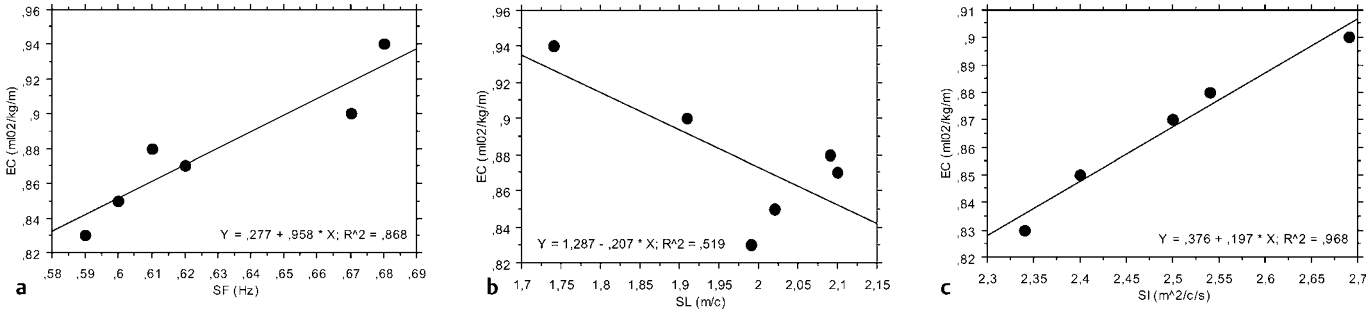

Fig. **2 a** to **c** Relation between: **a** energetic cost (EC) and the stroke frequency (SF); **b** EC and stroke length (SL); **c** EC and stroke index (SI) of one of the analyzed swimmers.

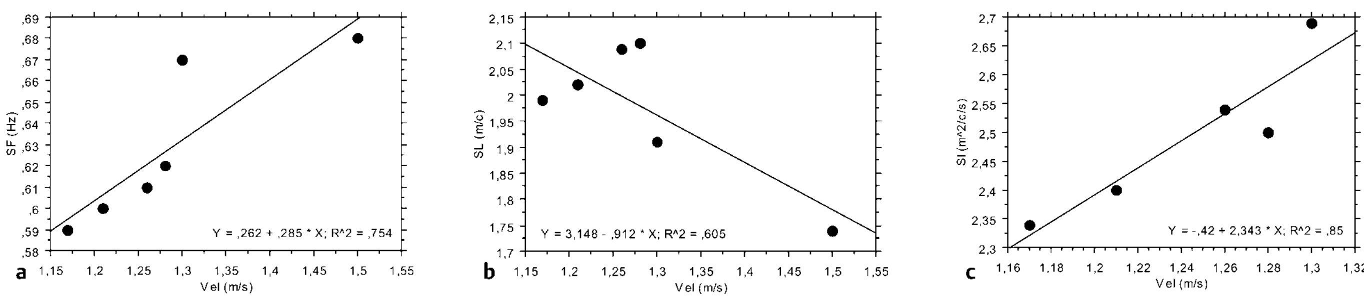

Fig. **3 a** to **c** Relation between: **a** stroke frequency (SF) and mean velocity (V); **b** stroke length (SL) and V; **c** stroke index and V for one of the evaluated swimmers.

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 ± SD		0.94 ± 0.05	0.68 ± 0.25	0.93 ± 0.05

Relations 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 relation 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.

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 of 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 [10, 30, 31]. According to these authors, the establishment of relations between $\dot{E}_{tot}$ and V^3 will be more suitable than the linear model. The main argument presented concerns 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 [7,17–19,26,28,29]. 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 suitable. However, for a higher spectrum of velocities, the exponential approach might be the most suitable.

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 [18,19,28,29]. 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 [11,28–31]. 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 $\dot{V}O_2$, but also from the blood lactate concentrations [8,30].

Concerning the relation between EC and SF and between EC and SI, the results of the present study are in agreement with studies conducted in other swimming strokes [2,15,23,24,30]. 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. [31]. Especially in the breaststroke and in the butterfly stroke, there is a high intracyclic variation in the average resultant impulse [1,27]. This variation results from the 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 behaviour 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 [23]. Wakayoshi et al. [31] 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 [13]. 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 [13].

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 [3–5,30]. So, the observed increase in SF with the increment of swimming velocity follows the biomechanical pattern described by Keskinen [10]. The relationship between SI and V was also significant. In fact, increments of the SI being strongly associated to increases of V is not new. Costill et al. [2] proposed, that SI 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. [5] 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. [32] also shared this idea, as they found a similar phenomenon, analyzing specialists in breaststroke, backstroke, and freestyle.

In 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.

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