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RELATIONSHIPS BETWEEN ENERGY COST, SWIMMING VELOCITY AND SPEED FLUCTUATION IN COMPETITIVE SWIMMING STROKES

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The purpose of the study was to analyse relationships between total energy expenditure ($\dot{E}_{tot}$), energy cost (EC), intra-cycle variation of the horizontal velocity of displacement of centre of mass (dv) and mean swimming velocity (v). 17 Portuguese elite swimmers (4 at Freestyle, 5 at Backstroke, 4 at Breaststroke and 4 at Butterfly) were submitted to an incremental set of nx200-m swims. Bioenergetical and biomechanical parameters presented significant interrelationships. For pooled data, the relationship between $\dot{E}_{tot}$ and v was $r=0.59$ ($p<0.01$), between EC and dv was $r=0.38$ ($p<0.01$) and the polynomial relationship, between dv and v was $r=0.17$ ($p=0.28$). Individual evaluation and identification of biomechanical critical points may help the swimmers to become more efficient at a certain swimming velocity.

Key Words: competitive strokes, energy expenditure, energy cost, speed fluctuation, velocity.

INTRODUCTION
In swimming science, economy of movement is an interesting field of research. Several investigations have been conducted to understand the role of bioenergetics and its repercussions in performance. Most of those studies focused exclusively on the contribution of aerobic system to produce energy for movement even though all competitive swimming events also require significant contribution from anaerobic energetic system to cover total energy expenditure. Particularly in swimming, environmental factors have hindered the measurement of cardiorespiratory variables within the actual field setting. However, machinery to explore human aerobic energetics during field conditions has become available with the improvement of miniaturized metabolic measurement systems.
Intra-cycle variation of horizontal velocity of centre of body mass (dv) is a widely accepted criterion for biomechanical description of swimming techniques. There is a positive relationship between high dv and increased energy cost, especially in Breaststroke (12) and Butterfly stroke (2). In Backstroke and Freestyle the relationship was not so evident (1). In this perspective, it is important to obtain a better understanding of the relationship between the energy cost and dv in the competitive strokes.
Some investigators suggested the possibility of high dv being related with lower swimming velocities (e.g., 2, 12). It was

observed a significant and negative relationship between the mean horizontal velocity and the speed fluctuation in Butterfly stroke (10) and Breaststroke (9). Nevertheless, there is no study in the literature about the relationship between swimming velocity and dv, in Freestyle and Backstroke.
The purpose of this study was to analyse the relationships between total energy expenditure, energy cost, intra-cycle variation of horizontal velocity of displacement of centre of body mass and mean velocity of swimming.

METHODS

Subjects

17 elite swimmers (5 females and 12 males) of the Portuguese national team, volunteered to serve as subjects. 4 swimmers were evaluated performing Breaststroke (including 2 female swimmers), 4 swimmers performing Butterfly (including 1 female swimmer), 5 swimmers performing Backstroke and 4 swimmers performing Freestyle (including 2 female swimmers).

Design

The subjects were submitted to an incremental set of nx200-m swims. The starting velocity was set at a speed, which represented a low training pace, approximately 0.3 $m.s^{-1}$ less than a swimmer's best performance. The last trial should represent the swimmers all out pace. After each successive 200-m swim, the velocity was increased by 0.05 $m.s^{-1}$ 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, Aveiro, Portugal), on the bottom of the 25-m pool, were used to control the swimming velocity 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 (7, 11), connected to a telemetric portable gas analyzer (K4 b^2, Cosmed, Rome, Italy). The oxygen consumption (VO_2) was measured for each swim breath-by-breath. Blood samples (25 μl) from the hyperemisized ear lobe were collected to analyze blood lactate concentration (YSI 1500 L, Yellow Springs, Ohio, USA) before and after each swim, as well as, 1, 3, 5 and 7 minutes after the last swim. Total energy expenditure (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 (5). The energy cost (EC) was calculated dividing the E_{tot} by the swimming velocity (v).
The swims were videotaped (50 Hz) in sagital plane with a pair of cameras (JVC GR-SX1 SVHS and JVC GR-SXM 25 SVHS, Yokoama, Japan), providing a dual-media images from both underwater and above the water perspectives as described elsewhere (2). The images of the two cameras were real time synchronized and edited on a mixing table (Panasonic Digital Mixer WJ-AVE55 VHS, Japan) to create one single image. Ariel Performance Analysis System (Ariel Dynamics Inc, California, USA) and a VCR (Panasonic AG 7355, Japan) at a frequency of 50 Hz were used to perform a kinematical analysis of the stroke cycles, including the dv of the centre of mass.
Zatsiorsky's model with an adaptation by de Leva (3) was used with the division of the trunk in 3 articulated parts. A filter with a cut-off frequency of 5Hz was used for the analysis of the horizontal velocity curve of the centre of mass.

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 E_{tot} and v, between EC and dv and polynomial regressions of 2nd order between dv and v were computed. Partial correlations between EC and dv controlling v and between EC and v controlling dv were also calculated. The level of statistical significance was set at $p \leq 0.05$.

RESULTS AND DISCUSSION

Figure 1 presents the relationships between the bioenergetical and biomechanical variables studied. The relationship between E_{tot} and v was r=0.70 (p<0.01) at Butterfly stroke, r=0.88 (p<0.01) at Breaststroke, r=0.67 (p<0.01) at Backstroke and r=0.85 (p<0.01) at Freestyle. The relationship between EC and dv was r=0.55 (p=0.01) at Butterfly stroke, r=-0.20 (p=0.43) at Breaststroke, r=0.38 (p=0.05) at Backstroke and r=0.79 (p<0.01) at Freestyle. Polynomial model presented a better adjustment than the linear approach, for the relationship between dv and v. The polynomial relationship between dv and v was r=0.47 (p=0.05) at Butterfly stroke, r=0.65 (p=0.02) at Breaststroke, r=0.45 (p=0.06) at Backstroke and r=0.65 (p<0.01) at Freestyle. For pooled data the relationship between E_{tot} and v was r=0.59 (p<0.01), between EC and dv was r=0.38 (p<0.01), and the polynomial relationship between dv and v was r=0.17 (p=0.28).

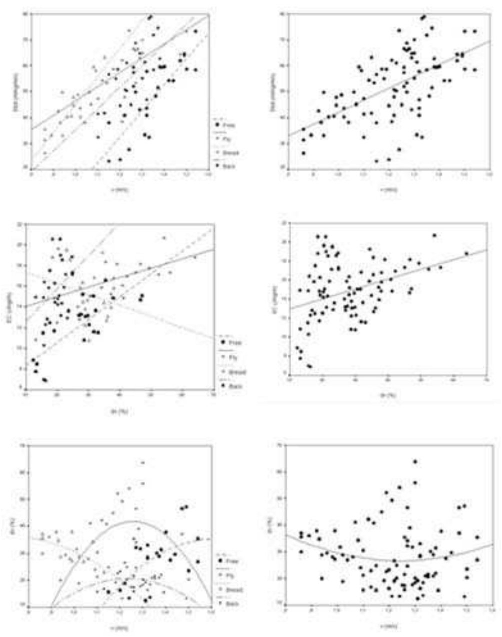

Figure 1. Relationships analysed between the bioenergetical and biomechanical variables, for each competitive stroke and for pooled sample.

In all situations, increases of E_{tot} were significantly related to increases in swimming velocity. The increase of E_{tot} is due to the necessity to overcome drag force, which is related to v. The higher adjustment of the linear relationship compared to the cubic one is due to the decrease of internal mechanical work to compensate the hydrostatic torque at higher velocities (4). Increases of the dv promoted significant increases of the EC, except for Breaststroke. Speed fluctuation while swimming as compared to swimming with constant velocity leads to an increase in the amount of total energy expenditure done by the swimmer (2). This increase is related to the need of overcoming the inertia and the drag force. Polynomial relationship between dv and v presented a better adjustment than the linear one. This phenomenon is described on regular bases for terrestrial locomotion (8). The parabolic function is explained by the curve between force and velocity for neuromuscular activity (6, 8). So, the data suggests that the neuromuscular activation of several muscles in a multi-segment and multi-joint movement follows the force-velocity relationship pattern for a single joint system (6).
Table 1 presents the partial correlations between EC and dv controlling the effect of v and the partial correlation between EC and v controlling the effect of dv. It seems that the increases of EC are strongly related to dv. Moreover, increases of EC are also strongly related to v, when controlling the effect of dv in the four competitive strokes. However, when a large number of observations from several competitive strokes are pooled together, the dependence of EC from v it is not so evident.

Table 1. Partial correlations between energy cost (EC), speed fluctuation (dv) and swimming velocity (v).

	Correlation between EC and dv controlling v	Correlation between EC and v controlling dv
Freestyle	r= 0.62 ($p<0.01$)	r=0.43 ($p=0.05$)
Backstroke	r= 0.55 ($p<0.01$)	r=0.56 ($p<0.01$)
Breaststroke	r= 0.60 ($p=0.01$)	r=0.86 ($p<0.01$)
Butterfly stroke	r= 0.55 ($p=0.01$)	r=0.51 ($p=0.02$)
Pooled sample	r= 0.39 ($p<0.01$)	r=0.16 ($p=0.14$)

CONCLUSION
The bioenergetical and biomechanical parameters analyzed presented significant relationships in each of the competitive strokes, so that changes in dv enhanced EC and E_{tot} considerably. Biomechanical evaluation of swimming technique, and identification of execution critical points, may, consequently, be critical for performance enhancement in a biologically restricted supply of energy.

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METABOLIC AND MECHANICAL CHARACTERISTICS OF OLYMPIC FEMALE GOLD MEDALIST

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To clarify metabolic and mechanical characteristics of a superior swimmer, an Olympic gold medalist was compared to 16 elite Japanese college swimmers who belonged to an inter-college champion team. Maximal oxygen uptake ($\dot{V}O_2max$), maximal blood lactate concentration (LA_{max}), a drag coefficient, a drag exponent, drag-swimming speed relationship and maximal propulsive power (MPP) were determined. In the comparison of $\dot{V}O_2max$, LA_{max}, and MPP, no marked differences were observed between the gold medalist and the other swimmers. On the other hand, the drag-swimming speed relationship revealed lower drag for the gold medalist, especially at higher swimming speed (near race pace). Taken all, it is suggested that mechanical (technical) factors, such as propelling efficiency and the stroke technique to reduce drag, should be considered as more significant determinants of superior swimming performance.