Evaluation of the Energy Expenditure in Competitive Swimming Strokes

T. M. Barbosa[1]
R. Fernandes[2]
K. L. Keskinen[3,4]
P. Colaço[2]
C. Cardoso[2]
J. Silva[2]
J. P. Vilas-Boas[2]

Abstract

The purpose of this study was to measure and compare the total energy expenditure of the four competitive swimming strokes. Twenty-six 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 starting velocity was approximately 0.3 $m \cdot s^{-1}$ less than a swimmer's best performance and thereafter 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 analyze oxygen consumption ($\dot{V}O_2$) and other energetic parameters by portable metabolic cart (K4b², 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, Ohio, USA). 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 $m \cdot s^{-1}$ and of 1.2 $m \cdot s^{-1}$ 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 $m \cdot s^{-1}$, 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 $m \cdot s^{-1}$, the $\dot{E}_{tot}$ was significantly higher in Breaststroke and in Butterfly than 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.

Key words
Total energy expenditure · aerobic contribution · anaerobic contribution · swimming strokes

Introduction

During the 1960's physiological scientific data about swimming started to accumulate regularly. One of the landmarks in this area of knowledge were those of Holmér's [14].

Holmér [14] 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 [20, 27]. For a given velocity, and by this order, the Butterfly and the Breaststroke were the

Affiliation
[1] Department of Sports Sciences, Polytechnic Institute of Bragança, Bragança, Portugal
[2] Faculty of Sports Sciences, University of Porto, Porto, Portugal
[3] Finnish Society for Research in Sport and Physical Education, Helsinki, Finland
[4] Department of Biology of Physical Activity, Universisty of Jyväskylä, Jyväskylä, Finland

Correspondence
Tiago Barbosa · Department of Sports Sciences, Polytechnic Institute of Bragança · Campus Sta. Apolónia · Apartado 1101 · 5301–856 Bragança · Portugal · Phone: +351273303000 · Fax: +351273303135 · E-mail: barbosa@ipb.pt

Accepted after revision: December 5, 2005

Bibliography
Int J Sports Med 2006; 27: 894–899 © Georg Thieme Verlag KG · Stuttgart · New York · DOI 10.1055/s-2006-923776 · Published online April 11, 2006 · ISSN 0172-4622

least economical strokes, the Backstroke and the Freestyle being the most economical ones.

More recently, Troup [35] 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 [15] verified the same occurrence. At velocities higher than 2.5 feets $\cdot$ s^{-1}, the "side stroke" variant at Breaststroke presented a higher cost than the Butterfly.

Since the study of Holmér [14] three decades have passed. In this period of time, major changes in the training procedures and in the swimming strokes have occurred. Obviously, this cannot be disconnected from the evolution of research regarding swimming.

Several studies have only analyzed the aerobic contribution to the swimming economy [9,14,27,37]. Presently, however, the analysis of the energy expenditure should also allow understanding the role of the anaerobic contribution [6,7,12,33]. 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 [9,14,20, 42]. 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 [13,17,21, 24]. 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 easier 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.

Material and Methods

Subjects

Twenty-six swimmers (8 females and 18 males) of international level volunteered to serve as subjects. Five 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 percent of body fat measured using a bio-impedance (Tanita, TBF 305, Tokyo, Japan) for Breaststroke swimmers was 10.8 ± 6.3%, for Butterfly 9.3 ± 3.8%, for Backstroke 6.8 ± 2.4% and for Freestyle 11.9 ± 7.6%. Comparing the mean body fat of the swimmers, according to swimming technique and gender, there was no significant difference.

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 7th trial. The starting velocity was set at a speed, which represented a low training pace, approximately 0.3 $m \cdot s^{-1}$ below the swimmer's best performance. 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 30 s 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 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 [17,29] connected to a telemetric portable gas analyzer (K4b^2, Cosmed, Rome, Italy). Cardio-respiratory and gas exchange parameters were measured BxB for each swim to analyze oxygen consumption ($\dot{V}O_2$) and other energetic parameters.

Blood samples (25 µl) from the ear lobe were collected to analyze blood lactate concentration (YSI 1500 L, Yellow Springs, Ohio, USA) 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 $\dot{V}O_2$ 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 $mlO_2 \cdot kg^{-1} \cdot mmol^{-1}$ constant [12,33].

Individual regression equations were computed between the $\dot{E}_{tot}$ and the V, for all the swimmers. Fig. **1** presents, as an example, the relationship between $\dot{E}_{tot}$ and V obtained with two swimmers. $\dot{E}_{tot}$ was extrapolated for the velocities of 1.0 $m \cdot s^{-1}$, 1.2 $m \cdot s^{-1}$, 1.4 $m \cdot s^{-1}$ and 1.6 $m \cdot s^{-1}$, 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 [35]. The maximal swimming velocity achieved in Freestyle was 1.57 $m \cdot s^{-1}$, in Backstroke 1.46 $m \cdot s^{-1}$, in Breaststroke 1.18 $m \cdot s^{-1}$ and in Butterfly 1.30 $m \cdot s^{-1}$.

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 ($\dot{E}_{tot}$ × swimming technique) with Fisher's PLSD as post-hoc test. The level of statistical significance was set at $p \leq 0.05$.

Results

Fig. **2** presents the overall energy expenditure profile of the four swimming techniques. For all of the selected velocities, the Freestyle was the most economical 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 $1.0\,m \cdot s^{-1}$ [$F(3;\,22) = 5.48$, $p < 0.01$], at the velocity of $1.2\,m \cdot s^{-1}$ [$F(3;22) = 12.41$, $p < 0.01$], at the velocity of $1.4\,m \cdot s^{-1}$ [$F(3;\,22) = 12.04$, $p < 0.01$] and at the velocity of $1.6\,m \cdot s^{-1}$ [$F(3;\,22) = 5.19$, $p = 0.01$].

Fig. **3** presents the post-hoc comparison of $\dot{E}_{tot}$ at a given velocity. At the velocity of $1.0\,m \cdot s^{-1}$, 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 $1.2\,m \cdot s^{-1}$, 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 least economical swimming stroke and the Freestyle the most economical one. In the next selected velocity, $1.4\,m \cdot s^{-1}$, 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 ($p < 0.01$). These data confirmed the assumption that, at least at $1.4\,m \cdot s^{-1}$, the Freestyle was significantly more economical than any other competitive swimming stroke. Finally, at the selected velocity of $1.6\,m \cdot s^{-1}$, the $\dot{E}_{tot}$ was significantly higher in Breaststroke ($p < 0.01$) and in Butterfly ($p = 0.02$) than in Freestyle.

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 economical stroke, followed by the Backstroke, the Butterfly and the Breaststroke.

From the 26 swimmers evaluated, 8 were female swimmers. It is reported that swimming economy is influenced by the swimmer's gender. Female swimmers are more economical than male swimmers [26]. Those differences are related to anthropometrical characteristics, such as body density and hydrodynamic torque [26]. Female swimmers can adopt a better horizontal body alignment and are affected by a lower hydrodynamic torque [44,45]. In the present investigation, both females and males were included in the group of subjects. However, the comparisons were made between the strokes and the trends between the strokes were similar in both genders. Thus, the present data was not affected by gender differences. In Freestyle, six female swimmers were studied. In this part of the data, the large number of female swimmers could underestimate the $\dot{E}_{tot}$ in Freestyle. However, comparing the $\dot{E}_{tot}$ in Freestyle according

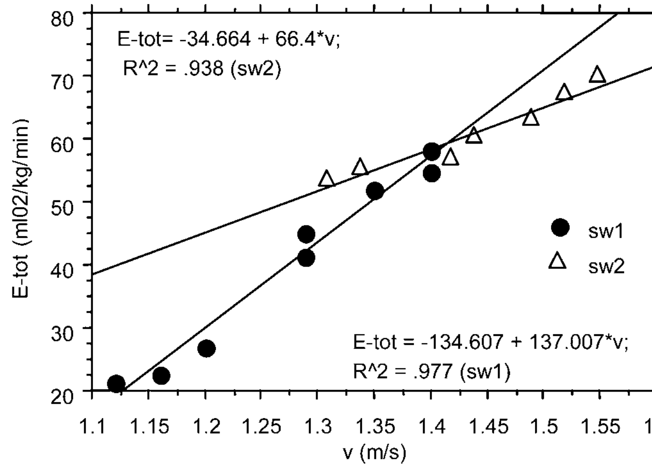

Fig. **1** Relationship between the total energy expenditure ($\dot{E}_{tot}$) and the swimming velocity (v) from two of the studied swimmers (sw). From the individual regression equations computed, $\dot{E}_{tot}$ was extrapolated or interpolated for $1.0\,m \cdot s^{-1}$, $1.2\,m \cdot s^{-1}$, $1.4\,m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

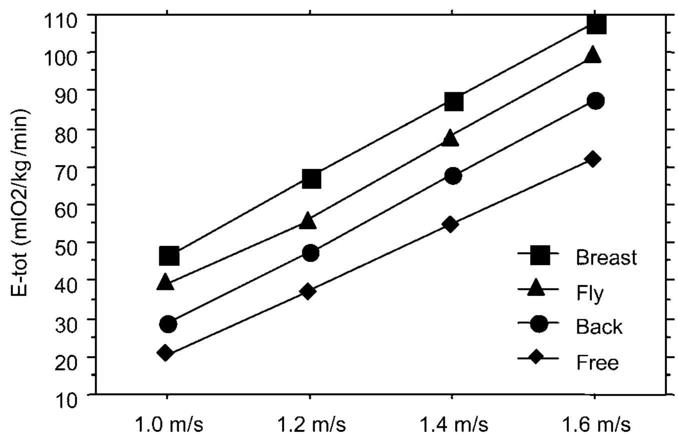

Fig. **2** Energy expenditure ($\dot{E}_{tot}$) profile, of the four swimming techniques, for the selected velocities.

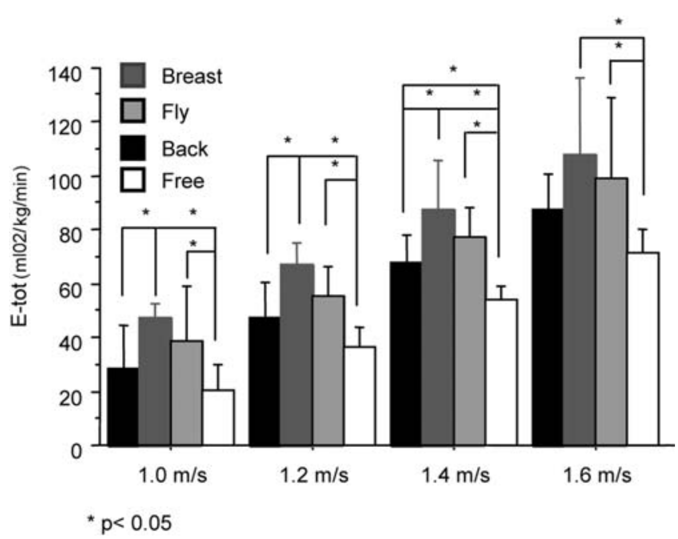

Fig. **3** Comparison of total energy expenditure ($\dot{E}_{tot}$) between the swimming stroke according to the Fisher's post-hoc test, in each selected velocity.

to gender, there were no significant differences in any swimming velocity selected. For example, at the velocity of $1.6\ m\cdot s^{-1}$, the mean $\dot{E}_{tot}$ for males swimmers was $70.9 \pm 7.4\ ml\cdot kg^{-1}\cdot min^{-1}$ and $71.8 \pm 9.8\ ml\cdot kg^{-1}\cdot min^{-1}$ for female swimmers. Moreover, comparing the mean body fat of the swimmers, according to swimming technique and gender, there was no significant difference. Therefore, the comparison of the $\dot{E}_{tot}$ of the individual 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 [9,14,27,37,42,43]. 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 Rodriguez [28], Vilas-Boas and Santos [40] or Vilas-Boas [41]. The relative contribution of this bioenergetical system to the overall energy expenditure should not be disregarded [6,7,12,33]. For example, Troup [35], in a 200-m swim, observed a contribution of approximately 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 [36]. 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 [9,14,20,42]. However, BxB analysis provides new insights into this field [17]. The feasibility of this system to measure the oxygen uptake of incremental free swimming has been proved [29] to offer a convenient tool to explore cardiorespiratory adaptations during swimming in a more detailed manner [17,29].

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 [14,20,27] 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 [4,38,39]. The high amplitude of the swimmer's impulse is explained by the extreme intracyclic variations of the swimming velocity [5,19,23,30,34,41]. 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 [4]. 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 [38,39]. 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 [25].

Holmér [14] presented a higher $\dot{V}O_2$, for a given velocity, for Butterfly stroke than for the Breaststroke. Karpovich and Millman [15] observed the same fact up to velocities of $2.5\ feets\cdot s^{-1}$. At higher velocities, the Butterfly was more economical than the Breaststroke. Troup [35] 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 [14] 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 [18]. 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 [32]. But at higher velocities the swimmer pushes both legs forward through the water more quickly [10] leading to significant increases of the speed fluctuation [22] and therefore in the energy cost [41].

The Freestyle was the most economic competitive technique, followed by the Backstroke, at all selected velocities. This is in agreement with several studies [14,15,20,27,35]. These strokes are characterized by the lower intracyclic variations of the swimming velocity [3,8,16]. 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 [1] 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.

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 to its biomechanical characteristics [11,19,25,31,42,43]. Nevertheless, few studies focused on the relationship between swimming economy and swimming mechanics, as in the cases of Alves et al. [2], Vilas-Boas [41] or Wakayoshi et al. [42,43].

One major question may be posed: Are there any differences in the swimming economy between modern measurements and those over the past decades? Are the swimmers from the 2000's more economical that the swimmers evaluated by Holmér [14] in the 1970's? First of all, it is important to emphasize that the evaluation procedures used by Holmér [14] and in the present study are quite different. Holmér used Douglas bags and a flume; in the present study BxB apparatus was used in a real swimming pool and with an under water pace maker. Secondly, the parameters evaluated were not the same. Holmér [14] measured the absolute $\dot{V}O_2$; in the present study the parameter evaluated being the $\dot{E}_{tot}$. Nevertheless, a comparison between the absolute $\dot{V}O_2$ reported by Holmér [14] and the absolute $\dot{E}_{tot}$ from the present investigation was made, at the swimming velocity of $1.0\ m\cdot s^{-1}$. This swimming velocity was chosen because it is the only common velocity selected by Holmér [14] and the present study, for all strokes. It was verified for all strokes that the swimming economy was higher in the present data as compared to those in the 1970's. 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 between these two data. In comparison to these swimming techniques, Breaststroke was the one with true lowest increase. The low increase can be related to the strong restrictions imposed in the rules of this swimming technique, in what concerns to its biomechanical evolution. Even though this comparison was between two very different samples of data, the results show that differences may exist even between generations of swimmers, not only between measurement techniques.

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.

References

1 Alves F. Average resultant impulse per phase in swimming: a tool for technical analysis. In: Abrantes J (ed). Proceedings of the XIVth International Symposium on Biomechanics in Sports. Lisbon: Edition of Faculty of Human Movement of the Technical University of Lisbon, 1996: 281 – 284

2 Alves F, Gomes-Pereira J, Pereira F. Determinants of energy cost of front crawl and backstroke swimming and competitive performance. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA (eds). Biomechanics and Medicine in Swimming VII. London: E & FN Spon, 1996: 185 – 192

3 Alves F, Costa M, Gomes-Pereira J. The influence of swimming velocity on the kinematic characteristics of backstroke swimming. In: Riehle H, Vieten M (eds). Proceedings II of the XVIth International Symposium on Biomechanics in Sports. Konstanz: Universitätsverlag Konstanz, 1998: 104 – 107

4 Barbosa T, Santos Silva J, Sousa F, Vilas-Boas JP. Measurement of butterfly average resultant impulse per phase. In: Gianikellis K (ed). Proceedings of the XXth International Symposium on Biomechanics in Sports. Cáceres: Universidad de Extremadura, 2002: 35 – 38

5 Barbosa T, Santos Silva J, Sousa F, Vilas-Boas JP. Comparative study of the response of kinematical variables from the hip and the center of mass in butterfliers. In: Chatard J-C (ed). Biomechanics and Medicine in Swimming IX. St. Étienne: Publications de l'Université de St. Étienne, 2003: 93 – 98

6 Camus G, Fossiom A, Juchmès J, Burrette J. Equivalent énergétique de la production du lactate plasmatique dans la course intensité supramaximale. Arch Int Physiol Biochim 1984; 92: 361 – 368

7 Camus G, Thys H. An evaluation of the maximal aerobic capacity in man. Int J Sports Med 1991; 12: 349 – 355

8 Cappaert J, Pease D, Troup J. Biomechanical highlights of world champion and olympic swimmers. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA (eds). Biomechanics and Medicine in Swimming VII. London: E & FN Spon, 1996: 76 – 80

9 Chatard J-C, Lavoie J, Lacour J. Analysis of determinants of swimming economy in front crawl. Eur J Appl Physiol 1990; 61: 88 – 92

10 Chollet D, Tourny-Chollet C, Gleizes F. Evolution of co-ordination in flat breaststroke in relation to velocity. In: Keskinen K, Komi P, Hollander AP (eds). Biomechanics and Medicine in Swimming VIII. Jyväskylä: Gummerus Printing, 1999: 29 – 32

11 Costill D, Kovaleski J, Porter D, Fielding R, King D. Energy expenditure during front crawl swimming: predicting success in middle-distance events. Int J Sports Med 1985; 6: 266 – 270

12 Di Prampero P, Pendergast D, Wilson D, Rennie D. Blood lactatic acid concentrations in high velocity swimming. In: Eriksson B, Furberg B (eds). Swimming Medicine IV. Baltimore: University Park Press, 1978: 249 – 261

13 Hausswirth C, Bigard A, Le Chevalier J. The Cosmed K4 telemetry system as an accurate device for oxygen uptake measurements during exercise. Int J Sports Med 1997; 18: 449 – 453

14 Holmér I. Physiology of swimming man. Acta Phys Scand 1974; 407: Suppl: 1 – 55

15 Karpovich P, Millman N. Energy expenditure in swimming. Am J Physiol 1944; 142: 140 – 144

16 Keskinen K, Komi P. Intracycle variation in force, velocity and power as a measure of technique performance during front crawl swimming. In: Bouisset S, Mentral S, Mond H (eds). XIVth ISB Congress. Paris: Publ Société de Biomécanique, 1993: 676 – 677

17 Keskinen K, Rodríguez F, Keskinen O. Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming. Scand J Med Sci Sports 2003; 13: 322 – 329

18 Kolmogorov S, Rumyantseva O, Gordon B, Cappaert J. Hydrodynamic characteristics of competitive swimmers of different genders and performance levels. J Appl Biomechanics 1997; 13: 88 – 97

19 Kornecki S, Bober T. Extreme velocities of a swimming cycle as a technique criterion. In: Eriksson B, Furberg B (eds). Swimming Medicine IV. Baltimore, Maryland: University Park Press, 1978: 402 – 407

20 Lavoie J – M, Montpetit R. Applied Physiology of swimming. Sports Med 1985; 3: 165 – 188

21 Maiolo C, Melchiorri G, Lacopino L, Masala S, De Lorenzo A. Physical activity energy expenditure measured using a portable telemetric device in comparison with a mass spectrometer. Br J Sports Med 2003; 37: 445 – 447

22 Manley P, Atha J. Intra-stroke velocity fluctuations in paces breaststroke swimming. In: MacLaren D, Reilly T, Lees A (eds). Biomechanics and Medicine in Swimming VI. London: E & FN Spon, 1992: 151 – 160

23 Mason B, Tong Z, Richards R. Propulsion in the Butterfly stroke. In: MacLaren D, Reilly T, Lees A (eds). Biomechanics and Medicine in Swimming VI. London: E & FN Spon, 1992: 81 – 86

24 McLaughlin J, King G, Howley E, Bassett D, Ainsworth B. Validation of the COSMED K4b2 portable metabolic system. Int J Sports Med 2001; 22: 280 – 284

25 Nigg B. Selected methodology in biomechanics with respect to swimming. In: Hollander AP, Huijing PA, de Groot G (eds). Biomechanics and Medicine in Swimming. Champaign, Illinois: Human Kinetics Publishers, 1983: 72 – 80

26 Onodera S, Miyachi M, Yano H, Yano L, Hoshijnma Y, Harada T. Effects of buoyancy and body density on energy cost during swimming. In: Keskinen K, Komi P, Hollander AP (eds). Biomechanics and Medicine in Swimming VIII. Jyväskylä: Gummerus Printing, 1999: 355 – 358

27 Pendergast D, di Prampero P, Craig A, Rennie D. The influence of some selected biomechanical factors on the energy cost of swimming. In: Eriksson B, Furberg B (eds). Swimming Medicine IV. Baltimore: University Park Press, 1978: 367 – 378

28 Rodríguez F. Cardiorespiratory and metabolic field testing in swimming and water polo: from physiological concepts to practical methods. In: Keskinen K, Komi P, Hollander AP (eds). Biomechanics and Medicine in Swimming VIII. Jyväskylä: Gummerus Printing, 1999: 219 – 226

29 Rodríguez F, Keskinen K, Keskinen O, Malvela M. Oxygen uptake kinetics during free swimming: a pilot study. In: Chatard J-C (ed). Biomechanics and Medicine in Swimming IX. St. Étienne: Publications de l'Université de St. Étienne, 2003: 279 – 384

30 Sanders R. Some aspects of butterfly technique of New Zealand Pan Pacific squad swimmers. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA (eds). Biomechanics and Medicine in Swimming VII. London: E & FN Spon, 1996: 23 – 28

31 Smith H, Montpetit R, Perrault H. The aerobic demand of backstroke swimming, and its relation to body size, stroke technique, and performance. Eur J Appl Physiol 1988; 58: 182 – 188

32 Takagi H, Sugimoto S, Miyashita M, Nomura T, Wakayoshi K, Okuno K, Ogita F, Ikuta Y, Wilson B. Arm and leg coordination during breaststroke: analysis of 9th FINA World Swimming Championship Fukuouka 2001. In: Chatard J-C (ed). Biomechanics and Medicine in Swimming IX. St. Étienne: Publications de l'Université de St. Étienne, 2003: 301 – 306

33 Thevelein X, Daly D, Persyn U. Measurement of total energy use in the evaluation of competitive swimmers. In: Bachl N, Prakup L, Suckert R (eds). Current Topics in Sports Medicine. Wien: Urban & Schwarzenberg, 1984: 668 – 676

34 Togashi T, Nomura T. A biomechanical analysis of the swimmer using the butterfly stroke. MacLaren D, Reilly T, Lees A (eds). Biomechanics and Medicine in Swimming VI. London: E & FN Spon, 1992: 87 – 91

35 Troup JP. Aerobic characteristics of the four competitive strokes. In: Troup JP (ed). International Center for Aquatic Research Annual. Studies by the International Center for Aquatic Research (1990 – 1991). Colorado Spring: US Swimming Press, 1991: 3 – 7

36 Troup J, Hollander A, Bone M, Trappe S, Barzdukas A. Performance-related differences in the anaerobic contribution of competitive Freestyle swimmers. In: MacLaren D, Reilly T, Lees A (eds). Biomechanics and Medicine in Swimming VI. London: E & FN Spon, 1992: 271 – 278

37 Van Handel P, Katz A, Morrow J, Troup J, Daniels J, Bradley P. Aerobic economy and competitive performance of US elite swimmers. In: Ungerechts B, Wilke K, Reischle K (eds). Swimming Science V. Champaign, Illinois: Human Kinetics Books, 1988: 219 – 227

38 Van Tilborgh L, Willems E, Persyn U. Estimation of breaststroke propulsion and resistance-resultant impulses from film analyses. In: Ungerechts B, Wilke K, Reischle K (eds). Swimming Science V. Champaign, Illinois: Human Kinetics Books, 1988: 67 – 71

39 Vilas-Boas JP. Maximum propulsive force and maximum propulsive impulse in breaststroke swimming technique. In: Barbaras A, Fábian G (eds). Proceedings of the XIIth International Symposium on Biomechanics in Sports. Budapest: Hungarian University of Physical Education, 1994: 307 – 310

40 Vilas-Boas JP, Santos P. Comparison of swimming economy in three breaststroke techniques. In: Miyashita M, Mutoh Y, Richardson A (eds). Medicine and Science in Aquatic Sports. Karger: Basel, 1994: 48 – 54

41 Vilas-Boas JP. Speed fluctuations and energy cost of different breaststroke techniques. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA (eds). Biomechanics and Medicine in Swimming VII. London: E & FN Spon, 1996: 167 – 171

42 Wakayoshi K, D'Acquisto J, Cappaert J, Troup J. Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. Int J Sports Med 1995; 16: 19 – 23

43 Wakayoshi K, D'Acquisto J, Cappaert J, Troup JP. Relationship between metabolic parameters and stroking technique characteristics in front crawl. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA (eds). Biomechanics and Medicine in Swimming VII. London: E & FN Spon, 1996: 152 – 158

44 Yanai T. Rotational effect of buoyancy in front crawl: does it really cause the legs to sink? J Biomechanics 2001; 34: 235 – 243

45 Zamparo P, Antonutto G, Capelli C, Francescato M, Girardis M, Sangoi R, Soule R, Pendergast D. Effects of body density, gender and growth on underwater torque. Scan J Med Sci Sports 1996; 6: 273 – 280