Time limit at the minimum velocity corresponding to $\dot{V}O_2max$: characterisation and determinant factors

A study conducted in swimmers with different competitive levels and gender

Tese apresentada às provas de Doutoramento no ramo das Ciências do Desporto, nos termos do Decreto-Lei n.º 216/92, de 13 de Outubro, orientada pelo Professor Doutor João Paulo Vilas-Boas

Presentation of Doctoral Thesis in Sport Sciences according to the Decree-Law nº 216/92, of 13 of October, under the supervision of Professor Doutor João Paulo Vilas-Boas

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Porto, 2006

Fernandes, Ricardo J. P. (2006). Time limit at the minimum velocity corresponding to $\dot{V}O_2max$ characterisation and determinant factors. A study conducted in swimmers with different competitive levels and gender. Doctoral Thesis in Sport Sciences according to the Decree-Law nº 216/92, of 13 of October. University of Porto, Faculty of Sport.

KEY WORDS: SWIMMING, TIME LIMIT, ENERGY COST, OXYGEN CONSUMPTION, LACTATE CONCENTRATIONS, STROKING PARAMETERS

PALAVRAS CHAVE: NATAÇÃO, TEMPO LIMITE, CUSTO ENERGÉTICO, CONSUMO DE OXIGÉNIO, LACTATEMIA, PARÂMETROS BIOMECÂNICOS GERAIS

Acknowledgments

At this point, I would like to take the opportunity to express my gratitude to all that have supported me on the process of elaboration of this Doctoral Thesis.

First, I would like to deeply acknowledge the University of Porto, in particular to the Faculty of Sport, for enabling me to get a PhD and to give me all the facilities and means to proceed with all the implicit tasks of a work of this nature. In particular, I have to thank Prof. Dr. João Paulo Vilas-Boas, who gave me the honour of been my promoter. This Thesis was completed under his guidance and the PhD design was made following his suggestions. I wish to express my personal admiration for Professor João Paulo work and for being one of the major European swimming personalities. I also want to thank him for the entire support trough my academic career.

Next, I would like to express my appreciation to Prof. Dr. Véronique Billat. Being a great stimulator of the “time to exhaustion” topic of research, Professor Véronique gave specific suggestions and ideas for some of the experiments that followed. Her advice was very important for me.

I owe warm thanks for the contribution of Prof. Dr. Kari Keskinen. His generous help being in Porto for the several days of physiological and biomechanical evaluations of the Portuguese National Swimming Team was invaluable. Professor Keskinen, with his professionalism, but also with his friendship, inspired me, and gave me strength to fulfil this objective.

I am indebted to Prof. Dr. José Soares, from the Biology Department of our Faculty, for his cooperation in borrowing the Sensormedisc 2900 oximeter, the YSI1500LSport auto-analyser and the Polar cardiofrequencimeters. Also, I would like to express appreciation for the invaluable discussions had with Prof. Dr. José Alberto Duarte, from the Biochemistry Department and Prof. Dr. Paulo Santos, Prof. Dr. José Magalhães and Prof. Dr. António Ascensão, from the

Biology Department of our Faculty. Additionally, I'm very grateful to them for their help in some experimental proceedings and in revising some manuscripts.

I want to thank Prof. Dr. Tiago Barbosa, Prof. Dr. António Barroso Lima and MSc Paulo Colaço, my earlier fellows of graduate studies, for their participation in experimental procedures, technical support and friendship. A warm thanks also to MSc Carla Cardoso that accompany me along this journey.

I also want to thank To MSc Susana Soares, for her help in collecting capillary blood, for the statistical expertise and for all her collaboration in the day-to-day routine tasks in the Swimming Department. I also owe MSc Carla Carmo a warm thank you for all her friendship and for being a very important member of the Swimming Department of our Faculty.

Special thanks go also for the members of the Biomechanics Department of FADEUP, namely Prof. Dr. Leandro Machado and Eng. Pedro Gonçalves for all their help in solving the emerging "natural" problems, and to MSc Filipa Machado for her friendship. Thanks to Dr. João Carvalho for his comradeship, interesting ideas and his commitment to "our" Faculty.

Thanks to Mr Rui Biscaia and Mr Fernando Teixeira for their help with the swimming-pool experimental equipment.

Thanks to all my students of Methodology I - Swimming, that actively participated in the experimental proceedings.

Special thanks to the swimmers, and their coaches, who participated in these studies, for their time, commitment and enthusiasm. I want to express also my recognition to Prof. Dr. Francisco Alves and MSc Paulo Cunha, from the Portuguese Swimming Federation, for their cooperation. My personal recognition to Paulo Cunha and to Luís Cardoso.

A warm thanks to my swimmers. During all my academic carer I have never stopped being a coach. My swimmers are also one of the reasons I started, and finished, this Thesis. Complementarily, I wish to thank my earlier assistance coaches, especially MSc Ana Querido, for their professionalism understanding and friendship.

Very special thanks for my true friends: Paulo, Toni, Filipe, Tiago, Susana, Sandra (we all miss you), Pedro, João, Zé and André David. Thanks to Sónia, for her help in revising the manuscript, and for being herself. This work is also yours.

All my gratitude I express to my family, namely to Bárbara, in her innocence, for the future that I see in her eyes.

This Thesis is based on the following papers, which are referred in the text by their Arabic and Roman numerals, respectively:

1.

Fernandes, R.; Billat, V.; Vilas-Boas, J. P. (2003). Time limit at v$\dot{V}O_2$max and $\dot{V}O_2$max slow component in swimming. A pilot study in university students. In J.-C. Chatard (Ed.), **Biomechanics and Medicine in Swimming IX** (pp. 331-336). Publications de l'Université de Saint-Étienne, Saint-Étienne: France.

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Fernandes, R.J.; Cardoso, C.S.; Soares, S.M.; Ascensão, A.A.; Colaço, P.J.; Vilas-Boas, J.P. (2003). Time limit and $\dot{V}O_2$ slow component at intensities corresponding to $\dot{V}O_2$max in swimmers. **Int. J. Sports Med.**, 24, 576-81.

3.

Fernandes, R.J.; Billat, V.L.; Cruz, A.C.; Colaço, P.J.; Cardoso, C.S.; Vilas-Boas, J.P. Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? **J. Sports Med. Phys. Fitness.** (in press).

4.

Fernandes, R.J., Billat, V.L., Cruz, A.C., Colaço, P.J., Cardoso, C.S., Vilas-Boas, J.P. (2005). Has gender any effect on the relationship between time limit at $\dot{V}O_2$max velocity and swimming economy? **J. Hum. Movement Stud.**, 49, 127-148.

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7.

Fernandes, R.J.; Cardoso, C.S.; Silva, J. A.; Vilar, S. O.; Colaço, P.J.; Barbosa, T.M.; Keskinen, K.L.; Vilas-Boas, J.P. (2006). Assessment of time limit at lowest speed corresponding to maximal oxygen consumption in the four competitive swimming strokes. In J.P. Vilas-Boas; F. Alves; A. Marques (Eds), **Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences**, 6(2), 128-130.

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Barbosa, T.M.; Fernandes, R.; Keskinen, K.L.; Colaço, P.J.; Cardoso, C.S.; Silva, J.A.; Vilas-Boas, J.P. (2006). Evaluation of the energy expenditure in competitive swimming strokes. **Int. J. Sports Med.**, first on-line April 11. DOI: 10.1055/s-2006-923776.

II.

Cardoso, C.; Fernandes, R.; Vilas-Boas, J. P. (2003). Comparison of continuous and intermittent incremental protocols for direct $\dot{V}O_2max$ assessment. In J.-C. Chatard (Edt.), **Biomechanics and Medicine in Swimming IX** (pp. 313-318). Publications de l'Université de Saint-Étienne, Saint-Étienne: France.

III.

Marinho, D.A.; Vilas-Boas, J.P.; Keskinen, K.L.; Rodríguez, F.A.; Soares, S.M.; Carmo, C.M.; Vilar, S.O.; Fernandes, R.J. Behaviour of the kinematic parameters during a time to exhaustion test at $\dot{V}O_2max$ in elite swimmers. **J. Hum. Movement Stud.** (in press)

IV.

Fernandes, R.; Almeida, M.; Morais, P.; Machado, L.; Soares, S.; Ascensão, A.; Colaço, P.; Morouço, P.; Vilas-Boas, J. P. (2005). Individual anaerobic threshold assessment in a swimming incremental test for $\dot{V}O_2max$ evaluation. In N. Dikic, S. Zivanic, S. Ostojic, Z. Tornjanski (Eds.), **Abstract Book of the 10th Annual Congress of the European College of Sport Science** (pp. 266). Belgrade, Serbia.

V.

Machado, L.; Almeida, M.; Morais, P.; Fernandes, R.; Vilas-Boas, J.P. (2006). Assessing the individual anaerobic threshold: the mathematical model. In J.P. Vilas-Boas; F. Alves; A. Marques (Eds), **Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences**, 6(2), 142-144.

VI.

Querido, A.; Machado, L.; Keskinen, K.; Vilar, S.; Cardoso, C.; Cruz, A; Vilas-Boas, J. P.; Fernandes, R. (2006). Comparison between different methods for the assessment of the $\dot{V}O_2$ slow component of front crawl swimmers. In J.P. Vilas-Boas; F. Alves; A. Marques (Eds), **Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences**, 6(2), 165-167.

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Abstract

The duration of exercise in which the intensity corresponding to the minimum velocity that elicits maximal oxygen consumption can be maintained is a new area of interest in swimming. This parameter, usually called Time Limit (TLim-v$\dot{V}O_2$max), expresses the maintenance of this specific constant velocity up to the point of exhaustion. TLim-v$\dot{V}O_2$max in swimming was adapted from earlier studies conducted in treadmill running. The general purpose of this thesis was to characterize and compare TLim-v$\dot{V}O_2$max, performed in normal swimming-pool conditions, between swimmers of different levels and genders, as well as to identify its major influencing factors. The experimental protocol contained two distinct phases: (i) an intermittent incremental test for v$\dot{V}O_2$max assessment and (ii) an all-out test to measure TLim-v$\dot{V}O_2$max. During tests, respiratory parameters (through direct oximetry), lactate concentrations, heart rate and stroke parameters were measured. Swimming velocity was controlled using a visual pacer. Results pointed out TLim-v$\dot{V}O_2$max values ranging from 215 to 260 s (elite swimmers), 230 to 260 s (high level swimmers) and 310 to 325 s (low level swimmers), with no differences observed between genders. TLim-v$\dot{V}O_2$max main determinants were swimming economy, oxygen slow component, stroke length and stroke index (direct relationship) and v$\dot{V}O_2$max, velocity corresponding to anaerobic threshold, lactate production and stroke frequency (inverse relationship). In general, TLim-v$\dot{V}O_2$max was not related to $\dot{V}O_2$max. It seems that the higher v$\dot{V}O_2$max values achieved by elite and high level swimmers impose also higher energy cost of exercise, and superior recruitment of the anaerobic energy system, which leads to earlier fatigue stages and consequently lower TLim-v$\dot{V}O_2$max.

Key words: Swimming, time limit, energy cost, oxygen consumption, lactate concentrations, stroking parameters

Resumo

O tempo de exercício durante o qual a intensidade correspondente à velocidade mínima que despoleta o consumo máximo de oxigénio é mantida é uma nova área de interesse em natação. Este parâmetro, usualmente denominado Tempo Limite (TLim-v$\dot{V}O_2$max), expressa a manutenção dessa velocidade específica até à exaustão. O TLim-v$\dot{V}O_2$max em natação foi adaptado de estudos realizados em tapete rolante. O principal objectivo desta tese foi caracterizar e comparar o TLim-v$\dot{V}O_2$max, implementado em piscina e em nadadores dos dois géneros e de diferentes níveis, assim como identificar os seus principais factores influenciadores. O protocolo experimental consistiu em dois momentos diferenciados: (i) um teste incremental e intervalado para determinação da v$\dot{V}O_2$max e (ii) um teste até à exaustão para determinação do TLim-v$\dot{V}O_2$max. Durante os testes foram determinados parâmetros respiratórios (através de oximetria directa), lactatemia, frequência cardíaca e parâmetros biomecânicos gerais. Os resultados evidenciaram valores do TLim-v$\dot{V}O_2$max compreendidos entre 215 a 260 s (nadadores de elite), 230 a 260 s (nadadores de nível nacional) e 310 a 325 s (nadadores de baixo nível de proficiência), não se tendo observado diferenças entre géneros. Os factores determinantes do TLim-v$\dot{V}O_2$max foram a economia de nado, a componente lenta do $\dot{V}O_2$, a distância por ciclo e o *stroke índex* (relação directa), assim como a v$\dot{V}O_2$max, a velocidade correspondente ao limiar anaeróbio, a produção de lactato e a frequência gestual (relação inversa). Sugeriu-se que os valores superiores de v$\dot{V}O_2$max alcançados pelos nadadores de nível superior implicam valores mais elevados de custo energético, aliado a uma também superior solicitação dos sistema anaeróbio, o que implicou estados precoces de fadiga e, consequentemente, valores inferiores de TLim-v$\dot{V}O_2$max.

Palavras chave: Natação, tempo limite, custo energético, consumo de oxigénio, lactatemia, parâmetros biomecânicos gerais

Résumé

La durée d'exercice à l'intensité correspondant à la vitesse minimale permettant de solliciter la consommation maximale d'oxygène est un nouveau sujet d'intérêt en natation. Ce paramètre, dit Temps Limite (TLim-v$\dot{V}O_2$max), correspond au temps de maintien de cette vitesse spécifique, et ce jusqu'à épuisement. L'étude du TLim-v$\dot{V}O_2$max en natation fait suite à des études réalisées dans le passé sur tapis roulant. Le principale objectif de cette thèse était de caractériser et comparer le TLim-v$\dot{V}O_2$max, meduré en piscine entre des nageurs de sexes e de niveaux différents, et aussi d´identifier ses principaux facteurs déterminants. Le protocole expérimentale regroupait deux phases: (i) un test incrémental et intervallaire pour déterminer la v$\dot{V}O_2$max et (ii) un test jusqu'à là exhaustion pour déterminer TLim-v$\dot{V}O_2$max. Au cours des tests, es paramètres respiratoires (par oxymétrie direct), la concentration de lactate, la fréquence cardiaque et les paramètres spatio-temporels étaient mesurés. La vitesse de nage était contrôlée par un pacer visuel. Les résultats montrent que les valeurs de TLim-v$\dot{V}O_2$max se situent entre 215 et 260 s (nageurs élites), 230 et 260 s (nageurs de niveau nationale) et 310 et 325 s (nageurs de bas niveaux). Aucune différence entre les sexes n'a été observée. Les facteurs déterminants du TLim-v$\dot{V}O_2$max sont, en relation directe : l'économie de nage, la composant lent de $\dot{V}O_2$, la distance par cycle et l'indice de nage ; et en relation inverse : la v$\dot{V}O_2$max, la vitesse correspondant au seuil anaérobique, la production de lactate et la fréquence de nage. Il est suggéré que les valeurs supérieurs de v$\dot{V}O_2$max obtenues chez les nageurs de niveau élevé entraînent des coûts énergétiques plus importants, avec une plus grand sollicitation du métabolisme anaérobique, occasionnant ainsi un état de fatigue précoce et, en conséquence, valeurs inférieures de TLim-v$\dot{V}O_2$max.

Mots-clé: natation, temps limite, coût énergétique, consommation d'oxygène, lactate, paramètres spatio-temporels

Abbreviations and Symbols

Abbreviation/Symbol - Term (unit)

AnT - anaerobic threshold

BxB - breath-by-breath

BM - body mass

$b.min^{-1}$ - beats per minute

ºC - degree Celius

C - energy cost of exercise

C1.30 - energy cost at the specific swimming velocity of 1.30 $m.s^{-1}$

cm - centimeter

C_{slope} - slope of the regression line obtained from the relationship between energy expenditure and corresponding velocities in a incremental test

C_{inc} - ratio obtained by the mean energy expenditure value and the velocity mean value of the incremental test

Cv$\dot{V}O_2max$ - energy cost corresponding to v$\dot{V}O_2max$

DLim-v$\dot{V}O_2max$ - distance to exhaustion at v$\dot{V}O_2max$

$\dot{E}$ - energy expenditure

e.g. - example

et al. - and collaborators

$\dot{E}\dot{V}O_2$ - ventilatory equivalent for oxygen

$\dot{E}\dot{V}O_2max$ - ventilatory equivalent for oxygen

FINA - Federation Internationale de Natation

h - hour

H - height

HR - heart rate ($b.min^{-1}$)

HRmax - maximal heart rate

i.e. - this is

IndAnT - individual anaerobic threshold

J - joules

kg - kilogram

[La^-] - blood lactate concentrations ($m.mol^{-1}$)

[La^-]max - maximal blood lactate concentrations ($m.mol^{-1}$)

$l.min^{-1}$ - liter per minute

m - meter

min - minute

$mmol.l^{-1}$ - millimoles per litter

$m.s^{-1}$ - meter per second

n - number of subjects

O_2SC - oxygen uptake slow component

P - probability

R - respiratory exchange ratio or respiratory quotient

r - correlation coefficient

r^2 - determination coefficient

RR - respiratory rhythm

RRmax - maximal respiratory rhythm

s - second

SA - surface area

SD - standard deviation

SE - swimming economy

SI - stroke index

SL - stroke length

SPSS - statistical package for social sciences

SR - stroke rate

v - velocity

VT - tidal volume (l)

VTmax - maximal tidal volume (l)

vAnT - velocity corresponding to the anaerobic threshold

$\dot{V}CO_2max$ - maximal volume of carbon dioxide production ($ml.kg^{-1}.min^{-1}$)

$\dot{V}_E$ - pulmonary minute ventilation ($l.min^{-1}$)

$\dot{V}_{Emax}$ - maximal pulmonary minute ventilation ($l.min^{-1}$)

$\dot{V}O_2$ - volume of oxygen consumed ($ml.min^{-1}$ or $ml.kg^{-1}.min^{-1}$)

$\dot{V}O_2max$ - maximal volume of oxygen consumed ($ml.min^{-1}$ or $ml.kg^{-1}.min^{-1}$)

$\dot{V}O_2RMus$ - oxygen uptake associated to specific work of the respiratory muscles

$v\dot{V}O_2max$ - minimum velocity that elicits maximal oxygen consumption

TLim-$v\dot{V}O_2max$ - time limit at $v\dot{V}O_2max$

$\Delta[La^-]$ - difference between the maximal $[La^-]$ values measured after the test and those measured after the warm-up ($m.mol^{-1}$)

$\Delta\dot{V}_E$[end-2] - difference between the last $\dot{V}O_2$ measurement of the TLim-$v\dot{V}O_2max$ test and the mean value measured during the 2nd minute of exercise

< - less than

> - higher than

* - denotes a significant difference

% - percentage

± - more or less

= - equal

Chapter 1. General Introduction

Science plays an important role in the understanding
and development of performance
J. Troup (1996, pg 3)

Swimming is a specific, continuous, cyclic and closed sport modality, in which both bioenergetical and biomechanical factors assume a fundamental performance-influencing role. Swimming has been, along the years, one of the primary areas of research in Sport Sciences, being published scientific experimental studies since the 1930s (Cureton, 1975; Lewillie, 1983; Clarys, 1996; Pelayo, 2003; Hamill and Haymes, 2005). In addition, swimming is a discipline with the “strength” of being able to get together coaches, sport scientists and academics in several well-consolidated working groups and periodic meetings (e.g. the International Symposium on Biomechanics and Medicine in Swimming and the FINA World Sports Medicine Congress).

From the four conventional swimming techniques, front crawl has been the most studied one. The major focus in front crawl might be explained through the fact of being the swimming stroke performed in most of the events in official competitions: six competitive distances, in opposition to the three events of backstroke, breaststroke and butterfly. As front crawl is the technique that allows the highest swimming velocity, and, in consequence, is used in the most important swimming event - the 100 m freestyle -, it is, in consequence, the most used stroke in the training practice. Complementarily, the fact that front crawl is the fastest technique may be explained by its lower intra-cyclic velocity variation (Miyashita, 1971; Holmér, 1979; Keskinen and Komi, 1993; Cappaert et al., 1996; Alves et al., 1998), which seems to imply a lower energy cost of exercise (Belokovsky and Kuznetsov, 1976; Kornecki and Bober, 1978; Holmér, 1983) and higher propulsive efficiency (Holmér, 1974a; Pendergast et al., 1978).

The classical work of Holmér (1974b), conducted in a swimming flume, compared the bioenegetical profile of the four swimming techniques, and sustained that front crawl was the most economical one. More recently, Troup (1991) confirmed the above-sentence referred fact, again with swimmers performing in a flume. A study of our group conducted a re-evaluation of the swimming economy of the four strokes, and tried to re-establish a new comparative profile of them (**Appendix I**).

Swimming is an aerobic modality in which the anaerobic system contribution has significant influence (Capelli et al., 1998; Ogita, 2000; Olbrecht, 2000; Pyne et al., 2000; Ogita, 2006). Thus, maximal oxygen consumption ($\dot{V}O_2max$), as expression of maximal metabolic aerobic performance, plays a central role among the energy-yielding mechanisms (di Prampero, 2003), seeming to be a very important swimming performance determinant (Klissouras and Sinning, 1978; Costill et al., 1985; Chatard et al., 1986; Olbrecht, 2000).

Nonetheless the fact that the fundamental areas of interest in swimming are already identified (Whipp et al., 1982; Smith et al., 2002) and, consequently, submitted to the attention and study of the technical and scientific communities, a new area of interest emerged recently: the study of the maximum duration of exercise in which the intensity corresponding to the minimum velocity that elicits maximal oxygen consumption ($v\dot{V}O_2max$) can be maintained. This parameter, usually denominated as Time Limit (TLim-$v\dot{V}O_2max$), expresses the maintenance of that specific constant velocity to the point of exhaustion, defined by the inability to maintain speed. So, in the TLim-$v\dot{V}O_2max$ test, the measure of performance is time duration.

TLim-$v\dot{V}O_2max$ in swimming was based and adapted from earlier studies conducted in treadmill running. To our knowledge, there was a big temporal gap between the first approach to TLim-$v\dot{V}O_2max$, by Hill and Lupton (1923), in which $\dot{V}O_2max$ of running was assessed and TLim-v$\dot{V}O_2max$ was only predicted, and the study of Volkov et al. (1975). These last authors used running v$\dot{V}O_2max$ to measure the total $\dot{V}O_2$ at that effort intensity, asking the subjects to maintain v$\dot{V}O_2max$ as long as possible. Reviewing the literature for this topic, Billat and Koralsztein (1996) found 17 experimental studies published between 1975 and 1995, almost all of them using laboratory procedures, conducting TLim-v$\dot{V}O_2max$ tests in special running and cycling ergometers. Afterwards, TLim-v$\dot{V}O_2max$ assessments were also applied in rowing and kayaking ergometers (Billat et al. 1996; Hill et al., 2003). From the above-referred studies appear two relevant facts: (i) TLim-v$\dot{V}O_2max$ appear to give precious information for various matters of training and performance of endurance athletes and (ii) TLim-v$\dot{V}O_2max$ evaluations are accomplished, manly, in specific ergometers.

In swimming, there is a lack of studies about the thematic of TLim-v$\dot{V}O_2max$, and the few studies found in the literature were mainly performed on a specific ergometer, i.e., in swimming flume, not in normal swimming-pool conditions (Billat et al., 1996; Faina et al., 1997; Demarie et al., 2001). Additionally, the study of Demarie et al. (2001) was not performed at v$\dot{V}O_2max$, but at lower exercise intensities: 96% of v$\dot{V}O_2max$. Knowing that, due to the specificity of the physiological demand in swimming, only sports-specific testing provide meaningful results (Holmér, 1992), the evaluation of TLim-v$\dot{V}O_2max$ in normal swimming conditions is required. To our knowledge, there is only one study in TLim-v$\dot{V}O_2max$ conducted in a conventional pool: Renoux (2001) estimated TLim-v$\dot{V}O_2max$ with swimmers performing in a 25 m swimming-pool. However, this study did not assessed respiratory parameters (e.g. $\dot{V}O_2$ and ventilation), being the v$\dot{V}O_2max$ and TLim-v$\dot{V}O_2max$ measurements performed without the confirmation of the major traditional physiological criteria for the achievement of $\dot{V}O_2max$ - the occurrence of a plateau in $\dot{V}O_2$ despite an increase in swimming velocity (Howley et al., 1995).

Since the enhancing of swimming performance can no longer be obtained by the increasing of training volume (Costill, 1999), more objective and specific training sets are required to improve the quality of the training process of the swimmers. Therefore, the importance of the knowledge on performance determinant factors, on performance diagnosis methods, and on training evaluation and control is rising in the last two decades, and TLim-v$\dot{V}O_2max$ is starting to be recognised as an important topic of interest in this area.

In our opinion, the great actual relevance in the study of TLim-v$\dot{V}O_2max$ is three-fold: (i) TLim-v$\dot{V}O_2max$ can be considered as a complementary parameter to $\dot{V}O_2max$ and v$\dot{V}O_2max$, the major indicators of maximal aerobic performance (aerobic power); (ii) TLim-v$\dot{V}O_2max$ seems to be a kind of effort well related to the 400 m front crawl performance, with an effort duration and intensity very close to this event (Termin and Pendergast, 2000; Ogita, 2006); (iii) new data are needed, collected in normal swimming conditions, without the possible mechanical constraints of performing in a swimming flume (Hay and Carmo, 1995; Reer et al., 2004; Thompson et al., 2004). In the literature, it has been shown that TLim-v$\dot{V}O_2max$ in swimming depends on some factors, namely accumulated oxygen deficit (Faina et al., 1997) and v$\dot{V}O_2max$ (Billat et al., 1996; Faina et al., 1997; Renoux, 2001). Complementarily, it has been observed that TLim-v$\dot{V}O_2max$ apparently was not related with $\dot{V}O_2max$ (Billat et al., 1996; Faina et al., 1997).

The purpose of this thesis was to characterize and compare TLim-v$\dot{V}O_2max$ in front crawl swimmers of different levels and genders, and to define, and analyse, its determinant factors. Hence, always testing in normal swimming-pool conditions, and obtaining physiological and biomechanical data in real time, it was tried to answer the following questions: (i) what is the typical duration of the TLim-v$\dot{V}O_2$max effort in front crawl swimming? Did TLim-v$\dot{V}O_2$max change significantly with swimming proficiency or gender? (ii) How is the typical $\dot{V}O_2$ kinetics during a swimming TLim-v$\dot{V}O_2$max effort? Is it evident an appearance of a $\dot{V}O_2$ slow component (O_2SC)? (iii) TLim-v$\dot{V}O_2$max and $\dot{V}O_2$max are well related in swimming or, effectively, there is not any observable relationship between these two physiological and functional parameters, as reported in the literature for running and cycling? (iv) Is TLim-v$\dot{V}O_2$max positively related with two major bioenergetical swimming performance influencing factors: the anaerobic threshold (AnT) and the energy cost of exercise (C)? Did swimming level or subjects gender affect the relationship between those referred parameters? (v) Is TLim-v$\dot{V}O_2$max positively related to two major swimming general biomechanical influencing factors: stroke rate (SR) and stroke length (SL)? Is stroke index (SI), a parameter that seems to express the swimmer technical efficiency (Costill et al., 1985), related with TLim-v$\dot{V}O_2$max?

Several experimental moments were accomplished, intending to answer the above-referred questions. Those studies are presented in Chapters 2 to 8 of this thesis. Additionally, a general discussion was elaborated upon the results obtained from the six independently carried out studies and with the reports of the specialized literature (Chapter 9). The main corresponding conclusions, and some suggestions for future studies, are also presented (Chapter 10 and 11, respectively).

Firstly, in **Chapter 2**, it is presented a pilot study which aimed to characterize TLim-v$\dot{V}O_2$max in swimming. The referred study was performed with low-level swimmers and employed a traditional incremental continuous protocol for v$\dot{V}O_2$max assessing. The hypothesis of the existence of an O_2SC in front crawl swimming was also tested.

In **Chapter 3** it is presented a study about front crawl TLim-v$\dot{V}O_2$max, performed by high-level swimmers, in which an intermittent protocol for v$\dot{V}O_2$max evaluation was used. This intermittent protocol was previously developed and validated in a recent study of our group (**Appendix II)** due to the need of collecting capillary blood for assessing lactate concentrations ([La$^-$]) during the most typical triangular protocols for $\dot{V}O_2$max assessment. Individualized [La$^-$] values, as indirect indicators of the anaerobic system contribution, are essential to evaluate some fundamental parameters in swimming, like AnT and C. In Appendix II several cardio-respiratory and metabolic parameters were analysed and compared between continuous and intermittent incremental protocols.

The study of Chapter 3 proposed to characterize TLim-v$\dot{V}O_2$max in well-trained male swimmers, and to analyse the possible existence of statistical relationships between TLim-v$\dot{V}O_2$max and some cardio-respiratory and metabolic parameters associated with performance (e.g. $\dot{V}O_2$max, v$\dot{V}O_2$max, maximal [La$^-$], maximal ventilation, maximal heart rate and AnT). The existence of an O_2SC in front crawl swimming in well-trained swimmers was also analysed.

Being well known that swimming economy (SE), usually quantified as C, is a major performance influencing factor (Troup and Daniels, 1986; Chatard et al., 1990; Capelli et al., 1995), it was accomplished an investigation that aimed to analyse if C affects TLim-v$\dot{V}O_2$max (**Chapter 4**). For that purpose, three SE related parameters were used: (i) the net energy cost corresponding to v$\dot{V}O_2$max (Cv$\dot{V}O_2$max); (ii) the slope of the regression line obtained from the energy expenditure ($\dot{E}$) and corresponding velocities during an incremental test (C_{slope}) and (iii) the ratio between the $\dot{E}$ mean value and the velocity mean value of the incremental test (C_{inc}). As it is well established that C changes with the subjects proficiency level (di Prampero, 1986), this experiment was conducted with two different swimming proficiency level groups for multi-level comparison purposes.

Knowing, as well, that SE also varies according to gender (di Prampero et al., 1974; Pendergast et al., 1977; Montpetit et al., 1983), in **Chapter 5** it is presented an investigation, conducted with 23 experienced competitive swimmers, in order to analyse gender influences on the relationship between TLim-v$\dot{V}O_2$max and C. Moreover, it was suggested that the referred effect was higher in the female swimmers group, once female are reported as more economical than their male counterparts (Pendergast et al., 1977; Costill et al., 1985; Onodera et al., 1999). Complementarily, as it is accepted that C is affected by some physical characteristics (Pendergast et al., 1977; di Prampero, 1986; Montpetit et al., 1988), it was also studied, by gender, the influence of body surface area (SA) in C, and its relation with TLim-v$\dot{V}O_2$max.

Afterwards, evidencing that the ability to achieve and maintain a specific velocity in a swimming event is as well related to metabolic parameters as to biomechanical factors (Keskinen and Komi, 1988; Toussaint and Hollander, 1994; Termin and Pendergast, 2000), it was studied, in highly trained swimmers, the relationship between TLim-v$\dot{V}O_2$max, v$\dot{V}O_2$max and stroking parameters (**Chapter 6**). Thus, studying SR, SL, and SI in trained swimmers, it was analysed the relevance of technical ability and motor skills in typically prolonged aerobic power efforts.

After observing strong relationships between the stroking parameters and TLim-v$\dot{V}O_2$max, a complementary study of our group tried to better understand the evolution of the SR, SL, and SI during the referred test (**Appendix III**). Being aware of the existence of a biomechanical boundary, very well related to a specific swimming intensity, beyond which the SL becomes compromised (Wakayoshi et al., 1996 and Dekerle et al., 2005), it was proposed to observe modifications in the propelling efficiency during the course of the referred bout.

In **Chapter 7**, a new experimental study is presented. This work aimed to assess TLim-v$\dot{V}O_2$max in elite front crawl swimmers, and to observe its main bioenergetical and biomechanical determinants. Knowing that top-level swimmers have their specificities (Lavoie and Montpetit, 1986; Sardella et al., 1991; Cappaert et al., 1996; Pelayo et al., 1996), and that TLim-v$\dot{V}O_2$max was never assessed in elite swimmers, the pertinence of this study was clearly stated. Moreover, respiratory parameters were measured through a new validated telemetric portable gas analyzer (Keskinen et al., 2003), which allowed more precise breath-by-breath collection of data. Several bioenergetical and biomechanical parameters were studied, namely those that were considered most relevant in the earlier presented studies.

Some of the bioenergetical parameters considered in Chapter 7 were assessed, in that study, through more specific and complex methodologies than those used in the earlier presented works (Chapter 2 to Chapter 6). Those more advanced techniques required specific mathematical methods for its application. Therefore, in **Appendix IV,** it is described the alternative method for individual swimming AnT (IndAnT) assessment that was used in Chapter 7. This new technique was based in mathematical modelling of the $[La^-]$/velocity curve, which was achieved with the data obtained in the selected intermittent incremental protocol for v$\dot{V}O_2$max assessment (Chapter 3). This new IndAnT assessment methodology seems to be a good individualized solution, in opposition to the traditionally used mean $[La^-]$ values of 4 $mmol.l^{-1}$ (Mader et al., 1976) or 3.5 $mmol.l^{-1}$ (Heck et al., 1985), that seems not to express the reported great variability of $[La^-]$ corresponding to AnT among swimmers (Jacobs, 1986; Urhausen et al., 1993).

Persisting in finding more specific and individualized methodologies for the assessment of bioenergetical parameters, it is presented, in **Appendix V**, a mathematical model to obtain the characteristics of the O_2SC kinetics in the TLim-v$\dot{V}O_2$max test. O_2SC was determined before in the earlier presented studies (Chapters 2 and 3), but its assessment was based in the method of the rigid time intervals, which was recently considered to be prone to error (Bearden and Moffatt, 2001). The mathematical modelling of O_2SC kinetics at heavy exercise intensities is not a new subject in the literature, namely in studies conducted in cycle ergometer (Barstow and Molé, 1991) and treadmill running (Carter et al., 2000), but was never before applied to swimming.

Strictly related with the above-referred study, in **Appendix VI**, it is shown a comparison between 2 types of techniques to measure the amplitude of O_2SC kinetics during the TLim-v$\dot{V}O_2$max test: (i) the use of a predetermined rigid interval, more specifically the difference between the last $\dot{V}O_2$ measurement and the mean $\dot{V}O_2$ value corresponding to the third (Whipp and Wasserman, 1972) or second minute of exercise (Koppo and Bouckaert, 2002) and (ii) the mathematical model, using a three component exponential model with independent time delays, developed by Barstow and Molé (1987) for legs exercise. In this study it is possible to observe a comparison between the O_2SC assessment methods used in the studies of Chapters 2, 3 and 7.

In **Chapter 8**, the last experimental study of this thesis is presented. Since no studies have been carried out based on other swimming techniques than front crawl, the purpose of this experiment was to characterize, and compare, TLim-v$\dot{V}O_2$max in the four competitive strokes, as well as to observe its relationships with two major performance determinants: $\dot{V}O_2$max and anaerobic threshold (AnT). The subjects were 23 elite swimmers (8 front crawlers, 5 backstrokers, 4 butterfliers and 6 breaststrokers), and their respiratory parameters were measured by the new validated telemetric portable gas analyzer (Keskinen et al., 2003) used before in Chapter 7. Likewise, AnT was assessed through mathematical modelling of the $[La^-]$/velocity curve, to obtain individual results. HR measurements were also carried out.

The present thesis is based upon the exercise physiology sub-disciple of research, but also aims to assess some well-described biomechanical swimming performance influencing factors. Thus, the sequence of studies referred above, which are all inter-related, is situated in the area of Biophysics, in the area of confluence of bioenergetics and biomechanics (Vilas-Boas, 1993; Pendergast et al., 2006). The biophysical investigation of swimming performance seems to be one of today's major areas of interest (Barbosa, 2005), which possibly can be explained by the fact that performance, in this sport discipline, is strongly influenced by the swimmers bioenergetical profile, swimming technique, and training process.

Chapter 2

Time limit at $v\dot{V}O_2max$ and $\dot{V}O_2max$ slow component in swimming. A pilot study in university students.

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Published on Biomechanics and Medicine in Swimming IX (2003), pp. 331-336.

Abstract

The aim of this study was to measure, on swimming-pool conditions, the time to exhaustion at the minimum velocity that elicits maximal oxygen consumption (TLim-v$\dot{V}O_2$max) and to verify the existence of an oxygen uptake slow component (O_2SC) in front crawl swimming. Ten university students performed a continuous incremental protocol for v$\dot{V}O_2$max assessment. Forty-eight hours later, they swam to exhaustion at v$\dot{V}O_2$max to assess TLim-v$\dot{V}O_2$max and O_2SC. $\dot{V}O_2$ was directly measured and swimming velocity was controlled by a visual pacer. Blood lactate concentrations ([La$^-$]) and heart rate (HR) values were also measured. Mean $\dot{V}O_2$max for the incremental test was 54.2 ± 8.2 ml.kg^{-1}.min^{-1}, and the correspondent v$\dot{V}O_2$max was 1.19 ± 0.08 m.s^{-1}. The mean duration of the TLim-v$\dot{V}O_2$max test was 325 ± 76.5 s. O_2SC appeared in the all-out swim at v$\dot{V}O_2$max (279.0 ± 195.2 ml.min^{-1}) and it was found to significantly correlate with the TLim-v$\dot{V}O_2$max (r = 0.744, p = 0.014). These results demonstrated that O_2SC is observed also in swimming-pool conditions and that TLim-v$\dot{V}O_2$max values are in accordance with typical formulations of aerobic power training sets for swimmers.

Key words: swimming, maximal oxygen uptake, time limit, $\dot{V}O_2$ slow component.

Introduction

The determination of the time of exercise to exhaustion at the minimum velocity that elicits maximal oxygen consumption (TLim-v$\dot{V}O_2$max) has arisen in the last years, and seems to be a very interesting matter for assessing various aspects of performance and training of endurance athletes (Billat et al., 1994). Although swimming isn't considered to be a typical endurance sport, it seems very important to study the swimmer's ability to sustain intensities that elicits their maximal aerobic power. This is not a new issue in physiological assessment of athletes, but almost all studies have been conducted in non-specific training and competition conditions. Reviewing the literature for this topic, Billat and Koralsztein (1996) found 17 experimental approaches published from 1979 until 1995, almost all of them using laboratory procedures, and performing the TLim-v$\dot{V}O_2$max tests in special ergometers (namely in treadmill and cycle ergometer).

In swimming, the investigation of the TLim-v$\dot{V}O_2$max is much more recent. To our knowledge, there are only 3 studies available in this area (Billat et al., 1996; Faina et al., 1997 and Demarie et al., 2001). Nevertheless, none of them was conducted in free swimming conditions, but in swimming flumes. In fact, presumed technical differences between swimming on a pool vs. on a flume, could justify changes in some physiological parameters such as TLim-v$\dot{V}O_2$max and O_2SC.

The purpose of this pilot study was to measure the TLim-v$\dot{V}O_2$max in front crawl swimming, and to verify the existence of an oxygen uptake slow component (O_2SC) in swimming, on swimming-pool conditions, as it was observed for Demarie et al. (2001) in flume swimming for pentathletes.

Materials and Methods

Ten physical education university students voluntarily participated in this study. Subject's characteristics (mean ± SD) were as follows: age = 23.1 ± 3.3 years, height = 169.5 ± 8.5 cm and weight = 61.9 ± 9.3 kg. All subjects were informed of the protocol before beginning the measurement procedures.

In a 25m indoor pool, each subject performed a continuous incremental protocol for front crawl $v\dot{V}O_2max$ assessment, starting at 0.9 $m.s^{-1}$, with increments of 0.05 $m.s^{-1}$ per 200m stages. VO_2 was directly measured using a *Sensormedics 2900* oximeter mounted on a special *charriot* running along the pool (Vilas-Boas and Santos, 1994), and connected to the swimmer by a respiratory valve (Toussaint et al., 1987). Expired gas concentrations were averaged every 20 s. Swimming velocity was controlled using a visual pacer (*GBK-Portugal*) with flashing lights every 2.5 m. $\dot{V}O_2max$ was considered to be reached according to traditional physiological criterions (Lacour et al., 1991; Howley et al., 1995) and $v\dot{V}O_2max$ was consider as the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$. If a plateau less than 2.0 $ml.min^{-1}.kg^{-1}$ higher could not be demonstrated, the $v\dot{V}O_2max$ was calculated using an equation used by Faina et al. (1997):

$$v\dot{V}O_2max = V + \Delta V. (n/120) \qquad \text{(Eq. 1)}$$

where V is the velocity correspondent to the last stage accomplished, ΔV is the velocity increment, and n indicates the number of seconds that the subjects were able to swim during the last stage.

Capillary samples for blood lactate concentration ($[La^-]$) analysis were collected from the ear lobe at rest, and immediately after exercise, and at 3 min and, if necessary, 5 min during the recovery period. Those analyses were obtained from a *YSI1500LSport* auto-analyser. Heart rate (HR) was monitored and registered continuously each 5 s through a *Polar Advantage* system.

Forty-eight hours later, all subjects swam to exhaustion at their $v\dot{V}O_2max$ to assess TLim-$v\dot{V}O_2max$. This protocol consisted in three different phases: (i) a 10 min warm-up at an intensity correspondent to 60% $v\dot{V}O_2max$, followed by a short rest (20 s) for ear lob blood collection; (ii) a 50 m distance performed at progressive velocity, allowing the swimmers to reach their individual $v\dot{V}O_2max$, and (iii) the maintenance of that swimming velocity ($v\dot{V}O_2max$) until exhaustion. The $\dot{V}O_2max$ determined in the incremental test was compared with the peak VO_2 reached in the TLim-$v\dot{V}O_2max$ test. O_2SC was calculated as the difference between the last VO_2 measurement of the TLim test and the one measured during the 3rd minute of exercise (Whipp and Wasserman, 1972). $[La^-]$ were, again, measured before and immediately after exercise, and at 3 min and, if necessary, at 5 min of the recovery period. HR was also registered continuously, using the same procedure previously described.

Swimmers were instructed to use an open turn, always performed to the same lateral wall side, without underwater gliding, and encouraged to perform as long as possible during the test period. Both tests were carried out in the same conditions for each subject (e.g. water and air temperature, and time of the day).

Statistical procedures included means and standard deviation computations for descriptive analysis, and Pearson correlation coefficient and paired *t*-test Student were used for correlation and mean differences analysis. All statistical procedures were conducted through SPSS statistical package. The level of significance was set at $\alpha = 0.05$.

Results

Data concerning $\dot{V}O_2max$ (in absolute and relative values), $v\dot{V}O_2max$, TLim-$v\dot{V}O_2max$, [La$^-$] and HR, from the present study, and those from the previously published studies conducted in swimming flume, are presented in Table 1. Note that, in all this studies, $\dot{V}O_2max$ was assessed trough direct methods and continuous test protocols.

Non statistical significant differences were noticed in $\dot{V}O_2max$ and HRmax values between the incremental and TLim-$v\dot{V}O_2max$ tests. Moreover, $\dot{V}O_2max$ (relative and absolute) and HRmax presented a high correlation values between those two tests (r = .86, .94 and .82, respectively - $P < 0.05$). Nevertheless, [La$^-$]max was significantly different between the two tests ($P = 0.001$).

Table 1. Age, weight, and height, $\dot{V}O_2max$, $v\dot{V}O_2max$, TLim-$v\dot{V}O_2max$, [La$^-$] and HR values in the final of the incremental (Inc) and TLim-$v\dot{V}O_2max$ (TLim) tests. Results of the present study are presented in comparison with those from Billat et al. (1996), Faina et al. (1997) e Demarie et al. (2001).

Parameters	Tests	Present study (n=10)	Billat et al. (96) (n=9)	Faina et al. (97) (n=8)	Demarie et al. (01) (n=6)
Age (years)	---	23.1 ± 3.3	18.4 ± 2.3	18 ± 2	18.8 ± 2
Weight (kg)	---	61.9 ± 9.3	74.5 ± 8.9	75 ± 2	62.4 ± 6
Height (cm)	---	169.5 ± 8.5	1.81 ± 0.7	183 ± 7	169.2 ± 10
$\dot{V}O_2max$ (ml.min^{-1}.kg^{-1})	Inc	54.2 ± 8.19	59.6 ± 6.7	60 ± 4	50.5 ± 3.3
	TLim	57.0 ± 9.90	----	----	----
$\dot{V}O_2max$ (ml.min^{-1})	Inc	3372 ±842	4444 ± 729	----	3100 ± 358
	TLim	3536 ± 863	4419 ± 716	----	3560 ± 586
$v\dot{V}O_2max$ (m.s^{-1})	Inc	1.19 ± 0.08	1.46 ± 0.09	1.54 ± 0.1	1.28 ± 0.07
TLim (s)	TLim	325 ± 76.5	287 ± 160	302 ±136	375 ± 38
[La$^-$]max (mmol.l^{-1})	Inc	7.8 ± 1.38	4.3 ± 1.6	----	7.1 ± 3.5
	TLim	10.9 ± 2.33	4.9 ± 1.2	----	8.2 ± 4.4
HRmax (b.min^{-1})	Inc	184.5 ± 7.89	179 ± 5	----	----
	TLim	184.5 ± 9.13	177 ± 8	----	----

In Figure 1 it's possible to observe a typical $\dot{V}O_2$ pattern during the TLim-v$\dot{V}O_2$max test. Notice the three moments of this test: (i) the warm-up followed by a short pause for blood collection (20 s); (ii) the 50m progressive velocity distance, and (iii) the maintenance of the swimming workload correspondent to v$\dot{V}O_2$max until exhaustion.

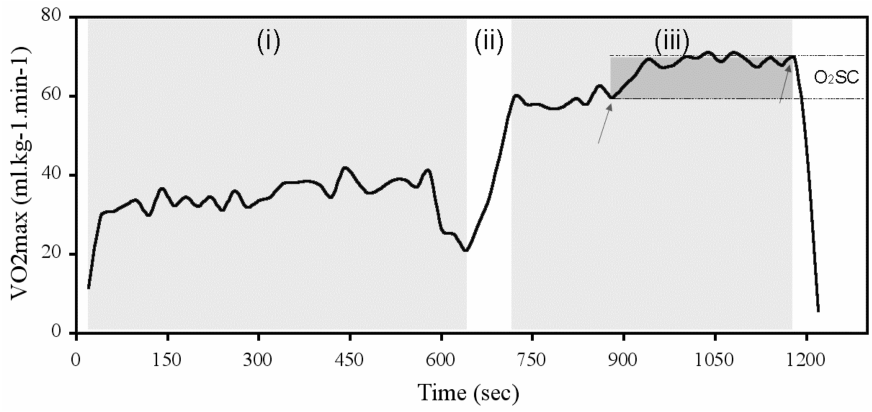

Figure 1. A typical example of the $\dot{V}O_2$ pattern during the TLim-v$\dot{V}O_2$max test. The arrows delimit the period where the O_2SC was calculated.

It was possible to observe a O_2SC in the TLim-v$\dot{V}O_2$max test of all subjects, presented a mean value of 279.0 ± 195.2 ml.min^{-1}. This O_2SC was found to be significantly correlated with the TLim-v$\dot{V}O_2$max ($r = 0.744$, $P = 0.014$). No correlation ($r = -0.184$, $P = 0.612$) was found between O_2SC and [La$^-$]max in the TLim-v$\dot{V}O_2$max test.

Discussion

The values of $\dot{V}O_2$max (expressed in absolute and relative forms) obtained in the incremental test with direct oximetry are in accordance with those previously published for unskilled swimmers or swimming non-specialized athletes (Troup, 1990; Demarie et al., 2001). Meanwhile, they were smaller than those obtained for elite front crawl swimmers for a number of authors (Holmér et al., 1974;

Troup, 1990; Billat et al., 1996 and Faina et al., 1997). This “medium” level of swimming proficiency of our subjects is also well perceived from the obtained low values of $v\dot{V}O_2max$.

The non existence of significant statistical differences between the $\dot{V}O_2max$ values assessed from the incremental and TLim-$v\dot{V}O_2max$ tests are also in accordance with previously published reports (Billat et al., 1996; Demarie et al., 2001).

HRmax didn’t show, also, statistical difference between the two tests (as found by Billat et al., 1996). The obtained mean value is very similar to the 186 $b.min^{-1}$ value reported for elite middle distance swimmers by Holmér (1974). Is seems that, for this kind of intensity of exercise (aerobic power zone) values ranging from 180 to 200 $b.min^{-1}$ are consensual (Maglischo, 1988).

The significantly higher value of $[La^-]max$ obtained in the TLim-$v\dot{V}O_2max$ test compared with the incremental test, may be explained by a hypothetical higher anaerobic energy contribution associated with less low intensity periods of exercise, as can be observed in the beginning of the progressive test. One other and more controverse possibility was presented by Poole et al. (1991), assuming the possibility of a major recruitment of fast twitch muscle fibbers associated with the fatigue of the previously recruited ones. This hypothesis is also associated to the possible explanation of O_2SC through an increased number of recruited motor units (Poole et al., 1991). This is in accordance with Faina et al. (1997), who referred that the anaerobic energy contribution is not negligible in such exercise. Nevertheless, Billat et al. (1996) and Demarie et al. (2001) did not reported any statistically significant difference between the two tests in what concerns to $[La^-]max$.

As it was possible to observe in Table 1, our mean value of TLim-$v\dot{V}O_2max$ is in between the lower values obtained by Billat et al. (1996) and Faina et al.

(1997), and the higher values presented by Demarie et al. (2001). Those results suggests a lower variation of this parameter in swimming, compared with the results presented for other sports by Billat et al. (1994), namely treadmill running (range 4-11 min). The inverse relationship between TLim-v$\dot{V}O_2$max and $\dot{V}O_2$max (and v$\dot{V}O_2$max), proposed by Billat et al. (1994) and Billat et al. (1996) for running, and by Billat et al. (1996) and Faina et al. (1997) for swimming, was not observed in this study. In this regard, it was not possible to confirm the possibility that the athletes who had the highest $\dot{V}O_2$max and the highest v$\dot{V}O_2$max reach their exhaustion earlier.

A slow component of $\dot{V}O_2$ kinetics appeared in the TLim-v$\dot{V}O_2$max test, as it was reported by Demarie et al. (2001). This O_2SC superimposed upon the rapid phase of the $\dot{V}O_2$ rise, is well documented on Figure 1. Notice that, as Whipp (1994) said, this slow phase continues until a delayed steady state is attained, or values equal to, or higher, than $\dot{V}O_2$max are reached.

The amplitude of the O_2SC measured in this group of subjects is in agreement with the report of Demarie et al. (2001), and seems to be different from running and cycling (Billat et al., 1998). Billat (2000) refers that the values of O_2SC can reach 500 $ml.min^{-1}$ and is generally considered to be significant when the value is above 200 $ml.min^{-1}$. The physiological ethiology of the O_2SC stays unclear (Demarle et al., 2001), but the O_2SC differences between sports are probably attributable to a different muscular contraction regimen and different mechanical efficiencies (Jones and McConnel, 1999). The obtained strong relationship between O_2SC and TLim-v$\dot{V}O_2$max, is not in accordance with the absence of significant correlation (r = -.009) presented by Demarie et al. (2001), and seems to traduce that the higher the TLim-v$\dot{V}O_2$max amplitude is, the higher O_2SC is expected to be.

In conclusion, O_2SC is observed also in swimming-pool conditions, and it is correlated with TLim-v$\dot{V}O_2max$. Meanwhile, TLim-v$\dot{V}O_2max$ is in accordance with typical formulations of aerobic power training sets for swimmers.

Acknowledgements

We wish to thank Prof. Dr. José Soares, from the Laboratory of Exercise Physiology of our faculty, for his significant contribution.

Chapter 3

Time limit and $\dot{V}O_2$ slow component at intensities corresponding to $\dot{V}O_2max$ in swimmers

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Published on Int. J. Sports Med. (2003), 24, 576-81.

Abstract

The purpose of this study was to measure, in swimming-pool conditions and with high level swimmers, the time to exhaustion at the minimum velocity that elicits maximal oxygen consumption (TLim-v$\dot{V}O_2$max), and the corresponding VO_2 slow component (O_2SC). The v$\dot{V}O_2$max was determined through an intermittent incremental test (n=15). Forty-eight hours later, TLim-v$\dot{V}O_2$max was assessed using an all-out swim at v$\dot{V}O_2$max until exhaustion. VO_2 was measured through direct oximetry and the swimming velocity was controlled using a visual light-pacer. Blood lactate concentrations and heart rate values were also measured. Mean $\dot{V}O_2$max for the incremental test was 5.09 ± 0.53 $l.min^{-1}$ and the corresponding v$\dot{V}O_2$max was 1.46 ± 0.06 $m.s^{-1}$. Mean TLim-v$\dot{V}O_2$max value was 260.20 ± 60.73 s and it was inversely correlated with the velocity of anaerobic threshold ($r = -0.54$, $p < 0.05$). This fact, associated with the inverse relationship between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max ($r = -0.47$, but only for $p < 0.10$), suggested that swimmers' lower level aerobic metabolic rate might be associated with a larger capacity to sustain that exercise intensity. O_2SC reached 274.11 ± 152.83 $l.min^{-1}$ and was correlated with TLim-v$\dot{V}O_2$max ($r = 0.54$), increased ventilation in TLim-v$\dot{V}O_2$max test ($r = 0.52$) and energy cost of the respiratory muscles ($r = 0.51$), for $p < 0.05$. These data suggest that O_2SC was also observed in the swimming-pool, by high level swimmers performing at v$\dot{V}O_2$max, and that higher TLim-v$\dot{V}O_2$max seems to correspond to higher expected O_2SC amplitude. These findings seem to bring new data with application in middle distance swimming.

Key words: Swimming, assessment, high intensity exercise

Introduction

High values of maximal oxygen uptake ($\dot{V}O_2max$) have been commonly accepted as a prerequisite for excellence in swimming. Furthermore, $\dot{V}O_2max$ is widely assumed as a standard of maximal aerobic power (Holmér et al., 1974; Vilas-Boas and Santos, 1994; Adams, 1998), and is associated to an exercise intensity related to one of the primary areas of interest in training and performance diagnostic in swimming (Smith et al., 2002). Although a number of authors had studied the velocity that elicits $\dot{V}O_2max$ in swimming, only few of them were interested in determining Time Limit, i. e., the time during which that intensity can be sustained until exhaustion (Billat and Koralsztein, 1996). From those, Billat et al. (1996) and Faina et al. (1997) studied swimmers in swimming flume, and Demarie et al. (2001) analysed pentatheletes, also in swimming flume. Once swimming in a flume may impose particular mechanical constraints when compared to free swimming in a conventional pool (Hay and Carmo, 1995), it is expected that some changes may also occur in some physiological parameters (e.g. $\dot{V}O_2max$, and Time Limit). Nevertheless, to our knowledge, only Fernandes et al. (in press) studied $\dot{V}O_2max$ and Time Limit in swimming-pool conditions, but in low performance level swimmers. Hence, being Time Limit a recent subject of study in swimming and considered as a very interesting matter for assessing various aspects of performance and training of athletes (Billat et al., 1994), further knowledge is needed, namely concerning trained high level swimmers in swimming-pool conditions.

The special purpose of this study was to assess, in free swimming conditions and with high level swimmers, the time to exhaustion at the minimum velocity that elicits $\dot{V}O_2max$ (TLim-v$\dot{V}O_2max$). We hypothesised that mean values of TLim-v$\dot{V}O_2max$ achieved in real swimming conditions are distinct from those previously obtained in swimming flume, for swimmers of similar level of proficiency.

Additionally, we proposed to verify the existence of an oxygen uptake slow component (O_2SC) during the TLim-v$\dot{V}O_2max$ test, as it has been previously found in high intensity cycling and running (Barstow and Molé, 1991; Whipp, 1994; Gaesser and Poole, 1996; Billat et al., 1998). The O_2SC is characterised by an additional slow rise in VO_2 kinetics, which is superimposed upon the rapid phase of VO_2 initiated at the exercise onset (Gaesser and Poole, 1996). The O_2SC was previously observed only in flume swimming in pentathletes performing at exercise intensities under v$\dot{V}O_2max$ (Demarie et al., 2001), and in swimming-pool conditions for swimmers of low level of proficiency (Fernandes et al., in press). Following some expert' perspectives (Whipp, 1994; Gaesser and Poole, 1996), it was hypothesised that O_2SC is a determinant factor of exercise intensity tolerance, in this case of Time Limit at intensities related to v$\dot{V}O_2max$. Relationships between other parameters studied were also searched.

In our understanding, new findings in TLim-v$\dot{V}O_2max$ and O_2SC will have great interest and application in the training processes of swimmers specialised in middle distance events (e.g. 400 m), namely due to the fact that they were assessed in real swimming conditions and at the swimming intensities supposedly used in the 400 m event. These new contributions will allow a better understanding of the full potential of the swimmer's aerobic characteristics and may contribute to a more precise definition of aerobic power training sets.

Materials and Methods

Fifteen Portuguese high-level male swimmers volunteered to participate in this study. Their mean (± SD) age, body mass and height were, respectively, 17.5 ± 1.5 years, 67.0 ± 6.8 kg and 175.7 ± 6.3 cm. The criterion performance level for participating in this study was the personal best time, for that moment of the season, under 4:20 in the 400 m front crawl event. All subjects were informed about the details of the experimental protocol before beginning the measurement procedures.

All the test sessions took place in a 25 m indoor pool. Briefly, each subject performed an intermittent incremental protocol for front crawl $v\dot{V}O_2max$ assessment. This test had increments of 0.05 $m.s^{-1}$ each 200 m stage, with 30 s intervals until exhaustion. Initial velocity was established according to the individual level of fitness and it was set at the swimmer's individual performance on the 400 m front crawl minus seven increments of velocity (for more details see Cardoso et al., in press). VO_2 was directly measured using a metabolic measurement cart (*Sensormedics 2900 oximeter, Yorba Linda - California, USA*) mounted on a special *chariot* running along the pool (Vilas-Boas and Santos, 1994), and connected to the swimmer by a special respiratory valve (Toussaint et al., 1987). Expired air was continuously measured during the entire test and averaged every 20 s. Swimming velocity was controlled using a visual pacer (*TAR.1.1, GBK-electronics, Aveiro, Portugal*) with flashing lights in the bottom of the pool.

$\dot{V}O_2max$ was considered to be reached according to primary and secondary traditional physiological criteria (Howley et al., 1995; Adams, 1998): (i) occurrence of a plateau in oxygen uptake despite an increase in swimming velocity and (ii) high levels of blood lactic acid concentrations ($[La^-] \geq 8 mmol.l^{-1}$), elevated respiratory exchange ratio ($R \geq 1.0$), elevated heart rate [> 90% of (220 - age)] and exhaustive perceived exertion (controlled visually, and case to case, by the respective coaches and scientific staff). $v\dot{V}O_2max$ was considered as the swimming velocity corresponding to the first stage that elicits $\dot{V}O_2max$. If a VO_2 plateau less than 2.1 $ml.min^{-1}.kg^{-1}$ could not be demonstrated, the $v\dot{V}O_2max$ was calculated using the Equation 1 (Kuipers et al., 1985):

$$v\dot{V}O_2max = V + \Delta V*(n .N^{-1}) , \qquad \text{(Eq. 1)}$$

where V is the velocity corresponding to the last stage accomplished, ΔV is the velocity increment, n indicates the number of seconds that the subjects were able to swim during the last stage and N the theoretical number of seconds of this step.

Capillary blood samples for $[La^-]$ analysis were collected from the earlobe at rest, in the 30 s rest interval, immediately after the end of each exercise step, and at 3 min (and 5 min) during the recovery period. These blood samples were analysed using an *YSI1500LSport* auto-analyser (*Yellow Springs Incorporated, Yellow Springs - Ohio, USA)* which allowed us to assess the velocity corresponding to the anaerobic threshold (vAnT) by interpolating the mean lactate value of 3.5 $mmol.l^{-1}$ (Heck et al., 1985) with the exponential lactate/velocity curves of each subject. Heart rate (HR) was monitored and registered continuously each 5 s through a heart rate monitor system (*Polar Vantage NV, Polar Electro Oy, Kempele, Finland*).

The second test session occurred forty-eight hours later. All subjects swam until exhaustion at their previously determined $v\dot{V}O_2max$, to assess TLim-$v\dot{V}O_2max$. This protocol consisted in three different phases, all paced with the referred visual light-pacer: (i) a 10 min warm-up at an intensity corresponding to 60% $v\dot{V}O_2max$, followed by a short rest period (20 s) for blood collection; (ii) a 50 m distance performed at progressive velocity, allowing the swimmers to reach their individual $v\dot{V}O_2max$, and (iii) the maintenance of that swimming $v\dot{V}O_2max$ until exhaustion. TLim-$v\dot{V}O_2max$ was considered to be the total swimming duration at $v\dot{V}O_2max$. During TLim-$v\dot{V}O_2max$ test, O_2SC was determined, according with Koppo and Bouckaert (2002), as the difference between the last $\dot{V}O_2$ measurement of the TLim-$v\dot{V}O_2max$ test and the mean value measured during the 2^{nd} minute of exercise ($\Delta VO_{2[end-2]}$). The estimation of O_2 uptake associated to specific work of the respiratory muscles (VO_{2RMus}) was also determined during TLim-$v\dot{V}O_2max$ test. Briefly, after assessing the difference between the last VE measurement and the mean value measured during the 2^{nd} minute of exercise ($\Delta VE_{[end-2]}$), $\Delta VE_{[end-2]}$

was multiplied by 2.85 $ml.l^{-1}$ (the value of energy cost of breathing for ventilation in the range of 117-147 $L.min^{-1}$) to obtain the final result (Aaron et al., 1992).

$[La^-]$ were assessed at rest, during the 20 s intervals, immediately after exercise, and at 3 min (and 5 min) of the recovery period. The lactate production ($\Delta[La^-]$) was determined as the difference between the maximal values measured after the test and those measured after warm-up. HR was registered continuously using the same procedure previously described.

Swimmers were instructed to perform an open turn, always done to the same lateral wall side without underwater gliding, and were verbally encouraged to swim as long as possible during the test period. Both tests were carried out in the same conditions for each subject, i.e., temperature, humidity and time of day.

Statistical procedures included means and standard deviations, Pearson correlation coefficient and paired Student's *t* test. All data was checked for normality. All statistical procedures were conducted with SPSS 10.05, and the significance level was set at 5%.

Results

Data concerning metabolic, cardiorespiratory and functional variables from the present study are presented in Table 1. Maximal blood lactate concentrations ($[La^-]$max), maximal ventilation ($\dot{V}Emax$) and maximal respiratory quotient (Rmax) were higher in TLim-v$\dot{V}O_2$max test than in the incremental one. Considering all subjects of the sample, TLim-v$\dot{V}O_2$max ranged from 188 to 400 s, and O_2SC from 96 to 576 $ml.l^{-1}$.

Table 1. Mean (± SD) values for maximal oxygen uptake ($\dot{V}O_2max$), maximal production of carbon dioxide ($\dot{V}CO_2max$), minimum velocity that elicits $\dot{V}O_2max$ ($v\dot{V}O_2max$), maximal ventilation ($\dot{V}Emax$), maximal respiratory quotient (Rmax), maximal ventilatory equivalent for oxygen ($E\dot{V}O_2max$), maximal ventilatory equivalent for carbon dioxide ($E\dot{V}CO_2max$), maximal respiratory rhythm (RRmax), maximal tidal volume (VTmax), maximal heart rate (HRmax), velocity of the anaerobic threshold (vAnT), maximal blood lactate concentrations $[La^-]max$, lactate production ($\Delta[La^-]$), time to exhaustion at $v\dot{V}O_2max$ (TLim-$v\dot{V}O_2max$), VO_2 slow component (O_2SC), ventilation increase in the TLim-$v\dot{V}O_2max$ test ($\Delta VE_{[end-2]}$), and $\dot{V}O_2$ uptake associated to the respiratory muscles ($\dot{V}O_{2RMus}$) for the incremental and TLim-$v\dot{V}O_2max$ tests.

Parameters	Incremental test	TLim-vVO_2max test	t-test (*P*)
$\dot{V}O_2max$ ($ml.min^{-1}.kg^{-1}$)	76.81 ± 6.54	79.93 ± 6.39	0.11
$\dot{V}O_2max$ ($l.min^{-1}$)	5.09 ± 0.53	5.43 ± 0.48	0.09
$\dot{V}CO_2max$ ($l.min^{-1}$)	4.73 ± 0.34	5.51 ± 0.56	0.20
$v\dot{V}O_2max$ ($m.s^{-1}$)	1.46 ± 0.06		---
$\dot{V}Emax$ ($l.min^{-1}$)	129.94 ± 19.21	138.41 ± 19.71	0.02*
Rmax	0.94 ± 0.03	1.02 ± 0.03	0.03*
$E\dot{V}O_2max$ ($ml.min^{-1}$)	25.60 ± 3.65	25.83 ± 4.23	0.31
$E\dot{V}CO_2max$ ($ml.min^{-1}$)	28.63 ± 5.51	26.23 ± 2.59	0.21
RRmax ($breath.min^{-1}$)	49.12 ± 3.56	50.21 ± 7.81	0.46
VTmax ($ml.breath^{-1}$)	2.64 ± 0.25	2.78 ± 0.35	0.13
HRmax ($b.min^{-1}$)	189.70 ± 6.72	188.52 ± 7.22	0.07
vAnT ($m.s^{-1}$)	1.38 ± 0.05		---
$[La^-]max$ ($mmol.l^{-1}$)	8.38 ± 1.12	9.60 ± 2.02	0.00**
$\Delta[La^-]$ ($mmol.l^{-1}$)		8.49 ± 1.77	
TLim-$v\dot{V}O_2max$ (s)	----	260.20 ± 60.73	---
O_2SC ($ml.min^{-1}$)	----	274.11 ± 152.83	---
$\Delta VE_{[end-2]}$ ($l.min^{-1}$)	----	12.70 ± 7.37	---
VO_{2RMus} ($ml.min^{-1}$)	----	36.21 ± 21.00	---

As it is possible to observe in Figure 1, TLim-v$\dot{V}O_2$max was inversely related to vAnT (r = -0.54, $p < 0.05$ and $r^2 = 0.29$). TLim-v$\dot{V}O_2$max was also inversely related to v$\dot{V}O_2$max (r = -0.47), although only for P < 0.10. No significant correlations were found between TLim-v$\dot{V}O_2$max and absolute $\dot{V}O_2$max (r = 0.11), relative $\dot{V}O_2$max (r = 0.21), VO_{2Rmus} (r = 0.34), $\dot{V}$Emax (r = 0.11), $\Delta VE_{[end-2]}$ (r = 0.34), $[La^-]$max (r = -0.22), $\Delta[La^-]$ (r = -0.25) and HRmax (r = -0.18), all for a P > 0.10.

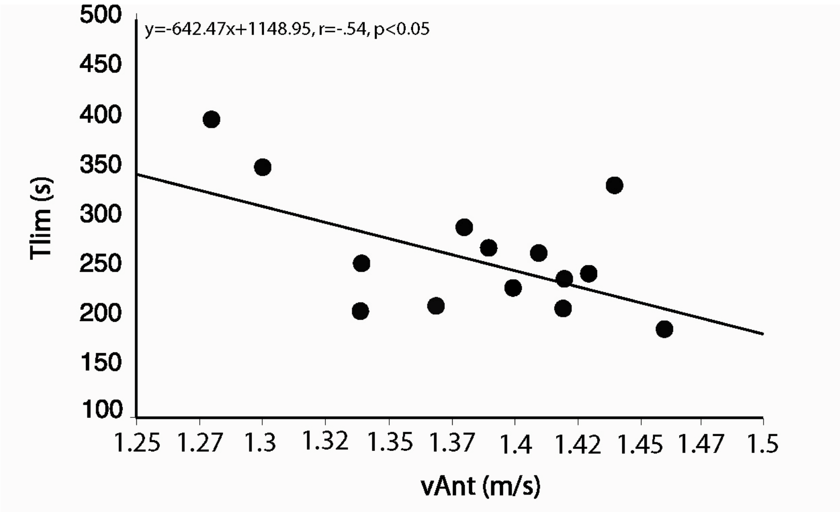

Figure 1. Inverse relationship between TLim-v$\dot{V}O_2$max and vAnT, for n = 15.

In Figure 2, it's possible to observe a typical VO_2 pattern in the TLim-v$\dot{V}O_2$max test with the appearance of an O_2SC.

The O_2SC was correlated with the TLim-v$\dot{V}O_2$max (r = 0.54, P < 0.05 and r^2 = 0.30) and VO_{2RMus} (r = 0.51, P < 0.05 and r^2 = 0.27), as we can see in Figure 3. O_2SC is also correlated with $\Delta VE_{[end-2]}$ (r = 0.52, P < 0.05 and r^2 = 0.27). No significant correlations were observed between O_2SC and absolute (r = 0.31) and relative $\dot{V}O_2$max (r = 0.01), VEmax (r = 0.35), vAnT (r = 0.20), $[La^-]$max (r = -0.32), $\Delta[La^-]$ (r = -0.34) and HRmax (r = -0.29).

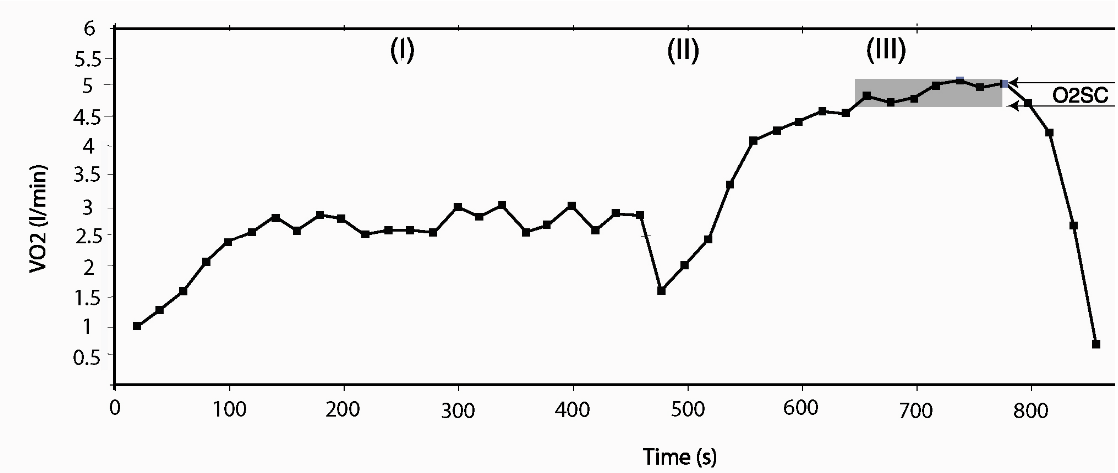

Figure 2. A typical example of the VO_2 pattern during the TLim-$v\dot{V}O_2max$ test: (I) warm-up and 20 s rest; (II) 50 m progressive swimming velocity and (III) maintenance of swimming $v\dot{V}O_2max$ until exhaustion. The arrows delimit the period when the O_2SC was determined.

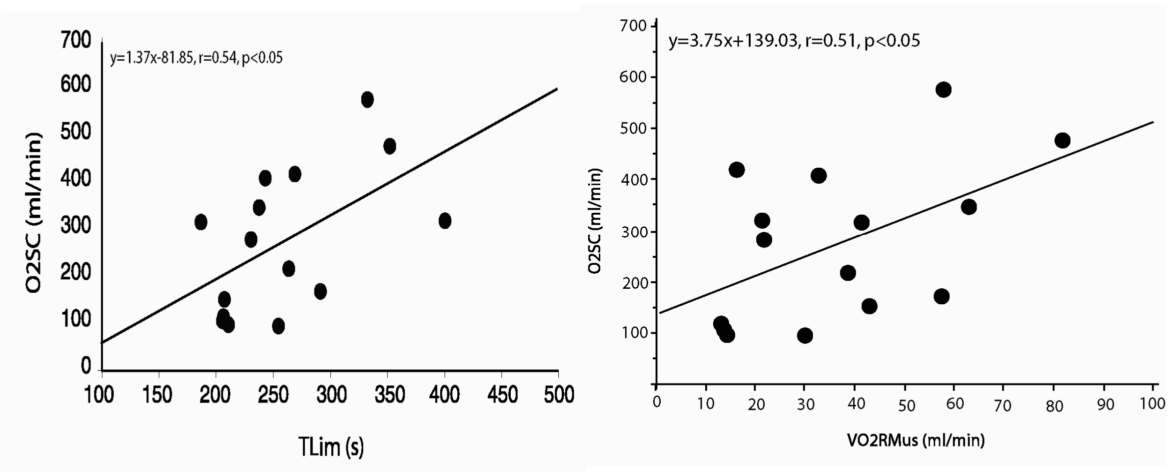

Figure 3. Relationship between O_2SC and TLim (left panel) and between O_2SC and VO_2RMus (right panel), for n = 15.

Discussion

To our knowledge, this is the first study in which Time Limit and O_2SC were determined in high level swimmers, performing in swimming-pool, at intensities corresponding to maximal aerobic power ($v\dot{V}O_2max$). So, it is expected to allow additional data to the better understanding of middle distance swimming performance and training.

Although $\dot{V}O_2max$ and $v\dot{V}O_2max$ have been conventionally assessed through continuous progressive protocols, there is considerable evidence that $\dot{V}O_2max$ shows similar values when measured using continuous or non-continuous protocols in many sports (McArdle et al., 1973; Stamford, 1976; Howley et al., 1995), and specifically in swimming (Cardoso et al., in press). Thus, we chose the intermittent test, which allowed the swimmer to rearrange the breathing valve during the intervals, to collect blood for $[La^-]$ analysis and allowed the researchers and coaches to give appropriated informative and motivational feedbacks.

The values of $\dot{V}O_2max$ obtained in the incremental test, seem to be higher than the majority of values previously published, perhaps due to differences in the competitive level of the group and/or the testing methodologies used. Nevertheless, some studies also reported considerable high values of $\dot{V}O_2max$ in elite male front crawl swimmers (Holmér et al., 1974; Costill et al., 1985).

The lack of significant difference between the $\dot{V}O_2max$ values obtained in the incremental and TLim-$v\dot{V}O_2max$ tests is in accordance with previously published reports in swimming (Billat et al., 1996; Demarie et al., 2001; Fernandes et al., in press). Nonetheless, the O_2SC brought the $\dot{V}O_2max$ values above those measured in the incremental test for the majority of the subjects (n=11), as previously stated (Barstow and Molé, 1991; Gaesser and Poole, 1996; Demarie et al., 2001). Additionally, HRmax did not show statistical differences between the two tests, which is in accordance with the available literature (Billat et al., 1996; Fernandes et al., in press). The obtained HRmax mean value is very similar to those previously reported in elite middle distance swimmers (Holmér et al., 1974).

An higher value of $[La^-]max$ obtained in the TLim-$v\dot{V}O_2max$ test compared with the incremental test was also found in less proficient swimmers (Fernandes et al., in press), and is in accordance with $[La^-]$ values for this kind of high intensity in prolonged effort (Holmér et al., 1974). In the same way, an increase in the VEmax values in the TLim-v$\dot{V}O_2$max test was previously described (Poole et al., 1991). This increase, also demonstrated by the higher Rmax value, can probably be explained by a higher metabolic acidosis in TLim-v$\dot{V}O_2$max test compared to the incremental test for v$\dot{V}O_2$max assessment.

The mean value of TLim-v$\dot{V}O_2$max obtained in this study is similar to other values reported in flume for competitive swimmers (Billat et al., 1996; Faina et al., 1997), and lower than those obtained with less proficient swimmers (Demarie et al., 2001; Fernandes et al., in press) (some of them performing at exercise intensities under v$\dot{V}O_2$max - Demarie et al., 2001). These results, and the inverse relationship between the TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max found in this study, suggested that the swimmers' lower level of maximal aerobic metabolic rate might be associated with a larger capacity to sustain that exercise intensity. This hypothesis was previously pointed out for running (Billat et al., 1994; Billat et al., 1996) and swimming (Billat et al., 1996; Faina et al., 1997), and suggests that the anaerobic capacity can be at least one of the explanations for the inverse relationship discussed above (Billat and Koralsztein, 1996; Faina et al., 1997). In this sense, the energetic pathways used to ascribe the demands imposed by the intensity corresponding to v$\dot{V}O_2$max could be different among the swimmers. Moreover, the increased intra-cellular buffer capacity of short distance swimmers, probably allowed them to sustain more deleterious intra-cellular environments, such as low pH values, than long and middle distance swimmers. Unfortunately, we had no available specific data concerning anaerobic *vs* aerobic time training of our swimmers, which could enrich the discussion of this topic. However, the correlation of TLim-v$\dot{V}O_2$max with $[La^-]$max and $\Delta[La^-]$ was not significant. In a recently published article (Messonnier et al., 2002), it was observed a direct relationship between Time Limit, performed in cycle ergometer, and the lactate exchange ability. Future studies on TLim-v$\dot{V}O_2$max in swimming should consider this important parameter.

Other possible explanation for the inverse relationship between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max can probably be attributed, at least in part, to methodological features in the determination of v$\dot{V}O_2$max, despite the fact that the usual criteria to assess $\dot{V}O_2$max, and consequently v$\dot{V}O_2$max, were achieved in all subjects. In fact, v$\dot{V}O_2$max can eventually be underestimated in those swimmers who were less capable (regarding maximal aerobic power), and technically less proficient in late "fatigue" stages of the incremental test.

Accordingly, an inverse correlation between TLim-v$\dot{V}O_2$max and vAnT was found. However, the mean vAnT value for the subjects of this study was high when we compare it with the v$\dot{V}O_2$max, i.e., about 94% of this parameter. Despite this fact, which means that the swimmers were aerobically fit (the experimental tests were carried in the end of the general preparatory period), the inverse correlation between TLim-v$\dot{V}O_2$max and vAnT (and v$\dot{V}O_2$max) can also be explained by rather distinct phenotypes, which probably influenced motor units recruitment patterns during the tests. In fact, the R^2 value (R^2 = 0.29) of the referred correlation means that there are other factors responsible for TLim-v$\dot{V}O_2$max, since only 29% of the variability is explained by vAnT. In fact, probably distinct buffer capacities and energy subtracts mobilised as a consequence of different anaerobic capacities among swimmers could, at least in part, influence motor units recruitment pattern during the tests, and thus be an additional contribution for understanding the results.

A O_2SC seems also to occur in this study, which is in accordance with numerous studies centred on cycling and running (Barstow and Molé, 1991; Whipp, 1994; Gaesser and Poole, 1996; Billat et al., 1998), and also in swimming, but with pentatheletes performing in a flume (Demarie et al., 2001) and low proficient swimmers (Fernandes et al., in press). The use of the $\Delta VO_{2[end-2]}$ (Koppo and Bouckaert, 2002) formula for determining O_2SC instead of $\Delta VO_{2[end-3]}$ (Whipp and Wasserman, 1972; Whipp, 1994; Billat et al., 1998), was justified by the fact that, in the case of intense exercise, the O_2SC seems to appear after a delay of 80 -120 s following the onset of exercise (Barstow and Molé, 1991; Barstow, 1994; Koppo and Bouckaert, 2002). Although a considerable use of exponential models in the study of VO_2 kinetics, we chose a simpler alternative method based on the literature arguments: (i) an increased methodological complexity when studding the second exponential function of VO_2 kinetic (Gaesser and Poole, 1996; Billat, 2000); (ii) the O_2 analyser used in the present study was not a breath-by-breath one (Demarie et al., 2001); (iii) there is no consensus about whether the O_2SC fits better in an exponential or linear process (Gaesser and Poole, 1996; Faina et al., 1997; Demarie et al., 2001); (iv) the considerable variability of the amplitude and time constant of O_2SC (Özyener et al., 2001) and (v) the fact that single exercise transitions often yield low signal-to-noise ratios (Koppo and Bouckaert, 2002).

The mean value of O_2SC had physiological meaning (Billat, 2000), although it seems to be lower than the mean values published for running and cycling (Billat et al., 1994). Nevertheless, the high exercise intensity chosen in this work, the high level of endurance training of these swimmers and the specificity of this sport, could have influenced the lower amplitude of the O_2SC. The significant relationship between O_2SC and TLim-v$\dot{V}O_2max$ appears to indicate that higher TLim-v$\dot{V}O_2max$ seems likely to correspond to higher expected O_2SC amplitude. These data are in accordance with our previous data in university students (Fernandes et al., in press) and with others (Whipp, 1994; Gaesser and Poole, 1996).

The hypothesis that the appearance of the O_2SC phenomenon is related to a major recruitment of fast twitch muscle fibbers, with high glycolytic capacity, associated with the fatigue of the previously recruited fibbers (Poole et al., 1991; Barstow, 1994; Whipp, 1994; Barstow and Molé, 1996; Gaesser and Poole, 1996), wasn't directly confirmed either by us or Demarie et al. (2001) for swimming: no relationship was obtained between O_2SC and $[La^-]max$ or $\Delta[La^-]$. Nevertheless, it is unlikely that blood lactate *per se* can be responsible for the O_2SC phenomenon, but rather by accompanying acidosis. This fact allows to keep suggesting that one of the O_2SC major contributors is probably related to the superior rates of recruitment of Type II fibbers and additional energy cost of contraction (Whipp, 1994).

Another possible contributor for the arising of the O_2SC may be the increasing VE in response to the changes in stroke technique caused by higher levels of fatigue (Demarie et al., 2001). Additionally, it is known (Aaron et al., 1992; Gaesser and Poole, 1996) that, at very high exercise intensities with increased pulmonary ventilation, characteristic of the O_2SC phase, there is an additional O_2 uptake related to the specific work of the respiratory muscles. This additional VO_2 uptake was significantly correlated with O_2SC and represented, in our study, 13.2% of the O_2SC mean value. This fact, associated with the significant increase of VEmax in the TLim-v$\dot{V}O_2$max test when compared with the incremental test, suggests that the ventilatory muscles probably accounts for some, despite low, percentage of the total O_2SC, as previously mentioned (Poole et al., 1991; Whipp, 1994; Gaesser and Poole, 1996).

In conclusion, TLim-v$\dot{V}O_2$max value obtained in swimmers in real conditions, i.e., in swimming-pool, is similar to that previously reported in flume swimming and is lower than previously obtained for less proficient swimmers. TLim-v$\dot{V}O_2$max seems to be higher in the swimmers who presented lower vAnT and v$\dot{V}O_2$max. O_2SC was also observed in high level swimmers, performing in swimming-pool conditions, and was moderately correlated with TLim-v$\dot{V}O_2$max and to the energy cost of the respiratory muscles. These findings seem to bring new data in one of the most important performance determinant factors for middle distance swimming, and seem to highlight the principle of training individualisation in the design of aerobic power training sets. Furthermore, it is possible to suggest that swimmers with higher values of vAnT and $v\dot{V}O_2max$ should use less extensive training sets for aerobic power improvement purposes.

Chapter 4

Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity?

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J. Sports Med. Phys. Fitness (in press)

Abstract

The purpose of the present study was to examine the relationship between time limit at the minimum velocity that elicits the individual's maximal oxygen consumption (TLim-v$\dot{V}O_2$max) and three swimming economy related parameters: the net energy cost corresponding to v$\dot{V}O_2$max (Cv$\dot{V}O_2$max), the slope of the regression line obtained from the energy expenditure ($\dot{E}$) and corresponding velocities during an incremental test (C_{slope}) and the ratio between the $\dot{E}$ mean value and the velocity mean value of the incremental test (C_{inc}). Complementarily, we analysed the influence of Cv$\dot{V}O_2$max, C_{slope} and C_{inc} on TLim-v$\dot{V}O_2$max by swimming level. Thirty swimmers divided into ten low-level - LLS (4 male and 6 female) and twenty highly trained swimmers – HTS (10 of each gender) performed an incremental test for v$\dot{V}O_2$max assessment and an all-out TLim-v$\dot{V}O_2$max test. TLim-v$\dot{V}O_2$max, v$\dot{V}O_2$max, Cv$\dot{V}O_2$max, C_{slope} and C_{inc} averaged, respectively, 313.8±63.0 s, 1.16±0.1 $m{\cdot}s^{-1}$, 13.2±1.9 $J{\cdot}kg^{-1}{\cdot}m^{-1}$, 28.0±3.2 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ and 10.9±1.8 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ in the LLS and 237.3±54.6 s, 1.40±0.1 $m{\cdot}s^{-1}$, 15.6±2.2 $J{\cdot}kg^{-1}{\cdot}m^{-1}$, 36.8±4.5 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ and 13.0±2.3 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ in the HTS. TLim-v$\dot{V}O_2$max was inversely related to C_{slope} (r = -0.77, P < 0.001), and to v$\dot{V}O_2$max (r = -0.35, P = 0.05), although no relationships with the Cv$\dot{V}O_2$max and the C_{inc} were observed. The findings of this study confirmed exercise economy as an important factor for swimming performance. The data demonstrated that the swimmers with higher C_{slope} and v$\dot{V}O_2$max performed shorter time in TLim-v$\dot{V}O_2$max efforts.

Key words: Swimming, time limit, $\dot{V}O_2$max, energy cost.

Introduction

Time limit is defined as the duration during which a certain intensity of exercise can be sustained until exhaustion (Billat and Koralsztein, 1996). Time limit at intensities corresponding to the individual's maximal oxygen uptake ($\dot{V}O_2max$) has been mostly studied in running and in cycling but is a new subject of interest in swimming training and performance diagnosis. The first study that assessed time limit in swimming compared cyclists, kayak paddlers, swimmers and runners, performing in their specific ergometers, although not in their performance specific field conditions (Billat et al., 1996). In this study, time limit was performed at the velocity that elicits $\dot{V}O_2max$ (TLim-v$\dot{V}O_2max$) and was only different between cycling and running. In addition, an inverse relationship between TLim-v$\dot{V}O_2max$ and v$\dot{V}O_2max$ was found in swimming. Afterwards, two studies, also performed in swimming flume, not in normal swimming, characterised swimming TLim-v$\dot{V}O_2max$ and tried to find out the main factors that affected it (Faina et al., 1997; Demarie et al., 2001). The authors addressed that TLim-v$\dot{V}O_2max$ correlated positively with accumulated oxygen deficit and negatively with $\dot{V}O_2max$, and observed the occurrence of a $\dot{V}O_2$ slow component in the TLim-v$\dot{V}O_2max$ trial. Arguing that exercising in a flume may impose particular mechanical constrains that impair its comparison with free swimming in a conventional pool, Fernandes et al. (2003) proposed a new TLim-v$\dot{V}O_2max$ protocol implemented in normal swimming specific conditions. It was shown that TLim-v$\dot{V}O_2max$ is negatively related with v$\dot{V}O_2max$ and to the 3.5 $mmol \cdot l^{-1}$ anaerobic threshold in high-level male swimmers. In addition, a positive relationship between TLim-v$\dot{V}O_2max$ and $\dot{V}O_2$ slow component was reported. Also in this research field, Renoux (2001) examined the effect of 12-week training program on TLim-v$\dot{V}O_2max$ and v$\dot{V}O_2max$ and designed an intermittent training regimen to develop those parameters. The training program allowed an improvement in v$\dot{V}O_2max$ although such evolution was not seen for

TLim-v$\dot{V}O_2$max. Complementarily, it was observed an inverse relationship between those parameters.

Despite these last studies, no report was published relating time limit and one major swimming performance determinant: swimming economy (SE) (Van Handel et al., 1988; Chatard et al., 1990; Kjendlie et al., 2004) SE, usually quantified as the energy cost of locomotion (C), has been well reported since the seventies for different workloads and for distinct swimming levels (Holmér, 1972). Hence, SE has been considered a fundamental parameter of swimming science applied to training (Toussaint and Hollander, 1994; Smith et al., 2002) and could be one of the main contributors for an improved TLim-v$\dot{V}O_2$max effort. Meanwhile, several authors have been determining C by simply estimating the contribution of aerobic metabolism, through the monitoring of $\dot{V}O_2$ at submaximal (or even maximal) intensities (Costill et al., 1985; Montpetit et al., 1988; Poujade et al., 2003). The negligence of the anaerobic contribution to the overall energy requirement in the referred models can be justified by the difficulties imposed by the assessment of the glycolytic system when performing in normal swimming conditions, i.e., in a swimming-pool. As TLim-v$\dot{V}O_2$max duration and intensity are closely related to the 400 m front crawl event (Termin and Pendergast, 2002; Fernandes et al., 2003), in which the anaerobic contribution is approximately 20% of the total energy expenditure, (Toussaint and Hollander, 1994; Gastin, 2001) it was proposed to bridge that difficulty and assess C based on data from aerobic and anaerobic energy pathways.

In this regard, the main purpose of this study was to analyse the relationship between TLim-v$\dot{V}O_2$max and SE. For that we considered three SE profile related parameters: (i) the C at v$\dot{V}O_2$max (Cv$\dot{V}O_2$max); (ii) the slope of the regression line obtained from the relationship between energy expenditure values ($\dot{E}$) and corresponding velocities in an incremental test (C_{slope}) and (iii) the ratio between the mean $\dot{E}$ value and the mean velocity value of the incremental test (C_{inc}). It was hypothesized that TLim-v$\dot{V}O_2$max should be negatively affected by Cv$\dot{V}O_2$max, C_{slope} and C_{inc}. Complementarily, given that C differs according to the subjects' level (Holmér, 1972; Costill et al., 1985; di Prampero, 1986), we observed the influence of Cv$\dot{V}O_2$max, C_{slope} and C_{inc} on the TLim-v$\dot{V}O_2$max by swimming level, in both low-level and high-level groups. For better comparison between the two groups, we also assessed the C at the swimming velocity of 1.20 $m \cdot s^{-1}$ ($C_{1.20}$).

Materials and Methods

The subjects (*n* = 30) were divided into two groups: (i) a group of 10 low-level swimmers (LLS) - Triathletes and Physical Education students - and (ii) a group of 20 highly trained competitive swimmers (HTS). The groups were matched for gender being 4 males and 6 females in the LLS group and 10 swimmers of each gender in the HTS group. The criterion to be included in the HTS group was a personal best in the 400 m front crawl event under 4:20 and 4:40 for male and female, respectively. Mean and standard deviation (mean ± SD) values for physical characteristics and swimming frequency of training are described in Table 1. All subjects volunteered to participate in this study and signed a written informed consent, where the experimental protocol was described. The Ethics Committee of our Faculty approved the experimental protocol.

Table 1. Mean ± SD values for physical characteristics and weekly swimming training frequencies of the subjects.

Parameters	Low-level swimmers (n = 10)	Highly trained swimmers (n = 20)	P value
Age (years)	23.0 ± 3.3	17.2 ± 2.2	0.000
Body mass (kg)	60.4 ± 9.1	60.9 ± 7.6	0.887
Height (m)	1.68 ± 0.08	1.70 ± 0.06	0.305
Training frequency ($n \cdot wk^{-1}$)	3.1 ± 0.7	8.3 ± 0.6	0.000

n, number of subjects.

All the test sessions took place in a 25 m indoor swimming-pool, during the final of the winter general preparatory training period. The water was maintained at 27.5ºC for all experiments. Briefly, each subject performed an individualized intermittent incremental protocol for front crawl $v\dot{V}O_2max$ assessment, with increments of 0.05 $m{\cdot}s^{-1}$ each 200 m stage and 30 s rest intervals until exhaustion (for more details see Cardoso et al., 2003). $\dot{V}O_2$ was directly measured using a metabolic cart (Sensormedics 2900 oximeter, Yorba Linda - California, USA) mounted on a special chariot running alongside the pool (Vilas-Boas, 1996) and connected to the swimmer by a 1.80 m hose, and a respiratory valve with low airflow resistance and small dead space (Toussaint et al., 1987). This extended hose was shown to do not affect $\dot{V}O_2max$ results (Toussaint and Hollander, 1994). Expired gas concentrations were averaged every 20 s. Swimming velocity was controlled using a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal) with flashing lights on the bottom of the pool.

$\dot{V}O_2max$ was considered to be reached according to primary and secondary traditional physiological criteria (Howley et al., 1995), namely the occurrence of a plateau in $\dot{V}O_2$ despite an increase in swimming velocity, high levels of blood lactic acid concentrations ($[La^-] \geq 8$ $mmol{\cdot}l^{-1}$), elevated respiratory exchange ratio ($R \geq 1.0$), elevated heart rate [HR > 90% of (220 - age)] and exhaustive perceived exertion (controlled visually and case to case). $v\dot{V}O_2max$ was considered to be the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$. If a plateau less than 2.1 $ml{\cdot}min^{-1}{\cdot}kg^{-1}$ could not be observed (7 cases reported), the $v\dot{V}O_2max$ was calculated as proposed by Kuipers et al. (1985): $v\dot{V}O_2max = v + \Delta v{\cdot}(n/N)$, where v is the velocity corresponding to the last stage accomplished, Δv is the velocity increment, n indicates the number of seconds that the subjects were able to swim during the last stage and N the pre-set protocol time (in seconds) for this step.

Capillary blood samples for [La^-] analysis were collected from the earlobe at rest (after previous local hyperaemia with Finalgon®), in the 30 s rest interval between each exercise step and at the end of exercise (YSI1500LSport auto-analyser - Yellow Springs Incorporated, Yellow Springs, Ohio, USA). HR was monitored and registered continuously each 5 s through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland). The $\dot{E}$ values for each exercise step were obtained through the addition of the net $\dot{V}O_2$ values (difference between the averaged value of the last minute of exercise and the resting value) and the values that result from the transformation of the net [La^-] (difference between last step [La^-] and the previous step) into O_2 equivalents. For this last procedure, we used the proportionality constant of 2.7 $mlO_2 \cdot kg^{-1} \cdot mM^{-1}$ (di Prampero et al., 1978), which was latter verified for capillary blood (Thevelein et al., 1984). The energetic contribution of high-energy phosphates was considered negligible (Vilas-Boas, 1996; Termin and Pendergast, 2002). $Cv\dot{V}O_2max$ was assessed as the ratio obtained by $\dot{E}$ and the corresponding $v\dot{V}O_2max$ that elicits $\dot{V}O_2max$ (di Prampero, 1986), C_{slope} was considered as the slope of the regression line obtained by the overall relationship established between $\dot{E}$ and the corresponding velocities in the incremental test (Schmidt-Nielsen, 1972; Wakayoshi et al., 1995; Kjendlie et al., 2004) and C_{inc} was assessed as the ratio obtained by the mean $\dot{E}$ value and the mean velocity value of the incremental test. The $C_{1.20}$ was also assessed as a swimming velocity commonly achieved by both LLS and HTS.

The second test session occurred 48 hours later. All subjects swam at their previously determined $v\dot{V}O_2max$ to assess TLim-$v\dot{V}O_2max$. This protocol consisted of three different phases, all paced: (i) a 10 min warm-up at an intensity correspondent to 60% $v\dot{V}O_2max$, followed by a short rest (20 s) for earlobe blood collection; (ii) a 50 m distance performed at progressive velocity, allowing the swimmers to reach their individual $v\dot{V}O_2max$, and (iii) the maintenance of that $v\dot{V}O_2max$ until volitional exhaustion or until the moment that the swimmers were unable to swim at the selected pace. TLim-v$\dot{V}O_2$max was considered the total swimming duration at the previously determined v$\dot{V}O_2$max.

$[La^-]$ were assessed at rest, during the 20 s rest intervals and immediately after exercise. The lactate production ($\Delta[La^-]$) was determined as the difference between the maximal values measured after the test and those measured after the warm-up. HR was registered continuously using the same procedure previously described.

Swimmers were instructed to use a surface open turn, always performed to the same lateral wall side, without gliding. In-water starts were also used. Swimmers were verbally encouraged to perform as long as possible during the tests. Both tests were carried out in the same conditions for each subject (i.e. water and air temperature, and time of the day) and all were instructed not to exercise hard before and between the evaluations.

Mean and SD computations for descriptive analysis were obtained for all variables for the two performance level groups and for the entire group of subjects (all data where checked for distribution normality with the Shapiro-Wilk test). Pearson’s correlation coefficient and unpaired Student's *t* test were also used. All statistical procedures were conducted with SPSS 10.05 and the significance level was set at 5%.

Results

Data concerning the variables obtained in the incremental test: $\dot{V}O_2$max, $[La^-]$max, HRmax, v$\dot{V}O_2$max, $\dot{E}$v$\dot{V}O_2$max, Cv$\dot{V}O_2$max, C_{slope}, C_{inc}, $C_{1.20}$ and the parameters assessed in the Time Limit test: TLim-v$\dot{V}O_2$max, $[La^-]$max and $\Delta[La^-]$ are reported in Table 2. In each level group, no differences by gender were observed regarding the TLim-v$\dot{V}O_2$max performance: mean ± SD values were 242.6 ± 59.1 and 231.9 ± 52.3 in HTS, and 321.5 ± 70.7 and 308.7 ± 63.8 in LLS, respectively for male and female swimmers.

Table 2. Mean ± SD values for $\dot{V}O_2$max (absolute and relative), [La$^-$]max, HRmax, v$\dot{V}O_2$max, $\dot{E}$v$\dot{V}O_2$max, Cv$\dot{V}O_2$max, C_{slope}, C_{inc}, $C_{1.20}$ (incremental test) and TLim-v$\dot{V}O_2$max, [La$^-$]max and Δ[La$^-$] (TLim test), for the two swimming level groups.

Parameters	Low-level swimmers (*n* = 10)	Highly trained swimmers (*n* = 20)	*P* value
$\dot{V}O_2$max (ml· min^{-1}·kg^{-1})	52.1 ± 6.5	69.9 ± 9.3	0.002
$\dot{V}O_2$max (l·min^{-1})	3.18 ± 0.71	4.28 ± 0.91	0.000
[La$^-$]max (mmol· l^{-1})	9.0 ± 2.0	8.0 ± 1.9	0.107
HRmax (b·min^{-1})	187.2 ± 8.3	190.4 ± 7.6	0.307
V$\dot{V}O_2$max (m·s^{-1})	1.16 ± 0.10	1.40 ± 0.06	0.000
$\dot{E}$v$\dot{V}O_2$max (mlO_2·kg^{-1}·min^{-1})	43.9 ± 7.7	62.1 ± 9.6	0.000
Cv$\dot{V}O_2$max (J·kg^{-1}·m^{-1})	13.2 ± 1.9	15.5 ± 2.2	0.007
C_{slope} (J·kg^{-1}·m^{-1})	28.0 ± 3.2	36.8 ± 4.5	0.000
C_{inc} (J·kg^{-1}·m^{-1})	10.9 ± 1.8	13.1 ± 2.3	0.008
$C_{1.20}$ (J·kg^{-1}·m^{-1})	13.6 ± 2.2	11.7 ± 2.3	0.040
TLim-v$\dot{V}O_2$max (s)	313.8 ± 63.0	237.3 ± 54.6	0.002
[La$^-$]max TLim (mmol· l^{-1})	10.6 ± 1.9	9.3 ± 1.8	0.095
Δ[La$^-$] (mmol· l^{-1})	6.8 ± 2.2	8.2 ± 1.6	0.049

$\dot{V}O_2$max, maximal oxygen consumption; [La$^-$]max, maximal blood lactic acid concentrations; HRmax, maximal heart rate; v$\dot{V}O_2$max, minimum velocity at $\dot{V}O_2$max; $\dot{E}$v$\dot{V}O_2$max, net equivalent oxygen consumption (aerobic plus anaerobic) of energy expenditure at v$\dot{V}O_2$max; Cv$\dot{V}O_2$max, energy cost at v$\dot{V}O_2$max; C_{slope}, slope of the regression line obtained from the relationship between $\dot{E}$ and corresponding velocities in the incremental test; C_{inc}, ratio obtained by the mean $\dot{E}$ value and the velocity mean value of the incremental test; $C_{1.20}$, energy cost at the swimming velocity of 1.20 m·s^{-1}; TLim-v$\dot{V}O_2$max, time limit at v$\dot{V}O_2$max; Δ[La$^-$], lactate production; n, number of subjects.

The relationship between $\dot{E}$ and swimming velocity in the incremental test for $v\dot{V}O_2max$ assessment is shown in Figure 1 for all subjects. The last 1 or 2 steps were performed at competitive intensities, i.e., at or above $v\dot{V}O_2max$, which are intensities similar to that of the 400 m event (Fernandes et al., 2003). The individual $\dot{E}$ vs. velocity determination coefficients ranged from $r^2 = 0.84$ ($P \leq 0.05$) to $r^2 = 0.99$ ($P \leq 0.01$), with a mean r^2 value of 0.962 ± 0.03.

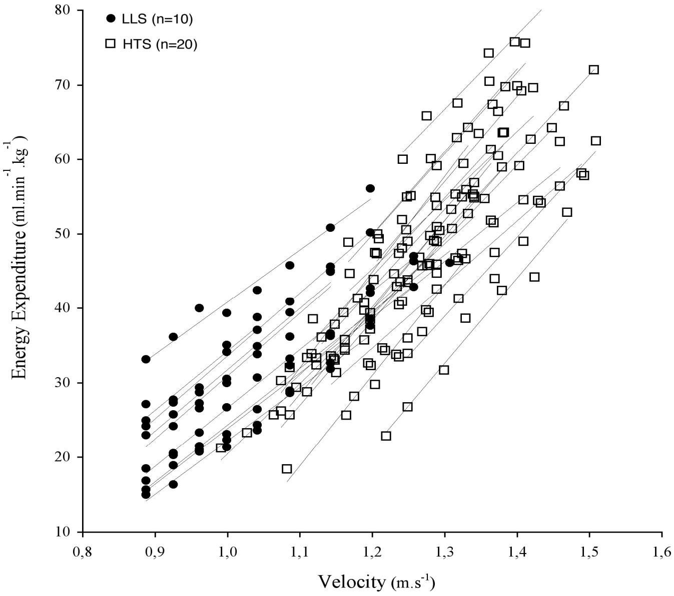

Figure 1. Relationship between $\dot{E}$ and swimming velocity in the incremental test for $v\dot{V}O_2max$ assessment. Highly trained swimmers (HTS) are identified by an □ and low-level swimmers (LLS) by a ●.

Figure 2 shows a weak, although significant, inverse relationship between TLim-$v\dot{V}O_2max$ and $v\dot{V}O_2max$ ($r = -0.35$, $P \leq 0.05$), i.e., as a group, the swimmers that obtained the highest $v\dot{V}O_2max$ seem to reach the exhaustion earlier. When considering the HTS and LLS (and also the subgroups divided by gender), no significant relationship between TLim-$v\dot{V}O_2max$ and $v\dot{V}O_2max$ was noted. For the entire sample, it was also observed moderate significant relationships between $v\dot{V}O_2max$ and $Cv\dot{V}O_2max$ ($r = 0.23$, $P < 0.01$), C_{slope} ($r = 0.22$, $P < 0.001$) and C_{inc} ($r = 0.44$, $P < 0.05$).

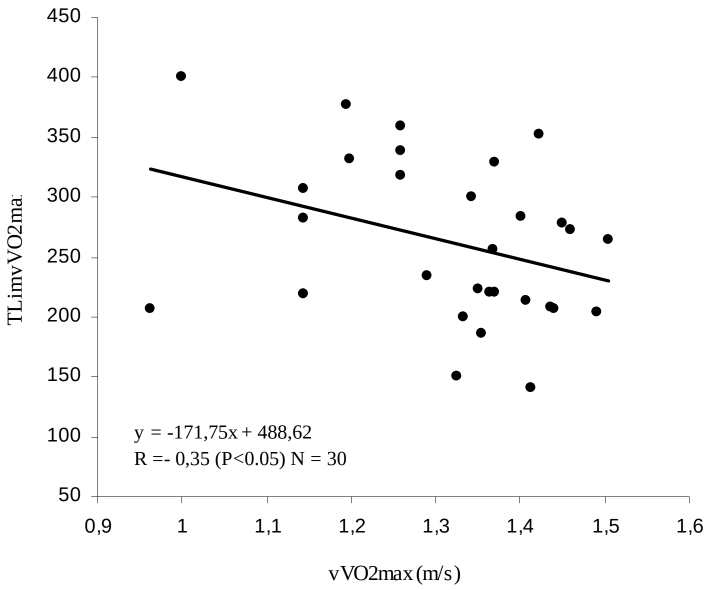

Figure 2. Relationship between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max in the entire group. Linear regression equation and correlation values are indicated.

As can be observed in Figure 3, TLim-v$\dot{V}O_2$max and C_{slope} were inversely correlated both when the entire group ($r = -0.77$, $P < 0.001$) and the two level groups: HTS ($r = -0.68$, $P < 0.001$) and LLS ($r = -0.61$, $P = 0.05$) were considered. However, no significant correlations were found between TLim-v$\dot{V}O_2$max and Cv$\dot{V}O_2$max ($r = -0.25$, $P = 0.18$), and C_{inc} ($r = -0.15$, $P = 0.43$). Complementarily, despite the moderate and negative correlation observed between v$\dot{V}O_2$max and $C_{1.20}$ ($r = -0.47$, $P < 0.01$), TLim-v$\dot{V}O_2$max did not correlate with $C_{1.20}$ ($r = 0.20$, $P = 0.30$).

No significant correlations were found between TLim-v$\dot{V}O_2$max and absolute $\dot{V}O_2$max ($r = -0.16$), relative $\dot{V}O_2$max ($r = -0.30$), $\dot{E}$v$\dot{V}O_2$max ($r = -0.33$), $[La^-]$max ($r = 0.20$) and HRmax ($r = 0.20$), obtained in the incremental test ($P > 0.05$). Likewise, no significant relationships ($P > 0.05$) were reported between TLim-v$\dot{V}O_2$max, $[La^-]$max ($r = 0.05$) and $\Delta[La^-]$ ($r = -0.20$) in the Time Limit test.

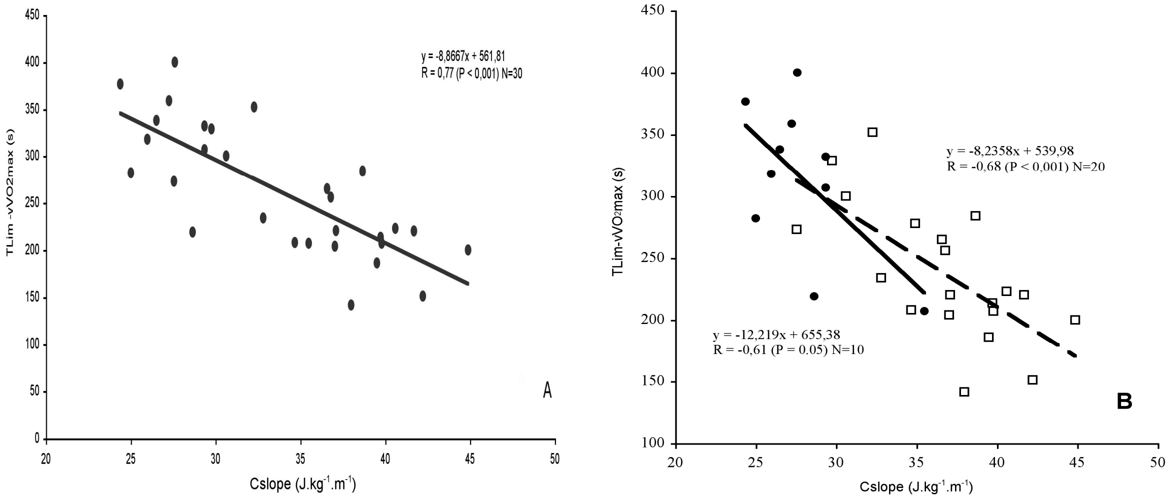

Figure 3. Relationship between TLim-v$\dot{V}O_2$max and C_{slope} for the entire group (n = 30, Panel A) and for the two swimming proficiency subgroups (n = 20 in HTS – dotted line - and n = 10 in LLS – full line, Panel B). Linear regression equation and correlation values are also indicated.

Discussion

To our knowledge, this is the first study that analyse the relationship between TLim-v$\dot{V}O_2$max and SE. The used experimental approach seems to be pertinent because it combines two of the primary areas of interest in swimming training and performance diagnosis: the speed at maximal aerobic power (and the respective duration of sustained effort) and C (Smith et al., 2002). Complementarily, this study has the advantage of been made with two level groups, to be conducted in normal swimming conditions and to consider both aerobic and anaerobic energy pathways to estimate the overall metabolic power in swimming performance. In this regard, although some authors remain defining C as the oxygen uptake at a given absolute exercise intensity, (Wakayoshi et al., 1995; Poujade et al., 2003; Kjendlie et al., 2004) it was considered fundamental to quantify the contribution of the two main energy sources: (i) oxidative phosphorylation and (ii) anaerobic glycolysis (di Prampero et al., 1978; Capelli et al., 1998). Considering that TLim-v$\dot{V}O_2$max has an effort duration and intensity very similar with the 400 m front crawl event (Termin and Pendergast, 2002; Fernandes et al., 2003) it was tried to assess C relating the more traditional aerobic energy measurements with the assessment of anaerobic energy contribution, which has been proved to be significantly present in efforts lasting from 2-4min (Toussaint and Hollander, 1994; Gastin, 2001; Termin and Pendergast, 2002).

Both HTS and LLS presented mean values of $\dot{V}O_2max$ similar to those previously described by others: higher values in HTS, like those found in well trained swimmers (Billat et al., 1996; Capelli et al., 1998; Termin and Pendergast, 2002) and moderate values in LLS, in accordance with the data for recreational and non-specialized swimmers (Costill et al., 1985; Capelli et al., 1998; Demarie et al., 2001). As expected, $v\dot{V}O_2max$ and $\dot{E}v\dot{V}O_2max$ were higher in HTS compared with LLS, which seems to reflect the superior training and performance level of the HTS group.

The TLim-$v\dot{V}O_2max$ values reported in this study for each group were similar to the data reported in swimmers of the same level (Billat et al., 1996; Demarie et al., 2001; Fernandes et al., 2003). In fact, low-level athletes seem to present higher TLim-$v\dot{V}O_2max$ values than the high-level athletes, in different sports, and particularly in swimming (Billat and Koralsztein, 1996; Fernandes et al., 2003). This subject will be addressed latter in the discussion. No differences between genders were observed in this parameter, indicating that the level groups were matched for gender regarding TLim-$v\dot{V}O_2max$.

From the present results and from the available data provided by the literature, (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003), it is likely that the individual performance in TLim-$v\dot{V}O_2max$ test does not depend directly on the swimmers' $\dot{V}O_2max$. Despite the importance of the evaluation of $\dot{V}O_2$ kinetics in swimming, $\dot{V}O_2max$ by itself seems not to be considered anymore as one of the main performance determinants in this sport (Van Handel et al., 1988;

Ribeiro et al., 1991; Toussaint and Hollander, 1994). This simply denotes that other factors rather than aerobic power may be taken into account, particularly in specific TLim-v$\dot{V}O_2$max-like efforts. Until this moment, the literature points out that the TLim-v$\dot{V}O_2$max in swimming seems to be direct and positively influenced by accumulated oxygen deficit (Faina et al., 1997), as well by the oxygen slow component (Fernandes et al., 2003), and inversely related to v$\dot{V}O_2$max (Billat et al., 1996; Renoux, 2001; Fernandes et al., 2003), which was confirmed by the results of the present study, and to the 3.5 $mmol \cdot l^{-1}$ anaerobic threshold (Fernandes et al., 2003).

The first study that analysed swimming TLim-v$\dot{V}O_2$max, hypothesized that v$\dot{V}O_2$max depended on the energy cost of locomotion, even though no relationship between efficiency or C and TLim-v$\dot{V}O_2$max was reported until then (Billat et al., 1996). The data of the present study contributes, for the first time, with new insights into this topic.

Firstly, it was noted a linear increase in the individual $\dot{E}$ values with swimming velocity. This is an open subject in the literature because other authors found out a cubic (Toussaint and Hollander, 1994; Wakayoshi et al., 1995; Kjendlie et al., 2004) relationship between those two parameters. These cubic relationships seem to be explained by the fact that the total $\dot{E}$ rate appears to adjust reasonably to the theoretical model, in which the power to overcome drag will equal the drag forces times the velocity and, thus, varies as a function of the cube of velocity (Toussaint and Hollander, 1994). Despite this formulation and the late findings, the literature suggests a linear $\dot{E}$ / v relationship (Toussaint et al., 1988; Chatard et al., 1990; Vilas-Boas, 1996). One possible explanation may be that, at higher velocities, swimming efficiency can rise, namely by the possible reduction of intra-cyclic speed fluctuations (Kornecki and Bober, 1978; Vilas-Boas, 1996). Naturally, it is likely that, at even faster velocities, efficiency can drop once again (assuming a “U” inverted shape for the efficiency/velocity function) (Cavanagh and Kram, 1985), imposing that, considering even higher swimming speeds, C can increase relatively more than expected by the proposed model.

Secondly, we reported positive relationships between C_{slope} (and Cv$\dot{V}O_2$max) and v$\dot{V}O_2$max, and an inverse relationship between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max (Fig. 2). This last finding, previously reported in running and cycling (Billat and Koralsztein, 1996; Billat et al., 1996) and in swimming (Faina et al., 1997; Renoux, 2001; Fernandes et al., 2003), and the lower TLim-v$\dot{V}O_2$max values obtained by the high-level athletes, seem to suggest that the lower level of maximal aerobic metabolic rate of the less proficient swimmers may be associated with a large capacity to sustain that exercise intensity. In this sense, it must be realised that LLS performed the incremental test at lower absolute velocities than HTS, denoting that they could not perform at higher velocities (and longer) due to lower energetic capacity and to lower mechanical efficiency in late test steps (Costill et al., 1985). The reduction in the technical ability due to fatigue in LLS is well described (Costill et al., 1985; di Prampero, 1986; Demarie et al., 2001) namely that advanced swimmers are able to swim with a greater distance per stroke than poorer swimmers at a given velocity (Costill et al., 1985; Wakayoshi et al., 1995).

Thus, the fact that HTS presented significantly higher absolute v$\dot{V}O_2$max, Cv$\dot{V}O_2$max and $\Delta[La^-]$ values than LLS seems to suggest that the TLim-v$\dot{V}O_2$max effort made by the HTS was a more strenuous one. So, the use of a higher percentage of anaerobic capacity in the TLim-v$\dot{V}O_2$max test by the HTS can be, at least, one of the explanations for the reduced time at this specific effort, due to a more deleterious intracellular ambient (with accumulation of waste products), which could contribute to an earlier fatigue stage (Billat et al., 1996; Faina et al., 1997; Laursen et al., 2003). However, we did not found any relationship between TLim-v$\dot{V}O_2$max, Cv$\dot{V}O_2$max and $\Delta[La^-]$.

For better comparison of the two level groups, it was considered the $C_{1.20}$ specific value, which was similar to those previously described (Montpetit et al., 1988; Chatard et al., 1990; Capelli et al., 1998). The HTS and LLS' $C_{1.20}$ values allowed the observation, for this velocity, that HTS had a lower C than LLS. This suggests that HTS require less energy for the same absolute velocity and/or they have highly efficient stroking mechanics or lower drag values (Table 2 and Figure 1).

Thirdly, it was verified the existence of a strong and inverse relationship between TLim-v$\dot{V}O_2$max and C_{slope}, both when the entire group and each performance level groups were considered (Fig. 3). This means that the swimmers with a lower SE slope profile, irrespectively of their performance level, can sustain longer swimming exercise at v$\dot{V}O_2$max. Similar results were presented before relating C and the 400 m swimming distance (Costill et al., 1985; Ribeiro et al., 1991; Poujade et al., 2003). This fact seems to suggest that technical ability, considered as the ratio between drag and propelling efficiency (di Prampero, 1986), is a fundamental parameter in TLim-v$\dot{V}O_2$max (and in swimming in general). In this regard, the better the swimming technique is, more metabolic power is devoted to move the body forward (overcoming drag) and less is wasted in giving to masses of water a kinetic energy change. Complementarily, it was observed that the aerobic metabolism did not directly influence the TLim-v$\dot{V}O_2$max, being, probably, the anaerobic performance capacity a very relevant parameter to these specific type of efforts, as suggested earlier (Capelli et al., 1998; Fernandes et al., 2003).

The fact that the HTS presented a C_{slope} greater than LLS seems to contradict some data present in the specialized literature (di Prampero, 1986; Chatard et al., 1990; Toussaint and Hollander, 1994). However, it must be realized that the velocities performed in the incremental test were very different between the two level groups and, assuming that there is a strong link between the anaerobic capacity and SE profiles (Troup, 1990), it keeps suggesting that the HTS seems to reach more severe steps in the incremental test with higher anaerobic energy contribution.

This study confirmed SE as an important performance-influencing factor, appearing that the swimmers with higher C_{slope} and v$\dot{V}O_2$max performed less in TLim-v$\dot{V}O_2$max efforts. Despite aerobic processes mainly supply TLim-v$\dot{V}O_2$max, the contribution of the anaerobic energy system might play an important role in this kind of workload in swimming. For a better knowledge of the complex group of factors that influence TLim-v$\dot{V}O_2$max, it is suggested a combined metabolic (with focus on anaerobic assessments) and biomechanical approach, relating some important technical parameters (e.g. stroke rate or stroke length) to the studied metabolic parameters.

Chapter 5

Has gender any effect on the relationship between time limit at $\dot{V}O_2max$ velocity and swimming economy?

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Published on J Human Movement Studies (2005), 49, 127-48.

Abstract

The purpose of this study was to examine the effect of gender in the relationship between time limit at the minimum velocity that elicits maximal oxygen consumption (TLim-v$\dot{V}O_2max$) and three swimming economy (SE) related parameters: the energy cost corresponding to v$\dot{V}O_2max$ (Cv$\dot{V}O_2max$), the slope of the regression line obtained from the relationship between energy expenditure ($\dot{E}$) and corresponding velocities in a incremental test (C_{slope}) and the ratio obtained by the mean $\dot{E}$ value and the velocity mean value of the incremental test (C_{inc}). Each subject of two gender groups – 11 male and 12 female swimmers - performed an incremental test for v$\dot{V}O_2max$ assessment and an all-out TLim-v$\dot{V}O_2max$ test. TLim-v$\dot{V}O_2max$, v$\dot{V}O_2max$, Cv$\dot{V}O_2max$, C_{slope} and C_{inc} averaged, respectively, 244.6 ± 56.5s, 1.45 ± 0.04m·s^{-1}, 15.9 ± 2.2J·kg^{-1}·m^{-1}, 35.0 ± 4.8J·kg^{-1}·m^{-1} and 14.3 ± 2.4J·kg^{-1}·m^{-1} in the male group and 248.0 ± 60.5s, 1.33 ± 0.04m·s^{-1}, 14.3 ± 1.8J·kg^{-1}·m^{-1}, 35.7 ± 6.4J·kg^{-1}·m^{-1} and 11.5 ± 1.5J·kg^{-1}·m^{-1} in the female group. An inverse correlation was found between TLim-v$\dot{V}O_2max$ and C_{slope} for the entire group ($r = -0.78$, $p < 0.001$) and for each gender group ($r = -0.90$, $p < 0.001$ and $r = -0.61$, $p < 0.05$, for female and male respectively), confirming that SE is a very important performance-influencing factor. Complementarily, despite the relationship between energy cost and TLim-v$\dot{V}O_2max$ efforts is evident in each gender, the TLim-v$\dot{V}O_2max$ tests performed by the female swimmers seem to depend more on their own SE than on male swimmers.

Key words: Swimming, time to exhaustion, energy cost, gender.

Introduction

Swimming economy (SE) is being considered as one of the most important swimming performance determinants (Van Handel et al., 1988; Chatard et al., 1990; Smith et al., 2002). To quantify SE**,** as a valuable parameter to be used both in training and in testing of competitive swimmers, the assessment of the energy cost of swimming (C) is well reported since the 1970's. More recently, di Prampero (1986) defined C as the amount of energy, above pre-exercise resting value, spent per unit of distance. In this sense, some publications aimed to study C at distinct workloads and reported differences by strokes, levels of swimming proficiency, gender and age (Holmér 1972; di Prampero et al., 1974; Pendergast et al., 1977; di Prampero 1986; Montpetit et al., 1988; Toussaint and Hollander 1994; Vilas-Boas, 1996; Capelli et al., 1998; Poujade et al., 2002; Kjendlie et al., 2004).

One recent topic of interest in swimming training and performance diagnosis is the concept of Time Limit, i.e., the time duration during which a certain intensity of exercise can be sustained until exhaustion (Billat and Koralsztein, 1996). Time Limit in swimming has been studied mainly at intensities corresponding to maximal oxygen uptake (TLim-v$\dot{V}O_2$max), being firstly conducted in swimming flume (Billat et al., 1996; Faina et al., 1997; Demarie et al., 2001) and after in free swimming in a conventional pool (Renoux, 2001; Fernandes et al., 2003). The main findings of the above-mentioned studies were: (i) TLim-v$\dot{V}O_2$max seems to be direct and positively influenced by accumulated oxygen deficit (Faina et al., 1997) and $\dot{V}O_2$ slow component (Fernandes et al., 2003); (ii) TLim-v$\dot{V}O_2$max seems to be inversely influenced by v$\dot{V}O_2$max (Billat et al., 1996; Faina et al., 1997; Renoux, 2001; Fernandes et al., 2003) and 3,5mmol l^{-1} blood lactate anaerobic threshold (Fernandes et al., 2003); (iii) TLim-v$\dot{V}O_2$max seems to be not related to $\dot{V}O_2$max (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003) and maximal blood lactic acid concentrations ($[La^-]$max) (Fernandes et al., 2003) and (iv) TLim-v$\dot{V}O_2$max seems to be a kind of effort very well related to the 400 m front crawl performance (Termin and Pendergast, 2000; Fernandes et al., 2003).

Despite these last studies, no report was published relating TLim-v$\dot{V}O_2$max and C, taking into account the swimmers' gender. So, as it is accepted since the pioneer work of Liljestrand and Stenstrom (1919) that C, even when related to the body size, depends on gender and that female swimmers, in general, are more economical than male, the main purpose of this study was to analyse the effect of gender in the relationship between TLim-v$\dot{V}O_2$max and SE. For that purpose it were studied three SE profile related parameters: (i) the C corresponding to v$\dot{V}O_2$max (Cv$\dot{V}O_2$max); (ii) the slope of the regression line obtained from the relationship between energy expenditure values ($\dot{E}$) and corresponding velocities in a incremental test (C_{slope}) and (iii) the ratio obtained by the mean $\dot{E}$ value and the mean velocity value of the incremental test (C_{inc}). It was hypothesized that TLim-v$\dot{V}O_2$max should be negatively affected by Cv$\dot{V}O_2$max, C_{slope} and C_{inc} in the entire group of subjects and in each gender subgroup. Moreover, it was suggested that the gender effect of C in TLim-v$\dot{V}O_2$max efforts will be of greater amplitude in the female swimmers group once they are reported as more economical than their male counterparts. For better comparison purposes between the two groups, it was also assessed the C corresponding to the swimming velocities of 1.30 $m \cdot s^{-1}$ ($C_{1.30}$). Complementarily, as it is known that C is affected by some physical characteristics, namely by body surface area (SA) (Pendergast et al., 1977; di Prampero 1986; Montpetit et al., 1988), it was also studied the influence of this anthropometric parameter in Cv$\dot{V}O_2$max, C_{slope} and C_{inc} and its relation with TLim-v$\dot{V}O_2$max by gender.

Some referential studies conducted around this topic determined C estimating only the contribution of aerobic energy processes, by assessing the "oxygen cost", normally at submaximal intensities (di Prampero et al., 1974; Pendergast et al., 1977; Costill et al., 1985; Montpetit et al., 1988; Troup and Daniels 1988;

Van Handel et al., 1988; Chatard et al., 1990; Wakayoshi et al., 1995; Poujade et al., 2002; Kjendlie et al., 2004). This fact imposes the negligence of the anaerobic contribution to the overall energy requirement, which may be justified by methodological difficulties. In this study it was tried to overlap that difficulty and assess C with the data of both energy sources. In doing so, it was possible to obtain new data about the behaviour of some SE related parameters, by gender, at swimming velocities well related to the 400 m front crawl competition event, where the anaerobic contribution has been regarded to achieve a value of approximately 20% of the total energy expenditure (Toussaint and Hollander 1994; Gastin 2001; Rodriguez and Mader, 2003). To our knowledge only di Prampero (1986), Vilas-Boas (1996), Capelli et al. (1998) and Rodriguez (1999) assessed C at velocities at, or very near, competition intensities.

Materials and Methods

The entire sample (n = 23) was divided into two groups: a group of 11 male and a group of 12 female experienced competitive swimmers. The inclusion criterion was a $v\dot{V}O_2max$ higher than 1.40 m s^{-1} and 1.25 m s^{-1} for male and female swimmers, respectively. The two gender subgroups were matched for performance by converting the individual $v\dot{V}O_2max$ values into the Ligue Européenne de Natacion Point Score System (no difference between groups was observed, $p = 0.90$). All the subjects volunteered for the study and signed an informed consent form.

Mean and standard deviation (mean ± SD) values for physical characteristics and weekly frequency of training of the male and female groups are described in Table 1. After measuring the standing height (H) and body mass (BM) of the subjects, the surface area (SA) was estimated using the equation of Du Bois and Du Bois (revisited by Shuter and Aslani 2000):

$$SA = H^{0.655} \times BM^{0.441} \times 94.9 \qquad \text{(Eq. 1)}$$

Table 1. Mean ± SD values for physical characteristics and weekly training frequencies of the subjects. * Represents a significant difference between the two gender groups (*P* ≤ 0.001).

Parameters	Male swimmers (n = 11)	Female swimmers (n = 12)
Age (years)	17.73 ± 1.49	17.42 ± 3.18
Body mass (kg)	67.27 ± 6.02*	54.75 ± 2.14*
Height (cm)	175.55 ± 4.61*	165.33 ± 3.11*
Surface area (m^2)	1.79 ± 0.08*	1.57 ± 0.04*
Training session ($n.wk^{-1}$)	8.32 ± 0.51	7.96 ± 1.14
$v\dot{V}O_2max$ (LEN points)	534.82 ± 43.35	537.08 ± 48.58

$v\dot{V}O_2max$ (LEN points), minimum velocity corresponding to $\dot{V}O_2max$ converted in Ligue Européenne de Natacion Point Score System; *n*, number of subjects.

All the test sessions took place in a 25 m indoor swimming-pool. Briefly, each subject performed an individualized intermittent incremental protocol for front crawl $v\dot{V}O_2max$ assessment, with increments of 0.05 m s^{-1} each 200 m stage and 30 s rest intervals until exhaustion (Fernandes et al., 2003). Initial velocity was established according to the individual level of fitness and it was set at the swimmer's individual performance on the 400 m front crawl minus seven increments of velocity. $\dot{V}O_2$ was directly measured using a metabolic cart (Sensormedics 2900 oximeter, Yorba Linda - California, USA) mounted on a special chariot running along the pool (Vilas-Boas, 1996) and connected to the swimmer by a respiratory valve (Toussaint et al., 1987). Expired gas concentrations were averaged every 20 s. Swimming velocity was controlled using a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal) with flashing lights on the bottom of the pool.

$\dot{V}O_2max$ was considered to be reached according to primary and secondary traditional physiological criteria (Howley et al., 1995), namely the occurrence of a plateau in $\dot{V}O_2$ despite an increase in swimming velocity, high levels of $[La^-]$ (≥ 8 mmol l^{-1}), elevated respiratory exchange ratio (R ≥ 1.0), elevated heart rate

[HR > 90% of (220 - age)], and exhaustive perceived exertion (controlled visually and case to case). v$\dot{V}O_2max$ was considered to be the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$. If a plateau less than 2.1 ml min^{-1} kg^{-1} could not be observed, the v$\dot{V}O_2max$ was calculated as follows (Kuipers et al., 1985):

$$v\dot{V}O_2max = v + \Delta v \cdot (n\ N^{-1}), \qquad \text{(Eq. 2)}$$

where v is the velocity corresponding to the last stage accomplished, Δv is the velocity increment, n indicates the number of seconds that the subjects were able to swim during the last stage and N the pre-set protocol time (in seconds) for this step.

Capillary blood samples for [La^-] analysis were collected from the earlobe at rest, in the 30 s rest interval, at the end of exercise and during the recovery period (YSI1500LSport auto-analyser - Yellow Springs Incorporated, Yellow Springs, Ohio, USA). HR was monitored and registered continuously each 5 s through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland). The $\dot{E}$ values for each exercise step were obtained through the addition of the net $\dot{V}O_2$ values (difference between the averaged value from the last minute of exercise and the rest value) and the values resultant from the transformation of the net [La^-] (difference between last step [La^-] and the previous step) into O_2 equivalents. For this last procedure it was used the proportionality constant of 2.7 mlO_2 kg^{-1} mM^{-1} proposed by di Prampero et al. (1978) and verified for capillary blood by Thevelein et al. (1984). The energetic contribution of high-energy phosphates was considered negligible (Vilas-Boas 1996; Termin and Pendergast, 2000). Cv$\dot{V}O_2max$ was assessed as the ratio of $\dot{E}$ and the corresponding swimming minimum velocity that elicits $\dot{V}O_2max$ (di Prampero, 1986), C_{slope} was considered as the slope of the regression line obtained by the overall relationship established between $\dot{E}$ and the corresponding velocities in the incremental test (Schmidt-Nielsen, 1972; Wakayoshi et al., 1995; Kjendlie et al., 2004) and C_{inc} was assessed as the ratio obtained by the mean $\dot{E}$ value and the mean velocity value of the incremental test. The $C_{1.30}$ was also assessed as it corresponds to a swimming velocity commonly achieved by both male and female swimmers.

The second test session occurred 48 hours later. All subjects swam at their previously determined $v\dot{V}O_2max$ to assess TLim-$v\dot{V}O_2max$. This protocol consisted in three different phases, all paced: (i) a 10 min warm-up at an intensity correspondent to 60% $v\dot{V}O_2max$, followed by a short rest (20 s) for earlobe blood collection; (ii) a 50 m distance performed at progressive velocity, allowing the swimmers to reach their individual $v\dot{V}O_2max$, and (iii) the maintenance of that swimming $v\dot{V}O_2max$ until volitional exhaustion or until the moment that the swimmers were unable to swim at the selected pace. TLim-$v\dot{V}O_2max$ was considered to be the total swimming duration at the pre-determined velocity. Distance limit (DLim-$v\dot{V}O_2max$) was, as well, registered as the distance performed (in meters) during the TLim-$v\dot{V}O_2max$ test.

$[La^-]$ were assessed at rest, during the 20 s intervals, immediately after exercise and at minute 3 (and minute 5) of the recovery period. The lactate production ($\Delta[La^-]$) was determined as the difference between the maximal values measured after the test and those measured after the warm-up. HR was registered continuously using the same procedure previously described.

Swimmers were instructed to use a surface open turn, always performed to the same lateral wall side, without underwater gliding. In-water starts were also used. Swimmers were verbally encouraged to perform as long as possible during the tests. Both tests were carried out in the same conditions for each subject (i.e. water and air temperature, and time of the day) and all were instructed not to exercise hard before and between the evaluations.

Mean and SD computations for descriptive analysis were obtained for all variables for the two gender groups and for the total group of subjects (all data where checked for distribution normality with the Shapiro-Wilk test). Pearson's correlation coefficient and unpaired and paired samples Student's *t* test were also used. All statistical procedures were conducted with SPSS 10.05 and a significance level of 5% was accepted.

Results

Data concerning the variables obtained in the incremental test: $\dot{V}O_2max$, $[La^-]max$, HRmax, $v\dot{V}O_2max$, $\dot{E}$ corresponding to $v\dot{V}O_2max$ ($\dot{E}v\dot{V}O_2max$), $Cv\dot{V}O_2max$, C_{slope}, C_{inc} and $C_{1.30}$ and the parameters assessed in the Time Limit test: TLim-$v\dot{V}O_2max$, DLim-$v\dot{V}O_2max$, $[La^-]max$ and $\Delta[La^-]$ are reported in Table 2.

The relationship, by gender, between $\dot{E}$ and swimming velocity in the incremental test for $v\dot{V}O_2max$ assessment is shown in Figure 1. The last 1 or 2 steps were performed at competitive intensities, i.e., at, or above, $v\dot{V}O_2max$, which are intensities very similar to the usual velocity of the 400 m event (Fernandes et al., 2003). The individual $\dot{E}$ vs. velocity determination coefficients ranged from $r^2 = 0.84$ ($p \leq 0.05$) to $r^2 = 0.99$ ($p \leq 0.001$), having a mean value of $r^2 = 0.96$ ($\pm$ 0.04).

An inverse significant correlation was found between TLim-$v\dot{V}O_2max$ and C_{slope}, for the entire group of individuals and for each gender group (Figure 2). DLim-$v\dot{V}O_2max$ and C_{slope} also presented a significant inverse relationship for the entire sample ($r = -0.76$, $P < 0.001$) and for the female ($r = -0.85$, $P < 0.001$) and male groups ($r = -0.66$, $P < 0.05$). However, no significant correlations were found between TLim-$v\dot{V}O_2max$ (or DLim-$v\dot{V}O_2max$) and $Cv\dot{V}O_2max$, and C_{inc}. TLim-$v\dot{V}O_2max$ and $v\dot{V}O_2max$ were not significantly related for the entire sample ($r = -0.12$, $P > 0.05$), or for each of the gender groups. $v\dot{V}O_2max$ was well related with $Cv\dot{V}O_2max$ in the male group ($r = 0.61$, $P < 0.05$), and with C_{inc} (r = 0.55 and r = 0.79, P < 0.01 for the total and female groups, respectively). The correlation value obtained between $v\dot{V}O_2max$ and C_{slope} in the all group of swimmers was only valid for a P < 0.10 (r = 0.37, P = 0.08).

Table 2. Mean ± SD values for $\dot{V}O_2max$ (absolute and relative), $[La^-]max$, HRmax, $v\dot{V}O_2max$, $\dot{E}v\dot{V}O_2max$, $Cv\dot{V}O_2max$, C_{slope}, C_{inc} and $C_{1.30}$ (incremental test) and TLim- $v\dot{V}O_2max$, DLim-$v\dot{V}O_2max$, $[La^-]max$ and $\Delta[La^-]$ (TLim test), for the two gender groups. Significant differences between the groups are shown by * (*P* ≤ 0.05) and ** (*P* ≤ 0.01).

Parameters	Male swimmers (n = 11)	Female swimmers (n = 12)
$\dot{V}O_2max$ (ml kg^{-1} min^{-1})	75.07 ± 8.65**	62.67 ± 5.80**
$\dot{V}O_2max$ (l min^{-1})	5.03 ± 0.56**	3.43 ± 0.34**
$[La^-]max$ (mmol l^{-1})	7.88 ± 1.31	7.70 ± 2.42
HRmax (b min^{-1})	188.45 ± 7.23	191.92 ± 6.86
$v\dot{V}O_2max$ (m s^{-1})	1.45 ± 0.04**	1.33 ± 0.04**
$\dot{E}v\dot{V}O_2max$ (mlO_2 kg^{-1} min^{-1})	66.05 ± 8.46**	54.82 ± 8.04**
$Cv\dot{V}O_2max$ (J kg^{-1} m^{-1})	15.91 ± 2.19*	14.11 ± 1.81*
C_{slope} (J kg^{-1} m^{-1})	34.95 ± 4.83	35.70 ± 6.42
C_{inc} (J kg^{-1} m^{-1})	14.26 ± 2.39**	11.45 ± 1.54**
$C_{1.30}$ (J kg^{-1} m^{-1})	13.79 ± 2.65	13.28 ± 1.19
TLim-$v\dot{V}O_2max$ (s)	244.63 ± 56.45	247.95 ± 60.49
DLim-$v\dot{V}O_2max$ (m)	354.54 ± 82.02	329.17 ± 76.00
$[La^-]max$ TLim (mmol l^{-1})	9.33 ± 1.91	9.58 ± 1.78
$\Delta[La^-]$ (mmol l^{-1})	8.33 ± 1.62	7.72 ± 2.54

$\dot{V}O_2max$, maximal oxygen consumption; $[La^-]max$, maximal blood lactic acid concentrations; HRmax, maximal heart rate; $v\dot{V}O_2max$, minimum velocity corresponding to $\dot{V}O_2max$; $\dot{E}v\dot{V}O_2max$, energy expenditure corresponding to $v\dot{V}O_2max$; $Cv\dot{V}O_2max$, energy cost corresponding to $v\dot{V}O_2max$; C_{slope}, slope of the regression line obtained from the relationship between $\dot{E}$ and corresponding velocities in the incremental test; C_{inc}, ratio obtained by the mean $\dot{E}$ value and the velocity mean value of the incremental test; $C_{1.30}$, energy cost corresponding to the swimming velocity of 1.30 m·s^{-1}; TLim-$v\dot{V}O_2max$, time limit at $v\dot{V}O_2max$; DLim-$v\dot{V}O_2max$, distance limit at $v\dot{V}O_2max$; $\Delta[La^-]$, lactate production; *n*, number of subjects.

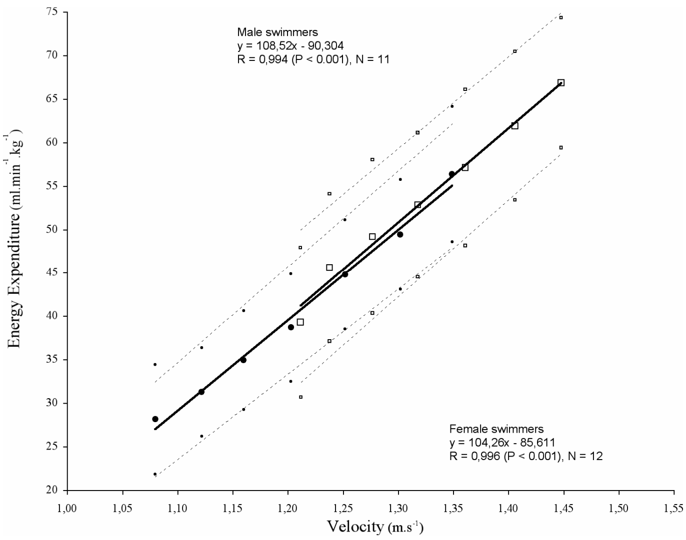

Figure 1. Relationship between $\dot{E}$ and swimming velocity in the incremental test for v$\dot{V}O_2$max assessment (male and female swimmers are identified by an □ and an ●, respectively). The 95% confidence intervals of the regression lines are also shown.

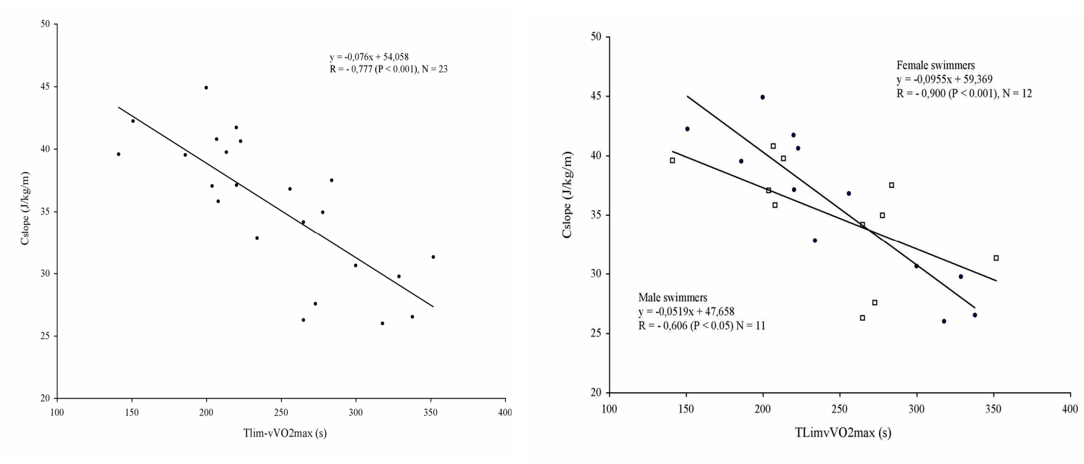

Figure 2. Relationship between TLim-v$\dot{V}O_2$max and C_{slope} for the entire group of subjects (left panel) and for each swimmer gender group (right panel, being male and female swimmers identified by an □ and an ●, respectively).

A direct relationship was observed between C_{inc} and SA for all subjects ($r = 0.44$, $P < 0.05$) and the female gender group ($r = 0.63$, $P < 0.05$). C_{slope} also presented a moderate positive correlation value with SA for the entire group of subjects but only when C was expressed in absolute terms – $j.m^{-1}$ ($r = 0.59$, $P <$

0.01). SA was not related at all with Cv$\dot{V}O_2$max, TLim-v$\dot{V}O_2$max and with DLim-v$\dot{V}O_2$max.

No significant correlations were found between TLim-v$\dot{V}O_2$max and absolute $\dot{V}O_2$max (r = -0.09), relative $\dot{V}O_2$max (r = -0.04), $\dot{E}$v$\dot{V}O_2$max (r = -0.24), [La$^-$]max (r = -0.02) and HRmax (r = 0.14), all these parameters obtained in the incremental test (P > 0.05). Likewise, no significant relationships (P > 0.05) were reported between TLim-v$\dot{V}O_2$max, [La$^-$]max (r = -0.11) and Δ[La$^-$] (r = -0.29).

Discussion

The precise relationship between the maximal metabolic power and the exhaustion time has been and still is a matter for debate (di Prampero, 2003). Combining the speed at $\dot{V}O_2$max (and its temporal sustainability) and SE - two of the primary areas of interest in swimming training and performance diagnosis (Smith et al., 2002) - the approach applied in this study seems to give a new contribution in the above-mentioned topic. Complementarily, the present study has the advantage of having been conducted in swimming-pool and to focus in the important combination between aerobic and anaerobic metabolic factors of the overall swimming specific metabolic power. So, although some authors remain defining C as the oxygen uptake required at a given absolute exercise intensity (Wakayoshi et al., 1995; Poujade et al., 2002; Kjendlie et al., 2004), it was considered fundamental to quantify the contribution of the two fundamental sources of energy for swimming performance (di Prampero et al., 1978; Capelli et al., 1998): (i) oxidative phosphorylation and (ii) anaerobic glycolysis. As it seems that TLim-v$\dot{V}O_2$max had an effort duration and intensity very close with the 400 m front crawl event (Termin and Pendergast, 2000; Fernandes et al., 2003), it was tried to assess SE relating the more traditional aerobic energy measurements with the assessment of lactic energy contribution, which has been proved to be significantly present in efforts lasting from 2-4min (Ribeiro et al., 1991; Toussaint and Hollander, 1994; Termin and Pendergast, 2000; Gastin 2001). The utilization of an intermittent incremental protocol for swimming v$\dot{V}O_2$max assessment has been noticed to be a valid method (Fernandes et al., 2003) and the intensities of the first step of the incremental protocol were also successfully used before (Capelli et al., 1998; Demarie et al., 2001; Fernandes et al., 2003).

Both male and female groups of swimmers presented $\dot{V}O_2$max mean values similar to those described in the literature for experienced competitive swimmers (Van Handel et al., 1988; Billat et al., 1996; Capelli et al., 1998; Termin and Pendergast, 2000; Rodriguez and Mader, 2003). The finding that male swimmers presented higher $\dot{V}O_2$max than female swimmers was also previously described (Holmér 1972; Pendergast et al., 1977; Costill et al., 1985; Rodriguez and Mader, 2003). The obtained mean values of $[La^-]$max and HRmax are, as well, in accordance with the literature for intensities of exercise corresponding to $\dot{V}O_2$max (Howley et al., 1995; Billat et al., 1996; Renoux, 2001; Fernandes et al., 2003). As expected, v$\dot{V}O_2$max and $\dot{E}$v$\dot{V}O_2$max were higher in the male group, when compared with the female swimmers, reflecting the male higher bioenergetic ($\dot{V}O_2$max) and anthropometric characteristics (SA, H and BM). Notice that each gender group was homogeneous with respect to their individual v$\dot{V}O_2$max values (values lower than 1.40 m s^{-1} and 1.25 m s^{-1} for male and female groups, respectively, were not acceptable) and that there were no differences in age, training frequency and LEN points between sexes. Complementarily, the Cv$\dot{V}O_2$max mean values were also different between groups, with male swimmers having a higher Cv$\dot{V}O_2$max than female swimmers. This higher Cv$\dot{V}O_2$max in the male group could had some negative effect on their TLim-v$\dot{V}O_2$max results because it suggests that male specific effort was a more strenuous one, which could contribute to an earlier fatigue stage (in accordance with Billat et al., 1996 and Faina et al., 1997). However, it was not found any difference between genders in the TLim-v$\dot{V}O_2$max efforts as well as any statistical relationship between TLim-v$\dot{V}O_2$max (or DLim - v$\dot{V}O_2$max) and Cv$\dot{V}O_2$max.

Concerning to the C_{inc} mean values, it was also observed a higher mean value in the male group. This result seems to be logical due to the fact that the velocities of the incremental test performed by the male swimmers were higher than the velocities achieved by the female swimmers, which implies higher corresponding $\dot{E}$ values. The raise of the $\dot{E}$ values with the swimming velocity is justified by the increasing power output necessary to overcome drag as water resistance is related to the square of the swimming velocity (Toussaint and Hollander, 1994). Complementarily, male swimmers in general have a greater body cross-sectional area than female, which implies that they also have a greater drag to overcome, increasing C (Toussaint et al., 1988). In addition, male swimmers have as well higher hydrostatic torque values, which promote a "more vertical" position in water (namely due to the higher density in the lower limbs), being considered one of the main determinants of C (Pendergast et al., 1977; Zamparo et al., 1996). Unfortunately, body cross-sectional area and torque were not assessed in the present study. However, SA is accepted as a well-related parameter with those referred kineanthropometric parameters (Zamparo et al., 1996) and male swimmers had higher SA than female swimmers (as it was presented in Table 1).

Regarding to the last studied SE related parameter no difference between male and female groups was registered in C_{slope} mean values. To our knowledge, only Montpetit et al. (1988) and Van Handel et al. (1988) obtained this same result, i.e., the absence of difference between the slopes of the $\dot{E}$/v relationship between genders. In this context, similarly as in the present study, Montpetit et al. (1988) evidenced that swimmers of both genders were selected from equivalent performance groups and not from unmatched groups as found in previous studies (e.g. Pendergast et al., 1977 and Costill et al., 1985).

Moreover, in the first studies that assessed $\dot{E}$ and C in swimming, the body weight of the swimmers was not taken into account (e.g. Pendergast et al., 1977 and Costill et al., 1985), i.e., C values were not normalized for body weight. This fact implied that the higher and heavier swimmers, generally the male swimmers, had higher C values for the same absolute swimming velocity than the smallest and lighter ones. Following Montpetit et al. (1988) and Van Handel et al. (1988) it was used in the present study the $\dot{E}$ values adjusted to the body mass of the swimmers. For better comparison purposes between the two gender groups, as well as with the literature data, it was considered the $C_{1.30}$ specific value, corresponding to a common performed swimming velocity. It was observed that the $C_{1.30}$ mean values of the male and females groups did not differ significantly, suggesting that the well experienced swimmers of both genders require similar amount of energy and/or they have analogous efficient stroking mechanics to perform at the this same absolute velocity (Table 2 and Figure 1). Furthermore, the $C_{1.30}$ mean values of the two gender groups were coherent with the $C_{1.30}$ values usually presented in the literature for well-trained swimmers (Montpetit et al., 1988; Chatard et al., 1990; Capelli et al., 1998). This result suggests that, for common performed velocities, the advantage of female swimmers in having a low H, BM and SA (contributing for a lower torque) is matched by the greater aerobic power of male swimmers.

The TLim-v$\dot{V}O_2$max mean value observed for the male group was similar to the data reported in the literature for male experienced swimmers (Billat et al., 1996; Faina et al., 1997; Renoux, 2001; Fernandes et al., 2003). As an exception, Demarie et al. (2001) presented a higher time limit mean value, which can be explained by the lower swimming intensity used in their protocol (time to exhaustion at 95% v$\dot{V}O_2$max). No previously reports about TLim-v$\dot{V}O_2$max (or at other swimming intensities close to v$\dot{V}O_2$max) exclusively for female swimmers were found in the literature, which does not allow us to make any comparisons with our data. Nevertheless, the TLim-v$\dot{V}O_2$max effort of the female swimmers was not different from the results obtained by the male group.

Complementarily to the TLim-v$\dot{V}O_2$max data, Dlim-v$\dot{V}O_2$max was assessed, which demonstrates, one more time, that TLim-v$\dot{V}O_2$max is a kind of effort with a duration very similar with the 400 m front crawl event (in accordance with Termin and Pendergast, 2000 and Fernandes et al., 2003). In fact, if the TLim-v$\dot{V}O_2$max tests were performed with a block start and with the flip turns usually performed in the front crawl events, the Dlim-v$\dot{V}O_2$max mean values probably were even more close to the 400 m distance.

From the present results and from the literature data (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003), it seems that individual performance in TLim-v$\dot{V}O_2$max test does not depend directly on swimmer's $\dot{V}O_2$max. Despite the importance of the evaluation of $\dot{V}O_2$ kinetics in swimming, $\dot{V}O_2$max by itself seems not to be considered anymore as one of the main performance determinants in this sport (Costill et al., 1985; Troup and Daniels 1986; Van Handel et al., 1988; Ribeiro et al., 1991; Toussaint and Hollander, 1994). However, it is not credible to deny that $\dot{V}O_2$max plays a central role among the energy-yielding mechanisms (di Prampero, 2003) and that aerobic capacity is unimportant in swimming performance. This simply denotes that other factors may obscure the importance of aerobic energy production during swimming, namely in specific TLim-v$\dot{V}O_2$max efforts.

In the first research that studied swimming TLim-v$\dot{V}O_2$max, Billat et al. (1996) hypothesized that v$\dot{V}O_2$max depends on the C of locomotion, even though no relationship between efficiency or C and TLim-v$\dot{V}O_2$max was reported until then. The present study seems to bring new insights to this topic.

Firstly, it was observed (Fig. 1) that mean $\dot{E}$ values seem to have a linear increase with swimming velocity. Despite the fact that this is an open subject in literature, namely because other studies refer to an exponential relationship between those two parameters at submaximal velocities (Toussaint and

Hollander, 1994; Wakayoshi et al., 1995; Kjendlie et al., 2004), it were found similar references pointing out a linear $\dot{E}$ / v relationship (Montpetit et al., 1988; Toussaint et al., 1988; Chatard et al., 1990; Vilas-Boas, 1996; Rodriguez, 1999). This fact can be explained according to the possibility that, at higher velocities, the swimming efficiency can rise, namely by the possible reduction of intra-cyclic speed fluctuations (di Prampero et al., 1974; Kornecki and Bober 1978; Vilas-Boas, 1996).

Secondly, it was noticed the existence of some positive relationships between $v\dot{V}O_2max$ and the studied SE related parameters: (i) $Cv\dot{V}O_2max$ (in the male group), (ii) C_{inc} (in the entire sample and in the female group) and (iii) C_{slope} (in the total group, but only for a $p < 0.10$). These findings, previously found in running and cycling (Billat and Koralsztein, 1996; Billat et al., 1996) and swimming (unpublished data of our group), seem to suggest that the swimmers with a higher $v\dot{V}O_2max$ could have more difficulties to sustain that kind of maximal aerobic effort. Inclusively, it was found in previous studies, performed in running and swimming, that $v\dot{V}O_2max$ had an inverse relationship with TLim-$v\dot{V}O_2max$ (Billat and Koralsztein, 1996; Billat et al., 1996; Faina et al., 1997; Renoux, 2001; Fernandes et al., 2003), which could help to explain the fact that, in a heterogeneous group, the less proficient athletes have higher TLim-$v\dot{V}O_2max$ values than the better trained subjects. In the present study, however, it was not observed any (inverse) relationship between $v\dot{V}O_2max$ and TLim-$v\dot{V}O_2max$. This could be understood due to the fact that the swimmers' participation criterion was very restrictive, which increased considerably the homogeneity of the present sample.

Thirdly, it was verified the existence of an inverse relationship between TLim-$v\dot{V}O_2max$ and C_{slope} for the entire group of subjects and for each gender group (Fig. 2). This means that the swimmers with a lower SE slope profile, irrespective of their gender, can sustain longer an intensity of swimming effort corresponding to the $v\dot{V}O_2max$. Similar results were presented before, relating

C and the 400 m swimming performance (Costill et al., 1985; Ribeiro et al., 1991; Rodriguez, 1999; Poujade et al., 2002). This fact seems to suggest that technical ability, considered as the ratio between drag and propelling efficiency (di Prampero, 1986), is a fundamental parameter in TLim-v$\dot{V}O_2$max (and in swimming in general), because the better the swimming technique is, more metabolic power is devoted to move the body forward – overcoming drag - and less is wasted in giving to masses of water a kinetic energy change. This fact seems to be more evident for the female swimmers (the coefficient of determination was stronger for male than for female: 0.81 and 0.37, respectively) what can be understood by their higher floatability. Complementarily, as referred earlier, it was observed that the aerobic metabolism did not influence directly the TLim-v$\dot{V}O_2$max results. Thus, we could hypothesize that, probably, the anaerobic performance capacity a very relevant parameter to these specific type of efforts (as suggested by Capelli et al., 1998 and Fernandes et al., 2003). However, TLim-v$\dot{V}O_2$max did not presented any relationship with [La^-]max and Δ[La^-] in the TLim-v$\dot{V}O_2$max test. Probably, the oxidation of lactate during performance may account for this unexpected result.

As expected, SA related positively with C, namely with C_{inc} for the female group of swimmers (and in the entire sample of swimmers). Strangely this result did not appear in the male group, suggesting that other parameters than SA can strongly influence C.

In conclusion, this study confirmed that SE, expressed in C values, is a very important swimming performance influencing factor, especially in the specific typical TLim-v$\dot{V}O_2$max efforts. Despite the relationship between energy cost and TLim-v$\dot{V}O_2$max efforts is evident in each gender, the TLim-v$\dot{V}O_2$max tests performed by the female swimmers seem to depend more in their own SE than on male swimmers. For a better knowledge of the complex group of factors that influence TLim-v$\dot{V}O_2$max, it is suggested a combined metabolic and biomechanical approach, namely relating some important technical parameters connected to SE (e.g. stroke length and stroke index) to the studied metabolic parameters.

Acknowledgements

It was appreciated the help of Drs. António Ascensão and José Magalhães, from the Biology Department, and Prof. Dr. Leandro Machado, from the Biomechanics Department of our Faculty, for their significant contribution.

Chapter 6

Is Time Limit at the minimum swimming velocity of $\dot{V}O_2max$ influenced by stroking parameters?

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Published on Percept. Mot. Skills (2006), 103, 67-75.

Abstract

The aim of this study was to observe the relationship between time limit at the minimum velocity that elicits maximal oxygen consumption (TLim-v$\dot{V}O_2$max) and stroke rate, stroke length and stroke index. Twenty-three (13 men and 10 women) highly trained swimmers were studied. Each subject performed an intermittent incremental test for v$\dot{V}O_2$max assessment and an all-out swim to determine TLim-v$\dot{V}O_2$max. The mean ± SD TLim-v$\dot{V}O_2$max, v$\dot{V}O_2$max, stroke rate, stroke length and stroke index values were: 233.36 ± 53.92 sec., 1.40 ± 0.06 meter/sec., 35.58 ± 2.89 cycles/min, 2.39 ± 0.22 meter/cycle and 3.36 ± 0.41 $meter^2$/ (cycle*s). Negative correlation was observed between TLim-v$\dot{V}O_2$max and stroke rate (r = -0.51, p <0.01) and a direct relationship was found between TLim-v$\dot{V}O_2$max and stroke length (r = 0.52, p <0.01), and stroke index (r = 0.45, p <0.05). These results seem to suggest that technical ability is a key factor in typical efforts requiring prolonged aerobic power.

Key words: time to exhaustion, stroke rate, stroke length, stroke index

Introduction

Success in competitive swimming is based upon the time required to perform a specific distance. If the starts and turns are ignored, the time to cover a given distance can be determined by the swimming velocity. The ability to achieve and maintain a specific velocity in an event is related to biomechanical and metabolic factors (Termin and Pendergast, 2000). Among the important swimming biomechanical factors, the stroking parameters are some of the most studied and relevant for coaches: stroke rate (SR), the rate at which the stroke cycle is repeated; stroke length (SL), or the distance travelled at each cycle; and stroke index (SI), expressing the swimmer's ability to move at a given velocity with the fewest number of strokes (proposed by Costill et al., 1985). Since the pioneer work of East (1970), assessment of stroking parameters has been relevant for training and performance diagnosis proposes (Keskinen and Komi, 1993; Barbosa et al., 2005). Few studies have related SR, SL and SI with one of the most recent topics of interest in swimming research: the Time Limit performed at a specific velocity.

Time Limit has been previously defined as the time duration during which a certain intensity of exercise can be sustained until exhaustion (Billat and Koralsztein, 1996). In swimming, it has been studied mainly at intensities corresponding to maximal oxygen uptake (TLim-v$\dot{V}O_2$max). The TLim-v$\dot{V}O_2$max is the kind of effort related to the 400 meter front crawl performance (Fernandes et al., 2003), so the choice of this specific intensity seems to express the importance of the aerobic power training zone in this sport. TLim-v$\dot{V}O_2$max assessment was conducted in a swimming flume, i.e., a water treadmill, using trained swimmers (Billat et al., 1996; Faina et al., 1997) and pentatheletes (Demarie et al., 2001). Afterwards, trying to negate the possible particular mechanical constraints imposed by swimming against the water flow in a flume (Thompson et al., 2004), some studies were performed in free swimming in a conventional pool (Renoux, 2001; Fernandes et al., 2003; Fernandes et al., 2005). The main findings of the above-mentioned studies were purely physiological. It was observed that TLim-v$\dot{V}O_2$max seems to be directly and positively influenced by accumulated oxygen deficit (Faina et al., 1997) and the $\dot{V}O_2$ slow component (Fernandes et al., 2003). Negative relationships were found between TLim-v$\dot{V}O_2$max and a 3,5mmol/l blood lactate anaerobic threshold (Fernandes et al., 2003) and between TLim-v$\dot{V}O_2$max and energy cost (Fernandes et al., 2005). Furthermore, TLim-v$\dot{V}O_2$max apparently was not related to $\dot{V}O_2$max (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003) and maximal blood lactic acid concentrations (Fernandes et al., 2003).

The purpose of this study was to examine if TLim-v$\dot{V}O_2$max is also influenced by biomechanical parameters such as SR, SL and SI. TLim-v$\dot{V}O_2$max should be negatively related with SR and positively related with SL and SI.

Methods

Participants

Twenty-three (13 men and 10 women) highly trained swimmers volunteered for this study. The criterion for inclusion in this study was a v$\dot{V}O_2$max higher than 1.40 meter/sec. for male and 1.25 meter/sec. for female swimmers. It were converted the individual v$\dot{V}O_2$max values in LEN points and no statistical difference between gender groups was observed ($p > 0.05$). Mean and standard deviation (mean ± SD) values for physical characteristics and weekly training frequencies of the subjects are described in Table 1. All subjects volunteered to participate in this study and signed a written informed consent, where the experimental protocol was described. The Ethics Committee of our Faculty approved the experimental protocol.

Table 1. Mean ± SD values for physical characteristics and weekly training frequencies of the subjects. * Represents a significant difference between the two gender groups ($p \leq 0.001$).

Parameters	Men (n = 13)	Women (n = 10)	Total (n = 23)
Age (years)	17.54 ± 1.56	16.60 ± 2.72	17.13 ± 2.14
Body mass (kg) *	66.69 ± 5.71	54.90 ± 2.33	61.57 ± 7.46
Height (cm) *	175.08 ± 4.37	165.70 ± 3.30	171.00 ± 6.12
Training session (n wk^{-1})	8.35 ± 0.43	8.20 ± 0.71	8.28 ± 0.56
$v\dot{V}O_2max$ (LEN points)	533.38 ± 39.75	554.10 ± 30.88	542.39 ± 36.91

$v\dot{V}O_2max$ (LEN points), minimum velocity corresponding to $\dot{V}O_2max$ converted in Ligue Européenne de Natacion Point Score System; n, number of subjects.

Procedures and Material

Each subject performed an intermittent incremental protocol for front crawl $v\dot{V}O_2max$ assessment. The increments were 0.05 meter/sec. per each 200 meter stage with 30 sec. resting intervals until voluntary cessation. Initial velocity was established according to the swimmers' individual performance of the moment on the 400 m front crawl minus 7 increments of velocity (Cardoso et al., 2003; Fernandes et al., 2003). $\dot{V}O_2$ was directly and continuously measured using a metabolic cart (Sensormedics 2900 oximeter) mounted on a special chariot running along the pool (Vilas-Boas and Santos, 1994) and connected to the swimmer by a 1.80 meter hose, and a respiratory snorkel and valve system with low airflow resistance (Toussaint et al., 1987). Expired gas concentrations were averaged every 20 sec. Swimming velocity was controlled using a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal) with successive flashing lights, 2.5 m apart, on the bottom of the pool.

$\dot{V}O_2max$ was considered to be reached according to primary and, at least, three secondary conventional physiological criteria (Howley et al., 1995), namely the occurrence of a plateau in VO_2 despite an increase in swimming velocity, high levels of blood lactate concentrations ($\geq$ 8 mmol l^{-1}), elevated respiratory exchange ratio ($R \geq 1.0$), elevated heart rate [HR > 90% of (220 - age)], and exhaustive perceived exertion (controlled visually and case by case).

$v\dot{V}O_2max$ was considered to be the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$. If a plateau less than 2.1 ml min^{-1} kg^{-1} could not be observed (n = 6), the $v\dot{V}O_2max$ was calculated as indicated in Equation 1 (adapted from Kuipers et al., 1985):

$$v\dot{V}O_2max = v + \Delta v \cdot (n\ T^{-1}), \qquad \text{(Eq. 1)}$$

where v is the velocity corresponding to the last stage accomplished, Δv is the velocity increment, n indicates the number of sec. that the subjects were able to swim during the last stage and T the pre-set protocol time (in sec.) for this step.

Capillary blood samples for blood lactate concentrations analysis were collected from the earlobe at rest, in the 30 sec. rest interval and at the end of exercise (YSI1500LSport auto-analyser - Yellow Springs Incorporated, Yellow Springs, Ohio, USA). Heart rate was monitored and registered continuously each 5 sec. through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland).

Forty-eight hours later all subjects swam at their previously determined $v\dot{V}O_2max$ to assess TLim-$v\dot{V}O_2max$. This protocol consisted of three different phases, all paced with the referred visual light-pacer. The first phase was a 10 min warm-up at an intensity corresponding to 60% $v\dot{V}O_2max$, followed by a short rest (20 sec.) for blood collection. The second phase was a 50 m distance performed at progressive velocity, allowing the swimmers to reach their individual $v\dot{V}O_2max$. The third phase was the maintenance of that swimming $v\dot{V}O_2max$ until exhaustion. TLim-$v\dot{V}O_2max$ was considered to be the total swimming duration at the pre-determined velocity, i. e., from the beginning of the test until the moment that the swimmer stopped following the pacer lights, or to the occurrence of a voluntarily ending of exercise.

In each 25 meter of the TLim-$v\dot{V}O_2max$ test, SR was determined as the number of cycles per min, registered by the number of strokes in the length of the pool. SL was calculated by dividing velocity by SR and the product of SL to the velocity allowed assessing SI (Craig and Pendergast, 1979; Costill et al., 1985). SI was considered, as proposed by Costill et al. (1985), as a valid indicator of swimming efficiency. Both testing sessions took place in a 25 m indoor swimming-pool. In-water starts and open turns without underwater gliding were used.

Data Analysis

Means and standard deviations were calculated for all variables. All data were checked for distribution normality with the Shapiro-Wilk test. Pearson’s correlation coefficient and unpaired samples Student's *t* test were also used.

Results

The mean ± SD values for $\dot{V}O_2max$ and v$\dot{V}O_2max$ obtained in the incremental test, and mean ± SD values for TLim-v$\dot{V}O_2max$, SR, SL and SI assessed in the Time Limit test, are present in Table 2.

In Figure 1 it is possible to observe a negative correlation between TLim-v$\dot{V}O_2max$ and SR. It was possible to observe also a direct relationship between TLim-v$\dot{V}O_2max$ and SL, and SI (see Figure 2). No relationships were found between TLim-v$\dot{V}O_2max$ and $\dot{V}O_2max$, and with v$\dot{V}O_2max$. A positive relationship was also found between v$\dot{V}O_2max$ and SL ($r = 0.47$, $p < 0.05$), and SI ($r = 0.72$, $p < 0.01$).

Table 2. Subjects' mean ± SD values for $\dot{V}O_2max$ and $v\dot{V}O_2max$ (incremental test) and TLim-$v\dot{V}O_2max$, SR, SL and SI (Time Limit test). * Represents a significant difference between the two gender groups ($p \leq .05$).

Parameters	Men (n = 13)	Women (n = 10)	Total (n = 23)
$\dot{V}O_2max$ (ml/kg/min) *	75.14 ± 8.20	63.94 ± 5.49	70.27 ± 9.01
$v\dot{V}O_2max$ (meter/sec.) *	1.45 ± 0.04	1.35 ± 0.03	1.40 ± 0.06
TLim-$v\dot{V}O_2max$ (sec.)	234.49 ± 57.19	231.90 ± 52.37	233.37 ± 53.92
Stroke rate (cycle/min)	35.44 ± 3.35	35.78 ± 2.31	35.59 ± 2.89
Stroke length (meter/cycle) *	2.49 ± 0.24	2.27 ± 0.14	2.39 ± 0.22
Stroke index [(meter^2/(cycle*sec.)] *	3.60 ± 0.38	3.06 ± 0.18	3.36 ± 0.38

$\dot{V}O_2max$, maximal oxygen consumption; $v\dot{V}O_2max$, minimum velocity corresponding to $\dot{V}O_2max$; TLim-$v\dot{V}O_2max$, time limit at $v\dot{V}O_2max$; n, number of subjects.

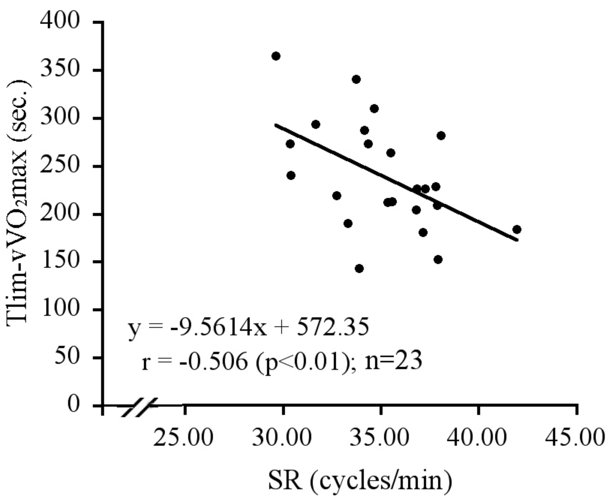

Figure 1. Relationship between TLim-$v\dot{V}O_2max$ and stroke rate (SR) for highly trained swimmers.

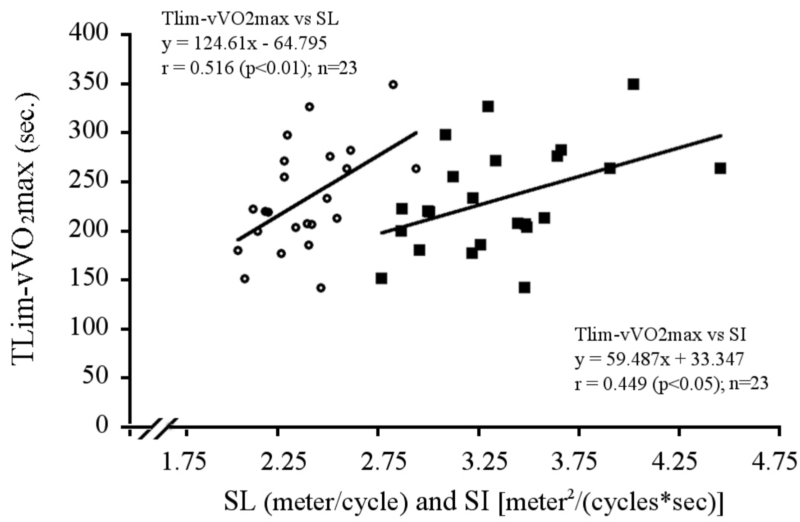

Figure 2. Relationships between TLim-v$\dot{V}O_2$max, stroke length (SL) and stroke index (SI) for highly trained swimmers.

Discussion

The mean ± SD values of TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max are similar with the data presented in the literature for trained swimmers performing in a flume (Billat et al., 1996; Faina et al., 1997) or in a conventional swimming-pool (Renoux, 2001; Fernandes et al., 2003). The referred results are all obtained using front crawl swimming. In the literature there is no data referring to the assessment of TLim-v$\dot{V}O_2$max in the other three swimming techniques: backstroke, butterfly and breaststroke. The mean ± SD values of SR and SL obtained in this study are naturally lower for SR and higher for SL when compared to the previous studies relating to shorter and more intensive swimming events such as using 50, 100 and 200 m distances.

The major findings of this study were the observed negative relationship between TLim-v$\dot{V}O_2$max and SR ($r^2 = 0.26$, $p < 0.01$) and the positive relationship found between TLim-v$\dot{V}O_2$max and SL ($r^2 = 0.27$, $p < 0.01$), and SI ($r^2 = 0.20$, $p < 0.05$). These results seem to suggest that swimmers with a higher SR and lower SL experienced more difficulties to sustain this kind of maximal aerobic effort. Indeed, Keskinen and Komi (1993) and Wakayoshi et al. (1996) had already noticed a SL decrease for exercise intensities higher than the lactate threshold during submaximal constant load tests. Dekerle et al. (2005) observed, inclusively, the existence of a biomechanical boundary, very well related to the swimming intensity corresponding to maximal lactate steady state, beyond which the SL becomes compromised. Hence, the capacity to maintain high mechanical propulsive efficiency, i.e., high rates of SL and SI during the TLim-v$\dot{V}O_2max$, seems to indicate an improved bioenergetic capacity to delay the appearance of increased local muscular fatigue and/or a high capacity to support this situation. In this sense, technical efficiency seems to be a very important influencing factor in TLim-v$\dot{V}O_2max$ efforts.

Moreover, no relationship was found between TLim-v$\dot{V}O_2max$ and $\dot{V}O_2max$, as observed before (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003), which seems to indicate that individual performance in TLim-v$\dot{V}O_2max$ test does not depend directly on swimmer's $\dot{V}O_2max$. Furthermore, TLim-v$\dot{V}O_2max$ and v$\dot{V}O_2max$ did not presented any relationship, which is not in accordance with the negative relationship described previously (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003). It is possible that the homogeneity of this sample, imposed by skilled inclusion criteria might have diminished the high inter-subject variability described in the above-phrase referred studies.

As expected, v$\dot{V}O_2max$ related positively with SL ($r^2 = 0.22$, $p < 0.05$) and SI ($r^2 = 0.52$, $p < 0.01$), which seems to express that the fastest swimmers were also the more technically proficient. The fact that the faster swimmers tend to show a smaller decrease in SL was previously suggested by Chollet et al. (1997) and by Laffite et al. (2004) when analysing, respectively, the 100 meter and 400 meter front crawl events. So, the more pronounced problems in maintaining SL for the less skilled swimmers may be a reflection of a diminishing capacity to deliver power output (Toussaint and Beek, 1992). Perhaps this occurs due to a deterioration of body horizontal alignment, which increases drag, and a decrease in the amplitude of the body roll, which consequently induces a decrease in SL. This positive relationship between v$\dot{V}O_2$max and SL is also a main insight of this study due to the fact that SL is considered, according to numerous studies (Costill et al., 1985; Craig et al., 1985; Chatard et al., 1990; Kennedy et al., 1990; Chengalur and Brown, 1992; Cardelli et al., 2000), as a dominant feature of a successful swimming performance.

This study confirmed that the improvement of SL and SI, as expressions of technical ability and motor skills, should be promoted and controlled in training. In this sense, the implementation of training sets that actually increase the ability of the swimmers to maintain their technical proficiency should be dally routine in order to achieve higher mechanical propulsive efficiency in high intensity prolonged efforts. Future studies are indicated to analyse the evolution of the stroking parameters during the course of a TLim-v$\dot{V}O_2$max test, namely to observe eventual changes due to the installation of fatigue.

Chapter 7

Time limit at $\dot{V}O_2max$ velocity in elite crawl swimmers

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Int. J. Sports Med. (submitted)

Abstract

The purpose of this study is to assess, with elite crawl swimmers, the time limit at the minimum velocity corresponding to maximal oxygen consumption (TLim-v$\dot{V}O_2$max), and to analyse its main determinants. Eight subjects performed an incremental test for v$\dot{V}O_2$max assessment and, forty-eight hours latter, an all-out swim at v$\dot{V}O_2$max until exhaustion. $\dot{V}O_2$ was directly measured using a telemetric portable gas analyzer and a visual pacer was used to help the swimmers keep the predetermined velocities. Blood lactate concentrations, heart rate and stroke parameters values were also measured. TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max, averaged, respectively, 243.2±30.5s and 1.45±0.08m·s^{-1}. TLim-v$\dot{V}O_2$max correlated directly $\dot{V}O_2$ slow component (r=0.76, p<0.05). Inverse correlations were found between TLim-v$\dot{V}O_2$max and body surface area (r=-0.80) and lactate production (r=-0.69) (p <0.05), and with v$\dot{V}O_2$max (r=-0.63), v corresponding to anaerobic threshold (r=-0.78) and the energy cost corresponding to v$\dot{V}O_2$max (r=-0.62) (p<0.10). No correlations were observed between TLim-v$\dot{V}O_2$max and stroking parameters. This study confirmed the tendency to TLim-v$\dot{V}O_2$max be lower in the swimmers who presented higher v$\dot{V}O_2$max and vAnT, namely due to their higher surface area, energy cost and anaerobic rate. Additionally, O_2SC seems to be a determinant of TLim-v$\dot{V}O_2$max.

Key words: time limit, velocity at $\dot{V}O_2$max, elite swimmers

Introduction

In swimming, maximal oxygen consumption ($\dot{V}O_2max$) - the maximal rate of oxygen consumption during exercise to exhaustion - is considered to be an important performance-influencing factor. Despite the concept of $\dot{V}O_2max$ is well known for over 80 years and its assessment in swimming was accomplished since the 1960s (Astrand and Saltin, 1961), the capacity to sustain it in time has been neglected and very little explored. To our knowledge, the number of studies on the capacity to maintain a swimming effort at the velocity corresponding to $\dot{V}O_2max$ - the time limit at v$\dot{V}O_2max$ (TLim-v$\dot{V}O_2max$) - is very much scarce. Complementarily, the few available studies were mainly conducted in swimming flume, not in normal swimming-pool conditions (Billat et al., 1996; Faina et al., 1997; Demarie et al., 2001), or did not assess the swimmers main respiratory parameters (Renoux, 2001).

Nonetheless the small amount of TLim-v$\dot{V}O_2max$-related studies found in the literature, TLim-v$\dot{V}O_2max$ is becoming a new criterion for evaluation of maximal aerobic capacity of swimmers. Billat (1998) refers that TLim-v$\dot{V}O_2max$ can bring new references for the selection of the duration of the $\dot{V}O_2max$ training sets, and could be a new criterion of aerobic power assessment, more sensible and complementary to $\dot{V}O_2max$.

Following the literature studies, and including some recent publications of our group, the principal current understandings about TLim-v$\dot{V}O_2max$ are the following: (i) TLim-v$\dot{V}O_2max$ test is reproducible (Billat et al., 1994); (ii) there is not large inter-individual variability in the swimming TLim-v$\dot{V}O_2max$ values, ranging between 4 min (Fernandes et al., in press) and 6.15 min (Demarie et al., 2001); (iii) there is an inverse relationship between TLim-v$\dot{V}O_2max$ and v$\dot{V}O_2max$, i. e., swimmers with slower aerobic power velocities can perform longer at that precise intensities (Billat et al., 1996; Faina et al., 1997; Renoux, 2001; Fernandes et al., in press); (iv) the variability of TLim-v$\dot{V}O_2$max and its inverse relationship with v$\dot{V}O_2$max seems to be explained by differences in the anaerobic capacity of swimmers (Faina et al., 1997; Billat, 1998; Fernandes et al., in press); (v) TLim-v$\dot{V}O_2$max seems to be directly influenced by some precise bioenergetical parameters, namely by accumulated oxygen deficit (Faina et al., 1997) and $\dot{V}O_2$ slow component (O_2SC) (Fernandes et al., 2003); (vi) TLim-v$\dot{V}O_2$max seems to be inversely related with some specific bioenergetical parameters, namely by 3,5mmol/l blood lactate anaerobic threshold (Fernandes et al., 2003) and energy cost of exercise (C) (Fernandes et al., in press) and (vii) TLim-v$\dot{V}O_2$max seems to be not related to $\dot{V}O_2$max (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003).

The purpose of this study is to assess TLim-v$\dot{V}O_2$max in elite front crawl swimmers, performing in swimming-pool, and to analyse its main bioenergetical and biomechanical determinants. Knowing that top-level swimmers have their specificities that could distinguish them from regular practitioners (Lavoie and Montpetit, 1986) and that TLim-v$\dot{V}O_2$max was never assessed in elite swimmers, the pertinence of this study is clearly stated. In addition, as it is well accepted that exercising against the water flow in a flume implies some mechanical constraints that make it different than performing in normal swimming-pool conditions (Thompson et al., 2004), it was tried to evaluate the swimmer in a more specific training and competition situation.

Methods

Subjects

Eight front crawl elite swimmers (3 males and 5 females) of the Portuguese National Swimming Team volunteered to participate in this study and signed an informed consent form. Individual and mean (±SD) values for physical characteristics of the subjects are described in Table 1. Body mass, fat and lean body mass were assessed through bioelectric impedance analysis method (Tanita TBF 305, Japan). Body mass index was calculated with the traditionally used formula: body mass·height^{-2}. The surface area (SA) was estimated using the equation of Du Bois and Du Bois (Shuter and Aslani, 2000):

$$SA = Height^{0.655} \cdot Body\ Mass^{0.441} \cdot 94.9. \qquad (1)$$

For greater group homogeneity, swimmers were matched for performance by converting the individual $v\dot{V}O_2max$ values into the Ligue Européenne de Natacion Point Score System (LENpoints), with no difference between gender observed ($p = 0.49$). The weekly training frequencies of the swimmers were higher than 9 training units per week.

Table 1. Individual and mean (±SD) values for some physical characteristics of the subjects.

Swimmer	Age (years)	Height (cm)	Body mass (kg)	Body mass index	Fat (kg)	Lean body mass (kg)	Surface area (m^2)
#1 (f)	18.8	164.0	60.4	22.5	14.6	45.8	1.63
#2 (f)	17.2	170.0	63.2	21.9	12.6	50.6	1.71
#3 (f)	16.7	165.0	58.4	21.5	12.2	46.2	1.61
#4 (f)	14.7	168.0	58.2	20.6	10.2	48.0	1.63
#5 (f)	17.2	162.0	54.8	20.8	11.0	43.6	1.56
Mean (±SD)	16.9 (1.5)	165.8 (3.2)	59.0 (3.1)	21.5 (0.8)	12.1 (1.7)	46.8 (2.6)	1.63 (0.05)
#6 (m)	18.9	184.0	80.6	23.8	6.2	74.4	2.01
#7 (m)	18.0	168.0	68.6	21.9	5.0	63.6	1.76
#8 (m)	20.3	192.0	83.0	22.5	5.2	77.8	2.09
Mean (±SD)	19.1 (1.1)	181.3 (12.2)	77.4 (7.7)	22.7 (1.0)	5.5 (0.6)	71.9 (7.4)	1.95 (0.17)

Test protocol

Briefly, each subject performed an individualized intermittent incremental protocol for front crawl $v\dot{V}O_2max$ assessment, with increments of 0.05 $m.s^{-1}$ each 200 m stage and 30 s intervals until exhaustion (Fernandes et al., 2003). $\dot{V}O_2$ was directly measured using a telemetric portable gas analyzer (K4 b^2, Cosmed, Italy) connected to the swimmer by a respiratory snorkel and valve system (Keskinen et al., 2003). Expired gas concentrations were measured breath-by-breath (BxB). A visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal), with flashing lights on the bottom of the pool, was used to help the swimmers keep the predetermined swimming velocities. All equipment was calibrated prior to each experiment.

$\dot{V}O_2max$ was considered to be reached according to primary and secondary traditional physiological criteria (Howley et al., 1995). $v\dot{V}O_2max$ was considered to be the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$. If a plateau less than 2.1 $ml.min^{-1}.kg^{-1}$ could not be observed, the $v\dot{V}O_2max$ was calculated as proposed by Kuipers et al. (1985):

$$v\dot{V}O_2max = v + \Delta v \cdot (n.N^{-1}), \qquad (2)$$

where v is the velocity corresponding to the last stage accomplished, Δv is the velocity increment, n indicates the number of seconds that the subjects were able to swim during the last stage and N the pre-set protocol time (in seconds) for this step.

Capillary blood samples (25 µl) for lactate concentrations ($[La^-]$) analysis were collected from the earlobe at rest (after previous local hyperaemia with Finalgon®), in the 30 s rest interval, at the end of exercise and during the recovery period (YSI1500LSport auto-analyser - Yellow Springs Incorporated, Yellow Springs, Ohio, USA). Those data allowed to assess individual anaerobic threshold (AnT), that was determined by $[La^-]$/velocity curve modelling method (least square method) (Fernandes et al., 2005). With this referred mathematical method for the AnT assessment, it was possible to determine the exact point for the beginning of an [La$^-$] exponential rise. HR was monitored and registered continuously each 5 s through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland).

The energy expenditure ($\dot{E}$) values for each exercise step were obtained through the addition of the net $\dot{V}O_2$ values and the values resultant from the transformation of the net [La$^-$] into O_2 equivalents, using the proportionality constant of 2.7 $mlO_2\ kg^{-1}.mM^{-1}$ (di Prampero et al., 1978; Fernandes et al, in press).

C was assessed using two swimming economy related parameters: (i) the C corresponding to $v\dot{V}O_2max$ ($Cv\dot{V}O_2max$), determined as the ratio of $\dot{E}$ and the corresponding swimming minimum velocity that elicits $\dot{V}O_2max$ (di Prampero, 1986) and (ii) the slope of the regression line obtained from the relationship between $\dot{E}$ and corresponding velocities in the incremental test (C_{slope}) (Wakayoshi et al., 1995).

The second test session occurred 48 hours later. All subjects swam at their previously determined $v\dot{V}O_2max$ to assess TLim-$v\dot{V}O_2max$. This protocol consisted in two different phases, all paced: (i) a 10 min warm-up at an intensity correspondent to 60% $v\dot{V}O_2max$, followed by a short rest (20 s) for earlobe blood collection, and (ii) the maintenance of that swimming $v\dot{V}O_2max$ until volitional exhaustion or until the moment that the swimmers were unable to swim at the selected pace. TLim-$v\dot{V}O_2max$ was considered to be the total swimming duration at the pre-determined velocity.

[La$^-$] were assessed at rest, during the 20 s intervals, immediately after exercise and at the third and fifth min of the recovery period. The lactate production

(Δ[La$^-$]) was determined as the difference between the maximal values measured after the test and those measured after the warm-up. HR was registered continuously using the same procedure previously described. O_2SC was assessed through mathematical modeling, using three exponential terms, with the three terms describing the cardiodynamic phase, the fast component and the O_2SC, respectively (Barstow and Molé, 1991).

Stroke rate (SR) was determined as the number of cycles per min (registered by the number of strokes in each 25 m), stroke length (SL) was calculated by dividing velocity by SR, and the product of SL to the velocity allowed the assessment of stroke index (SI) (Costill et al., 1985).

Both testing sessions took place in a 25 m indoor swimming-pool. In-water starts and open turns, without underwater gliding, were used.

Statistical analyses

Mean (±SD) computations for descriptive analysis were obtained for all variables (all data were checked for distribution normality with the Shapiro-Wilk test). Pearson's correlation coefficient and unpaired samples Student's *t* test were also used. A significance level of 5% was accepted.

Results

Data concerning the variables obtained in the incremental test: $\dot{V}O_2$max, [La$^-$]max, HRmax, AnT (velocity and [La$^-$] values), v$\dot{V}O_2$max, Cv$\dot{V}O_2$max, C_{slope} and the parameters assessed in the Time Limit test: TLim-v$\dot{V}O_2$max, [La$^-$]max, Δ[La$^-$], HRmax, O_2SC, SR, SL and SI, are reported in Table 2 (for the total group of subjects and for each gender group). Considering all subjects of the sample TLim-v$\dot{V}O_2$max ranged from 195 to 293 s and O_2SC from 202 to 649 ml.l^{-1}.

Table 2. Mean (±SD) values for $\dot{V}O_2max$ (absolute and relative), [La$^-$]max, HRmax, AnT, v$\dot{V}O_2max$, Cv$\dot{V}O_2max$ and C_{slope} (incremental test), and TLim-v$\dot{V}O_2max$, [La$^-$]max, Δ[La$^-$], HRmax, O_2SC, SR, SL and SI (Time Limit test), for the total group of subjects and for male and female swimmers. Significant differences between genders are shown by * ($p \leq 0.05$).

Parameters	Total group (n = 8)	Male swimmers (n = 3)	Female swimmers (n = 5)
$\dot{V}O_2max$ (ml.kg^{-1}.min^{-1})	64.28 ± 10.27	71.74 ± 6.09	59.80 ± 9.97
$\dot{V}O_2max$ (l.min^{-1}) *	4.34 ± 1.32	5.68 ± 0.79	3.53 ± 0.77
[La$^-$]max (mmol. l^{-1})	8.34 ± 3.02	7.77 ± 3.36	8.69 ± 3.15
HRmax (b.min^{-1})	182.50 ± 5.73	180.33 ± 4.04	183.80 ± 6.61
AnT (mmol.l^{-1})	2.59 ± 0.97	3.36 ± 1.19	2.13 ± 0.47
vAnT (m.s^{-1}) *	1.34 ± 0.10	1.45 ± 0.05	1.27 ± 0.03
v$\dot{V}O_2max$ (m.s^{-1}) *	1.45 ± 0.08	1.55 ± 0.02	1.39 ± 0.02
Cv$\dot{V}O_2max$ (J.kg^{-1}.m^{-1}) *	14.20 ± 2.02	16.23 ± 0.57	12.98 ± 1.42
C_{slope} (J.kg^{-1}.m^{-1})	32.54 ± 11.59	37.74 ± 9.95	30.47 ± 12.56
TLim-v$\dot{V}O_2max$ (s)	243.17 ± 30.49	217.67 ± 20.84	258.46 ± 25.10
[La$^-$]max TLim (mmol.l^{-1})	6.92 ± 2.53	8.60 ± 1.97	5.92 ± 2.43
Δ[La$^-$] (mmol.l^{-1})	6.23 ± 2.30	7.97 ± 1.67	5.19 ± 2.06
HRmax TLim (b.min^{-1})	180.00 ± 6.44	177.67 ± 3.22	181.40 ± 7.80
O_2SC (ml.min^{-1})	356.27 ± 168.16	283.54 ± 62.74	385.36 ± 194.25
SR (cycle.min^{-1})	44.27 ± 6.92	41.45 ± 7.31	45.96 ± 6.89
SL (meter.cycle^{-1})	2.02 ± 0.38	2.30 ± 0.40	1.86 ± 0.30
SI [(meter^2.(cycle.s)$^{-1}$] *	2.95 ± 0.68	3.55 ± 0.64	2.59 ± 0.42

$\dot{V}O_2max$, maximal oxygen consumption; [La$^-$]max, maximal blood lactic acid concentrations; HRmax, maximal heart rate; AnT, anaerobic threshold; vAnT, velocity corresponding to anaerobic threshold; v$\dot{V}O_2max$, minimum velocity corresponding to $\dot{V}O_2max$; Cv$\dot{V}O_2max$, energy cost corresponding to v$\dot{V}O_2max$; C_{slope}, slope of the regression line obtained from the relationship between $\dot{E}$ and corresponding velocities in the incremental test; TLim-v$\dot{V}O_2max$, time limit at v$\dot{V}O_2max$; Δ[La$^-$], lactate production; O_2SC, oxygen slow component; SR, stroke rate; SL, stroke length; SI, stroke index; n, number of subjects.

In Figure 1, it is possible to observe a direct relationship between TLim-v$\dot{V}O_2$max and O_2SC. In addition, inverse relationships were found between TLim-v$\dot{V}O_2$max and SA (Figure 2), Δ[La$^-$] (Figure 3) and LENpoints (r = -.80), all for a $p \leq 0.05$. TLim-v$\dot{V}O_2$max was also inversely related to absolute $\dot{V}O_2$max (r = -.69), v$\dot{V}O_2$max (r = -.63), vAnT (r = -.62), Cv$\dot{V}O_2$max (-.67) and [La$^-$]max TLim (r = -.63), but only for a $p < 0.10$.

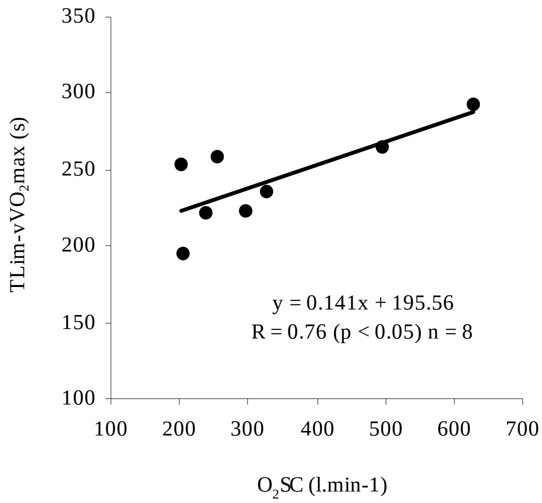

Figure 1. Relationship between TLim-v$\dot{V}O_2$max and O_2SC. Linear regression equation and correlation values are indicated.

No significant correlations were found between TLim-v$\dot{V}O_2$max and relative $\dot{V}O_2$max (r = -.47), HRmax (r = .60), C_{slope} (r = -.50) and [La$^-$]max (r = .33), parameters obtained in the incremental test, and between TLim-v$\dot{V}O_2$max and HRmax (r = .58), Cslope (r = -.50), SF (r = .29), SL (r = -.46) and SI (r = -.54), factors attained in the Time Limit test ($p > 0.10$)

A direct relationship was observed between Cv$\dot{V}O_2$max and SA (r = 0.86, $p < 0.01$). However, SA was not related with Cslope (r = 0.38, $p > 0.05$).

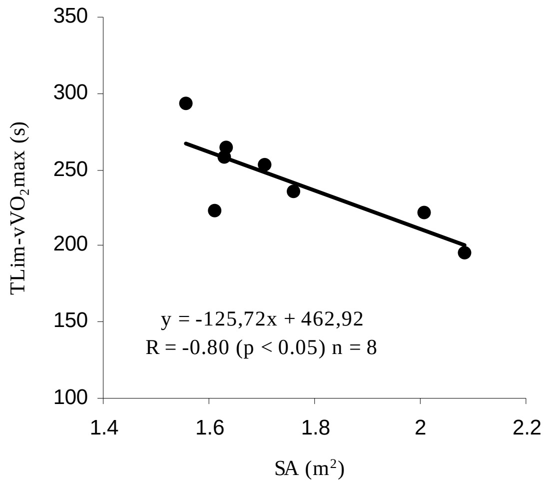

Figure 2. Inverse relationship between TLim-v$\dot{V}$ O_2max and SA. Linear regression equation and correlation values are indicated.

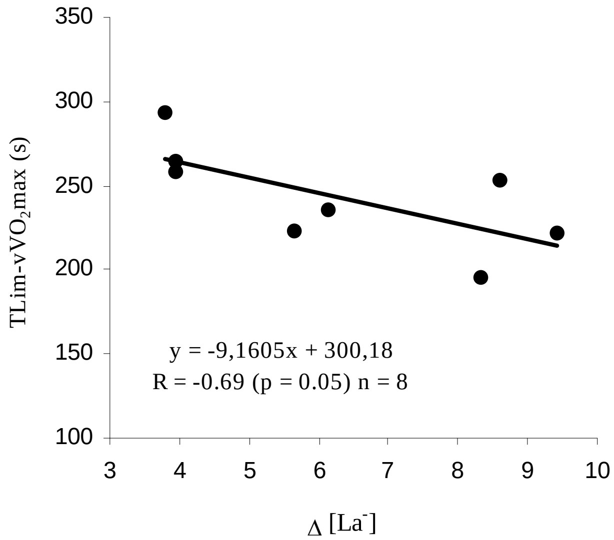

Figure 3. Inverse relationship between TLim-v$\dot{V}$ O_2max and Δ[La^-]. Linear regression equation and correlation values are indicated.

A direct relationship was observed between v$\dot{V}$ O_2max and vAnt ($r = 0.93$, $p < 0.01$), SI ($r = 0.79$, $p < 0.05$) and Cv$\dot{V}$ O_2max ($r = 0.74$, $p < 0.05$).

Discussion

The aim of this study was to assess TLim-v$\dot{V}O_2$max in elite freestyle swimmers and to identify its main determinants. The experimentations were conducted in normal swimming-pool conditions, using modern procedures for collecting and measuring BxB expired gas, which allowed the characterization of $\dot{V}O_2$ kinetics during swimming exercise. The modified snorkel and valve system, specific for BxB analysis, was earlier considered suitable for measurements during swimming (Keskinen et al., 2003). The utilization of an intermittent incremental protocol for swimming v$\dot{V}O_2$max assessment has been noticed to be a valid method (Fernandes et al., 2003).

The TLim-v$\dot{V}O_2$max values obtained in the present study confirm the low inter-individual variability of this parameter in swimming when comparing to running (Billat et al., 1994). However, elite male swimmers performed less time at v$\dot{V}O_2$max than the lower value reported in the swimming related literature (Fernandes et al., in press). This fact seems to be explained by elite male swimmers' higher v$\dot{V}O_2$max, and Cv$\dot{V}O_2$max, when comparing to elite female swimmers participant in this study, high trained (Billat et al., 1996; Renoux, 2001; Fernandes et al., 2003; Fernandes et al., in press) and low level swimmers (Fernandes et al., in press), and pentatheletes (Demarie et al., 2001).

Closely related to the above described finding, the inverse relationship observed between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max seems to indicate that the swimmers with higher aerobic power velocities perform shorter at those precise intensities. This fact was already described (Billat et al., 1996; Faina et al., 1997; Renoux, 2001; Fernandes et al., in press), and appears to be explained by two factors: (i) higher swimming velocities implies superior $\dot{E}$ and, consequently, higher C (Toussaint and Hollander, 1994), confirmed in this study by the high correlation value between v$\dot{V}O_2$max and Cv$\dot{V}O_2$max, and (ii) higher swimming velocities indicates more strenuous efforts, with more pronounced recruitment of anaerobic energy pathways, leading to earlier fatigue stages and, consequently, to lower TLim-v$\dot{V}O_2$max. In the present study TLim-v$\dot{V}O_2$max correlated inversely with Δ[La$^-$] and with [La$^-$]max, confirming the above referred idea, and corroborating the literature data (Faina et al., 1997; Billat, 1998; Fernandes et al., in press).

In the perspective above discussed, one of the main determinants of TLim-v$\dot{V}O_2$max seems to be C, since TLim-v$\dot{V}O_2$max is inversely related to Cv$\dot{V}O_2$max. The higher level of maximal metabolic rate of the more proficient swimmers may be associated with a smaller capacity to sustain that precise exercise intensity. Complementarily, and accordingly, knowing that C is affected by some physical characteristics, namely by SA (di Prampero, 1986), it was searched, and observed, a strong relationship between Cv$\dot{V}O_2$max and SA. This last relationship indicates that body characteristics also have an important role in TLim-v$\dot{V}O_2$max efforts, probably also the cross-sectional area, a parameter well related with SA (Zamparo et al., 1996), implying that higher body sizes imposes greater drag to be overcome by muscular work, increasing C (Toussaint et al., 1988).

In addition, TLim-v$\dot{V}O_2$max was also inversely related to vAnT. This negative correlation was already described before, but only for the averaged value of 3,5 mmol/l of [La$^-$] (Fernandes et al., 2003). Knowing that [La$^-$] corresponding to AnT has been reported to have great variability between swimmers, the methodology for vAnT assessment used in this study was considered more appropriated than the commonly used averaged values of 3,5 and 4 mmol/l of [La$^-$], because it allowed to find more specific and individualized values for aerobic/anaerobic transition intensities (Fernandes et al., 2005). As expected, vAnT was highly correlated to v$\dot{V}O_2$max ($r = 0.93$, $p < 0.01$), in accordance to previous available results (Billat et al, 1996; Faina et al., 1997; Renoux, 2001; Fernandes et al., in press).

Other main bioenergetical influencing factor of TLim-v$\dot{V}O_2$max seems to be O_2SC. In the present study, O_2SC was assessed through mathematical modelling (Barstow and Mole, 1991; Machado et al., in press), a more precise and accurate method, since its magnitude has been commonly determined rather simplistically by calculating the increase in $\dot{V}O_2$ between the second or the third min of exercise, and the time at which exhaustion occurs. The mean value obtained in this study for O_2SC seems to have physiological meaning once it was higher than 200 $ml.min^{-1}$ (Billat, 2000). Its significant relationship with TLim-v$\dot{V}O_2$max appears to indicate that higher TLim-v$\dot{V}O_2$max probably corresponds to higher expected O_2SC amplitude. These data are in accordance with a previous study conducted in high level swimmers (Fernandes et al., 2003).

From the present results, in accordance with the literature data (Billat et al., 1996; Faina et al., 1997; Fernandes et al., 2003), it was shown once again that TLim-v$\dot{V}O_2$max seems not to depend directly on swimmers relative $\dot{V}O_2$max. However, it was observed a relationship between TLim-v$\dot{V}O_2$max and absolute $\dot{V}O_2$max (although only for a $p < 0.10$). This possibly confirms that $\dot{V}O_2$max plays a central role among the energy-yielding mechanisms in swimming (di Prampero et al., 1978) and that aerobic power is important in swimming performance. The low and not significant correlation values obtained between TLim-v$\dot{V}O_2$max and relative $\dot{V}O_2$max could be explained by the influence of other factors that may obscure the importance of aerobic energy production during swimming, namely in specific TLim-v$\dot{V}O_2$max efforts. As it is well accepted that $\dot{V}O_2$max, in elite athletes, is very close its genetic limit, this parameter could be a poor predictor of performance due to its relatively insensitivity to detect variations in homogeneous samples of swimmers.

Understanding that the ability to achieve and maintain a specific swimming velocity in an event is related to metabolic but also to biomechanical factors (Toussaint and Hollander, 1994; Termin and Pendergast, 2000), it was also analysed the relationship between TLim-v$\dot{V}O_2$max and the stroking parameters. Nonetheless, the absence of studies relating the above referred parameters, it was expected TLim-v$\dot{V}O_2$max to be inversely related with SR and directely related with SL and SI. However, no significant correlation values were obtained. Nevertheless, SI was strongly related to v$\dot{V}O_2$max, meaning that faster swimmers were also the most technically proficient (Costill et al., 1985).

In conclusion, TLim-v$\dot{V}O_2$max values obtained by elite swimmers are situated in the lower extreme of the interval defined in the literature data. TLim-v$\dot{V}O_2$max seems to be lower in the swimmers who presented higher v$\dot{V}O_2$max and vAnT, which seems to be explained by the higher anaerobic rate in that specific effort. Complementarily, the faster swimmers also have higher energy cost, namely due to their greater SA. Additionally, O_2SC was observed in elite swimmers and seems to be a determinant of TLim-v$\dot{V}O_2$max. The faster swimmers were also the more technically proficient, but it was not find any evidence of a possible influence of biomechanical factors on TLim-v$\dot{V}O_2$max in a sample of elite swimmers. The findings of this paper seems to emphasize the importance of the individualization of the training process in elite swimmers, namely in what concerns TLim-v$\dot{V}O_2$max typical efforts, that are very well related to middle distance swimming events.

Acknowledgements

We acknowledge the Portuguese Swimming Federation and the swimmers, and their coaches, for the participation in this study.

Chapter 8

Assessment of time limit at lowest speed corresponding to maximal oxygen consumption in the four competitive swimming strokes

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Published on Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences (2006), 6(2), 128-130.

Abstract

Time limit at lowest speed of maximal oxygen consumption (TLim-v$\dot{V}O_2$max) was characterized in the 4 swimming strokes, and related with $\dot{V}O_2$max and anaerobic threshold (AnT). 23 elite swimmers performed an incremental protocol for v$\dot{V}O_2$max assessment. 48 hours later, Tlim-v$\dot{V}O_2$max was assessed. $\dot{V}O_2$ was directly measured BxB (K4 b^2, Cosmed, Italy) and AnT was assessed individually (YSI 1500L Sport, USA). Tlim-v$\dot{V}O_2$max values were 238.8±39.0, 246.1±51.9, 277.6±85.6 and 331.4±82.7 s in crawl, backstroke, butterfly, and breaststroke (no differences observed). No correlations were found between Tlim-v$\dot{V}O_2$max and $\dot{V}O_2$max, and AnT. However, inverse relationships were observed between Tlim-v$\dot{V}O_2$max and v$\dot{V}O_2$max ($r=-0.63$, $p<0.01$) and vAnT ($r=-0.52$, $p=0.01$), pointing out that the higher the velocities commonly related to aerobic proficiency, the lower the TLim- v$\dot{V}O_2$max.

Key words: Time to exhaustion, competitive strokes, oxygen consumption, anaerobic threshold

Introduction

Time limit at lowest speed of maximal oxygen consumption (TLim-v$\dot{V}O_2max$) was studied both in swimming flume (Billat et al., 1996; Faina et al., 1997; Demarie et al., 2001) and in normal swimming-pool conditions (Renoux, 2001; Fernandes et al., 2003; Fernandes et al., in press). While no studies have been carried out based on other swimming techniques than front crawl, the purpose of this experiment was to characterize, and compare, TLim-v$\dot{V}O_2max$ in the four competitive strokes, as well as to observe its relationships with two major performance determinants: $\dot{V}O_2max$ and anaerobic threshold (AnT). Complementarily, knowing that top-level swimmers have their specificities (Lavoie and Montpetit, 1986) and that TLim- v$\dot{V}O_2max$ was never assessed in elite swimmers, the pertinence of this study is clearly stated.

Methods

Subjects

Twenty-three elite swimmers (15 males of 19.4 ± 2.1 yy, 178.1 ± 6.2 cm and 71.8 ± 7.4 kg, and 8 females of 17.2 ± 1.4 yy, 166.0 ± 3.7 cm and 59.7 ± 4.3 kg) from the Portuguese National Swimming Team volunteered to participate in this study and signed an informed consent form.

Test protocol

Each subject performed, in their best technique, an individualized intermittent incremental protocol for v$\dot{V}O_2max$ assessment, with increments of 0.05 $m.s^{-1}$ each 200 m stage and, 30 s intervals, until exhaustion (Fernandes et al., 2003). $\dot{V}O_2$ was directly measured using a telemetric portable gas analyzer (K4 b^2, Cosmed, Italy) connected to the swimmers by a respiratory snorkel and valve system (Toussaint et al., 1987; Keskinen et al., 2003). Expired gas concentrations were measured breath-by-breath. Swimming velocity was controlled using a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal) with flashing lights on the bottom of the pool. $\dot{V}O_2max$ was considered to be reached according to primary and secondary traditional physiological criteria (Howley et al., 1995). $v\dot{V}O_2max$ was considered to be the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$. If a plateau less than 2.1 $ml.min^{-1}.kg^{-1}$ could not be observed, the $v\dot{V}O_2max$ was calculated as proposed by Kuipers et al. (1985):

$$v\dot{V}O_2max = v + \Delta v \cdot (n.N^{-1}), \qquad \text{(Eq. 1)}$$

where v is the velocity corresponding to the last stage accomplished, Δv is the velocity increment, n indicates the number of seconds that the subjects were able to swim during the last stage and N the pre-set protocol time (in seconds) for this step.

Capillary blood samples for lactate concentrations ($[La^-]$) analysis were collected from the earlobe at rest, in the 30 s rest interval, at the end of exercise and during the recovery period (YSI1500LSport auto-analyser - Yellow Springs Incorporated, Yellow Springs, Ohio, USA). Those data allowed to assess individual AnT, that was determined by $[La^-]$/velocity curve modelling method (least square method) (Fernandes et al., 2005). HR was monitored and registered continuously each 5 s through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland).

Forty-eight hours later, subjects swam until exhaustion at their pre-determined velocity, to assess Tlim-$v\dot{V}O_2max$. This protocol consisted in two different phases, all paced: (i) a 10 min warm-up at an intensity correspondent to 60% $v\dot{V}O_2max$, followed by a short rest (20 s) for earlobe blood collection, and (ii) the maintenance of that swimming $v\dot{V}O_2max$ until volitional exhaustion or until the moment that the swimmers were unable to swim at the selected pace. TLim-

$v\dot{V}O_2max$ was considered to be the total swimming duration at the pre-determined velocity. HR was registered continuously using the same procedure previously described.

Statistical analysis

Mean (±SD) computations for descriptive analysis were obtained for all variables (all data were checked for distribution normality with the Shapiro-Wilk test). One-way Anova, with a Bonferroni post-hock test, was also used. A significance level of 5% was accepted.

Results

Data concerning the variables obtained in the incremental test: $\dot{V}O_2max$, $[La^-]max$, HRmax, AnT (velocity and $[La^-]$ values) and $v\dot{V}O_2max$, and the parameters assessed in the Time Limit test: TLim-$v\dot{V}O_2max$, $[La^-]max$ and HRmax, are reported in Table 1 for each competitive stroke.

The values of $\dot{V}O_2max$ obtained in the incremental test are in accordance with those previously published for elite front crawl swimmers for a number of authors (Holmér, 1974; Billat et al., 1996; Faina et al., 1997). Studies that aim to compare $\dot{V}O_2max$ in elite front crawl, backstroke, butterfly and breaststroke swimmers are very scarce, so it is difficult to make valid comparisons. However, the observation of no differences between $\dot{V}O_2max$ values between techniques is in accordance with Troup (1991). The obtained values of HRmax are in agreement with the literature since that, for this kind of intensity of exercise (aerobic power zone), values ranging from 180 to 200 $b.min^{-1}$ are consensual (Maglischo, 1988). Likewise, the $[La^-]max$ mean values are in agreement with the typical requirements for $\dot{V}O_2max$ swimming intensities (Howley et al., 1995).

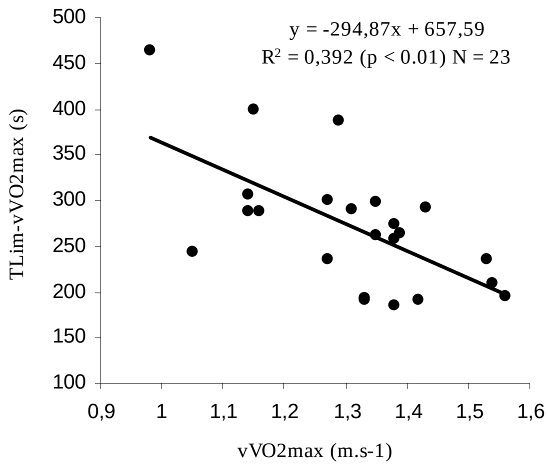
While no significant differences were observed between competitive strokes in TLim-v$\dot{V}O_2$max, pooled data were correlated with $\dot{V}O_2$max (ml/kg/min) and AnT (mmol/l), being observed no significant interrelationships. However, moderate inverse correlation values were observed between Tlim-v$\dot{V}O_2$max and v$\dot{V}O_2$max (r=-0.63, p=0.001, Figure 1A) and vAnT (r=-0.52, p=0.012, Figure 1B).

Table 1. Mean (±SD) values for $\dot{V}O_2$max (absolute and relative), [La$^-$]max, HRmax, AnT (velocity and [La$^-$] values) and v$\dot{V}O_2$max (incremental test), and TLim-v$\dot{V}O_2$max, [La$^-$]max and HRmax (Time Limit test), for each competitive stroke. Significant differences are shown through pairs of (1), (2), (3), (4), (5), (6), (7), (8), (9) and (10), $p \leq 0.05$.

Parameters	Front crawl (n = 8)	Backstroke (n = 5)	Butterfly (n = 4)	Breastrstroke (n = 6)
$\dot{V}O_2$max (ml.kg^{-1}.min^{-1})	64.28 ± 10.27	66.78 ± 11.40	53.95 ± 4.82	63.21 ± 8.14
$\dot{V}O_2$max (l.min^{-1})	4.34 ± 1.32	4.69 ± 1.11	3.57 ± 0.54	4.33 ± 0.71
[La$^-$]max (mmol. l^{-1})	8.34 ± 3.02	11.22 ± 3.63	8.22 ± 1.60	9.13 ± 1.99
HRmax (b.min^{-1})	182.50 ± 5.73	190.00 ± 6.60	179.25 ± 6.50	190.83 ± 7.33
AnT (mmol.l^{-1})	2.59 ± 0.97 (1)	4.56 ± 2.10	5.56 ± 2.30 (1)	3.03 ± 1.50
vAnT (m.s^{-1})	1.34 ± 0.10 (2)	1.25 ± 0.06 (3)	1.21 ± 0.07 (4)	1.01 ± 0.08 (2,3,4)
v$\dot{V}O_2$max (m.s^{-1})	1.45 ± 0.08 (5,6)	1.35 ± 0.04 (7)	1.29 ± 0.03 (5,8)	1.10 ± 0.07 (6,7,8)
TLim- v$\dot{V}O_2$max (s)	243.17 ± 30.49	246.08 ± 51.93	277.63 ± 85.64	331.43 ± 82.73
[La$^-$]max TLim (mmol.l^{-1})	6.92 ± 2.53 (9,10)	10.65 ± 2.40 (9)	9.04 ± 0.91	10.76 ± 1.34 (10)
HRmax TLim (b.min^{-1})	180.00 ± 6.44	176.60 ± 8.56	179.50 ± 4.44	185.67 ± 7.97

$\dot{V}O_2$max: maximal oxygen consumption; [La$^-$]max: maximal blood lactic acid concentrations; HRmax: maximal heart rate; AnT: anaerobic threshold; vAnT: velocity corresponding to anaerobic threshold; v$\dot{V}O_2$max: lowest speed of maximal oxygen consumption; TLim-v$\dot{V}O_2$max: time limit at v$\dot{V}O_2$max; n: number of subjects.

The observed inverse relationships between Tlim-v$\dot{V}O_2$max and v$\dot{V}O_2$max, and/or vAnT, confirms previous findings obtained in national level freestyle swimmers (Fernandes et al., 2003; Fernandes et al., in press), and point out that, whatever the swimming techniques the higher the swimming velocities commonly related to aerobic proficiency, the lower the TLim-v$\dot{V}O_2$max. This observation seems to be justified by the fact that higher swimming velocities indicates more strenuous efforts, with probably more pronounced recruitment of anaerobic energy pathways, leading to earlier fatigue stages and, consequently, to lower TLim-vVO2max. However, no relationship was found between Tlim-v$\dot{V}O_2$max and [La$^-$]max, in opposition with some previous findings (Faina et al., 1997; Fernandes et al., in press).



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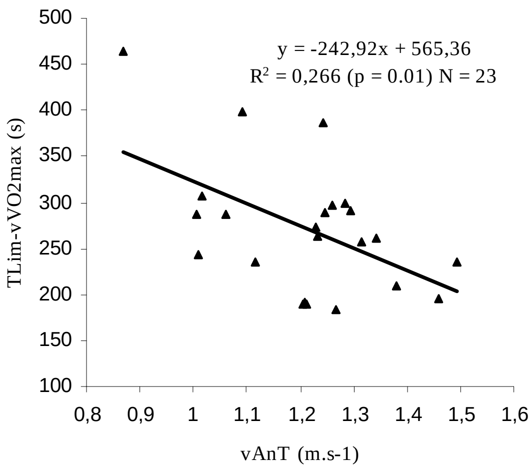

B

Figure 2. Relationshisp between Tlim-v$\dot{V}$ O_2max and v$\dot{V}$ O_2max (A panel), and vAnT (B panel).

Conclusions

TLim-v$\dot{V}O_2$max did not differ between swimming strokes, pointing out that the phenomenon is similar in all four strokes. TLim-v$\dot{V}O_2$max was lower in the swimmers who presented higher v$\dot{V}O_2$max and vAnT, which could be explained by the higher anaerobic rate in that specific exercise effort. $\dot{V}O_2$max and [La$^-$] values are poor predictors of TLim-v$\dot{V}O_2$max performance.

Chapter 9. General Discussion

The scientific approach can be used to minimize trial and error and help make sure that the selected training mode has the best chance of success

J. Troup (1996, pg 4)

The general purpose of this thesis was to characterize and compare TLim-v$\dot{V}O_2$max, performed in front crawl, in normal swimming-pool conditions, in swimmers of different levels and genders. Likewise, it was aimed to identify TLim-v$\dot{V}O_2$max major influencing factors.

The main conclusions pointed out that swimmers are able to maintain an exercise effort intensity corresponding to maximal aerobic power during a temporal interval ranging from 215 to 260 s (elite swimmers), 230 to 260 s (high level swimmers) and 310 to 325 s (low level swimmers). It was not observed any difference in TLim-v$\dot{V}O_2$max performance between genders. It was observed the existence of an O_2SC during the TLim-v$\dot{V}O_2$max test, in all levels of swimming proficiency, and its magnitude was considered to be significant according to the literature (Billat, 2000).

TLim-v$\dot{V}O_2$max main bioenergetic and functional determinants were SE and O_2SC (direct relationship) and v$\dot{V}O_2$max, vAnT and $\Delta[La^-]$ (inverse relationship). When analysing more homogeneous groups of swimmers, namely when the subjects were matched by level, the inverse correlation value between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max was not so evident. TLim-v$\dot{V}O_2$max seems also to be influenced by stroking parameters, presenting a direct relationship with SL and SI, and an inverse correlation with SF. In general, TLim-v$\dot{V}O_2$max was not related to $\dot{V}O_2$max.

Being aware of the principle of specificity in relation to exercise, training and testing (Bouchard et al., 1979; Wilmore and Costill, 1999; Keskinen and Keskinen, 1999), and knowing that this principle is even more important in swimming, namely in the thematic of aerobic power (McArdle et al., 1971; Magel et al., 1974; Lavoie and Thibault, 1981; Kohrt et al., 1987; Maglischo, 2003), the experimental procedures of this thesis had three mains characteristics: (i) being performed in front crawl; (ii) being conducted in normal swimming-pool conditions and (iii) using direct oximetry for $\dot{V}O_2$ kinetics analysis. The last study of this thesis (Chapter 8) was performed in the 4 competitive strokes, but its purpose was to compare TLim-v$\dot{V}O_2$max obtained in backstroke, breaststroke and butterfly with the data previously obtained in front crawl.

Front crawl is the fastest known form of human locomotion in an aquatic environment. The world records in the freestyle events, in which most swimmers, if not all, use the front crawl technique, demonstrate the level of sophistication in the skill of human locomotion in the water (Yanai, 2003). Complementarily, as it was observed in a study of our group conducted in normal swimming-pool conditions (**Appendix I**), front crawl was considered the most economic swimming technique, when compared to backstroke, butterfly and breaststroke. These referred findings are in accordance to what was earlier proposed by Holmér (1974a) and Troup (1991) but for flume swimming, and considering only the aerobic metabolism contribution.

The first studies that assessed TLim-v$\dot{V}O_2$max in swimming were conducted using front crawl, the swimming technique most used in training and competition (Billat et al., 1996; Faina et al., 1997; Demarie et al., 2001). The fact that only front crawl were used in TLim-v$\dot{V}O_2$max related studies could be explained by the facts presented in the previous paragraph, and by the evidence that the 400 m front crawl is commonly accepted as the typical aerobic power swimming event (Ribeiro et al., 1991; Costill et al., 1992; Rodriguez, 2000; Ogita, 2006). However, the referred works were performed in swimming flume, not in specific training and competition conditions. As it is accepted that performing in a flume could bring some mechanical constraints (Hay and Carmo, 1995; Reer et al., 2004; Thompson et al., 2004), the assessment of TLim-v$\dot{V}O_2$max in this thesis, using front crawl swimming, in normal swimming-pool conditions, is perfectly justified.

Complementarily, the measurement of swimming energy consumption through direct oximetry allowed the assessment of $\dot{V}O_2$ kinetics, as well as other respiratory parameters, in real time. This method is considered the most valid and precise one (Kemper et al., 1983; Cazorla, 1993; Vilas-Boas, 1996; Rodríguez et al., 2003), namely when comparing to the retro-extrapolation method or to the collection of O_2 trough the Douglas bag technique.

For assessing TLim-v$\dot{V}O_2$max it was necessary, in first place, to determine v$\dot{V}O_2$max. Knowing that v$\dot{V}O_2$max was usually assessed trough incremental continuous protocols (Billat and Koralsztein, 1996), it was conducted a pilot study for TLim-v$\dot{V}O_2$max characterization (**Chapter 2**), in which an incremental continuous protocol for v$\dot{V}O_2$max assessment was used. This study was made using ten low-level swimmers and presented mean (± SD) values of TLim-v$\dot{V}O_2$max situated in between the lower values obtained by Billat et al. (1996) and the higher values presented by Demarie et al. (2001), those two studies performed in non specific swimming conditions, i. e., in swimming flume. These results suggested a lower variation of TLim-v$\dot{V}O_2$max in swimming, when compared with the data presented by Billat et al. (1994) for other sports modalities, namely treadmill running (ranging between 4 and 11 min). The inverse relationship between TLim-v$\dot{V}O_2$max and $\dot{V}O_2$max, and v$\dot{V}O_2$max, proposed by Billat et al. (1994) and Billat et al. (1996) for running, and by Billat et al. (1996) and Faina et al. (1997) for swimming, was not observed.

The second purpose of the above-referred study was to verify the existence of a slow component of $\dot{V}O_2$ kinetics in swimming, on swimming-pool conditions, as it was observed for Demarie et al. (2001) in swimming flume for pentathletes. It is well documented, in previous studies performed in cycling and running, that exercise at metabolic rates above the AnT, i. e., in the heavy or severe intensity domains, evidences a slowly-developing component of the $\dot{V}O_2$ kinetics that is superimposed upon the rapid increase of $\dot{V}O_2$ initiated at exercise onset (Whipp and Mahler, 1980; Barstow, 1994; Bearden and Moffatt, 2000). It is also described that the referred slow increase in $\dot{V}O_2$ continues to rise until the end of the exercise, or until exhaustion (Poole et al., 1988; Whipp, 1994).

In fact, during the TLim-v$\dot{V}O_2$max test, it was confirmed the appearance of an O_2SC in all subjects, and its amplitude was in agreement with the report of Demarie et al. (2001), which seemed to be lower than running and cycling (Billat et al., 1998). The obtained strong relationship between TLim-v$\dot{V}O_2$max and O_2SC appear to express that the higher the TLim-v$\dot{V}O_2$max was, the higher the O_2SC amplitude was expected to be.

However, in order to the athlete be able to achieve higher intensity steps in the incremental protocol for v$\dot{V}O_2$max evaluation, several researchers from individual sport modalities introduced intermittent progressive protocols for the assessment of that specific effort intensity. The implementation of (short) rest intervals between steps in the incremental continuous protocol used in the study of Chapter 2, could brought some significant improvements in the v$\dot{V}O_2$max assessment methodology: (i) it allowed the swimmer to receive proper feedbacks from the coach and scientific personnel; (ii) the swimmer could expel some saliva and condensed that naturally was being accumulated in the mouth piece of the respiratory snorkel and valve system and (iii) it made possible to collect capillary blood from the ear lobe of the subjects, which allowed the researcher to assess, for each swimmer, some fundamental swimming determinant parameters, namely AnT and C. At this purpose Vilas-Boas and Santos (1994) referred that SE assessment requires both aerobic and anaerobic energy expenditure evaluation, if possible at different swimming velocities, to allow the computation of an economy curve. This procedure is only possible to be made in a swimming-pool when an intermittent incremental protocol is used.

In **Appendix II**, it is observable a study of our group where a comparison between the earlier used incremental continuous protocol for $v\dot{V}O_2max$ evaluation and a new intermittent incremental protocol was implemented. It was possible to observe no significant differences between protocols in the several cardio-respiratory and metabolic parameters analyzed, namely in ventilation, $\dot{V}O_2max$ and $v\dot{V}O_2max$ values. The only difference found was on $[La^-]$ values, but the results were, nevertheless, very similar. Complementarily, both protocols fulfilled the requirements of a maximal test for $\dot{V}O_2max$ assessment, namely $[La^-]$ near 8 $mmol.l^{-1}$, respiratory exchange ratio (R) values over 1, HR higher than 85% of the HRmax, and an exertion to exhaustion (Howley et al., 1995; Adams, 1998). In this sense, it was concluded that intermittent incremental protocol was suitable for $v\dot{V}O_2max$ assessment in swimming.

In the swimming related literature, the use of the “n x 200 m” intermittent protocol for $v\dot{V}O_2max$ assessment is not a new subject in what concerns coaching purposes (Atkinson and Sweetenham, 1999; Pyne et al., 2000; Pyne et al., 2001), as well as in scientific training control and evaluation of swimmers (Bonen et al., 1980; Van Handel et al., 1988a; Ribeiro et al., 2003; Bentley et al., 2005; Libicz et al., 2005), and have increased its popularity (Keskinen, 2006). Traditionally, $\dot{V}O_2max$ assessment protocols in swimming use steps of, and higher than, 4 min (McArdle et al., 1971; Holmér, 1974b; Magel et al., 1974; Kemper et al., 1983; Montpetit et al., 1983; Takahashi et al, 1983; Costill et al., 1985; Van Handel et al., 1988b; Vilas-Boas, 1990), which allows temperature to increase and pH to decrease in the muscle, fostering an environment which is optimal for oxygen extraction (Troup and Daniels, 1986; Rinehardt et al., 1991). However, following a proper warm-up, 2 to 3 min of exercise has been shown to be sufficient time for cardiovascular and biomechanical adaptations to occur in muscle in order to promote maximal oxygen extraction (Taylor et al., 1955; Astrand and Saltin, 1961; Holmér, 1974b; Kohrt et al., 1987; Serrese et al., 1988).

In this sense, there are some references in the literature to intermittent protocols for $\dot{V}O_2max$ and $v\dot{V}O_2max$ assessment that uses steps of 2 to 3 min or 200 m of duration (Bonen et al., 1980; Lavoie et al., 1985; Kohrt et al., 1987; Van Handel et al., 1988a; Sardella et al., 1991; Vilas-Boas and Santos, 1994; Pyne et al., 2000; Pyne et al., 2001; Reer et al., 2004; Bentley et al., 2005; Libicz et al., 2005). Notwithstanding the need to achieve a physiological steady state, the shorter 200 m steps are more specific to the training and competitive requirements of swimmers (Pyne et al., 2000). Rinehardt et al. (1991) refereed that the swimmers are more motivated to put forth a maximal effort if the swimming distance is relatively short, and coaches are more agreeable to have their swimmers tested if less time is taken from their workout schedule. So, the 200 m steps chosen in the $v\dot{V}O_2max$ assessment protocol, represents a compromise between achieving a steady state in metabolism and using swimming velocities more specific of competition levels.

The intensities of the first step of the incremental protocol for $v\dot{V}O_2max$ assessment used in the studies 3, 4, 5, 6, 7 and 8 of this thesis, were also successfully used before (Lavoie et al., 1985; Montpetit et al., 1987; Chatard et al., 1988; Faina et al., 1997; Capelli et al., 1998; Demarie et al., 2001; Reer et al., 2004; Ribeiro et al., 2004; Bentley et al., 2005; Libicz et al., 2005), as well as the velocity increments (Lavoie et al., 1985; Billat et al., 1996; Faina et al., 1997; Reer et al., 2004; Ribeiro et al., 2004; Bentley et al., 2005; Libicz et al., 2005), which were considered to be “comfortable” (Lavoie et al., 1985). Also, the 30 s rest between steps in the intermittent protocol were the minimum sufficient duration time for capillary ear lob blood collection. Complementarily, the pre-test preparations, namely the warm-up, were made accordingly with the specialized literature (Billat et al., 1996; Montpetit et al., 1988; Billat, 2000; Pyne et al., 2000): prior to pool testing, swimmers completed a standardized warm-up of 1000-1200 m, consisting primarily of aerobic swimming of low-to-moderate intensity, i. e, above the velocity corresponding to AnT. Swimmers undertaked the warm-up in front crawl swimming technique (studies 2 to 7) or in front crawl plus their best technique (study 8). It was also asked the swimmers for their previous rest period and if they were free of illness and injury, as proposed by Fricker and Fallon (2000).

So, the used intermittent test, with increments of 0.05 $m.s^{-1}$ each 200m stage, and 30s intervals until exhaustion, seems to be a valid protocol to assess $v\dot{V}O_2max$, providing useful information for the evaluation and advice of the swimmers' training. The used snorkel and valve systems, connected to the swimmers head, for specific respiratory gases collection, were considered suitable for measurements during swimming (Toussaint et al., 1987; Keskinen et al., 2000; Keskinen et al., 2002), without any significant additional increase in body drag (Keskinen et al., 2003). Complementarily, a similar snorkel and valve system, developed by Kjendlie and his group, showed little difference in swimming technique with the breathing valve, compared to swimming without valve (Kjendlie et al., 1999).

In **Chapter 3** is presented an investigation about TLim-$v\dot{V}O_2max$ and O_2SC in high-level male swimmers (n = 15). In this study the intermittent protocol for $v\dot{V}O_2max$ assessment was used, which allowed collecting capillary blood for blood lactate concentrations evaluation. To our knowledge, this was the first study in which TLim-$v\dot{V}O_2max$ and O_2SC were determined in high level swimmers, performing in swimming-pool.

Mean (± SD) $\dot{V}O_2max$ for the incremental test and the corresponding $v\dot{V}O_2max$ seemed to be higher than the majority of values previously published, perhaps due to differences in the competitive level of the group and/or the testing methodologies used. Nevertheless, some studies also reported considerable high values of $\dot{V}O_2max$ in elite male front crawl swimmers (Holmér et al., 1974; Costill et al., 1985).

Mean TLim-v$\dot{V}O_2max$ value was similar to other values reported in flume for competitive swimmers (Billat et al., 1996; Faina et al., 1997), and lower than those obtained with less proficient swimmers (Demarie et al., 2001; Chapter 2 of this thesis). These results, and the inverse relationships between the TLim-v$\dot{V}O_2max$ and the velocity of AnT, and between the TLim-v$\dot{V}O_2max$ and v$\dot{V}O_2max$, suggested that the swimmer's lower level of maximal aerobic metabolic rate might have been associated with a larger capacity to sustain that exercise intensity. This hypothesis was previously pointed out for running (Billat et al., 1994; Billat et al., 1996) and swimming (Billat et al., 1996; Faina et al., 1997; Renoux, 2001), and suggests that the anaerobic capacity can be at least one of the explanations for the inverse relationship discussed above (Billat and Koralsztein, 1996; Faina et al., 1997). However, the correlation of TLim-v$\dot{V}O_2max$ with $[La^-]max$ and $\Delta[La^-]$ was not significant, which does not allow to evidence the importance of the anaerobic system contribution.

Complementarily, O_2SC appears also to occur in this study and seems to have physiological meaning, once it was higher than 200 $ml.min^{-1}$ (Billat, 2000). However, O_2SC mean value was lower than the data published for running and cycling (Billat et al., 1994), which could be justified by the chosen high exercise intensity, the high level of endurance training of these swimmers and the specificity of this sport. The significant relationship between O_2SC and TLim-v$\dot{V}O_2max$ ($r = 0.54$, $p < 0.05$) appeared to indicate that higher TLim-v$\dot{V}O_2max$ seems likely to correspond to higher expected O_2SC amplitude. This may be a covariant effect being higher O_2SC and higher TLim-v$\dot{V}O_2max$ associated to the performance level of the subjects. These data are in accordance with our previous data in university students (Fernandes et al., Chapter 2) and with data obtained by other groups (Whipp, 1994; Gaesser and Poole, 1996).

The hypothesis that the appearance of the O_2SC phenomenon is related to a major recruitment of fast twitch muscle fibbers, with high glycolytic capacity, associated with the fatigue of the previously recruited fibbers (Poole et al., 1991; Barstow, 1994; Whipp, 1994; Barstow and Molé, 1996; Gaesser and Poole, 1996), wasn't confirmed either by us or Demarie et al. (2001) for swimming: no relationship was obtained between O_2SC and $[La^-]max$ or $\Delta[La^-]$. Nevertheless, it is unlikely that blood lactate *per se* can be responsible for the O_2SC phenomenon, but rather by accompanying acidosis. This fact allows keeping the suggestion that one of the O_2SC major contributors is probably related to the superior rates of recruitment of Type II fibbers, and additional energy cost of contraction (Whipp, 1994).

Another possible contributor for the arising of the O_2SC may be the increasing VE in response to the changes in stroke technique caused by higher levels of fatigue (Demarie et al., 2001). Additionally, it is known (Aaron et al., 1992; Gaesser and Poole, 1996) that, at very high exercise intensities with increased pulmonary ventilation, characteristic of the O_2SC phase, there is an additional O_2 uptake related to the specific work of the respiratory muscles. O_2SC was significantly correlated with this additional $\dot{V}O_2$ uptake, as well as with the energy cost of the respiratory muscles. This fact, associated with the significant increase of VEmax in the TLim-v$\dot{V}O_2$max test, when compared with the incremental test, suggests that the ventilatory muscles probably accounts for some, despite low, percentage of the total O_2SC, as previously mentioned (Poole et al., 1991; Whipp, 1994; Gaesser and Poole, 1996).

Knowing that SE is one of the major performance influencing factors (Troup and Daniels, 1986; Van Handel et al., 1988b; Chatard et al., 1990; Klentrou and Montpetit, 1991; Poujade et al., 2002; Smith et al., 2002; Kjendlie et al., 2004a), in **Chapter 4** is presented an investigation in which it was analysed if the net energy cost of swimming affects TLim-v$\dot{V}O_2$max. For that purpose, understanding that SE is usually quantified as the energy cost of locomotion (C), it where used three SE related parameters: the net energy cost corresponding to v$\dot{V}O_2$max (Cv$\dot{V}O_2$max), the slope of the regression line obtained from the energy expenditure ($\dot{E}$) and corresponding velocities during an incremental test (C_{slope}) and the ratio between the $\dot{E}$ mean value and the velocity mean value of the incremental test (C_{inc}). Complementarily, given that C differs according to the subjects level of proficiency (Holmér, 1972; Costill et al., 1985; di Prampero, 1986; Capelli, 2003), it was compaired the influence of Cv$\dot{V}O_2$max, C_{slope} and C_{inc} on the TLim-v$\dot{V}O_2$max in low-level (n=10) and high-level groups (n=20).

Both high trained (HTS) and low-level (LLS) swimmers presented mean values of $\dot{V}O_2$max similar to those previously described by others: higher values in HTS, like those found in well trained swimmers (Van Handel et al., 1988a, b; Billat et al., 1996; Capelli et al., 1998; Termin and Pendergast, 2000) and moderate values in LLS, in accordance with the data for recreational and non-specialized swimmers (Costill et al., 1985; Capelli et al., 1998; Demarie et al., 2001; Libicz et al., 2005). As expected, $\dot{V}O_2$max, v$\dot{V}O_2$max and the $\dot{E}$ corresponding to v$\dot{V}O_2$max were higher in HTS compared with LLS, which seems to reflect the superior training, proficiency and performance level of the HTS group.

TLim-v$\dot{V}O_2$max averaged 313.8±63.0 s in the LLS and 237.3±54.6 s in the HTS. These results are similar to the data reported for swimmers of the same or similar level (Billat et al., 1996; Demarie et al., 2001) and, one more time, showed that low-level athletes seem to present higher TLim-v$\dot{V}O_2$max values than the high-level athletes, in different sports, and particularly in swimming (Billat and Koralsztein, 1996).

TLim-v$\dot{V}O_2$max was inversely related to C_{slope}, both when the entire group and each performance level groups were considered, and to v$\dot{V}O_2$max, meaning that the swimmers with a lower SE slope profile and v$\dot{V}O_2$max, irrespectively of their performance level, can sustain longer swimming exercises at v$\dot{V}O_2$max. Similar results were presented before relating C and the 400 m swimming distance (Costill et al., 1985; Ribeiro et al., 1991; Poujade et al., 2003). As C is obtained by the quotient "$\dot{E} * v^{-1}$", and as this fraction is equal to the ratio obtained between drag (D) and propelling efficiency (e) (di Prampero et al., 1974; Rennie et al., 1975; Pendergast et al., 1978), the fact presented in the previous sentences seems to suggest that technical ability, considered as the result of "$D * e_p^{-1}$" (di Prampero, 1986), is a fundamental parameter in TLim-v$\dot{V}O_2$max (and in swimming in general). In this regard, the better the swimming technique is, more metabolic power is devoted to move the body forward, overcoming drag, and less is wasted in giving to masses of water a kinetic energy change. However, no relationships between TLim-v$\dot{V}O_2$max and Cv$\dot{V}O_2$max, and C_{inc} were observed.

The obtained inverse relationship between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max is in accordance with the findings of Chapter 3, seeming to suggest that the lower level of maximal aerobic metabolic rate of the less proficient swimmers may be associated with a large capacity to sustain that exercise intensity. In this sense, it must be realised that LLS performed the incremental test at lower absolute velocities than HTS, denoting that they could not perform at higher velocities, and longer, probably, due to lower energetic capacity and to lower mechanical efficiency in late test steps (Costill et al., 1985; Troup, 1990; Toussaint, 1992). The reduction in the technical ability due to fatigue in LLS is well described (Costill et al., 1985; di Prampero, 1986; Demarie et al., 2001; Leblanc et al., 2005), namely that advanced swimmers are able to swim with a greater distance per stroke than poorer swimmers at a given velocity (Costill et al., 1985; Wakayoshi et al., 1995). At this purpose, Cappaert et al. (1996) and Pendergast et al. (2006) refer that the better swimmers have enhanced whole body streamlining, with leads to lower frontal surface area, which reduces the drag forces from the water, allowing them to apply their muscle power to the water effectively through proper technique.

As it is accepted, since the pioneer work of Liljestrand and Stenstrom (1919), that C, even when related to the body size, depends on gender, and that female swimmers are, in general, more economical than males (di Prampero et al., 1974; Pendergast et al., 1977; Montpetit et al., 1983; Stager et al., 1984; Klentrou, 1991), in **Chapter 5** is presented an investigation in which it was tried to observe if gender has any effect on the relationship between TLim-v$\dot{V}O_2max$ and SE. Two gender groups, 11 male and 12 female swimmers each, were studied and Cv$\dot{V}O_2max$, C_{slope} and C_{inc} were again employed as three SE related parameters. Complementarily, as it is known that C is affected by some physical characteristics, namely by body surface area (SA) (Pendergast et al., 1977; di Prampero, 1986; Montpetit et al., 1988; Chatard et al., 1990), it was also studied the influence of this anthropometric parameter in Cv$\dot{V}O_2max$, C_{slope} and C_{inc}, and its relationship with TLim-v$\dot{V}O_2max$ by gender.

Both male and female groups of swimmers presented $\dot{V}O_2max$ mean values similar to those described in the literature for experienced competitive swimmers (Van Handel et al., 1988a, b; Billat et al., 1996; Capelli et al., 1998; Termin and Pendergast, 2000; Rodriguez and Mader, 2003). The finding that male swimmers presented higher $\dot{V}O_2max$ than female swimmers was also previously described (Holmér, 1972; Pendergast et al., 1977; Costill et al., 1985; Rodriguez and Mader, 2003). As expected, v$\dot{V}O_2max$ and $\dot{E}$v$\dot{V}O_2max$ were higher in the male group, when compared with the female swimmers, reflecting the male higher bioenergetic ($\dot{V}O_2max$) and anthropometric characteristics (SA, height and body mass).

Complementarily, the $Cv\dot{V}O_2max$ mean values were also different between groups, with male swimmers having a higher $Cv\dot{V}O_2max$ than female swimmers. This higher $Cv\dot{V}O_2max$ in the male group could had some negative effect on their TLim-$v\dot{V}O_2max$ results because it suggests that male specific effort was a more strenuous one, which could contribute to an earlier fatigue stage (Billat et al., 1996 and Faina et al., 1997). However, it was not found any difference between genders in the TLim-$v\dot{V}O_2max$ efforts, as well as any statistical relationship between TLim-$v\dot{V}O_2max$ and $Cv\dot{V}O_2max$. The fact that [La^-] were very similar between groups could justify, at least in part, the inexistence of differences in TLim-$v\dot{V}O_2max$ performances between genders.

The TLim-$v\dot{V}O_2max$ mean value observed for the male group was similar to the data reported in the literature for male experienced swimmers (Billat et al., 1996; Faina et al., 1997; Renoux, 2001). As an exception, Demarie et al. (2001) presented a higher TLim-$v\dot{V}O_2max$ mean value, which can be explained by the lower swimming intensity used in their protocol: time to exhaustion at 95% $v\dot{V}O_2max$. No previously reports about TLim-$v\dot{V}O_2max$, or at other swimming intensities close to $v\dot{V}O_2max$, exclusively for female swimmers, were found in the literature.

An inverse correlation was found between TLim-$v\dot{V}O_2max$ and C_{slope} for the entire group and for each gender group, seeming to confirm that SE is a very important performance-influencing factor. Van Handel et al. (1988b) had already observed that relationship between the two above-referred parameters. These data also seems to mean that the swimmers with a lower SE slope profile, irrespective of their gender, can sustain longer an intensity of swimming effort corresponding to the $v\dot{V}O_2max$. Additionally, the higher correlation value between the referred parameters obtained by female swimmers points out that the TLim-$v\dot{V}O_2max$ tests performed by females seem to depend more on their own SE than male swimmers. No significant correlations were found between TLim-v$\dot{V}O_2$max and Cv$\dot{V}O_2$max, and C_{inc}.

As expected, SA related positively with C, namely with C_{inc} for the female group of swimmers, and in the entire sample of swimmers. Strangely this result did not appear in the male group, suggesting that other parameters than SA, like body cross-sectional area, hydrostatic torque, horizontal alignment of the body and body density (Holmér, 1974c; Rennie et al., 1975; Pendergast et al., 1977; Astrand, 1978; Saibene et al., 1983; Zamparo et al., 1996; Onodera et al., 1999), can strongly influence C. C_{slope} also presented a moderate positive correlation value with SA for the entire group of subjects, but only when C was expressed in absolute terms. SA was not related at all with Cv$\dot{V}O_2$max and TLim-v$\dot{V}O_2$max.

To our knowledge, the studies presented in Chapters 4 and 5 were the first ones that analysed the relationship between TLim-v$\dot{V}O_2$max and SE. The observed findings confirmed exercise economy as an important factor for swimming performance, confirming that SE should be considered a fundamental parameter of swimming science applied to training (Toussaint and Hollander, 1994; Smith et al., 2002). Additionally, the referred studies have the advantage of having been conducted in swimming-pool, and to focus in the important combination between aerobic and anaerobic metabolic factors of the overall swimming specific metabolic power.

The experimental approaches used in Chapters 4 and 5 assessed C with the data obtained both from aerobic and anaerobic energy pathways, in opposition to several authors that have determined C by simply estimating the contribution of aerobic metabolism, through the monitoring of $\dot{V}O_2$ at submaximal (or even maximal) intensities (Montpetit, 1981; Costill et al., 1985; Montpetit et al., 1988; Wakayoshi et al, 1995; Poujade et al., 2003; Kjendlie et al., 2004b). The negligence of the anaerobic contribution to the overall energy requirement in the referred models can be justified by the difficulties imposed by the assessment of the glycolytic system when performing in normal swimming conditions, i.e., in a swimming-pool. However, as TLim-v$\dot{V}O_2$max duration and intensity are closely related to the 400 m front crawl event (Termin and Pendergast, 2000; Ogita, 2006), in which the anaerobic contribution is ranging between 17 and 40% of the total energy expenditure (Troup et al., 1992; Toussaint and Hollander, 1994; Trappe, 1996; Nomura et al., 1996; Gastin, 2001; Ogita, 2006), it was proposed to bridge that difficulty and assess C based on data from aerobic and anaerobic energy pathways. Complementarily, the experiments were conducted in normal swimming-pool conditions, not in swimming flume. At this concern, D'Acquisto et al. (1991) observed that flume swimming required greater C than swimming in a pool.

From the present results, and from the available data provided by the literature, (Billat et al., 1996; Faina et al., 1997), it is likely that the individual performance in TLim-v$\dot{V}O_2$max test does not depend directly on the swimmers $\dot{V}O_2$max. Despite the importance of the evaluation of $\dot{V}O_2$ kinetics in swimming, $\dot{V}O_2$max by itself seems not to be considered anymore as one of the main performance determinant factors in this sport (Costill et al., 1985; Troup and Daniels, 1986; Ribeiro et al., 1991; Toussaint and Hollander, 1994). However, it is not credible to deny that $\dot{V}O_2$max plays a central role among the energy-yielding mechanisms (di Prampero, 2003), and that aerobic capacity is not important for swimming performance. This simply denotes that other factors may obscure the importance of aerobic energy production during swimming, namely in specific TLim-v$\dot{V}O_2$max efforts. As it was observed that the aerobic metabolism did not directly influence the TLim-v$\dot{V}O_2$max, it was hypothesized that the anaerobic performance capacity could, probably, be a very relevant parameter to this specific type of effort, as suggested earlier in Chapeter 3 and in the literature (Capelli et al., 1998). However, TLim-v$\dot{V}O_2$max did not presented any relationship with $[La^-]$max and $\Delta[La^-]$ in the TLim-v$\dot{V}O_2$max test. Probably, the oxidation of lactate during performance may account for this unexpected result, mainly in expert swimmers, in which the lactate removal ability was found to be higher (Schnitzler et al., 2005).

For a better knowledge of the complex group of TLim-v$\dot{V}O_2$max determinant factors, it was suggested, in **Chapter 6**, a combined metabolic and biomechanical approach, relating some important technical parameters to the studied metabolic parameters. Thus, it was studied the relationship between TLim-v$\dot{V}O_2$max and the stroking parameters: stroke rate (SR), stroke length (SL), and stroke index (SI).

Since the pioneer work of East (1970), assessment of stroking parameters has been relevant for training and performance diagnosis proposes (Keskinen and Komi, 1993; Keskinen and Keskinen, 1999; Barbosa et al., 2005), becoming a usual evaluation procedure (Alves, 2000; Castro and Guimarães, 2006). SL is considered as a dominant feature of a successful swimming performance (East, 1971; Craig and Pendergast, 1979; Reischle, 1979; Hay and Guimarães, 1983; Swaine and Reilly, 1983; Toussain et al., 1983; Costill et al., 1985; Craig et al., 1985; Chatard et al., 1990; Kennedy et al., 1990; Chengalur and Brown, 1992; Chollet and Tourny, 1993; Cardelli et al., 2000). Complementarily, it is accepted that the SI, proposed by Costill et al. (1985), is an expression of the swimmer's ability to move at a given velocity with the fewest number of strokes.

However, few studies have related SR, SL and SI with the time to exhaustion performed at a specific velocity. Thus, twenty-three highly trained swimmers were studied in order to observe, accordingly to the suggestions presented in the literature for similar types of efforts (Keskinen and Komi, 1993; Laffite et al., 2004), and for shorter ones (Letzelter and Freitag, 1983; Arellano et al., 1994), if TLim-v$\dot{V}O_2$max was negatively related with SR and positively related with SL and SI.

The mean ± SD values of TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max are similar to the data presented in the literature for trained swimmers performing in a flume

(Billat, et al., 1996; Faina, et al., 1997) or in a normal swimming-pool (Renoux, 2001). The mean ± SD values of SR and SL obtained in this study are naturally lower for SR and higher for SL when compared to the previous studies relating to shorter and more intensive swimming events such as using 50, 100 and 200 m distances (Letzelter and Freitag, 1983; Arellano et al., 1994; Pelayo et al., 1996; Chollet et al., 1996; Chollet et al., 1997; Keskinen and Keskinen, 1999; Zhong and Liu, 2004; Castro and Guimarães, 2006). When compared to longer and less intensive distances as, for instance, the warm up pace and the 1500 freestyle event (Castro and Guimarães, 2006), the SR and SL mean values of obtained in this study are higher for SR and lower for SL.

The major findings of this study were the observed inverse relationship between TLim-v$\dot{V}O_2$max and SR and the direct relationships found between TLim-v$\dot{V}O_2$max and SL, and SI. These results seem to suggest that swimmers with a higher SR and lower SL experienced more difficulties to sustain this kind of maximal aerobic effort. Indeed, Keskinen and Komi (1993) and Wakayoshi et al. (1996) had already noticed a SL decrease for exercise intensities higher than the lactate threshold during submaximal constant load tests. Wakayoshi et al. (1996), Keskinen (1997) and Dekerle et al. (2005) observed, inclusively, the existence of a biomechanical boundary, very well related to the swimming intensity corresponding to maximal lactate steady state, beyond which the SL becomes compromised. Hence, the capacity to maintain high mechanical propulsive efficiency, i.e., high rates of SL and SI during the TLim-v$\dot{V}O_2$max, seems to indicate an improved bioenergetic capacity to delay the appearance of increased local muscular fatigue and/or a high capacity to support this situation. In this sense, technical efficiency seems to be a very important influencing factor in TLim-v$\dot{V}O_2$max efforts.

TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max did not present any significant relationship, which is not in accordance with the negative relationships described previously in some chapters of this thesis (Chapters 3 and 4) and in the literature (Billat et al., 1996; Faina et al., 1997). It is possible that the homogeneity of this sample, imposed by skill inclusion criteria, might have diminished the high inter-subject variability described in the above referred studies. Similar results were observed in Chapter 5 of this thesis.

As expected, $v\dot{V}O_2max$ related positively with SL and SI, which seems to express that the fastest swimmers were also the more technically proficient. The fact that the fastest swimmers tend to show a smaller decrease in SL was previously suggested by Letzelter and Freitag (1983) and Chollet et al. (1997), and by Laffite et al. (2004) when analysing, respectively, the 100 meter and 400 meter front crawl events. So, the more pronounced problems in maintaining SL for the less skilled swimmers may be a consequence of a diminished capacity to deliver power output (Toussaint and Beck, 1992). Perhaps this fact occurs due to a deterioration of body horizontal alignment, which increases drag, and a decrease in the amplitude of the body roll, which consequently induces a decrease in SL.

It is well documented that swimming race performance is, among other factors, affected by the strategies swimmers use to control the velocity, SR and SL during the various phases of the race (Kjendlie et al., 2006). To better understand the evolution of the stroking parameters during a TLim-$v\dot{V}O_2max$ test, a study of our group is presented in **Appendix III.** In that study, it was tried to observe if there was any changes in the SR, SL and SI during the course of a typical TLim-$v\dot{V}O_2max$ front crawl effort, performed in normal swimming-pool conditions. A group of eleven front crawl elite swimmers were tested.

As the distances obtained in the TLim-$v\dot{V}O_2max$ test (DLim-$v\dot{V}O_2max$) were different between swimmers, each DLim-$v\dot{V}O_2max$ was divided in 8 sections in order to make inter-subjects comparison. It was observed that SR increased and SL, and SI, decreased during the TLim-$v\dot{V}O_2max$ test, as a general tendency. When the differences in SR, SL and SI between each 12.5% section of the test duration were tested, a significant increase in SR and a decrease in

SL and SI was observed at 25% (74.00 ± 25.83 m), 50% (148.10 ± 51.66 m) and 87.5% (259.15 ± 90.41 m) of the TLim-v$\dot{V}O_2$max test. These results have some similarity with a previous study of Marinho et al. (2004), where an increase in SR and a decrease in SL during the TLim-v$\dot{V}O_2$max test were observed, with significant changes after 100 m of the swimming distance, corresponding to 33.3% of the test duration. The different level of the subjects (elite vs. trained swimmers), as well as the different oximeter apparatus for collection of respiratory parameters, can be the explanation for some of the slight differences observed between the two studies. It was also observed a reduction of SL and an increase in SR during the 400m freestyle event in testing (Keskinen and Komi, 1993) and competition situations (Haljand and Saagpakk, 1994; Smith et al., 1996; Haljand, 1999).

The above-referred results suggest that the changes observed in SR, SL and SI in the three points mentioned are critical in the TLim-v$\dot{V}O_2$max effort. High-speed swimming overloads the human neuromuscular system and may deteriorate the stroke performance during the event, which was already shown in previous studies (Craig et al., 1985; Keskinen and Komi, 1993; Wakayoshi et al., 1995; Keskinen and Keskinen, 1999; Alves, 2000; Laffite et al., 2004). The reduction in the mechanical propulsive efficiency is possibly due to the increased local muscular fatigue (Craig and Pendergast, 1979; Craig et al., 1985; Pai et al., 1986; Keskinen and Komi, 1989), which seems to reduce the swimmers' ability to maintain the "feel for the water" (Wakayoshi et al., 1996). This reduction in the quality of stroke technique, represented by the decrease in SL and SI, and consequent increase in SR to maintain the swimming velocity, is associated with a lower capacity of force production to overcome water resistance (Craig et al., 1985). Monteil et al. (1996) have already observed changes in force distribution and propelling efficiency throughout the different phases of the stroke cycle due of fatigue. It could be hypothesized that swimmers have to modify their coordination because the task constraints are maintained, whereas the swimmers have not the same capability to develop the corresponding speed (Dekerle et al., 2003). Alves (2000) refers the less body roll and the incapacity to create large propulsive force in the finish of the pull, compared to what happens in the beginning of the exercise, as possible consequences of local fatigue.

The data presented in Chapter 6 and Appendix 3 of this thesis confirmed that the improvement of SL and SI, as expressions of technical ability and motor skill, should be promoted and controlled in training. In this sense, the implementation of training sets that actually increase the ability of the swimmers to maintain their technical proficiency should be dally routine in order to achieve higher mechanical propulsive efficiency in high intensity prolonged efforts. Complementarily, it is also accepted the use of a “freely-chosen stroke rate” by each swimmer (Swaine and Reilly, 1983), which means that the combination of SR and SL in producing swimming velocity has great variability, that implies a highly individual process (Keskinen and Komi, 1988; Pelayo et al., 1996; Chollet et al., 1996). This is not a swimming specific phenomenon, being described similar situations in other sports (Van der Woude et al., 1989; Sargeant, 1990)

In **Chapter 7** it is presented an investigation where it were evaluated eight elite front crawl swimmers. Its main purpose was to assess TLim-v$\dot{V}O_2max$ in elite swimmers, performing in swimming-pool, and to analyse its main bioenergetical and biomechanical determinants.

Accepting that top-level swimmers have their specificities (Lavoie and Montpetit, 1986; Sardella et al., 1991; Cappaert et al., 1996; Pelayo et al., 1996), and that TLim-v$\dot{V}O_2max$ was never assessed in elite swimmers, it was tried to observe the TLim-v$\dot{V}O_2max$ influencing factors in close comparison to the results obtained in earlier studies (in the literature and in Chapters 2 to 6 of this thesis). Furthermore, respiratory parameters were measured through a new validated telemetric portable gas analyzer (Keskinen et al., 2003), which allowed more precise breath-by-breath collection of data. The validity of the use of this modern procedure for collecting and measuring BxB expired gas was earlier discussed in this chapter.

Considering all subjects of the sample, TLim-v$\dot{V}O_2$max ranged from 195 to 293 s. Considering the referred interval plus the TLim-v$\dot{V}O_2$max mean (± SD) value, it is possible to refer that these data confirm the low inter-individual variability of this parameter in swimming, when comparing to running (Billat et al., 1994). However, elite male swimmers performed less time at v$\dot{V}$O2max than the lower inferior interval value that is reported in the Chapter 4. This fact seems to be explained by elite male swimmer's higher v$\dot{V}$O2max, and Cv$\dot{V}$O2max, when comparing to: (i) elite female swimmers participant in this study; (ii) high trained swimmers (Billat et al., 1996; Renoux, 2001; Chapters 3 and 4 of this thesis); (iii) low level swimmers (Chapter 4 of this thesis); (iv) pentatheletes (Demarie et al., 2001).

Closely related to the above described finding, it was observed an inverse relationship between TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max, which is in accordance with previous data (Billat et al., 1996; Faina et al., 1997; Renoux, 2001; Chapter 4 of this thesis). This relationship seems to be explained by two factors: (i) higher swimming velocities implies superior $\dot{E}$ and, consequently, higher C (Toussaint and Hollander, 1994), confirmed in this study by the high correlation value between v$\dot{V}O_2$max and Cv$\dot{V}O_2$max, and (ii) higher swimming velocities indicates more strenuous efforts, with more pronounced recruitment of anaerobic energy pathways, leading to earlier fatigue stages and, consequently, to lower TLim-v$\dot{V}O_2$max. In the presently discussed study, TLim-v$\dot{V}O_2$max correlated inversely with $\Delta[La^-]$ and with $[La^-]$max, confirming the last referred idea, and corroborating the literature (Faina et al., 1997; Billat, 1998) and Chapter 4 data.

In the perspective above discussed, one of the main determinants of TLim-v$\dot{V}O_2$max seems to be C, since TLim-v$\dot{V}O_2$max is inversely related to Cv$\dot{V}O_2$max. The higher level of maximal metabolic rate of the more proficient swimmers may be associated with a smaller capacity to sustain that precise exercise intensity. Complementarily, knowing that C is affected by some physical characteristics, namely by SA (di Prampero, 1986), it was searched in Chapter 7 a possible relationship between Cv$\dot{V}O_2$max and SA. It was observed a strong correlation between Cv$\dot{V}O_2$max and SA. This last relationship indicates that body characteristics also have an important role in TLim-v$\dot{V}O_2$max efforts, probably also the cross-sectional area, a parameter well related with SA (Zamparo et al., 1996), implying that higher body sizes imposes greater drag to be overcome by muscular work, increasing C (Toussaint et al., 1988).

In addition, TLim-v$\dot{V}O_2$max was also inversely related to vAnT. This negative correlation was already described before, but only for the averaged value of 3,5 mmol/l of [La^-] (Chapter 3 of this thesis). Knowing that [La^-] corresponding to AnT has been reported to have great variability between swimmers, the methodology for vAnT assessment used in this study was considered more appropriated than the commonly used, because it seems to give more specific and individualized values for aerobic/anaerobic transition intensities (this subject will be addressed latter in the discussion). Complementarily, vAnT was highly correlated to v$\dot{V}O_2$max, in accordance to previous available results (Billat et al., 1996; Faina et al., 1997; Renoux, 2001; Chapter 4 of this thesis).

Other main TLim-v$\dot{V}O_2$max determinant seems to be O_2SC. In Chapter 7, O_2SC was assessed through mathematical modelling, a more precise and accurate method (this subject will be also attended latter in the discussion). As reported in Chapters 3 and 4 of this thesis, the mean value obtained in this study for O2SC seems to have physiological meaning, once it was higher than 200 $ml.min^{-1}$ (Billat, 2000). Its significant relationship with TLim-v$\dot{V}O_2$max appears to indicate that higher TLim-v$\dot{V}O_2$max probably corresponds to higher expected O_2SC amplitude, which is in accordance with the study of Chapter 3, conducted in high level swimmers.

From the present results, in accordance with the literature data (Billat et al., 1996; Faina et al., 1997), it was shown once again that TLim-v$\dot{V}O_2$max seems not to depend directly on swimmers relative $\dot{V}O_2$max. However, for the first time in this thesis, it was observed a significant relationship between TLim-v$\dot{V}O_2$max and absolute $\dot{V}O_2$max (although only for a $p < 0.10$). This fact is in accordance with the authors that stated that $\dot{V}O_2$max plays a central role among the energy-yielding mechanisms in swimming (Van Handel et al., 1988b; di Prampero, 2003) and to the common knowledge that aerobic power is important in swimming performance.

Despite the indubitable fact that the ability to achieve, and maintain, a specific swimming velocity in an event is related to metabolic but also to biomechanical factors (Toussain and Hollander, 1994; Termin and Pendergast, 2000; Pendergast et al, 2006), it was not found any relationship between TLim-v$\dot{V}O_2$max and the stroking parameters (SR, SL and SI). It was expected TLim-v$\dot{V}O_2$max to be inversely related with SR and directly related with SL and SI, as observed in Chapter 6 of this thesis. However, no significant correlation values were obtained. The small amount of subjects of this study could be one explanation for weak statistical values. Nevertheless, SI was strongly related to v$\dot{V}O_2$max, meaning that faster swimmers were also the most technically proficient (Costill et al., 1985).

Some of the TLim-v$\dot{V}O_2$max related parameters considered in Chapter 7, namely Ant and O_2SC, were assessed through more specific and complex mathematical methods than those used before in this thesis. In this sense, in a parallel study of our group, presented in **Appendix IV**, it is described the alternative method for individual swimming AnT (IndAnT) assessment that was used in Chapter 7.

The fact that the study of Chapter 7 was conducted in elite swimmers, turn the assessment of AnT into a critical point. It is well known that more accurate, specific and individualized testing protocols are needed when the subjects are top level athletes (Gore, 2000). Thus, due to the necessity to overcome some of the insufficiencies of the traditionally used mean values of 4 $mmol.l^{-1}$ (Mader et al., 1976) or 3.5 $mmol.l^{-1}$ $[La^-]$ (Heck et al., 1985) for assessing AnT, a new technique was developed. The reason to the above referred mean $[La^-]$ values to be no more seen as ideal methods, is the fact that the velocity corresponding to 4 (or 3.5) $mmol.l^{-1}$ $[La^-]$, determined by linear inter or extrapolation of the $[La^-]$/velocity curve, seem not to express the reported great variability of $[La^-]$ corresponding to AnT among swimmers (Stegmann et al., 1981; Stegmann e Kindermann, 1982; Jacobs, 1986; Urhausen et al., 1993). Complementarily, the other more specific and individualized methodologies, present in the literature, also contains some limitations (Bunc et al., 1982), which prevent us to use them.

Thus, the new AnT assessment technique, described in Appendix IV, was based in the mathematical modelling of the $[La^-]$/velocity curve, which was achieved with the data obtained in the intermittent incremental protocol for $v\dot{V}O_2max$ assessment earlier used in Chapters 3 to 7. The results pointed out that, according to the above paragraph referred literature, the swimming velocity corresponding to 4 $mmol.l^{-1}$ $[La^-]$ does not represent the individualized lactate threshold in trained swimmers. Additionally, $[La^-]$ at IndAnT averaged 2.89 ± 1.46 $mmol.l^{-1}$, which was considerably lower than the traditionally used 4 (and 3.5) $mmol.l^{-1}$ values. However, it was concluded that, in case of impossibility of using individualized methods for Ant assessment, namely during sessions of training control in large groups of swimmers, the velocity corresponding to 3.5 $mmol.l^{-1}$ $[La^-]$ could be better used than v4 in prescribing the training velocities for development of aerobic capacity in groups of trained subjects.

The other more specific and individualized methodology for the evaluation of TLim-$v\dot{V}O_2max$ related parameters is presented in **Appendix V:** a mathematical model to assess O_2SC kinetics in the TLim-$v\dot{V}O_2max$ test. O_2SC was determined before in earlier presented studies (Chapters 2 and 3), but its assessment was based in the method of the rigid time intervals, which was recently considered to be prone to error (Bearden and Moffatt, 2001). So, in Chapter 7, it was applied the mathematical method of modelling the O_2SC kinetics at heavy exercise intensities, which is not a new subject in the literature, namely in studies conducted in cycle ergometer (Barstow and Molé, 1991) and treadmill running (Carter et al., 2000), but, to our knowledge, was never before applied to swimming. This method is able to discriminate the different components of the oxygen uptake kinetics, including the basal, cardiodynamic, fast and slow components, allowing characterizing each one of these components, not only in amplitude, but also in respect to the time of the start of that component. The methods of rigid intervals are not so complete, being not able to assess amplitudes and time delays of the different components of $\dot{V}O_2$ kinetics.

Complementarily to Appendix V, another study of our group was presented. Indeed, in **Appendix VI**, it is shown a comparison between the above-referred two types of techniques to measure the amplitude of O_2SC kinetics during the TLim-v$\dot{V}O_2$max test: (i) the use of a predetermined rigid interval, more specifically the difference between the last $\dot{V}O_2$ measurement and the mean $\dot{V}O_2$ value corresponding to the third ($\dot{V}O_{2[end-3]}$) (Whipp and Wasserman, 1972) or second minute of exercise ($\dot{V}O_{2[end-2]}$) (Koppo and Bouckaert, 2002) and (ii) the mathematical model, using a three component exponential model with independent time delays, developed by Barstow and Molé (1987) for leg exercise. In this study it is possible to observe a comparison between the O_2SC assessment method used in the studies of Chapters 2, 3 and the methodology employed in Chapter 7.

The results of this study showed significant differences between the mathematical model for the O_2SC amplitude, and the method of $\dot{V}O_{2[end-3]}$. Additionally, it was not observed any significant differences between the mathematical model for the SC amplitude and the method of $\dot{V}O_{2[end-2]}$. Thus, it was expressed that the use of the $\dot{V}O_{2[end-3]}$ underestimates the results, since the O_2SC usually begins earlier than the third minute of exercise, and that the use of the $\dot{V}O_{2[end-2]}$ seems to be a good solution, being less accurate that the method of mathematical modelling of the $\dot{V}O_2$ kinetics, but more simple to use in a day-to-day basis, having in mind that the mathematical model involves more complex calculations.

In **Chapter 8**, the last experimental study of this thesis is presented. Since no TLim-v$\dot{V}O_2$max related studies have been carried out based on other swimming techniques than front crawl, the purpose of this experiment was to characterize, and compare, TLim-v$\dot{V}O_2$max in the four competitive strokes, as well as to observe its relationships with two major performance determinants: $\dot{V}O_2$max and AnT. Twenty-three elite swimmers (8 front crawlers, 5 backstrokers, 4 butterfliers and 6 breaststrokers) were evaluated through the same methodologies presented in Chapter 7.

The values of $\dot{V}O_2$max obtained are in accordance with those previously published for elite front crawl swimmers (Holmér, 1974a; Billat et al., 1996; Faina et al, 1997). It is very difficult to make valid comparisons regarding $\dot{V}O_2$max obtained in elite front crawl, backstroke, butterfly and breaststroke swimmers because there a very limited number of studies in this thematic. Nevertheless, the observation of no differences between $\dot{V}O_2$max values between techniques is in accordance with Troup (1991).

Additionally, despite the greater superior amplitudes of TLim-v$\dot{V}O_2$max values when comparing to the front crawl studies presented in the literature (Billat et al., 1996; Faina et al., 1997; Demarie et al., 2001; Renoux, 2001) and in former chapter of this thesis, no significant differences were observed between competitive strokes in TLim-v$\dot{V}O_2$max. In this sense, pooled data were correlated with $\dot{V}O_2$max (ml/kg/min) and AnT (mmol/l), as possible main determinant factors of TLim-v$\dot{V}O_2$max, being observed no significant relationships between those parameters.

Despite the absence of significant relationships between TLim-v$\dot{V}O_2$max, $\dot{V}O_2$max and AnT, moderate inverse correlation values were observed between Tlim-v$\dot{V}O_2$max and v$\dot{V}O_2$max and vAnT, confirming previous findings obtained in high trained front crawl swimmers (Chapters 3 and 4 of this thesis). These results pointed out that, whatever the swimming techniques, the higher the swimming velocities commonly related to aerobic proficiency, the lower will be the TLim-v$\dot{V}O_2$max. This observation seems to be justified by the fact that higher swimming velocities indicates more strenuous efforts, with probably more pronounced recruitment of anaerobic energy pathways, leading to earlier fatigue stages and, consequently, to lower TLim-v$\dot{V}O_2$max. However, no relationship was found in this study between Tlim-v$\dot{V}O_2$max and $[La^-]$max, in agreement with Chapters 3 to 5, but in opposition with some previous literature findings (Faina et al., 1997) and the results of Chapter 7 (for $\Delta[La^-]$).

Chapter 10. Conclusions

The key of success does not lie in training hard but in training purposively and carefully
J. Olbrecht (2000, pg xiii)

The findings obtained in the collection of studies presented in this thesis emphasize the importance of both bioenergetical and biomechanical parameters in the TLim-v$\dot{V}O_2$max performance. This fact is in accordance with Vilas-Boas (2000), who proposes a biophysical model of swimming performance, stressing the need of a clear recognition of the importance of technical training, at least in parity with physical training.

It seems reasonable to stress out the following conclusions:
(i) the "n x 200 m, 30 s rest" intermittent incremental protocol is suitable for v$\dot{V}O_2$max assessment in swimming and it allows to evaluate the individual anaerobic threshold of the subjects;
(ii) there is a low inter-individual variability in TLim-v$\dot{V}O_2$max values, ranging from 215 to 260 s (elite swimmers), 230 to 260 s (high level swimmers) and 310 to 325 s (low level swimmers);
(ii) no differences were observed in TLim-v$\dot{V}O_2$max values between genders;
(iii) TLim-v$\dot{V}O_2$max was directly related to swimming economy, oxygen slow component, stroke length and stroke index;
(iv) TLim-v$\dot{V}O_2$max was inversely related to v$\dot{V}O_2$max, velocity corresponding to anaerobic threshold, lactate production and stroke frequency;
(v) in general, TLim-v$\dot{V}O_2$max was not related to $\dot{V}O_2$max;
(vi) TLim-v$\dot{V}O_2$max was lower in the swimmers who presented higher v$\dot{V}O_2$max, which could be explained by the higher energy cost of exercise, and higher anaerobic rate, in that specific exercise effort;
(vii) TLim-v$\dot{V}O_2$max did not differ between swimming strokes, pointing out that the phenomenon is similar in all four strokes.

(viii) O_2SC was observed in all levels of swimming proficiency, performing in swimming-pool conditions. The mathematical method of modelling the O_2SC kinetics used seems to be more precise and accurate than the method of rigid time intervals, namely the one that uses $\dot{V}O_{2[end-3]}$.data;

(ix) $\dot{V}O_2max$ and [La$^-$] values are not good predictors of TLim-v$\dot{V}O_2max$ performance.

(x) the developed technique for individual anaerobic threshold assessment, trough mathematical modelling of the [La$^-$]/velocity curve, helped to overcome some of the insufficiencies of the traditionally used mean values of [La$^-$];

(xi) TLim-v$\dot{V}O_2max$ effort appeared to be characterised by a reduction of the propelling efficiency, namely due to the fact that SR increased and SL (and SI) decreased during the test, as a general tendency

In summary, the findings of the studies presented in this work may contribute to a better knowledge of the aerobic power training zone. With these new information, we highlight the importance of the aspects of physiology and biomechanics are bound together in order to increase training process allowing more objective, individualized and efficient prescriptions.

Chapter 11. Suggestions for future research

Despite the fact that the importance of the study of Biophysics in sports is nowadays well accepted, there is yet a lack of research trying to understand the relationships established between the bioenergetical and biomechanical variables in swimming. In this sense, it is our purpose to continue the study of TLim-v$\dot{V}O_2$max in swimming, namely in the following points:

(i) relate all the parameters previously studied with the one of the most relevant biomechanical swimming parameter: the intra-cyclic variation of the horizontal velocity of the centre of mass;

(ii) assess the distribution of the percentage of energy contribution from each energy system on the TLim-v$\dot{V}O_2$max effort, i.e., finding which is the aerobic and anaerobic participation percentages;

(iii) knowing that lactate production is not a truly good predictor of performance in swimming, we will look up to new indicators of anaerobic energy system participation like the O_2 deficit, the lactate exchange ability and the Δ respiratory quotient;

(iv) apply the TLim-v$\dot{V}O_2$max to training bout sets of intermittent exercise and assess the different physiological and biomechanical responses

As secondary goals, it is our aim to increase our knowledge about the $\dot{V}O_2$ kinetics during the intermittent incremental protocol for v$\dot{V}O_2$max assessment. In this sense, we purpose to group the 200 m steps before the occurrence of the individual anaerobic threshold, and the steps that occur after the boundary, and to characterize them. Complementarily, we will observe if the sampling interval of $\dot{V}O_2$ data could affect the prevalence of a plateau in $\dot{V}O_2$ at $\dot{V}O_2$max.

Lastly, when relating all the above-mentioned parameters, we will try to increase the number of subjects of the samples, in order to be able to do use more “strong” and reliable statistical methods, namely the use of prediction regression models. The increase of the samples will be also useful to consolidate the data obtained for backstroke, butterfly and breaststroke.

Appendix I

Evaluation of the energy expenditure in competitive swimming strokes

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Published on Int. J. Sports Med. (2006), first on-line April 11. DOI: 10.1055/s-2006-923776.

Abstract

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

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 (1974).

Holmér (1974) compared the swimming economy of several competitive swimming strokes in a flume. An obvious dichotomy was observed between the alternated (Freestyle and Backstroke) and the simultaneous (Breaststroke and Butterfly) techniques, later on confirmed by other authors (Pendergast et al., 1978; Lavoie and Montpetit, 1985). For a given velocity, and by this order, the Butterfly and the Breaststroke were the least economical strokes, the Backstroke and the Freestyle being the most economical ones.

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

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

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

Most studies about cardiorespiratory profiles in swimming have used Douglas bags or mixing chamber gas analyzers (Hólmer, 1974; Lavoie and Montpetit, 1985; Chatard et al., 1990; Wakayoshi et al., 1995). 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 (Hausswirth et al., 1997; McLaughlin et al., 2001; Keskinen et al., 2003; Maiolo et al., 2003). The last version of miniaturized metabolic carts has been developed for BxB gas analysis, allowing direct measurement of cardiorespiratory parameters during free swimming in an easiest way. Moreover, this apparatus allows the characterization of oxygen uptake kinetics in a more feasible and detailed manner, during direct measurement. Nevertheless, there is a lack of studies around this topic, using BxB technology, in swimming.

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

Materials and Methods

Subjects.

26 swimmers (8 females and 18 males) of international level volunteered to serve as subjects. 5 swimmers were evaluated performing Breaststroke (including one female swimmer), 4 swimmers performing Butterfly (including one female swimmer), 5 swimmers performing Backstroke and 12 swimmers performing Freestyle (including 6 female swimmers). The percent of body fat measured using a bio-impedance (Tanita, TBF 305, Japan) for Breaststroke swimmers was 10,8 ± 6.3%, for Butterfly 9,3 ± 3.8%, for Backstroke 6.8 ± 2.4%

and for Freestyle was 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 7^{th} trial. The starting velocity was set at a speed, which represented a low training pace, approximately 0.3 $m \cdot s^{-1}$ below less than a 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 30s to collect blood samples. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Portugal), on the bottom of the 25-m pool, were used to control the swimming speed and to help the swimmers keep an even pace along each step.

Data Collection.

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

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

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

Individual regression equations were computed between the $\dot{E}_{tot}$ and the V, for all the swimmers. Figure 1 presents, as an example, the relationship between $\dot{E}_{tot}$ and V obtained with two swimmers. $\dot{E}_{tot}$ was extrapolated for the velocities of 1.0 $m.s^{-1}$, 1.2 $m.s^{-1}$, 1.4 $m.s^{-1}$ and 1.6 $m.s^{-1}$, using the individual regression equations computed. These velocities were selected from the range of velocities swum during the incremental protocol and are similar to the ones previously used by Troup (1991). The maximal swimming velocity achieved in Freestyle was 1.57 $m.s^{-1}$, in Backstroke 1.46 $m.s^{-1}$, in Breaststroke 1.18 $m.s^{-1}$ and in Butterfly 1.30 $m.s^{-1}$.

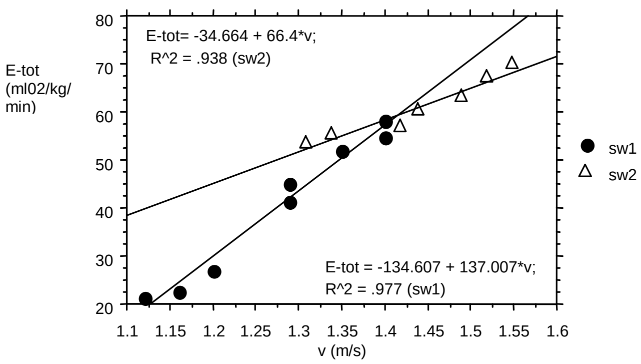

Figure 1. Relationship between the total energy expenditure (E-tot) and the swimming velocity (v) from two of the studied swimmers (sw). From the individual regression equations computed, $\dot{E}_{tot}$ was extrapolated or interpolated for 1.0 $m.s^{-1}$, 1.2 $m.s^{-1}$, 1.4 $m.s^{-1}$ and 1.6 $m.s^{-1}$,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

Statistical procedures.

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

Results

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

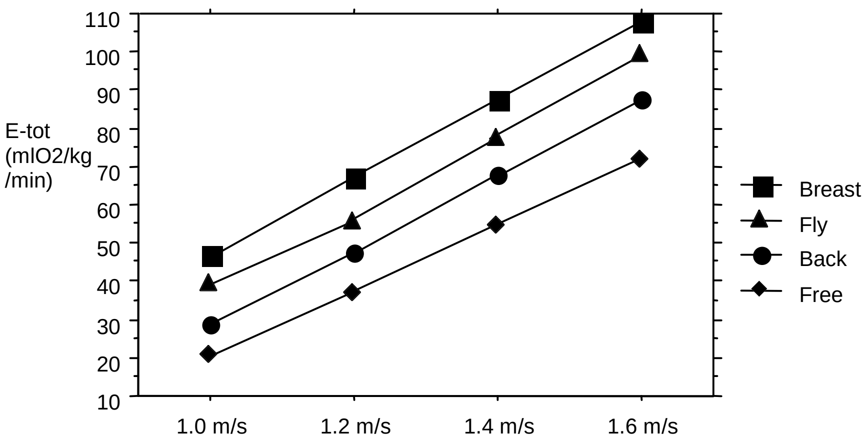

Figure 2. Energy expenditure (E-tot) profile, of the four swimming techniques, for the selected velocities.

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

Figure 3 presents the post-hoc comparison of $\dot{E}_{tot}$ at a given velocity. At the velocity of 1.0 $m.s^{-1}$ 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 $m.s^{-1}$ 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 $m.s^{-1}$, 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 $m.s^{-1}$, the Freestyle was significantly more economical than any other competitive swimming stroke. Finally, at the selected velocity of 1.6 $m.s^{-1}$, the $\dot{E}_{tot}$ was significantly higher in Breaststroke (p<0.01) and in Butterfly (p=0.02) than in Freestyle.

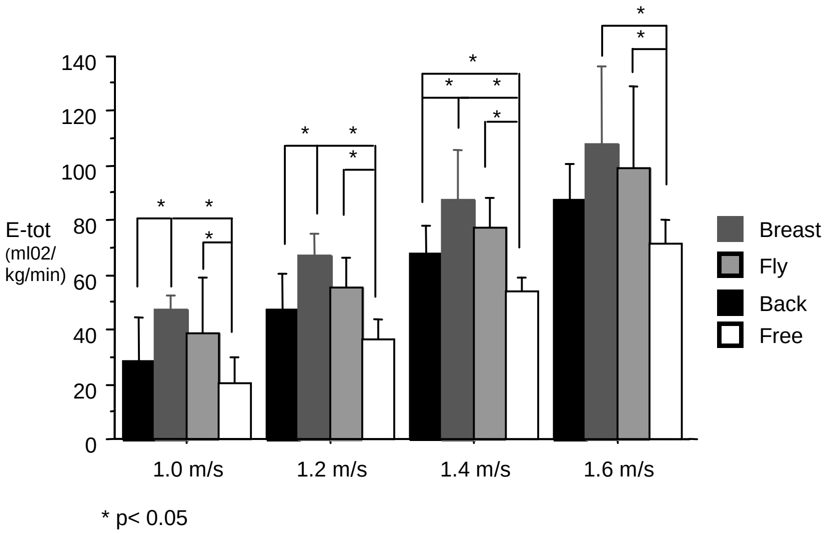

Figure 3. Comparison of total energy expenditure (E-tot) between the swimming stroke according to the Fisher's Post-hoc test, in each selected velocity.

Discussion/Conclusion

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

From the 23 swimmers evaluated, 8 were female swimmers. It is reported that swimming economy is influenced by the swimmer's gender. Female swimmers are more economical than male swimmers (Onodera et al., 1999). Those differences are related to anthropometrical characteristics, such as body density and hydrodynamic torque (Onodera et al., 1999). Female swimmers can adopt a better horizontal body alignment and are affected by a lower hydrodynamic torque (Zamparo et al., 1996; Yanai, 2001). In the present investigation, 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 under-estimate the $\dot{E}_{tot}$ in Freestyle. However, comparing the $\dot{E}_{tot}$ in Freestyle according to gender, there were no significant differences in any swimming velocity selected. For example, at the velocity of 1.6 $m.s^{-1}$, the mean $\dot{E}_{tot}$ for males swimmers was 70.9±7.4 $ml.kg^{-1}.min^{-1}$ and 71.8±9.8 $ml.kg^{-1}.min^{-1}$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 several strokes seems not to be significantly influenced by gender.

There are some studies in the literature concerned with the economy of the competitive swimming techniques (Hólmer, 1974; Pendergast et al., 1978; Van Handel et al., 1988; Chatard et al., 1990; Wakayoshi et al., 1995; Wakayoshi et al., 1996). However, the role of the anaerobic system to the total energy expenditure is not always taken in account. The few exceptions are the investigations developed by Rodriguez (1999), Vilas-Boas and Santos (1994) or Vilas-Boas (1996). The relative contribution of this bioenergetical system to the overall energy expenditure should not be disregarded (di Prampero et al., 1978; Camus et al., 1984; Thevelein et al., 1984; Camus and Thys, 1991). For example, Troup (1991) in a 200-m swim observed a contribution of 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 (Troup and

Hollander, 1992). Therefore, the study of the energy expenditure based exclusively on the oxygen consumption might both underestimate the values and reduce the validity and utility of the measurements.

Most studies about cardiorespiratory parameters in swimming used Douglas bags or mixing chamber gas analyses (Hólmer, 1974; Lavoie and Montpetit, 1985; Chatard et al., 1990; Wakayoshi et al., 1995). However, BxB analysis provides new insights into this field (Keskinen et al., 2003). The feasibility of this system to measure the oxygen uptake of incremental free swimming has been proved (Rodríguez et al., 2003) to offers a convenient tool to explore cardiorespiratory adaptations during swimming in a more detailed manner (Keskinen et al., 2003; Rodríguez et al., 2003).

For all selected velocities, the Breaststroke and the Butterfly strokes were the swimming techniques with higher $\dot{E}_{tot}$. These results are in agreement with data from other authors (Hólmer, 1974; Pendergast et al., 1978; Lavoie and Montpetit, 1985) who observed an obvious distinction between the alternated and the simultaneous techniques. This might be related with the higher variation of the swimmer's impulse along the stroke cycle in both techniques (Van Tilborgh et al., 1988; Vilas-Boas, 1994; Barbosa et al., 2002). The high amplitude of the swimmer's impulse is explained by the extreme intracyclic variations of the swimming velocity (Kornecki and Bober, 1978; Mason et al., 1992; Togashi and Nomura, 1992; Sanders, 1996; Vilas-Boas, 1996; Barbosa et al., 2003). This phenomenon promotes high peaks of accelerations and/or high peaks of deceleration. In the butterfly stroke, great intracyclic variations of the impulse are due to a greater reduction of this variable during the arm recovery (Barbosa et al., 2002). In breaststroke, great intracyclic variations are due to a great and positive peak during the leg spreading and a negative peak during the leg's recovery (Van Tilborgh et al., 1988; Vilas-Boas, 1994). Higher intracyclic variations of the impulse, such as the ones described above, induce an additional mechanical work done by the swimmers and, consequently, higher energy expenditure (Nigg, 1983).

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

The freestyle was the most economic competitive technique, followed by the backstroke, at all selected velocities. This is in agreement with several studies (Karpovich and Millman, 1944; Hólmer, 1974; Pendergast et al., 1978; Lavoie and Montpetit, 1985; Troup, 1991). These strokes are characterized by the lower intracyclic variations of the swimming velocity (Keskinen and Komi, 1993; Cappaert et al., 1996; Alves et al., 1998). Consequently one other important biomechanical repercussion is the low value of the swimmer's impulses during the stroke cycle to overcome inertial forces, in comparison to Breaststroke or to Butterfly stroke. Interestingly, in Backstroke, Alves (1996) verified that the impulse in the final downsweep differed significantly between a more economical and a less economical group of swimmers and correlated significantly with the best time in a 100-m event.

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

One major question may be posed: Is 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 (1974) in the 1970's? First of all, it is important to emphasize that the evaluation procedures used by Holmér (1974) 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 under-water pace-maker. Secondly, the parameters evaluated were not the same. Holmér (1974) measured the absolute VO_2; in the present study the parameter evaluated being the $\dot{E}_{tot}$. Nevertheless, a comparison between the absolute VO_2 reported by Holmér (1974) and the absolute $\dot{E}_{tot}$ from the present investigation was made, at the swimming velocity of 1.0 $m.s^{-1}$. This swimming velocity was chosen, because it is the only common velocity selected by Holmér (1974) 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 lower increase. The phenomenon can be related to the strong restrictions imposed in the rules of this swimming technique, in what concerns to its biomechanical evolution. 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 utilizing a new BxB technique. Freestyle was shown to be the most economic among the competitive swimming strokes, followed by the Backstroke, the Butterfly and the Breaststroke.

Appendix II

Comparison of continuous and intermittent incremental protocols for direct $\dot{V}O_2max$ assessment

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Published on Biomechanics and Medicine in Swimming IX (2003), pp. 313-318.

Abstract

The purpose of this study was to compare two incremental protocols for $\dot{V}O_2max$ and minimum swimming velocity that elicits $\dot{V}O_2max$ ($v\dot{V}O_2max$) assessment. The sample comprised 11 Portuguese swimmers: 6 females (21.00 ± 1.79 years, 54.83 ± 3.71 kg, and 163.83 ± 1.47 cm) and 5 males (25.40 ± 2.79 years, 69.00 ± 9.03 kg, and 175.00 ± 9.03 cm). They performed two incremental protocols (starting at 0.90 $m.s^{-1}$, with increments of 0.05 $m.s^{-1}$ per 200m stage) for freestyle $\dot{V}O_2max$ assessment, with a 48h interval and in the same general conditions. One protocol was a continuous test, and the other an intermittent one, with 30 s rest between incremental stages for $[La^-]$ assessment. Mean values of $\dot{V}O_2max$, $v\dot{V}O_2max$, VE, R, HR and $[La^-]$ for continuous and intermittent protocol, were respectively 52.5 ± 9.44 $ml.kg^{-1}.min^{-1}$ and 53.4 ± 8.74 $ml.kg^{-1}.min^{-1}$, 1.16 ± 0.099 $m.s^{-1}$ and 1.15 ± 0.099 $m.s^{-1}$, 95.3 ± 26.32 $l.min^{-1}$ and 95.8 ± 26.60 $l.min^{-1}$, 1.00 ± 0.044 and 1.00 ± 0.053, 183.1 ± 9.47 $b.min^{-1}$ and 187.5 ± 8.44 $b.min^{-1}$, 7.36 ±1.1313 $m.mol^{-1}$ and 8.86 ± 1.931 $m.mol^{-1}$. [La-] was only different parameter between both protocols ($p \leq 0.05$). Results pointed out that both protocols were suitable for $\dot{V}O_2max$ and $v\dot{V}O_2max$ assessment in swimming.

Key words: swimming, $\dot{V}O_2max$ assessment, maximal aerobic swimming velocity.

Introduction

With the very significant increase in training volume in the past recent years, especially during the eighties, recovery procedures and, mainly, improvements on training efficiency, seem to be the strategies to elicit performance improvement. Training efficiency, meanwhile, seems to be strongly determined by the availability of objective data about the particular needs, and capacities of each subject. So, training efficiency can only be improved, if we are also able to improve the methodology used for the specific evaluation of the determinant performance parameters of swimmers.

Aerobic energy seems to be very important for most of the competitive swimming events, especially after the recent recognition of a shift of the bioenergetic supply partition to a more aerobic zone, for any particular duration of a maximal competitive exercise (Gastin, 2001). Besides anaerobic threshold, the maximal oxygen consumption ($\dot{V}O_2max$) and the minimum swimming velocity that elicits $\dot{V}O_2max$ ($v\dot{V}O_2max$), seem to be some of the most important parameters for the evaluation of a swimmer's aerobic potential (Holmér, 1972; Bonen et al., 1980; Cazorla and Montpetit, 1983; Montpetit et al., 1983; Billat et al., 1996a; Billat et al., 1996b; Billat et al., 1999). Other parameters, such as the time that the swimmer is able to sustain on $v\dot{V}O_2max$, normally known as Time Limit, and the swimming economy, considered as the inverse of the swimming energy cost of locomotion, should be considered as also very important parameters to characterise the swimmer's performance capacity.

The evaluation of $\dot{V}O_2max$, $v\dot{V}O_2max$, Tlim-$v\dot{V}O_2max$, and economy on swimming subjects, requires specific oximetry procedures and protocols. Normally, the first two parameters are evaluated using progressive protocols, without resting periods between stages (Billat et al., 1996a; Billat et al., 1996b; Billat et al., 1999). However, swimming economy assessment requires both aerobic and anaerobic energy expenditure evaluation (Vilas-Boas and Santos, 1994), if possible at different swimming velocities to allow the computation of an economy curve. To do so, it is necessary to collect not only respiration parameters, but also blood parameters, such as lactate concentrations ([La$^-$]), which imposes the interruption of the protocol just after each stage. However, to our knowledge, it has not yet been demonstrated that an intermittent progressive protocol, even with small rest intervals, allow the assessment of the same values as a traditional continuous one.

The purpose of this study was to compare two progressive protocols for $\dot{V}O_2max$ and $v\dot{V}O_2max$ assessment: one continuous, and one intermittent to allow the collection of ear lob blood samples.

Materials and Methods

The subjects were eleven Portuguese water-polo players, triathletes, former swimmers, and/or physical education students, whose physical characteristics are given in table 1. All were previously informed about the protocol, and freely participated in this project.

Each subject performed two incremental protocols for freestyle $\dot{V}O_2max$ assessment in a 25 m pool, with a 48h interval and in the same general conditions. One was a continuous test, and the other an intermittent one, with 30s rest between incremental stages for [La$^-$] evaluation. Both protocols started at 0.9 $m.s^{-1}$, with increments of 0.05 $m.s^{-1}$ per 200 m stage. $\dot{V}O_2max$ was considered to be reached according to traditional physiological criteria, and $v\dot{V}O_2max$ was considered as the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$ according to the criteria of Lacour et al. (1991).

Expired gas was collected using a Toussaint et al. (1987) respiratory valve and VO_2, averaged each 20 s, was directly measured using a Sensormedics 2900 oximeter mounted on a special chariot running along the poolside.

Table 1. Physical characteristics of the subjects.

Subjects	Sex	Age	Height (cm)	Weight (kg)
(Student)	F	23	163	54
(Student)	F	20	164	54
(Swimmer)	F	21	162	52
(Swimmer)	F	18	165	52
(Water-polo)	F	22	166	62
(Water-polo)	F	22	163	55
(Mean ± SD)		21.00 ± 1.79	163.83 ± 1.47	54.83 ± 3.71
(Triathletes)	M	23	181	69
(Triathletes)	M	26	172	65
(Triathletes)	M	28	171	61
(Water-polo)	M	28	187	80
(Swimmer)	M	22	164	70
(Mean ± SD)		25.40 ± 2.79	175.00 ± 9.03	69.00 ± 7.11

Swimming velocity was controlled using a visual pacer (*GBK-Portugal*). $[La^-]$ were measured before, during the intermittent test, immediately and 3 min after both tests, using an *YSI-1500* auto-analyzer. Heart rate (HR) was continuously monitored with a *Polar advantage* system.

The HR, $[La^-]$, ventilation (V_E), ventilatory equivalent for oxygen (EVO_2), respiratory quotient (R), $v\dot{V}O_2max$, tidal volume (VT), respiratory rhythm (RR), and $\dot{V}O_2max$ obtained with both protocols, were treated for means difference significance statistical significance using a paired Student t-test.

Results

The main results of the study are presented in Table 2. The same results are presented in Table 3 averaged by gender. $\dot{V}O_2max$, $v\dot{V}O_2max$, V_E, R, HR, EVO_2, RR presented no significant differences between the continuous and intermittent incremental protocols. Meanwhile, $[La^-]$ and VT were significantly different between the studied protocols. [La$^-$] for the intermittent progressive protocol was significantly higher than the obtained concentrations for the continuous one, and the VT was, on the other hand, significantly higher for the continuous test.

Table 2. Main results of the study comparing continuous and intermittent protocols.

Parameter	Continuous	*Intermittent*	**P**
$\dot{V}O_2max$ (ml.min^{-1})	3069.7 ± 812.91	3136.6± 785.77	0.463
$\dot{V}O_2max$ (ml.kg^{-1}.min^{-1})	52.5 ± 9.44	53.4 ± 8.74	0.550
v$\dot{V}O_2max$ (m.s^{-1})	1.16 ± 0.099	1.15 ± 0.099	0.341
V_E (l.min^{-1})	95.3 ± 26.32	95.8 ± 26.60	0.809
R	1.00 ± 0.044	1.00 ± 0.053	0.940
HR (b.min^{-1})	183.1 ± 9.47	187.5 ± 8.44	0.167
[La$^-$] (mmol.l^{-1})	7.36 ± 1.313	8.86 ± 1.931	0.002*
EVO_2 (ml.min^{-1})	29.8 ± 3.31	28.5 ± 3.88	0.208
RR (breathing. min^{-1})	44.3± 7.02	46.4 ± 7.66	0.180
VT (ml)	2.20 ± 0.624	2.05 ± 0.575	0.032*

In Figure 1 it's possible to observe an example of the curves of VO_2 kinetics correspondent to the referred protocols.

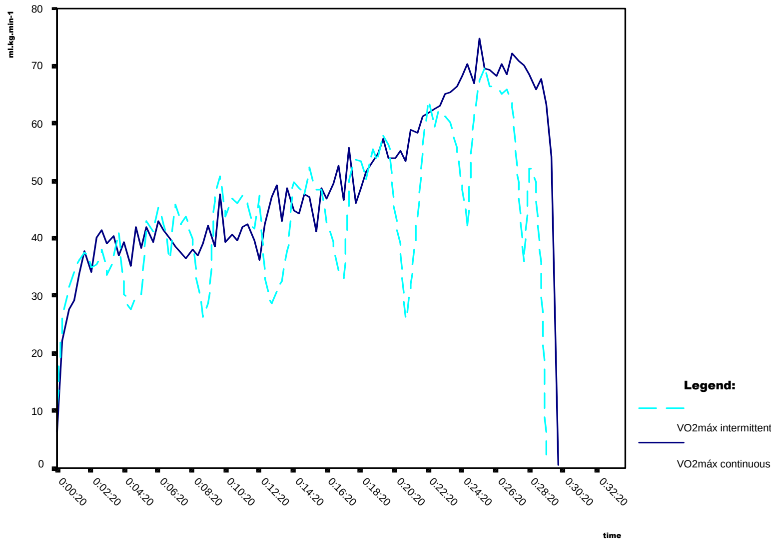

Figure 1. $\dot{V}O_2max$ values obtained during continuous and intermittent protocols.

Table 3. Main results of the study comparing continuous and intermittent protocols by gender.

Parameters	Tests	Female (n = 6)	Male (n = 5)	P
$\dot{V}O_2max$ (ml.min^{-1})	Continuous	2641 ± 353.6	3853 ± 618.5	.003*
	Intermittent	2680 ± 325.8	4072 ± 449.7	.000*
$\dot{V}O_2max$ (ml.kg^{-1}.min^{-1})	Continuous	48.49 ± 7.372	56.22 ± 9.651	.166
	Intermittent	49.03 ± 6.582	59.03 ± 5.557	.025*
v$\dot{V}O_2max$ (m.s^{-1})	Continuous	1.12 ± 0.125	1.19 ± 5.477	.287
	Intermittent	1.16 ± 0.138	1.19 ± 5.062	.631
HRmax (b.min^{-1})	Continuous	185.7 ± 10.25	179.8 ± 6.87	.305
	Intermittent	191.3 ± 5.75	183.2 ± 8.61	.094
[La$^-$] (m.mol^{-1})	Continuous	7.05 ± 1.663	7.74 ± 0.731	.418
	Intermittent	8.47 ± 2.370	9.32 ± 1.344	.497
EVO_2 (ml.min^{-1})	Continuous	29.0 ± 3.52	30.8 ± 3.11	.398
	Intermittent	28.2 ± 4.79	29.0 ± 2.92	.743
R	Continuous	1.00 ± 0.043	1.00 ± 0.051	.891
	Intermittent	0.99 ± 0.026	1.01 ± 0.076	.592
V_E (l.min^{-1})	Continuous	76.2 ± 11.05	118.6 ± 19.68	.001*
	Intermittent	73.9 ± 6.43	117.1 ± 21.29	.001*
RR (breath.min^{-1})	Continuous	44.7 ± 6.62	43.8 ± 8.23	.851
	Intermittent	46.5 ± 6.44	46.2 ± 9.73	.952
VT (ml.breath^{-1})	Continuous	1.72 ± 0.123	2.78 ± 0.427	.000*
	Intermittent	1.60 ± 0.148	2.58 ± 0.381	.000*

Male swimmers showed significantly higher values of $\dot{V}O_2max$, V_E and VT in both tests than their female's counterparts. When the $\dot{V}O_2max$ was expressed in $ml.kg^{-1}.min^{-1}$, it was only significantly different between genders for the intermittent incremental protocol. $v\dot{V}O_2max$, HR, $[La^-]$, R, EVO_2 and RR, were not significantly different between genders, for both the continuous and intermittent incremental protocols.

Discussion

The cardiorespiratory results obtained in this study were in close agreement with those published previously by Astrand and Saltin (1961), Holmér (1972), Holmér and Astrand (1972), Magel et al. (1974), Lavoie et al. (1983), and Butts et al. (1986). However, they were lower than those presented by Magel and Faulkner (1967), Armstrong and Davies (1981), Mckay et al. (1983), Handel et al. (1988), Alves (1995) and Billat et al. (1996a). The relatively low swimming proficiency and training status of our sample mainly composed of former swimmers, Physical Education Students, triathletes, and water-polo players, may contribute to explain this finding: similarities with old results obtained from competitive swimmers, and lower values when compared with more recent groups of competitive swimmers. The smaller cardiorespiratory values obtained, in this study, for the female subgroup can also contribute to reinforce this low values observed in our sample.

In fact, the values obtained for females seem to be especially low when compared to the literature, despite they were similar to those obtained by Butts et al. (1986) before subjects were submitted to a training program. Meanwhile, the results obtained for the male subgroup were similar to those presented by Magel et al. (1974), Eriksson et al. (1978), Mckay et al. (1983), Lavoie et al. (1983), Nomura (1983), Butts et al. (1986) and Billat et al. (1996a).

Continuous and intermittent protocols provided similar results, both for $\dot{V}O_2max$ and for $v\dot{V}O_2max$. The only significant difference was found on $[La^-]$, but results were, nevertheless, very similar. These differences can be attributed to a systematic prevalence of anaerobic metabolism after each rest interval during the intermittent test, which may be confirmed also through the higher R values found before VO_2 rise.

Both protocols fulfil the requirements of a maximal test for $\dot{V}O_2max$ assessment, namely: near to [La-] ≈ 8 $mmol.l^{-1}$, R values over 1, HR higher than 85% HRmax, and an exertion to exhaustion. R values, nevertheless, were lower than expected, despite they were higher than 1. In the same perspective, mean $[La^-]$ values for the continuous protocol were also slightly lower than the reference value.

We can conclude that both protocols are suitable for $\dot{V}O_2max$ and $v\dot{V}O_2max$ assessment in swimming, and that the use of the intermittent protocol imposes the consideration of the energetic equivalents of the $[La^-]$ to be used for economy profile evaluation.

Appendix III

Behaviour of the kinematic parameters during a time to exhaustion test at $\dot{V}O_2max$ in elite swimmers

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J Human Movement Studies (in press)

Abstract

The aim of this study was to analyse, in swimming-pool conditions, the behaviour of the kinematic parameters – stroke rate (SR), stroke length (SL) and stroke index (SI) - during a time to exhaustion test performed at the minimum velocity that elicits maximal oxygen uptake (TLim-v$\dot{V}O_2$max) in elite freestyle swimmers. Eleven swimmers from the National Portuguese Swimming Team (5 male and 6 female) performed an intermittent incremental test for v$\dot{V}O_2$max assessment and an all-out swim at v$\dot{V}O_2$max to determine TLim-v$\dot{V}O_2$max and to analyse the evolution of the kinematic parameters throughout the test. SR increased and SL (and SI) decreased during the TLim-v$\dot{V}O_2$max test, as a general tendency. When the differences in SR, SL and SI between each 12.5% section of the test were tested, a significant increase in SR and a decrease in SL and SI was verified at 25% [(74.00 (25.83 m)], 50% [(148.10 (51.66 m)] and 87.5% [(259.15 (90.41 m)] of the TLim-v$\dot{V}O_2$max duration. These data showed a reduction of the propelling efficiency throughout such a test. These findings could be useful when designing training programmes, namely of middle distance swimmers, taking into consideration maximum aerobic speed, time to exhaustion and propelling efficiency.

Key words: Swimming, time to exhaustion, kinematic parameters

Introduction

The assessment of the time required for a swimmer to reach exhaustion at the minimum velocity that elicits maximal oxygen uptake (TLim-v$\dot{V}O_2$max) is a recent topic of interest. The procedure developed by Billat et al. (1994) seems to be relevant to assess various determinants of training and performance in endurance athletes. While swimming has been considered to be among the endurance sports, it seems relevant to examine swimmers' ability to sustain intensities that elicit their $\dot{V}O_2$max.

TLim-v$\dot{V}O_2$max in free swimming was firstly studied in swimming flume (Billat et al., 1996) and later investigated in conventional pools (Renoux, 2001; Fernandes et al., 2003). TLim-v$\dot{V}O_2$max seems to be related to factors that determine fatigue, namely the energy cost of swimming (Fernandes et al., in press). Similarly, some simple biomechanical parameters, i.e., stroke rate (SR), stroke length (SL) and stroke index (SI), have been shown to reflect signs of fatigue during training (Toussaint and Beek, 1992; Keskinen and Komi, 1993), being SI considered a valid indicator of swimming efficiency (Costill et al., 1985). TLim-v$\dot{V}O_2$max concept seems to closely characterize the 400m freestyle performance (Fernandes et al., 2003) and the changes in the SR, SL and SI seem to reflect the changes of stroke performance. Thus, the combination of these two sources of information could bring new knowledge about technical ability in such type of swimming efforts and events. The purpose of this study was to analyse the SR, SL and SI during the course of a typical TLim-v$\dot{V}O_2$max freestyle effort, performed in normal swimming-pool conditions, using top-level swimmers.

Methods

Subjects

The subjects were 11 elite freestyle swimmers (5 male and 6 female) of the National Portuguese Swimming Team. The mean (SD) values for their physical characteristics, weekly training frequency and physiological parameters are presented in Table 1.

Table 1. Mean (SD) values for the physical characteristics, weekly frequency of training and physiological parameters of the subjects.

Parameters	Swimmers (n=11)
Age (years)	17.51 (1.69)
Body mass (kg)	66.02 (10.04)
Height (cm)	173.2 (9.6)
Training units (session/week)	8.8 (0.4)
$v\dot{V}O_2max$ (m/s)	1.46 (0.08)
TLim-$v\dot{V}O_2max$ (s)	202.73 (70.77)
DLim-$v\dot{V}O_2max$ (m)	296.01 (103.32)

Study protocol

The testing sessions took place in a 25 m indoor swimming-pool and in-water starts and open turns were used. The swimmers performed an incremental set of freestyle to assess $v\dot{V}O_2max$. The increments were 0.05 m/s per each 200 m stage with 30 s resting intervals until exhaustion. Initial velocity was established according to the swimmers' individual performance on the 400 m freestyle minus 7 increments of velocity (Fernandes et al., 2003). VO_2 was measured breath-by-breath (BxB) using a portable gas exchange system ($K4b^2$, Cosmed, Italy). The swimmers breathed through a respiratory snorkel and valve system rebuilt to enable BxB data collection, which has shown to be a valid tool to carry out measurements of swimmers' cardiorespiratory responses (Keskinen et al., 2003). Velocity was controlled using a visual pacer (TAR. 1.1, GBK-electronics, Aveiro, Portugal) with successive flashing lights, 2.5 m apart, on the bottom of the pool.

$\dot{V}O_2max$ was considered to be reached according to primary and secondary conventional physiological criteria (Howley et al., 1995), namely the occurrence of a plateau in VO_2 despite an increase in swimming velocity, high levels of [La-] ($\geq$ 8 mmol l^{-1}), elevated respiratory exchange ratio (R $\geq$ 1.0), elevated heart rate [HR > 90% of (220 - age)], and exhaustive perceived exertion (controlled visually and case to case). $v\dot{V}O_2max$ was considered to be the swimming velocity correspondent to the first stage that elicits $\dot{V}O_2max$. If a plateau less than 2.1 ml min^{-1} kg^{-1} could not be observed, the $v\dot{V}O_2max$ was calculated as follows (Kuipers et al., 1985):

$$v\dot{V}O_2max = v + \Delta v \cdot (n\ N^{-1}), \qquad \text{(Eq. 1)}$$

where v is the velocity corresponding to the last stage accomplished, Δv is the velocity increment, n indicates the number of seconds that the subjects were able to swim during the last stage and N the pre-set protocol time (in seconds) for this step.

Capillary blood samples for [La-] analysis were collected from the earlobe at rest, in the 30 s rest interval, at the end of exercise and during the recovery period (YSI1500LSport auto-analyser - Yellow Springs Incorporated, Yellow Springs, Ohio, USA). HR was monitored and registered continuously each 5 s through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland).

48 hours later all subjects swam an all-out swim at their previously determined $v\dot{V}O_2max$ to assess TLim-$v\dot{V}O_2max$. This protocol consisted in two different phases, all paced with the referred visual light-pacer: (i) a 10 min warm-up at an

intensity correspondent to 60% $v\dot{V}O_2max$ and (ii) the maintenance of that swimming $v\dot{V}O_2max$ until volitional exhaustion or until the moment the swimmers were unable to swim at the selected pace. TLim-$v\dot{V}O_2max$ was considered to be the total swimming duration at the pre-determined velocity. Distance limit (DLim-$v\dot{V}O_2max$) was, as well, registered as the distance performed (in meters) during the TLim-$v\dot{V}O_2max$ test.

SL was registered by the counting of the number of strokes in each 25 m, SR was calculated by dividing velocity by SL, and the product of SL by the velocity allowed to assess SI (according with Craig and Pendergast, 1979, and Costill et al., 1985).

Statistical analyses

As the distances obtained in the TLim-$v\dot{V}O_2max$ test (DLim-$v\dot{V}O_2max$) were different between swimmers, each DLim-$v\dot{V}O_2max$ was divided in 8 sections in order to make inter-subjects comparison. Then, the values of the stroking parameters, in each length, were converted to each 12.5% of the TLim-$v\dot{V}O_2max$ test.

Mean and SD computations for descriptive analysis were obtained for all variables (all data were checked for distribution normality with the Shapiro-Wilk test). A one-way repeated measures ANOVA was also used to compare the evolution of the kinematic parameters from one section to the next. A significance level of 5% was accepted.

Results

In Figure 1 it is possible to observe that SR increased and SL (and SI) decreased during the TLim-$v\dot{V}O_2max$ test, as a general tendency. When the differences in SR, SL and SI between each 12.5% section of the test duration were tested, a significant increase in SR and a decrease in SL and SI was verified at 25% [(74.00 (25.83 m)], 50% [(148.10 (51.66 m)] and 87.5% [(259.15 (90.41 m)] of the TLim-v$\dot{V}O_2$max.

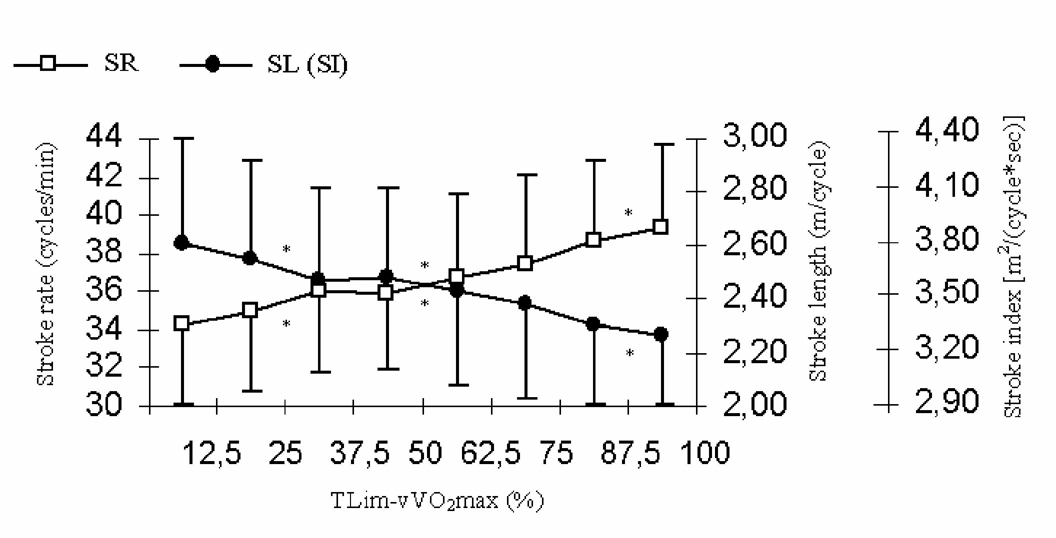

Figure 1. Mean (SD) values for SR, SL and SI during the TLim-v$\dot{V}O_2$max test (n=11), * $p<0,05$.

Discussion

Since the pioneer study by East (1970) that the analysis of the stroke kinematic parameters is one of the major points of interest in the biomechanical investigation of swimming. Following the previously studies that related TLim-v$\dot{V}O_2$max and some metabolic parameters (e.g. Billat et al., 1996; Renoux, 2001; Fernandes et al., 2003), it was tried in this study to go further in this analysis and observe the behavior of SR, SL and SI during a typical TLim-v$\dot{V}O_2$max effort.

The present results have some similarity with a previous study of Marinho et al. (2004), where an increase in SR and a decrease in SL during the TLim-v$\dot{V}O_2$max test were observed (with significant changes after 100 m during the swim, corresponding to 33.3% of the test duration). However, the subjects of that study were not elite swimmers and a less sensitive oximeter (Sensormedics 2900, Yorba Linda, USA), with 20 sec VO_2 averaged data, was used. In the present study all subjects were crawl specialists of the Portuguese National Swimming Team and the analysis of VO_2 kinetics was performed BxB. These facts may explain some of the observed differences between the two studies.

The present data suggest that the changes observed in SR, SL and SI in the three points mentioned above are critical in the TLim-v$\dot{V}O_2max$ effort. High-speed swimming overloads the human neuromuscular system and may deteriorate the stroke performance during the event, which was already shown in previous studies (cf. Keskinen and Komi, 1993; Wakayoshi et al., 1995; Laffite et al., 2004). Wakayoshi et al. (1996) and Dekerle et al. (2005) also observed the existence of a biomechanical boundary, very well related to the swimming intensity corresponding to anaerobic threshold, beyond which the SL becomes compromised. The reduction in the mechanical propulsive efficiency is possibly due to the increased local muscular fatigue, which seems to reduce the swimmers' ability to maintain the "feel for the water" (Wakayoshi et al., 1996). This reduction in the quality of stroke technique, represented by the decrease in SL and SI, and consequent increase in SR to maintain the swimming velocity, is associated with a lower capacity of force production to overcome water resistance (Craig et al., 1985). Monteil et al. (1996) have already verified changes in forces distributions and propelling efficiency throughout the different phases of the stroke cycle because of fatigue. It could be hypothesized that swimmers have to modify their coordination because the task constraints are maintained, whereas the swimmers have not the same capability to develop the corresponding speed (Dekerle et al., 2003). Further investigations should be conducted in this topic, namely in what concerns other major measure of swimming technique such as intra-cyclic velocity variations.

The findings of the present study can be useful in designing training programs based on intermittent exercises (Renoux, 2001). Distances beyond which the

SL becomes compromised should be design with especial care and swimmers and coaches should pay special attention to their stroking technique. Alves (2000) suggests that the decrease in SL during a 400 m freestyle event could be due to less body role and to the incapacity of create large amount of propulsive force in the finish of the pull. Coaches could use TLim-v$\dot{V}O_2$max and v$\dot{V}O_2$max data combined with the analysis of the stroking parameters. This would allow setting not only $\dot{V}O_2$max training loads, but also to control stroking technique during training, as suggested by Clipet et al. (2003). For example, the swimmers could swim an aerobic training set using a specific and controlled individual SR to cover each length.

In conclusion, this study showed that TLim-v$\dot{V}O_2$max typical effort appeared to be characterised by a reduction of the propelling efficiency. Results of this study could help swimming coaches to draw up individualized training programs for a given swimmer by taking into consideration maximum aerobic speed, time limit and propelling efficiency.

Appendix IV

Individual anaerobic threshold assessment in a swimming incremental test for VO_2max evaluation

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Published on the Abstract Book of the 10th Annual Congress of the European College of Sport Science (2005), pp. 266.

Introduction

Specifically in swimming related studies, the speed at blood lactate steady state is considered one of the primary areas of interest. In this sense, there are some previously described methods to assess the exercise intensity, after which the lactate production exceeds its removal, i.e., the anaerobic threshold (AnT) (Brooks et al., 2000). One of the most used methods for AnT assessment is based on the averaged value of 4 $mmol.l^{-1}$ of blood lactate concentration ($[La^-]$), proposed by Mader et al. (1976). However, $[La^-]$ corresponding to AnT has been reported to have great variability between swimmers. Other methodologies for AnT determination have been proposed to find more specific and individualized values for this parameter. These methods also contain some limitations, namely: (i) the subjectivity of the observation of the $[La^-]$/velocity curves' inflection point; (ii) the use of long test distances with significant velocity differences between steps (MaxLass) and (iii) the necessity of very high values of $[La^-]$ (15 $mmol.l^{-1}$), which implies strenuous exercise intensities (Bunc et al., 1982).

Thus, the purpose of this study was to present a new mathematical approach to assess individual AnT (IndAnT) trough a previous validated intermittent incremental protocol for VO_2max evaluation.

Materials and Methods

Thirty-two (19 male and 13 female) trained swimmers were studied: 18.9 (3.7) yy, 171.5 (7.7) cm and 62.8 (8.4) kg. Each subject performed, in a 25 m indoor swimming-pool, an intermittent incremental test for front crawl VO_2max assessment, with increments of 0.05 $m.s^{-1}$ each 200 m stage and 30 s intervals, until exhaustion (Fernandes et al., 2003). Velocity was controlled using a visual pacer with flashing lights on the bottom of the pool. In-water starts and open turns were used. $[La^-]$ were assessed at rest, during the 30 s intervals, immediately after each step and at minutes 3 and 5 of the recovery period

(YSI1500LSport auto-analyser). The velocity corresponding to 4 $mmol.l^{-1}$ $[La^-]$ (v4) was determined by linear inter or extrapolation of the $[La^-]$/velocity curve (v3.5 was also assessed as a more adequate value for trained swimmers, as suggested by Heck et al., 1985). IndAnT was determined by $[La^-]$/velocity curve modelling method (least square method), as described in Figure 1. IndAnT was assumed to be the intersection point, at the maximal fit situation, of a combined pair of regressions (linear and exponential). The individual ventilatory threshold was also calculated to validate the metabolic IndAnT. Mean (SD) computations for descriptive analysis were obtained for all variables. Pearson's correlation coefficient and *t-test* for repeated measures were also used. A significance level of 5% was accepted.

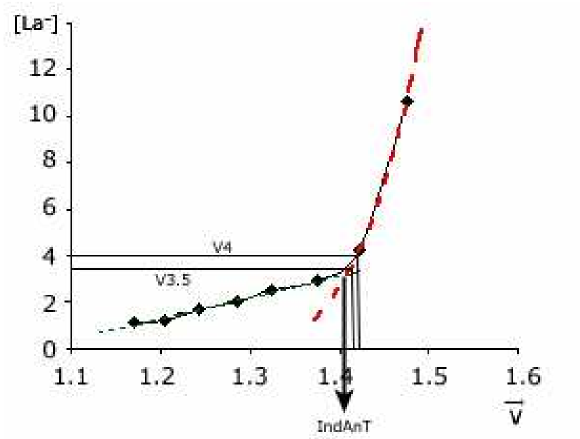

Figure 1. Individual $[La^-]$/velocity curve in the incremental test for VO_2max determination. IndAnT assessment is represented by the interception of a rectilinear and an exponential line (v4 and v3.5 are also marked).

Results

Concerning the swimming velocity, significant differences were observed between v4 and the velocity corresponding to IndAnT (Table 1). $[La^-]$ at IndAnT averaged 2.89 (1.46) $mmol.l^{-1}$, which was significantly lower than the 4 $mmol.l^{-1}$ value (as well as than the 3.5 $mmol.l^{-1}$ value). Complementarily, ventilatory threshold averaged 82.50 (31.49) $l.min^{-1}$ and correlated significantly with metabolic IndAnT (r = 0.63, P < 0.001).

Table 1: Mean (SD) values of swimming velocities for the v4, v3.5 and IndAnT methods. * represents statistical significant differences between methods (P < 0.01).

Parameter	v4	v3.5	IndAnT
v ($m.s^{-1}$)	1.27 (0.16) *	1.24 (0.17)	1.22 (0.14) *

Discussion/Conclusion

The protocol for VO_2max assessment used in the present study is specific for VO_2 kinetics analysis, but seems also to allow a specific and precise individual AnT assessment. The presented results seem to confirm the fact that v4 does not represent the individualized lactate threshold in trained swimmers. The present AnT assessment methodology could be useful in increasing the efficiency of training control and advising, resulting from VO_2max assessment programs. In the circumstance where the present protocol and methods are not applicable, the v3.5 could be better used than v4 in prescribing the training velocities for development of aerobic capacity in groups of trained subjects.

Appendix V

Mathematical modelling of the slow component of oxygen uptake kinetics in front crawl

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Published on Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences (2006), 6(2), 142-144.

Abstract

This work presents a mathematical method to model the V'O2 kinetics during heavy exercise. This method is able to discriminate between the different components of the oxygen uptake, including the basal, cardiodynamic, fast and slow components. Each of these components is fully characterized, not only in amplitude, but also in time of start of that component. The method is applied to two swimmers, and the results are presented, resulting in both cases in a good description of the slow component for oxygen uptake.

Key words: mathematical model, $\dot{V}O_2max$, slow component, swimming

Introduction

The $\dot{V}O_2$ kinetics has been the subject of several studies since the early 40's. In 1961 Astrand and Saltin (1961) observed the so called 'slow component' of oxygen uptake arising in heavy exercises, which has been since then the subject of several works. Most of these works are for exercises performed in cycle ergometers, and yet the first work dealing with swim only appeared in 2001 (Demarie et al., 2001). The present work follows this line of study, and tries to model the $\dot{V}O_2$ kinetics for front crawl swimming, paying particular attention to the slow component.

The data points for maximal $\dot{V}O_2$ used in this work were determined through direct ventilatory oximetry, using a portable breath-by-breath gas analyser (K4b^2, Cosmed, Italy) connected to the swimmers by a respiratory snorkel with low hydrodynamic resistance, in a test where the swimmers swam until exhaustion, at the previously determined velocity corresponding to $\dot{V}O_2max$ (Fernandes et al., 2003).

The typical aspect of the recorded breath-by-breath values of the oxygen uptake during heavy exercise is shown in Figure 1.

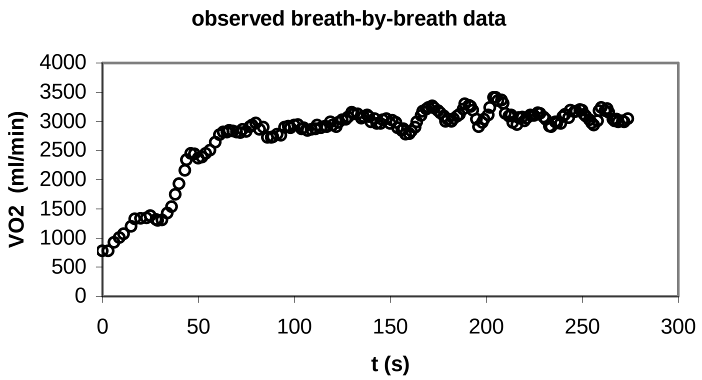

Figure 1. Observed breath-by-breath oxygen consumption by a swimmer during an exercise at maximal intensity. The origin of the time is set at the beginning of the exercise.

From the comparative analysis of the data collected through the years by different authors, it eventually turned out that the behaviour of the $\dot{V}O_2$ kinetics may be described by several components, as is schematically presented in figure 2 (e.g., Barstow and Molé, 1991). In the $\dot{V}O_2$ kinetics we may identify three distinct regions/components, apart from the constant basal value. The first component starts at the onset of the exercise, and is called the cardiodynamic component. A few seconds later starts the so called ‘fast component’, while the ‘slow component’ starts 2 to 3 minutes afterwards.

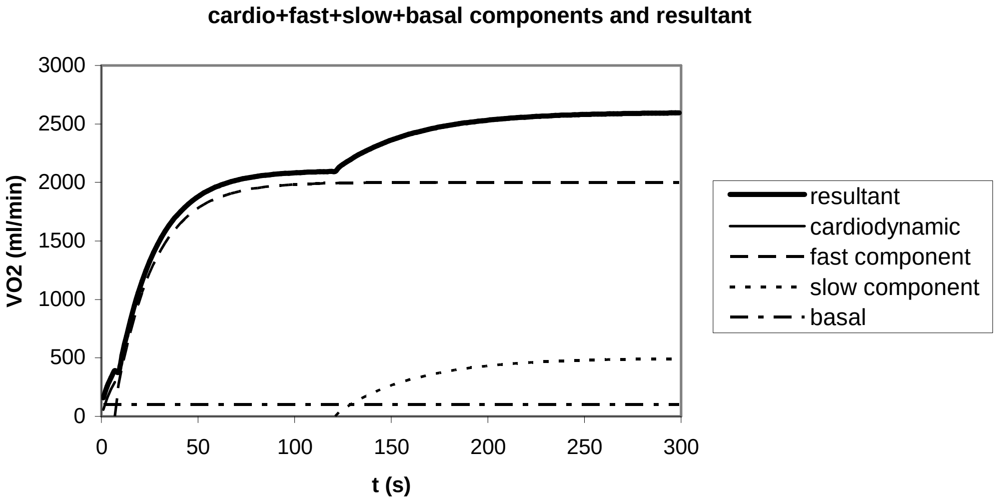

Figure 2. Plot representing schematically the different components of the $\dot{V}O_2$ kinetics.

The cardiodynamic component is caused by the increase of the heart rate, as demanded by the exercise, while the fast component is caused by the need of oxygen by the body, mainly the muscle fibres, as the exercise proceeds (e.g., Barstow, 1994). The cause of the slow component is still a matter of debate, the activation of the type II fibres being frequently referred as its cause (see, for example, Zoladz and Korzeniewski, 2001, for a review of several different hypothetical causes for its origin).

Methods

The $\dot{V}O_2$ kinetics is usually fitted by the following model:

$$\dot{V}O_2\,(t) = \dot{V}_b \qquad \text{(basal } \dot{V}O_2\text{)}$$

$$+A_0 \times (1 - e^{-(t/\tau 0)}) \qquad \text{(phase 1: cardiodynamic component)}$$

$$+ A_1 \times (1 - e^{-(t-TD1)/\tau 1}) \qquad \text{(phase 2: fast component)}$$

$$+ A_2 \times (1 - e^{-(t-TD2)/\tau 2}) \qquad \text{(phase 3: slow component)}$$

Where t is the time; A_i represents the various components amplitudes; TD_i are the times for the onset of the different components; and τ_i stands for the transition period needed for the component to attain the steady state, during which physiological adaptations adjust to meet the increased metabolic demand (Markovitz et al., 2004).

Analysis of the above mathematical expression shows that the $\dot{V}O_2$ kinetics is characterized by a constant value, the basal $\dot{V}O_2$, by an exponential function modelling the cardiodynamic component, and by two exponentials modelling the fast and slow components. These later components start after the time delays TD1 and TD2, respectively. The model cardiodynamic component acted from the beginning of the exercise until TD1, moment at which it was replaced by the fast component, which acted from this instant until the end of the exercise. The slow component started at TD2, being added to the fast component, and remained active until the end of the exercise. In figure 2, above, we can see a scheme with the four different components - cardiodynamic, fast, slow and basal –, as well as their sum, the resultant, that ultimately adjusts/models the observed data for the oxygen uptake.

The characteristics of the fitting function above, in particular the fact of being the sum of several exponentials, confers a nonlinear nature to it, which in this case is not removable, preventing its linearization. Consequently, for the adjustment of this function to the data points we used a nonlinear least squares method implemented in the MatLab[1] program, using the routine LSQCURVEFIT.

Prior to start the curve fitting we must perform some mathematical operations on the $\dot{V}O_2$ data. First of all, the oxygen consumption must be normalized to the body mass, such that it is presented as oxygen consumption per unit mass (ml/min/kg). In this way we can compare directly the amplitudes of the various components found for different persons. Dividing the oxygen consumption by the body mass is an operation performed simultaneously at all data points that do not alter the shape of the plot, it merely changes its scale.

Since this curve fitting uses a non-linear least squares method we must provide an initial guess for all the parameters (nine in this model), based on a visual inspection of the colleted data values. To further constrain the amplitude of variation the computational model parameters can have, we should impose the minimum (LB) and maximum (UB) ranges of variation for all parameters. Since all the parameters are positive, we must set the lower bound for all parameters to zero, with the exception of TD2 which clearly begins at a later time. Considering the upper bounds, they depend on the individual parameters, being conditioned by the collected data values for the oxygen uptake.

Results

We present two real situations for the adjusting of this model to data collected in front crawl swimming. These two swimmers were chosen such that one has a large amplitude slow component while the other has a small amplitude slow component, as is shown by the values of A2 in the following table. This table also displays the values of the remaining model parameters.

[1] http://www.mathworks.com/

Table 1. Values for the remaining model parameters.

Swimmer	$\dot{V}_b$ (ml/kg/min)	A0 (ml/kg/min)	τc (s)	A1 (ml/kg/min)	TD1 (s)	τ1 (s)	A2 (ml/kg/min)	TD2 (s)	τ2 (s)
1	8.6	20.3	57.2	42.6	21.9	20.5	3.0	105.0	59.7
2	22.9	23.2	25.5	37.9	6.7	21.2	12.0	95.0	14.1

Figures 3 and 4 display the graphics for swimmers 1 and 2, respectively. Both graphics show the collected data points normalized to the body mass, as well as the adjusted function, whose model parameters were already displayed in the table above.

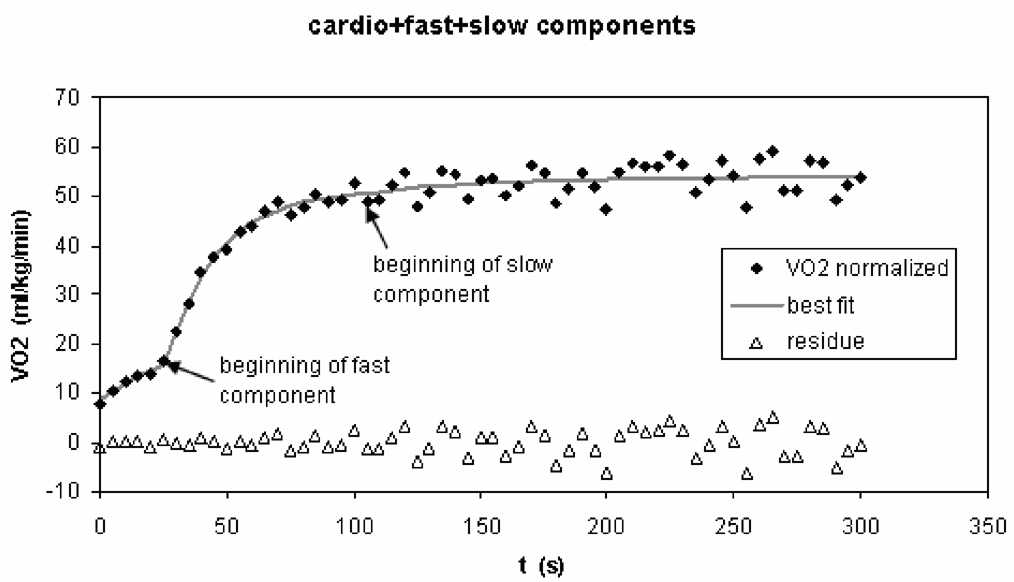

Figure 3. Curve fitting for swimmer 1, displaying a low amplitude slow component.

Analysis of these graphics shows that the implemented mathematical model is able to conveniently adjust the collected values for the oxygen uptake, regardless of the amplitude of the slow component.

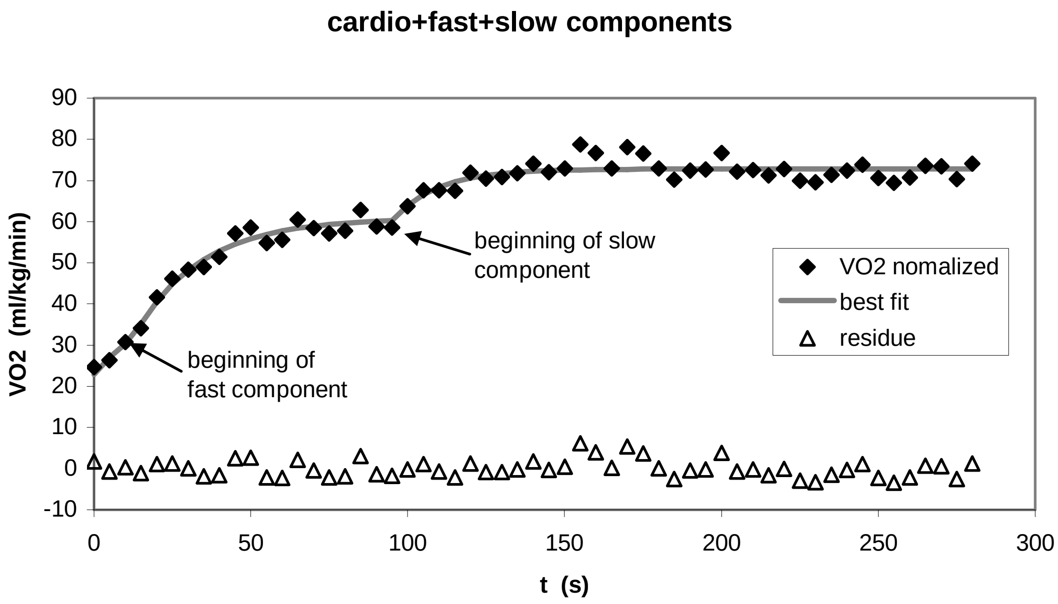

Figure 4. Curve fitting for swimmer 2, displaying a high amplitude slow component.

Discussion

The main conclusion of this work is that this method seems to model in an adequate way the collected data for $\dot{V}O_2$ in swimming, being possible to characterize the different components of the oxygen consumption, namely, the basal, the cardiodynamic, the fast and the slow components. This method describes the slow component in terms of amplitude, time of beginning and duration of the transition phase.

There are other methods to estimate the oxygen uptake components, particularly the slow component amplitude, some of them being described in (Querido et al., 2006). Nevertheless, comparison of those methods with the present mathematical model shows that the later gives the possibility to discriminate the different components of the $\dot{V}O_2$ kinetics, including the amplitude of the slow component, while the others usually fail in this respect.

Appendix VI

Comparison between different methods for the assessment of the $\dot{V}O_2$ slow component of freestyle elite swimmers

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Published on Biomechanics and Medicine in Swimming X, Portuguese Journal of Sport Sciences (2006), 6(2), 165-167.

Abstract

The purpose of this study is to compare different methods for the assessment of the Oxygen uptake Slow Component (O_2SC) in elite swimmers in a time limit test at the minimum velocity that elicits maximal oxygen consumption. Five females and two males participated in this study. $\dot{V}O_2$ was measured by a portable gas analyser connected to the swimmers by a respiratory snorkel. To describe the O_2SC kinetics was used a mathematical model with three exponential functions. This model was compared with different methods of rigid time intervals defined as the difference between the final $\dot{V}O_2$ and that at the 2nd min ($\Delta\dot{V}O_{2[end-2]}$) or at the 3rd min of exercise ($\Delta\dot{V}O_{2[end-3]}$). This study showed that the use of the $\dot{V}O_{2[end-3]}$ underestimates the results since the O_2SC usually begins earlier than the 3rd minute and that the use of the $\dot{V}O_{2[end-2]}$ seems to be a good solution, being less accurate but more simple to use in a day-to-day basis.

Key words: VO2 slow component, modelling, rigid time intervals, freestyle swimmers

Introduction

During exercise at heavy intensities, which engenders a sustained elevation in blood lactate, the $\dot{V}O_2$ kinetics becomes considerably more complex than for moderate exercise. We can observe a secondary slower component to the rise in $\dot{V}O_2$, such that attainment of a new steady-state, if attained, is delayed (Barstow and Molé, 1991). This Slow Component (O_2SC) usually begins 80s to 180s after the onset of the heavy exercise (Barstow and Molé, 1991).

In the literature we can find several methods for the assessment of the O_2SC. Many investigators have used a rigid interval to estimate the O_2SC (Bearden and Moffatt, 2001), most frequently the difference in oxygen consumption between the 3rd min and some later moment in the bout (e.g., Womack et al., 1995; Billat et al., 1998a; Billat et al., 1998b; Jones and McConell, 1999; Cater et al., 2000; Lucia et al., 2000; Demarie et al., 2001; Kolkhorst et al., 2004). Some authors have defined the 2nd min as the onset of the O_2SC (Koppo and Bouckaert, 2002; Fernandes et al., 2003; Nesi et al., 2004). Furthermore the use of a rigid interval as index of a physiologic parameter, which varies among subjects, is clearly prone to error, in addition the magnitude and significance of this error has not been investigated (Bearden and Moffatt, 2001).

The purposes of this study are: (i) verify the existence of a O_2SC in Portuguese elite freestyle swimmers; (ii) compare the results of the values of the O_2SC determined through the utilization of the mathematical model and the rigid time intervals, in a $\dot{V}O_2$ TLim test.

Methods

Subjects

Five females (16.9±1.5 yy, 59.0±3.1 kg and 165.8±3.2 cm) and two males (18.5±0.6 yy, 74.6±8.5 kg and 176.0±11.3 cm) elite freestyle swimmers volunteered to participate in this study. All subjects were informed about the details of the experimental protocol before beginning the measurement procedures.

Test protocol

The test sessions took place in a 25m indoor pool. First, each subject performed an intermittent incremental protocol for freestyle $v\dot{V}O_{2max}$ assessment (Fernandes et al., 2003). $\dot{V}O_2$ was directly measured by a portable gas analyser (K4 b^2 Breath by breath Pulmonary Gas Exchange System - COSMED, Italy) connected to the swimmers by a specific respiratory snorkel for swimming (Toussaint et al., 1987). Expired air was continuously measured during the entire test and averaged every 5s. Swimming velocity was controlled using a visual pacer (TAR.1.1, GBK-electronics, Aveiro, Portugal) with flashing lights in the bottom of the pool.

$\dot{V}O_{2max}$ was considered to be reached according to primary and secondary traditional physiological criteria (for more information see Fernandes et al., 2003). The velocity for maximal oxygen consumption, $v\dot{V}O_{2max}$, was considered to be the swimming velocity corresponding to the first stage that elicits $\dot{V}O_{2max}$.

Capillary blood samples for ($[La^-]$ analysis were collected from the earlobe at rest, in the 30s rest intervals, immediately after the end of each exercise step, and at 3min (and 5 min) during the recovery period. These blood samples were analysed using an YSI1500LSport auto analyser (Yellow Springs Incorporated, Yellow Springs – Ohio, USA). Heart rate (HR) was monitored and registered continuously each 5s through a heart rate monitor system (Polar Vantage NV, Polar Electro Oy, Kempele, Finland).

The second test session took place forty-eight hours later. All subjects swam until exhaustion at their previously determined $v\dot{V}O_{2max}$, to assess TLim. This protocol consisted in two different phases, all paced with the referred visual light-pacer: 1) a 10min warm-up at an intensity corresponding to 60% $v\dot{V}O_{2max}$, followed by a rest period of 20s for blood collection; 2) the maintenance of the swimming $v\dot{V}O_{2max}$ until exhaustion. TLim was considered to be the total swimming duration at $v\dot{V}O_{2max}$.

$[La^-]$ were assessed at rest, during the 20s intervals, immediately after the exercise, and at 3min (and 5min) of the recovery period. HR was registered continuously using the same procedure previously described.

Swimmers were instructed to perform an open turn, always done to the same lateral wall without underwater gliding, and were verbally encouraged to swim as long as possible during the test period. Both tests were carried out in the same conditions for each subject, i. e., temperature, humidity and time of day.

Slow Component assessment

Mathematical model

The mathematical model consisted in three exponential terms, representing each, one phase of the response. The first exponential term started at the onset of the exercise and the other terms started after independent time delays (TDi in the equation). The following equation describes the mathematical model for the $\dot{V}O_2$ kinetics (Machado et al., 2006):

$\dot{V}O_2\,(t) = \dot{V}_b$ (basal $\dot{V}O_2$)

$+A_0 \times (1 - e^{-(t/\tau 0)})$ (phase 1: cardiodynamic component)

$+ A_1 \times (1 - e^{-(t-TD1)/\tau 1})$ (phase 2: fast component)

$+ A_2 \times (1 - e^{-(t-TD2)/\tau 2})$ (phase 3: slow component)

where t is the time, A_i represents the various components amplitudes, TD_i are the times for the onset of the different components, and τ_i stands for the transition period needed for the component to attain the steady state, during which physiological adaptations adjust to meet the increased metabolic demand (Markovitz et al., 2004). For the adjustment of this function to the data points it was used a nonlinear least squares method implemented in the MatLab program, using the routine LSQCURVEFIT. For each test we averaged the data values every 5s.

Methods of rigid time intervals

To assess the O_2SC with the rigid time intervals methods we calculated: (i) the value for $\dot{V}O_2$ averaged over the 20s before the 2nd min (120s), the 3rd min (180s) and at the end of the exercise - $\Delta\dot{V}O_{2[end-2]}$20s before 2min and final; $\Delta\dot{V}O_{2[end-3]}$20s before 3min and final (3); (ii) $\dot{V}O_2$ averaged over the 30s before the 2nd min, the 3rd min and at the end of the exercise - $\Delta\dot{V}O_{2[end-2]}$30s before 2min and final; $\Delta\dot{V}O_{2[end-3]}$30s before 3min and final (iii) $\dot{V}O_2$ averaged over the 40s before the 2nd min, the 3rd min and at the end of the exercise - $\Delta\dot{V}O_{2[end-2]}$40s before 2min and final; $\Delta\dot{V}O_{2[end-3]}$40s before 3min and final (iv) $\dot{V}O_2$ averaged over the 20s before and 20s after the 2nd min, 3rd min (centred) and 20s before the end exercise – $\Delta\dot{V}O_{2[end-2]}$20s+20s around 2min and 20s before final; $\Delta\dot{V}O_{2[end-2]}$20s+20s around 3min and 20s before final; (v) $\dot{V}O_2$ averaged over the 20s before and 20s after the 2nd min, 3rd min (centred) and 30s before the end exercise $\Delta\dot{V}O_2$end - $\Delta\dot{V}O_{2[end-2]}$20s+20s around 2min and 30s before final; $\Delta\dot{V}O_{2[end-2]}$20s+20s around 3min and 30s before final; (vi) $\dot{V}O_2$ average of the 20s before and 20s after the 2nd min, 3rd min (centred) and 40s before the end exercise - $\Delta\dot{V}O_{2[end-2]}$20s+20s around 2min and 40s before final; $\Delta\dot{V}O_{2[end-2]}$20s+20s around 3min and 40" before final (Koppo and Bouckaert, 2002; Fernandes et al., 2003).

Statistical analysis

Statistical procedures included means, standards deviations and paired Student's t-test. All data were checked for normality. The statistical procedures were conducted with SPSS 13.0. The significance level was set at 5%.

Results and Discussion

In the table 1 we can see the different values of the parameters we used to describe the $\dot{V}O_2$ kinetics. The Amplitude 1 (A1), Time Delay 1 (TD1) and Time Constant (Tau1) refer to the $\dot{V}O_2$ fast component and the Amplitude 2 (A2), Time Delay 2 (TD2) and Time Constant 2 (Tau2) refer to the O_2SC.

Table 1. Parameters of the $\dot{V}O2$ kinetics.

Swimmer	A1 (ml/kg/min)	TD1 (s)	Tau1 (s)	A2 (ml/kg/min)	TD2 (s)	Tau2 (s)
1	33,11	32,39	10,88	4,21	103,87	30,00
2	42,61	21,94	20,50	3,04	105,00	59,71
3	34,24	17,70	11,09	5,05	115,00	21,32
4	34,36	24,76	14,93	8,87	108,82	46,58
5	37,87	6,67	21,20	12,00	95,00	14,13
6	39,14	5,94	20,54	2,97	105,00	59,76
7	54,63	19,34	11,98	4,78	98,92	11,57
Mean±SD	39,42±7,5	18,39±9,51	15,87±4,7	5,85±3,4	104,52±6,5	34,72±20,6

Our results indicate that all subjects present an O_2SC. Even considering the small number of studies about this theme in swimming, there where already some indications that this activity also presented a O_2SC in heavy exercise (Demarie et al., 2001; Fernandes et al., 2003; Millet et al., 2004). Although Billat et al. (1998b) referred that some studies presented the drawback of studying untrained subjects or poor trained subjects and considered the O_2SC magnitude as being almost negligible in resistance athletes (Billat et al., 1998a; Billat et al., 1998b), Carter et al. (2000) observed a significant O_2SC in running and cycling athletes. The authors referred that the O_2SC first becomes evident at about 2 min into exercise. Therefore, defining the O_2SC as an increase in $\dot{V}O_2$ above the value at 3 min of exercise will significantly underestimate the magnitude of the O_2SC (Carter et al., 2000).

In fact, our results also point the fact that the amplitude of the O_2SC using the 3rd min of exercise is, in all cases, different from that obtained from the mathematical model. Looking at Table 1, we can also see that the O_2SC begun 104.51s±6,47s (TD2) into exercise, clearly below the 3 min (180s).

Our results also hint for the fact that using the 2nd min of exercise for the O_2SC assessment does not present statistically significant differences with the mathematic model, meaning that the O_2SC onset may be close to the 2nd min of heavy exercise (Carter et al., 2000).

Table 2. Mean (± SD) values for the O_2SC amplitude (in $ml.kg^{-1}.min^{-1}$) calculated from the different methods.

Mathematical model (A_2)	$\Delta\dot{V}O_{2[end-2]}$ 20sbefore 2min and final	$\Delta\dot{V}O_{2[end-3]}$ 20s before 3min and final	$\Delta\dot{V}O_{2[end-2]}$ 30s before 2min and final	$\Delta\dot{V}O_{2[end-3]}$ 30s before 3min and final	$\Delta\dot{V}O_{2[end-2]}$ 40s before 2min and final	$\Delta\dot{V}O_{2[end-3]}$ 40s before 3min and final
5.8 ± 3.4	4.0 ± 1.7	0.2 ± 2.0*	4.5 ± 1.9	0.2 ± 1.8*	4.8 ± 2.1	0.3 ± 1.9*
	$\Delta\dot{V}O_{2[end-2]}$ 20s+20s around 2min and 20s before final	$\Delta\dot{V}O_{2[end-3]}$ 20s+20s around 3min and 20s before final	$\Delta\dot{V}O_{2[end-2]}$ 20s+20s around 2min and 30s before final	$\Delta\dot{V}O_{2[end-3]}$ 20s+20s around 3min and 30s before final	$\Delta\dot{V}O_{2[end-2]}$ 20s+20s around 2min and 40s before final	$\Delta\dot{V}O_{2[end-3]}$ 20s+20s around 3min and 40s before final
	3.0 ± 1.7	0.3 ± 1.9*	2.8 ± 1.8	0.1 ± 1.5*	2.8 ± 1. 7	0.1 ± 1.6*

* $p<0.05$ for differences between A_2 and the respective method of rigid intervals.

Conclusions

The present study confirms the existence of a $\dot{V}O_2$ O_2SC in elite freestyle swimmers performing in the heavy intensity domain; (ii) there were statistically significant differences between the mathematical model for the O_2SC amplitude and all methods of rigid time intervals using the 3rd min; (iii) there were not statistically significant differences between the mathematical model for the O_2SC amplitude and all methods of rigid time intervals using the 2nd min; (iv) in our understanding it seems reasonable to admit that the mathematic model is the most interesting and correct method for the assessment of the O_2SC in elite swimmers, since it allows an individual analysis of each subject and its evolution with training, as well as allowing the analysis of other important parameters for the O_2SC definition. Nerveless, the utilization of the 2nd min of exercise for the estimation of the O_2SC amplitude seems to be a good compromise solution for a day-to-day basis, having in mind that the mathematical model involves more complex calculations, although with modern computers it takes less than a second to perform them.

Chapter 12 References

Chapter 1

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Chapter 2

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