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UNIVERSIDADE DO PORTO

BIOPHYSICAL ANALYSIS OF AEROBIC ENDURANCE PERFORMANCE IN SWIMMING

Comparison of different methods for the aerobic capacity
evaluation

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Dedication

*For my parents, family and Juliana,
who has patiently waited me to fulfill my journey.*

Still moving forward in deeper water

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List of publications

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Abstract

Once aerobic capacity is one of the main determinant factors for long-distance performance, two main questions may be identified in this field: (i) is the ideal intensity to train aerobic capacity much sensitive to prescription variations? and (ii) do the different methods commonly applied to predict this intensity zone, may impose different load and biophysical requirements, and thus, compromising training and athlete's performance enhancement? Therefore, the purpose of this Thesis was to understand the physiological, energetic and biomechanical factors occurred at intensities around maximal lactate steady state (MLSS). In addition, these biophysical factors were compared between MLSS and main concurrent methods used for the evaluation and prescription of the swimming aerobic capacity training. The experimental protocols consisted in: (i) an intermittent incremental velocity (v) protocol until voluntary exhaustion to implement the main concurrent methods to MLSS, and three-to-five 30 min submaximal constant swimming tests at imposed paces for determination of the v at 97.5, 100 and 102.5%MLSS. Physiological, energetic and biomechanical parameters were determined in both continuous and intermittent exercise protocols. Results showed that at intensities up to the MLSS, bioenergetic and biomechanical factors are constant as a function of time. However, when exercise is performed 2.5% above MLSS, despite most bioenergetic factors were constant throughout time, metabolic unsteady state, hyperventilation and decreased ventilatory efficiency, as well as associated biomechanical changes, led most swimmers to do not complete the 30 min swim at 102.5%MLSS due to fatigue. Nevertheless, aerobic energy contribution plays a fundamental role controlling almost exclusively the athletes' supply at intensities up to and above MLSS. In addition, IAnT and VT were the best methods to predict biophysical factors and intensity corresponding to the MLSS. Therefore, the physiological analysis of the intensity where the maximal steady state occur, contribute to better understand the main intensity zone applied for the evaluation, control and prescription of aerobic capacity training.

KEY WORDS: BIOMECHANICAL PARAMETERS, FRONT CRAWL, GAS EXCHANGE, LACTATE, OXYGEN UPTAKE.

Resumo

Uma vez que a capacidade aeróbia é um dos principais determinantes do desempenho de longa duração, duas questões centrais podem ser identificadas nessa área: (i) a intensidade ideal no treinamento da capacidade aeróbia é muito sensível às variações na prescrição? (ii) os diferentes métodos usualmente utilizados para prever essa zona de intensidade podem impor diferentes exigências biofísicas e da carga do treino, e com isso, comprometer o treinamento e o rendimento dos atletas? Desta forma, o objetivo desta tese foi compreender os fatores fisiológicos, energéticos e biomecânicos ocorridos em intensidades próximas a máxima fase estável de lactato sanguíneo (MLSS). Além disso, esses fatores biofísicos foram comparados entre a MLSS e os principais métodos concorrentes utilizados para a avaliação e prescrição do treinamento da capacidade aeróbia na natação. Os protocolos experimentais consistiram em: (i) um teste de velocidade incremental e intermitente até a exaustão voluntária para determinação dos principais métodos concorrentes; (ii) três a cinco testes constantes e submáximos de 30 min de duração para determinação das intensidades de 97,5, 100 e 102,5%MLSS. Fatores fisiológicos, energéticos e biomecânicos foram determinados em ambos os exercícios contínuos e intermitentes. Os resultados mostraram que intensidades até a MLSS, fatores bioenergéticos e biomecânicos foram constantes em função do tempo; entretanto, quando o exercício foi realizado 2.5% acima da MLSS, apesar da maioria dos fatores bioenergéticos serem constantes ao longo do tempo, o estado metabólico instável, a hiperventilação e a diminuição da eficiência ventilatória, assim como as associadas alterações biomecânicas, levaram a maioria das nadadoras a não completarem os 30 min de nado aos 102,5%MLSS, devido à exaustão voluntária. Apesar disso, a contribuição de energia aeróbia apresentou um papel fundamental em controlar quase que exclusivamente a demanda energética das atletas até e acima da MLSS. Além disso, o limiar anaeróbio individual e o limiar ventilatório foram os melhores métodos preditivos dos fatores biofísicos e da intensidade correspondente a MLSS. Portanto, a análise da intensidade onde ocorre o máximo estado estável fisiológico contribui para melhor entender a principal zona de intensidade utilizada para a avaliação, controle e prescrição do treinamento da capacidade aeróbia.

PALAVRAS-CHAVE: PARÂMETROS BIOMECÂNICOS, NADO CRAWL, TROCA GASOSA, LACTATO, CONSUMO DE OXIGÊNIO

List of abbreviations

$\%SLVO_{2max}$	stroke length expressed as a percentage of maximal oxygen uptake
$\%SRVO_{2max}$	stroke rate expressed as a percentage of maximal oxygen uptake
$\%vVO_{2max}$	velocity expressed as a percentage of maximal oxygen uptake
[La-]	blood lactate concentration
ATP	adenosine triphosphate
A_c	amplitude of the cardiodynamic component
ANOVA	analysis of variance
AnT	anaerobic threshold
A_p	amplitude of the primary component
A_s	amplitude of the slow component
AT	anaerobic threshold
BLa	blood lactate collection
bpm	beats per minute
C	energy cost
CI	confidence intervals
CP	creatine phosphate
$\dot{E}$	total energy expenditure
ETP_aCO_2	end-tidal partial pressure of carbon dioxide
HCO_3^-	hydrogen carbonate
HR	heart rate
HR_{max}	maximal heart rate
HRT	heart rate threshold
IAnT	individual anaerobic threshold
IdC	index of coordination
IVV	intracyclic velocity variation
LT	lactate threshold

LT _{3.5}	lactate threshold fixed in 3.5 mmol.L ⁻¹
LT ₄	lactate threshold fixed in 4 mmol.L ⁻¹
MISS	maximal intensity on steady state
MLSS	maximal lactate steady state
OUE	oxygen uptake efficiency
OUEP	oxygen uptake efficiency plateau
OUES	oxygen uptake efficiency slope
P _a CO ₂	partial pressure of carbon dioxide
R ²	Pearson's coefficient of determination
S400	400 m front crawl race time
SF	stroke frequency
SI	stroke index
SI units	international system units
SL	stroke length
SR	stroke rate
SV	swimming velocity
TD _p	time delay of the primary component
TD _s	time delay of the slow component
TI	trunk inclination
T _{prop}	time allotted for propulsion per pool length
v	velocity
v@MLSS	velocity corresponding to maximal lactate steady state
VCO ₂	carbon dioxide production
VE	minute ventilation
VO ₂	oxygen uptake
VO ₂ basal	baseline oxygen uptake
VO ₂ baseline	baseline oxygen uptake
VO ₂ exercise	exercise oxygen uptake
VO ₂ max	maximal oxygen uptake
VO ₂ peak	peak oxygen uptake
VO ₂ relative	oxygen uptake corrected for body mass
VT	ventilatory threshold

$v\dot{V}O_{2max}$	minimal velocity that elicits maximal oxygen uptake
WR	world record
η_p	upper limb's propelling efficiency
$\dot{\eta}_p^2$	partial Eta square
τ_c	time constant of the cardiodynamic component
τ_p	time constant of the primary component
τ_s	time constant of the slow component

Chapter 1

General Introduction

Biophysics in swimming

The study of sports physiology encompasses neuromuscular processes (technical/biomechanical factors and neuromuscular coordination), chemical to biomechanical energy transfer (work, energy cost and efficiency), cardiovascular dynamics (hemodynamic and vascular components), intramuscular energy turnover (phosphagen, glycolytic and aerobic energy system), and respiratory elements (respiratory capability and efficiency, and alveolar diffusion capacity) (Aspenes & Karlsen, 2012; Capelli, 1999; Ettema, 1966; Margaria, 1968; Rodriguez & Mader, 2011; Toussaint & Beek, 1992). These performance determining parameters are differently interconnected across sprint (50-100 m), middle-distance (200-400 m), and long-distance swimming events (800, 1500 m and open water distances) (Aspenes & Karlsen, 2012; Capelli et al., 1998; Di Prampero et al., 1974; Maglischo, 2003; Rodriguez & Mader, 2011). Research has played a fundamental role to the better understanding of the interplay between energy supply (the different energy system's contributions) and the energy use during various swimming events and training sets. This Thesis tries to follow this pathway.

Rodriguez and Mader (2011) defined the relative contribution of the different bioenergetic systems throughout the different swimming events. According to the authors, sprint events (50-100 m; ~ 20-60 s) use a large muscle mass with a high percentage of recruited fast twitch fibers to produce a very high energy output, higher for the 50 m. The 50 m events require a high utilization of adenosine triphosphate (ATP) and creatine phosphate (CP) stores, which are both rapidly depleted, and then, glycolysis becomes the main energy input for muscle contraction. In these events the aerobic energy pathway has a low contribution comparing to the anaerobic sources. The 100 m competitions require both glycolytic and aerobic energy delivery processes (Ribeiro et al.,

2012), imposing high blood lactate concentrations ($[La^-]$) out of muscle contractions. Both 50 and 100 m events have shown high $[La^-]$ values, normally above 10 mmol.L^{-1} (Bonifazi et al., 1993; Neiva et al., 2014). For middle-distance events (200-400 m; ~ 100 -220 s), swimmers usually show the highest maximal oxygen uptake ($\dot{V}O_{2\text{max}}$) values, recruit a large body muscle mass, and make use of moderate (400 m) to high (200 m) glycolytic power. Finally, in the long-distance events (800, 1500 m and open water distances; ~ 7.5 min to 1-2 h or more), defined as predominantly controlled by the aerobic energy delivery processes, elite endurance swimmers present low glycolytic power and very high oxygen uptake ($\dot{V}O_2$) values, i.e. values close to those of middle-distance swimmers, and also close to their own $\dot{V}O_{2\text{max}}$. Indeed, once muscle glycogen oxidation occurs at a very high rate, a physiological steady state at high $\dot{V}O_2$ values may occur, close to $\dot{V}O_{2\text{max}}$. Accordingly, biomechanical parameters should also be expected to show different adjustments across swimming events.

As swimming velocity (v) depends on stroke rate (SR) and stroke length (SL), variations on v (increases or decreases) are determined by different combination of SR and SL (increases and/or decreases) (Barbosa et al., 2010; Craig et al., 1985; Toussaint et al., 2006). The evolution of biomechanical parameters (e.g. SR and SL) across sprint, middle- and long-distance swimming events has shown different combinations (Craig & Pendergast, 1979; Pelayo et al., 2007). Expectedly, shorter events showed the highest SR and lowest SL values compared to middle- and long-distance events; meanwhile longer events are characterized by an inverse behavior, i.e. lowest SR and highest SL values (Craig & Pendergast, 1979; Keskinen & Komi, 1993; Pelayo et al., 2007).

Furthermore, competitive swimming is unique in several aspects compared with most other sports. Indeed, swimmers are in a prone position during training and performance; both arms and legs are used for propulsion; water immersion results in a hydrostatic pressure on the body that allows buoyance and favors venous blood return, but constrains the respiratory movements. Moreover,

aside from start and turns, the forces are produced against water at all times; and the use of the swim-suit is supposed to minimally influence performance (Aspenes & Karlsen, 2012). Furthermore, competitive swimming is also determined by anatomical (anthropometric characteristics), the previous referred metabolic profile, i.e. aerobic and anaerobic energy contributions, and psychological (cognitive and emotional) factors (Aspenes & Karlsen, 2012; Fernandes et al., 2011; Lavoie & Montpetit, 1986; Smith et al., 2002; Toussaint & Beek, 1992; Toussaint & Hollander, 1994) and by training, which, probably following an improper tendency, has traditionally been mainly focused to improve the physiological capacities of the swimmers (Aspenes & Karlsen, 2012; Maglischo, 2003; Mujika et al., 1995; Ogita, 2011).

So, synthesizing, swimming performance knowledge should be searched through an integrated biophysical approach, gathering as much as possible the different dimensions that characterize it. This is also a central concern of this Thesis.

Stating the problem

The central problem of this Thesis is the capability of precisely define different biophysical dimensions of the optimal load for the aerobic capacity training. In this sense, our work is focused both in: (i) the study of the eventual differences in the magnitude of swimmer's response to small changes of a prescribed load, and (ii) in the analysis of the appropriateness of the outcomes provided by different methods to assess that optimal load.

The training load is normally characterized by the combination of intensity, volume and density, being well established that different combinations of those dimensions induce specific physiological adaptations to improve performance capacity (Chatard & Stewart, 2011; Mujika et al., 1995; Mujika, 1998; Ogita, 2011; Wenger & Bell, 1986). Many researchers have shown that training intensity is considered the key factor to enhance training effect in athletes of several sports (Acevedo & Goldfarb, 1989; Davies & Knibbs, 1971; Faria, 1970; Mikesell & Dudley, 1984; Neary et al., 1992; Rusko, 1987; Smith et al., 1999),

as well as in swimming (Costill et al., 1988; Costill et al., 1991; Faude et al., 2008; Mujika et al., 1995; Wilmore et al., 2008). Indeed, being able to select the proper training intensity at a given phase of the training process seems to be determinant to increase training efficiency, and easily lead athletes to improve performance. For example, training efficiency improvements may be caused by the most important and pertinent physiological adaptations on the aerobic energy system, resulting in a shift of the lactate/velocity curve to the right, and thus, allowing swimmers to perform faster in a physiological steady state. The same, however, may be obtained with an also highly efficient technical training, traduced in a reduced energy cost of swimming locomotion (C). So, it is possible to hypothesize that the really most efficient training process would be the one that integrates both dimensions in a harmonious way. Moreover, it seems more that probable, that small differences on load prescription, whatever its type, may imply also different adaptive mechanisms and effects, and, consequently, affecting training efficiency.

In addition, sport sciences have distinguished, during the last decades, between training prescription of anaerobic and aerobic energy processes. These different manners to approach the energy processes development through training have conducted to significant differences between sprint and aerobic endurance training, once the relative energy system's contributions changes with intensity and swim exercise duration (Ogita, 2006, 2011). According to Ogita (2006, 2011), anaerobic training has focused on enhancing the ATP/CP system, as well as to increase the enzymatic activity of the glycolytic system and the buffering capacity of the organism, once this type of training produces a high [La-]. Meanwhile, aerobic endurance training has focused on enhancing lactate removal, as well as to improve cardio-respiratory functions for oxygen delivery and muscular oxidative capacity for O₂ utilization. So, specialized knowledge must be developed for both types of the traditionally named bioenergetic training, both for its understanding and prescription, as well as for its assessment and control.

To improve the capability of diagnosing and prescribing the different dimensions of training load (intensity, volume and density), and so matching the specific and precise energy processes requirement (anaerobic and aerobic), it is necessary to better understand the parameters that characterized each specific training intensity and the best approaches to diagnose them. Among the different exercise intensities related to anaerobic and aerobic training, the aerobic power (associated to the $\text{VO}_{2\text{max}}$) has been considered one of the main exercise intensities that can be used to prescribe aerobic training, and as a determinant factor of athletic performance. However, the termed “aerobic capacity” has been considered the most discriminant parameter of long-duration performance ability of athletes with similar $\text{VO}_{2\text{max}}$, and then, become a major focus of interest of scientists, coaches and athletes (Bosquet et al., 2002; Dekerle & Pelayo, 2011).

Aerobic capacity is usually understood as the maximal exercise intensity where a physiological steady state is obtained (Bosquet et al., 2002). Considering the limitations of the concept (aerobic capacity may or should also be understood as the maximal amount of energy that a subject may deliver through the aerobic pathway) we decided to risk here a neologism to name this paramount physiologic capacity: the Maximal Intensity on Steady State (MISS), something similar to the concept of “endurance performance limit” (Hollmann, 1959, 2001); this, unfortunately was chosen to express a test procedure to assess this “capacity”, not the capacity itself. We dare this proposal to allow better distinguish the “capacity” itself and the most recognized method for its assessment: the Maximal Lactate Steady State (MLSS) test. Indeed, a convergent methodology to assess aerobic endurance performance potential should be the assessment of the highest intensity that may be maintained during prolonged sub-maximal and constant workload without continuous accumulation of [La-], which is the conceptual background for the MLSS test (Beneke & von Duvillard, 1996; Beneke, 2003; Faude et al., 2009).

However, several other methods claim to also assess this performance relevant parameter (MISS), most of them using intermittent triangular tests, instead of

rectangular testing loads like MLSS. Unfortunately, literature still did not provide final and conclusive outcomes regarding the appropriateness of the different testing procedures, and further knowledge is decisive. In this domain, most of the previous literature focused on the v values pointed out by the different tests. Heart rate (HR) and [La-] have also congregated the attention of most of the research teams. Nevertheless, other parameters should be explored to guarantee that a similar workload is being reached, like those characteristic from VO_2 kinetics and relevant biomechanical parameters.

Different tests were proposed by scientists to determine MLSS, i.e. the limit load for the aerobic capacity training, and corresponding physiologic state where a significant increase in [La-] and gas exchange occur. The first tests were termed “endurance performance limit” and “point of optimum ventilatory efficiency” (Hollmann, 1959, 2001). These were, respectively, based on metabolic (arterial and venous [La-] and pH) and ventilatory (VE , VE/VO_2) parameters. Only afterwards emerged many other tests, like the most popular aerobic-anaerobic threshold test (Mader et al., 1976), the individual anaerobic threshold (IAnT), defined through different assessment methods (Baldari & Guidetti, 2000; Berg et al., 1980; Bunc et al., 1985; Dickhuth et al., 1991; Dickhuth et al., 1999; Fernandes et al., 2008; Keul et al., 1979; Machado et al., 2006; Simon et al., 1981; Stegmann et al., 1981; Stegmann & Kindermann, 1982), the anaerobic threshold (AnT), determined by ventilatory threshold (VT) and measured by ventilatory and gas exchange parameters (Kindermann et al., 1979; Wasserman & McIlroy, 1964; Wasserman et al., 1973), the lactate turnpoint (Smith & Jones, 2001), the individual lactate minimum (Tegtbur et al., 1993), the Dmax test, i.e. maximal distance from [La-] curve to the line formed by its endpoints (Cheng et al., 1992), and the Dmod method, i.e. maximal distance from [La-] to the line formed by the point before the first rise in [La-] and the value at cessation of exercise (Bishop et al., 1998).

Among the previously mentioned methods, in this Thesis, we aimed to study the IAnT and the VT tests, based on metabolic and ventilatory parameters, respectively. Our choice has been based on the apparent popularity of these

procedures on specialized literature when metabolic and ventilatory approaches are considered. By the same reason we also considered the test of the $\dot{V}$ corresponding to a fixed $[\text{La-}]$. For this purpose we choose the value of 3.5 mmol.L^{-1} (lactate threshold fixed in 3.5 mmol.L^{-1} - $\text{LT}_{3.5}$) once it was demonstrated (Heck et al., 1985) that this is a more realistic method for swimmers compared to the very well-known $\dot{V}_4$ test (lactate threshold fixed in 4 mmol.L^{-1} - LT_4) (Mader et al., 1978). We also considered the HR deflection point – the Heart Rate Threshold test (HRT) –, also known as Conconi test (Cellini et al., 1986; Conconi et al., 1982) due to the alleged facility of HR assessment in training.

The IAnT was determined by the $[\text{La-}]$ and $\dot{V}$ curve modelling method (least square method), initially proposed by Machado et al. (2006), and subsequently applied several times for swimming assessment (Fernandes et al., 2008; Fernandes et al., 2010; Fernandes et al., 2011; Figueiredo et al., 2013a). This method was previously claimed to assess in an adequate and individual manner the MISS (Machado et al., 2006). Meanwhile, a previous comparison between IAnT and the gold-standard method applied for the evaluation of aerobic capacity (MLSS) (Fernandes et al., 2011) showed similar $\dot{V}$ values between both methods (1.10 ± 0.04 and $1.09 \pm 0.14 \text{ m.s}^{-1}$, respectively), but IAnT imposed lower $[\text{La-}]$ (2.1 ± 0.1 and $2.9 \pm 1.2 \text{ mmol.L}^{-1}$, respectively) and HR values (145.4 ± 14.7 and $156.0 \pm 16.3 \text{ bpm}$, respectively). In the previous cited paper (Fernandes et al., 2011), only few parameters were studied, namely $\dot{V}$, HR and $[\text{La-}]$, leaving other important parameters, such as ventilatory (gas exchange), energetic (energy cost – C and total energy expenditure – $\dot{E}$) and biomechanical factors (SR and SL), without a specific comparative analysis between methods. It is our intention to explore these comparisons in this Thesis.

The VT is determined by the $\dot{V}$ -slope method based on pulmonary ventilation ($\dot{V}_E$) divided by $\dot{V}\text{O}_2$, being VT defined as a disproportional $\dot{V}_E/\dot{V}\text{O}_2$ increase (Bentley et al., 2005; Libicz et al., 2005; Roels et al., 2005; Svedahl & MacIntosh, 2003). Van Schuylenbergh et al. (2004) showed similar values for intensity (302 ± 11 and $311 \pm 9 \text{ W}$, respectively) and HR (175 ± 2 and 169 ± 2

bpm, respectively), but higher values for [La-] (5.4 ± 0.3 and 3.3 ± 0.4 mmol.L⁻¹, respectively) when VT and MLSS were compared in cycling. Also, Leti et al. (2012) showed similar values for intensity (16.2 ± 1.4 and 15.5 ± 1.1 km.h⁻¹, respectively) and HR (173 ± 15 and 174 ± 13 bpm, respectively) between VT and MLSS in running. In the wake of previous results for IAnT, the available comparisons between VT and MLSS are scarce and examining a limited number of parameters, also requiring a deeper insight.

Trying to simplify the metabolic assessment of MISS, Mader et al. (1978) proposed a two speed test to assess v₄ (LT₄), assuming this as the mean [La-] value corresponding to most of the more sophisticated tests based on [La-]. This LT₄ test becomes very popular among the scientific and coaching communities in several sports, and particularly in swimming. However, different contributions have shown that 4 mmol.L⁻¹ seems to overestimate the mean [La-] values corresponding to MISS or to concurrent tests in swimmers, point to lower values like 3.5 mmol.L⁻¹ (Fernandes et al., 2011; Heck et al., 1985). Having the opportunity to easily study also this test procedure, we decided to include it on the scope of this Thesis.

Moreover, since the research by Conconi et al. (1982), some investigators have used the HR deflection point test (de Wit et al., 1997; Jones & Doust, 1995), called in this Thesis as HRT, also to determine the physiologic state where beyond there is a significant increase in [La-] and gas exchange (Bodner & Rhodes, 2000; Bunc et al., 1995; Cellini et al., 1986; Conconi et al., 1996; Jones & Doust, 1995). The HRT is characterized by a distinctive change (deflection) in the linear response of HR and v, obtained during progressive incremental exercise testing (Bodner & Rhodes, 2000; Conconi et al., 1982). This has also been known as deflection velocity (Cellini et al., 1986; Conconi et al., 1982), HR break point (Ribeiro et al., 1985), slope variation point (Maffulli et al., 1987), HR threshold (Bunc et al., 1995; Hofmann et al., 1994), or HR turnpoint (Pokan et al., 1998; Pokan et al., 1999). In swimming, Cellini et al. (1986) showed similar v values between the HR deflection point (HRT) and the onset of blood lactate accumulation (AnT). However, we are unaware of any

swimming study that compared the bioenergetic and biomechanical factors evolved between HRT and MLSS.

The previous referred tests, which be subject of analysis in this Thesis, will be necessarily compared with the direct and gold-standard method for the evaluation of aerobic capacity and prescription of aerobic training, as largely accepted in sport science community: the MLSS test (Beneke & von Duvillard, 1996; Billat et al., 2003; Dekerle et al., 2005a; Faude et al., 2009; Heck et al., 1985; Mader & Heck, 1986; Pelarigo et al., 2011). MLSS is defined by the maximal intensity that can be maintained over time without blood lactate accumulation (Beneke & von Duvillard, 1996; Beneke et al., 2000). It requires several days of testing to be determined, consisting in series of 30 min constant speed trials while assessing the [La-] throughout the exercise (Beneke, 1995, 2003; Heck et al., 1985; Pelarigo et al., 2011).

MLSS has been also extensively used for the definition and distinction of the intensity domains in continuous exercise (Beneke et al., 2003; Burnley & Jones, 2007; Gaesser & Poole, 1996; Xu & Rhodes, 1999). During exercise intensities performed at and below MLSS, it could be expected a physiological steady state of both [La-] and VO_2 (Baron et al., 2005; Whipp & Wasserman, 1972; Whipp & Ward, 1990), and no biomechanical adjustments may be necessary (Dekerle et al., 2005a) precisely due to the installed metabolic steady state. On the contrary, exercise intensities performed above MLSS are expected to imply a significant increase in [La-] and VO_2 as a function of time (Beneke, 2003; Billat et al., 2003; Poole et al., 1988; Whipp & Ward, 1990), as well as biomechanical changes associated to fatigue and voluntary exhaustion (Beneke & von Duvillard, 1996; Dekerle et al., 2005a; Heck et al., 1985; Pelarigo et al., 2011; Poole et al., 1988; Poole & Richardson, 1997).

Besides, it is well accepted by literature that sustaining exercise intensities around MLSS over time induces fatigue associated with hypoglycemia and/or glycogen depletion (Baron et al., 2005; Billat et al., 2003; Genovely & Stamford, 1982; Glass et al., 1997; Sahlin et al., 1990). The incapability to maintain a predetermined swimming intensity as a function of time (above MLSS, i.e.

fatigue over time) may be also due to the inability to sustain optimal biomechanical parameters (Pelarigo et al., 2011), or aspects related to VO_2 kinetics, particularly the VO_2 slow component occurrence throughout time (Burnley & Jones, 2007; Gaesser & Poole, 1996). Moreover, biomechanical factors could change the MLSS (Dekerle et al., 2005a; Oliveira et al., 2012a; Pelarigo et al., 2011) due to differences expected in swimming economy. Those variables could lead to significant changes in swimming v and/or exercise time duration determined by physiological mechanisms, other than metabolism, which are time-dependent, such as the ability to sustain force and its application to the water.

Thus, the most complete understanding of this specific intensity where the swimmers may support the highest v in a physiological steady state relies on both mechanical load (v times resistive forces - drag), and the capability of the physiological systems to sustain the imposed swim intensity. Therefore, the application of these different methods require a deep knowledge related to physiological, energetic and biomechanical aspects to better understand the interplay of these areas and the methods previously reported to evaluate swimming aerobic capacity.

Purpose of the study

Since long, swimming training is characterized by a large volume and density, with intensity submitted to the former dimensions of load (Chatard & Stewart, 2011; Counsilman, 1968; Faude et al., 2008; Mujika et al., 1995; Ogita, 2011). In accordance, it might be said that swimming training is traditionally based on aerobic demands, and that performance progression have been commonly perceived as a matter of training volume dynamics.

There are two main drawbacks in this assumption: the first is that aerobic ability is not the main determinant factor of swimming performance, not even in the bioenergetic domain; the second is that swimming training volume has a limit to evolve. In accordance, modern tendencies are pointing both for an intensity specification of training load, and for the growth of training efficiency; coaches

are nowadays concerned with anaerobic performance, and with the proper establishment of the real edges of the different training intensity zones. So, one of the main concerns of modern training is the improvement of the diagnosis and prescription capabilities of coaches and related professionals. This means: (i) to better understand each one of the limit intensities and mechanical loads that define the different training zones, and (ii) to develop and enhance the tests allowing to individually assess those intensities.

Meanwhile, the swimming mechanical load is determined both by biomechanical and physiological parameters, like hydrodynamic drag, gross propelling efficiency, and the aerobic and anaerobic muscles ability, and the entire organism to support each required particular biomechanical power output. So, to better understand the swimming training requirements and load prescription characteristics, knowledge about physiologic condition, energy supply and biomechanical load are mandatory. These variables are, indeed, some of the most studied parameters in swimming science (Vilas-Boas, 2010).

The focus of this Thesis was to concentrate efforts on the biophysical understanding of MISS, or the aerobic capacity limit intensity. This will be carried out exploring two research lines: (i) how much that particular intensity is “fine-tuned”, i.e. if it is much or less sensitive to small v variations, able or unable to accommodate prescription (scientists and coaches) and training practice (swimmers) errors, and (ii) how different and differently time and budget consuming methods may met the training load profile of the gold-standard method: the MLSS. We will chase these objectives combining physiological, energetic, and biomechanical data.

Particularly, it intends to answer the following research questions: (i) is the boundary intensity for the aerobic capacity training zone – the MISS intensity – sensitive to small changes in exercise intensity?, and (ii) are the concurrent progressive triangular tests able to characterize the physiological, energetic and biomechanical parameters that define the MLSS swimming intensity?

Schematic design of the Thesis structure

The design of this Thesis is presented in Figure 1.1. The Thesis is composed of a General Introduction, in which the research problem is presented; a brief literature review and overall purposes are included. This overall purpose of the Thesis was divided in two main purposes. The first main purpose was to understand the interplay between biophysical factors around the MLSS. This goal was addressed through three different studies (**Chapters 2 and 3, and Appendix I**). The first one aimed to analyze biophysical factors around MLSS (**Chapter 2**), the second one to examine VO_2 kinetics around MLSS (**Chapter 3**), and the last study aiming to analyze a kinematical changes of swimming technique along the MLSS test (**Appendix I**).

The second main purpose was to biophysically compare the MLSS and the concurrent methods used for the evaluation of aerobic capacity. This was also accomplished through three different studies (**Chapters 4, 5 and 6**). The first study aimed to compare bioenergetic factors (**Chapter 4**), the second one aimed to compare biomechanical parameters (**Chapter 5**). The last study of this research line aimed to compare two methods used for the evaluation of aerobic capacity: one well-known method in swimming science (IAN_T) and the other, a novel method for swimming, using a ventilatory parameter – the oxygen uptake efficiency plateau (OUEP), usually used for untrained subjects and patients evaluation (**Chapter 6**). The final study - a case study - was conducted to analyze an elite long-distance swimmer concerning biophysical factors around MLSS, and the information extracted from the most common methods used for the evaluation of aerobic capacity, emphasizing the particular adaptations that may help the achievement of the best results (**Chapter 7**). Indeed, the question behind this study was: how much the use of sampling inferential studies can hide particularly relevant individual results? Finally, the General Discussion (**Chapter 8**) and Conclusions (**Chapter 9**) are presented to analyze the common ground and extract the inter-studies and global conclusions.

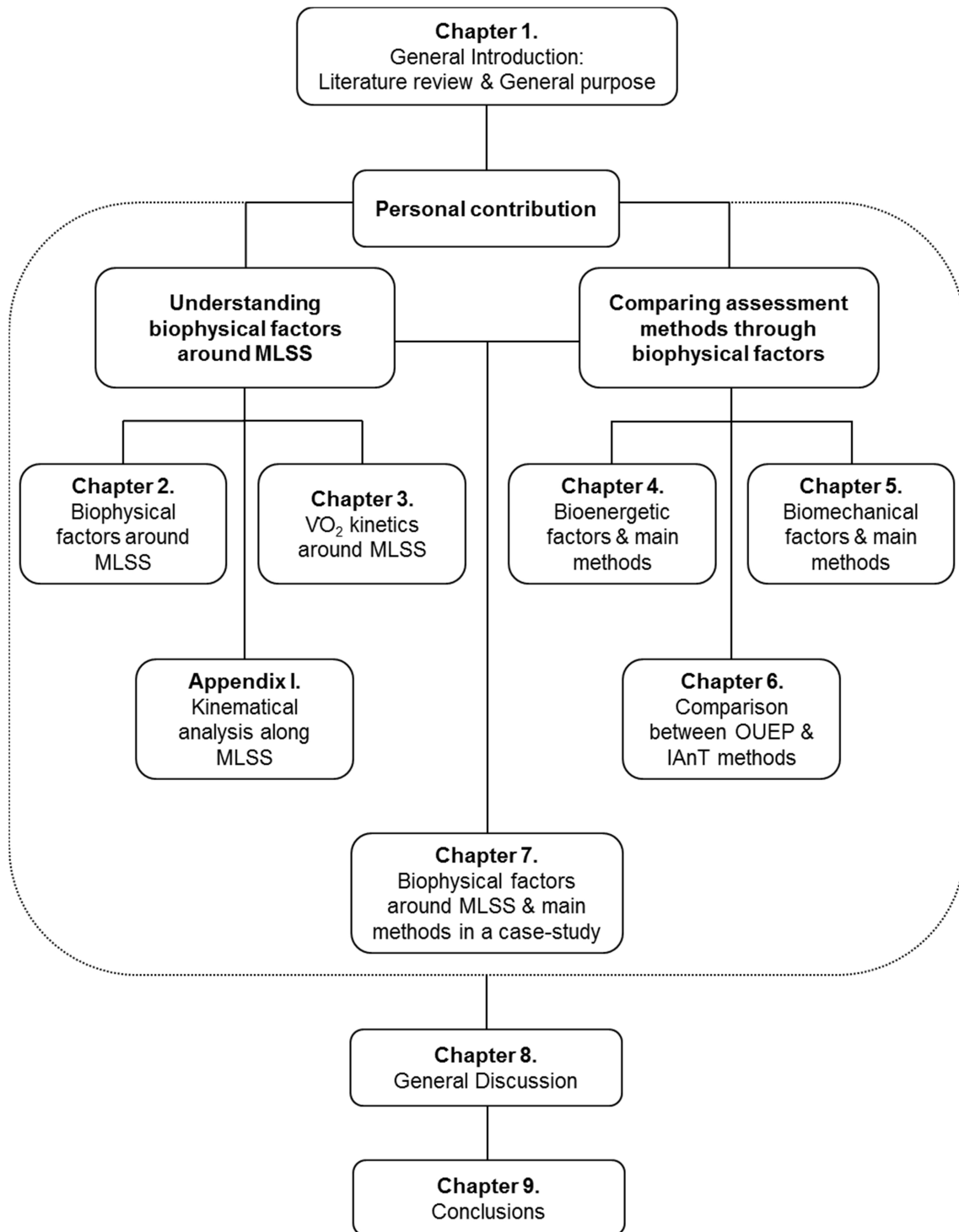


Figure 1.1. Schematic design of the Thesis structure.

Chapter 2

Does 5% changes around maximal lactate steady state lead to swimming biophysical modifications?

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Abstract

Our purpose was to examine the swimming biophysical modifications at 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS). Ten elite female swimmers performed three-to-five 30 min constant tests at imposed paces to determine 100%MLSS velocity (v). Energetic (gas exchange and blood lactate concentration - [La-]) and biomechanical (stroke rate - SR and v) variables were determined during each velocity. The v values were 1.21 ± 0.07 , 1.24 ± 0.07 and $1.27 \pm 0.07 \text{ m}\cdot\text{s}^{-1}$ at 97.5, 100 and 102.5%MLSS, respectively. Oxygen uptake (VO_2) increased as function of v , but did not change as function of time at all speeds. Pulmonary ventilation (VE) increased as a function of intensity and time during the 102.5%MLSS. During all swims, stroke length (SL) decreased (3.5%) and SR increased (3.5%) as a function of time. Bioenergetic and biomechanical factors were constant as a function of time at intensities up to the 100%MLSS. However, 102.5%MLSS there was hyperventilation, most likely caused by respiratory compensation for metabolic acidosis, decreasing the oxygen uptake efficiency (OUE). The changes in OUE were associated with the biomechanical changes and together they were associated with the inability of most swimmers to complete the 30 min swim (fatigue) at 102.5%MLSS.

Key words: aerobic capacity, gas exchange, oxygen uptake, oxygen uptake efficiency, biomechanical parameters

Introduction

As exercise intensity increases, metabolism switches from totally aerobic to a mixture of aerobic and anaerobic contributions, leading to increased lactate in muscle and blood. Since the 1960s, researchers have struggled to understand and define the physiologic state where there is a significant increase in blood lactate concentration ([La-]) (anaerobic threshold – AnT). Of these attempts, the initial definition was termed endurance performance limit (Hollmann, 2001), which was then refined as aerobic-anaerobic threshold, individual anaerobic threshold, anaerobic threshold, lactate turnpoint, and individual lactate minimum, among others terms (Faude et al., 2009). Another physiological state also related to the AnT is the maximal intensity that can be maintained as function of time without blood lactate accumulation, i.e. the maximal lactate steady state – MLSS (Beneke, 2003). This exercise intensity has been used for the evaluation of aerobic capacity for endurance performance and training prescription (Beneke & von Duvillard, 1996; Faude et al., 2009).

Until now, the MLSS is considered the direct and gold-standard method for the evaluation of aerobic capacity (Beneke & von Duvillard, 1996; Beneke, 2003; Faude et al., 2009), and identified as the highest steady state blood lactate concentration ([La-]) that can be maintained during prolonged sub-maximal and constant workload exercise (Beneke & von Duvillard, 1996; Beneke, 2003). Moreover, when the exercise is performed at intensities above the MLSS intensity, a significant increase in [La-] is observed as function of time, which is associated with voluntary exhaustion (Beneke & von Duvillard, 1996; Heck et al., 1985). Whereas at intensities below and at the MLSS there is a physiological steady state of [La-] as function of time and exercise can be sustained (Baron et al., 2005).

Although the concepts of AnT and MLSS were previously used to characterize swimming performance, it is commonly accepted that there are bioenergetic and biomechanical factors that influence these parameters. Further examination of these factors is needed to better understand their possible interaction,

helping to understand the swimmers' adjustments that occur at intensities around MLSS (Faude et al., 2009).

The inability to maintain a predetermined swimming intensity (fatigue) may be due to the inability to sustain optimal biomechanical parameters (Pelarigo et al., 2011), in spite of the stability of the aerobic system bioenergetics as a function of time (Baron et al., 2005). Thus, biomechanical factors could change the MLSS swimming v , leading to a reduced velocity or swim time, as physiological mechanisms other than metabolism may be time-dependent, such as the ability to sustain force and its application to the water (Baron et al., 2005; Dekerle et al., 2005a; Pelarigo et al., 2011).

We are unaware of any studies that have evaluated bioenergetic and biomechanical factors at intensities at or around the 100%MLSS in swimming. It is important for coaches and swimmers to understand the consequences of training at intensities around MLSS. To examine further these interrelationships measurements of biophysical factors have to be evaluated not only as a function of intensity, but also as a function of exercise duration. Thus, our purpose was to analyze bioenergetic and biomechanical factors while swimming at 97.5, 100 and 102.5%MLSS. We hypothesized that swimming above 100%MLSS would compromise bioenergetic and biomechanical factors requiring progressive adjustments (of pace) to sustain exercise intensity. We also hypothesized that swimming intensities up to 100%MLSS would not require progressive adjustments.

Material and Methods

Ten elite female swimmers (mean $\pm$ SD; aged 17.6 ± 1.9 years, height 1.70 ± 0.05 m, body mass 61.3 ± 5.8 kg and percentage of body fat mass $15.5 \pm 2.9\%$; maximal oxygen uptake - $\dot{V}O_{2\max}$ 54.9 ± 6.7 mL.kg.min⁻¹), specialized in middle- and long-distance swimming events, participated in the present study. Subjects had, at the least, seven years of experience as competitive swimmers and their mean performance over the 400 m freestyle swim was $88.0 \pm 3.4\%$ of the 2014 short course world record. The study was approved by the local ethics

committee and was performed according to the Declaration of Helsinki. Subjects and/or parents gave their written informed consent before participation in experiments.

The test sessions were performed in a 25 m indoor swimming pool, with water temperature of 27-28°C and air humidity of 40-60%. Swimmers were advised to refrain from intense training at least 24 h before the experiments. The tests were all conducted within a seven day period, at the same time of the day (± 2 h) to minimize the effect of circadian rhythm. In all test sessions, the swimmers performed a 1000 m warm-up at low/moderate aerobic intensity. During the tests, swimmers swam front crawl and used in-water starts and open turns without underwater glides. The measurements of body mass and fat were assessed by a segmental body composition analyzer (Tanita, TBF 305, Tokyo, Japan).

First, the swimmers performed an intermittent progressive protocol until voluntary exhaustion to determine the individual anaerobic threshold (IAnT). The predetermined velocity of the last step was the subjects' best time for the 400 m front crawl race time (S400), and was also used to define the step increments (Fernandes et al., 2006). The distance of each step of the incremental test was 200 m, and the velocity started at $\sim 80\%$ S400 and was increased by $0.05 \text{ m}\cdot\text{s}^{-1}$ for each step until exhaustion. Thirty seconds rest intervals were observed in-between each swim.

Earlobe capillary blood samples (5 μL) were collected and analyzed through a portable lactate analyzer (Lactate Pro, Arkray, Inc., Kyoto, Japan): at rest and in the first 30 s after each intermediate step of the incremental test and, immediately after exhaustion and at each 2 min of recovery from the last step, until the [La-] recovery peak was found. The IAnT was assessed by the relationship between [La-] and velocity with the lactate inflexion point determined as the interception between linear and exponential regressions to estimate the velocity where [La-] increased exponentially (Fernandes et al., 2006; Machado et al., 2006). In the case a swimmer did not attain the maximal

velocity and/or exhaustion with the pre-defined steps, the last step the subject completed was used to determine the minimum v eliciting the $\text{VO}_{2\text{max}}$.

After determining IAnT, each swimmer performed three-to-five 30 min submaximal constant swimming tests at imposed paces to assess the velocity where a MLSS was achieved and maintained (100%MLSS). [La-] was determined at rest, and at the 10th and 30th min (or voluntary exhaustion) of each continuous test as described above. The first trial was performed at the IAnT velocity, and, if during the first trial a steady state or a decrease in [La-] was observed, further subsequent trials with 2.5% higher velocity were performed until no [La-] steady state was observed. If the first trial resulted in a clearly identifiable increase of the [La-] and/or could not be sustained due to exhaustion, further trials were conducted with subsequently reduced velocities (Pelarigo et al., 2011). The MLSS was defined as the highest [La-] that increased by no more than 1 mmol.l⁻¹ between the 10th and the 30th min of the test (Heck et al., 1985). The corresponding [La-] value was assumed as the average of the 10th and 30th min of exercise.

Bioenergetic factors were divided in two categories: gas exchange (oxygen uptake - VO_2 and pulmonary ventilation - VE) and energetic (total energy expenditure – $\dot{E}$ and energy cost – C) parameters. Gas exchange parameters were measured by a telemetric portable gas analyzer (K4b², Cosmed, Italy), which was connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (New AquaTrainer®, Cosmed, Italy). This system has been previously validated and used in similar studies (Baldari et al., 2013; Sousa et al., 2014). The equipment was calibrated for VE with a calibrated syringe and the O₂ and CO₂ analyzers with standard calibration gases before each test. The values of gas exchange were measured breath-by-breath during all the tests and averaged every 5 s (Fernandes et al., 2012). The ratio of VO_2 and VE termed oxygen uptake efficiency (OUE) was calculated for all conditions (Baba et al., 1996). Heart rate (HR) was monitored and registered continuously by a HR monitor system (Polar Vantage NV, Polar electro Oy,

Kempele, Finland) and transferred telemetrically to the K4b² device. The values of HR were also averaged for 5 s intervals.

The energetic parameters were $\dot{E}$ and C. The C was determined using the caloric equivalent of the $\dot{V}O_2$ ($\text{kcal.L}^{-1} \text{O}_2$) calculated by the respiratory exchange quotient (Fletcher et al., 2009). The C was calculated using the Equation 2.1:

$$C = \dot{V}O_2 \cdot \text{caloric equivalent} \cdot v^{-1} \quad 2.1$$

where C is energy cost of locomotion calculated by indirect calorimetry expressed as kJ.m^{-1} , $\dot{V}O_2$ was measured in L.min^{-1} , caloric equivalent is in kcal.L^{-1} , and v is velocity in m.min^{-1} . The energy equivalent was converted according to the SI units, where 1 kcal is equivalent to 4.184 kJ. The $\dot{E}$ was determined by the product of C and v, corrected by the body mass, where $\dot{E}$ is the total energy expenditure expressed as $\text{mL.kg}^{-1}.\text{min}^{-1}$, C was measured in kJ.m^{-1} , v is velocity in m.min^{-1} , body mass is in kg. The energy equivalents was converted into the SI units according to di Prampero (1986) where 1 mL O_2 is equivalent to 20.9 J.

Biomechanical factors measured were stroke rate (SR), stroke length (SL) and the product of v and SL (stroke index - SI) at each v studied. The biomechanical analysis was conducted during pure swimming phase of each lap (middle of the pool – between 7.5 and 17.5 m) based on the images of an above-water video camera (DCR-HC42E, Sony, Japan) operating at a frequency of 50 Hz. Two upper limbs cycles were measured for each condition and the data averaged. The video data were then used to calculate v (m.s^{-1}) and SR (cycles.min^{-1}). SR was determined by the number of upper limb cycles per unit of time and SL was calculated by the ratio of v and SR.

The swimming v was set and maintained using a visual underwater pacer (GBK-Pacer, GBK Electronics, Aveiro, Portugal), with a light strip on the bottom of the pool with lights located 2.5 m apart. The swimmers followed the flashing lights to maintain the predetermined velocities. The swimmers were instructed to keep their head above each visual signal as the lights proceeded along the

pool length. Exhaustion was defined and the test finalized when the swimmers remained 5 m behind the lights. A 24 h interval was imposed between all the tests.

To normalize for differences in velocity and time for each subject, the data for the continuous tests were normalized to the total time duration (100%). The data were split into eight time points corresponding to rest, the initial steady state determined during the 4th min of the swim and then 25, 33, 50, 66, 75 and 100% of the total duration of exercise.

The data are presented as mean and standard deviation ($\pm$ SD). Normality and sphericity of data were checked with the Shapiro-Wilk's W and Mauchley tests. When the assumption was not attained, Greenhouse-Geisser or the Huynh-Feld adjusted univariate tests for repeated measures were used. Beyond descriptive statistics, the analyses of gas exchange, energetic and biomechanical parameters were performed using multivariate ANOVA. The [La-] and v values were performed using the univariate ANOVA. All analyses were repeated measures ANOVAs, complemented with the Tukey correction post-hoc test. The significance level of $p < 0.05$ was used for all comparisons.

Results

The results of the experiments are presented for the 97.5, 100 and 102.5% MLSS intensities. For each intensity, data at rest, at the 4th min, and at 25, 33, 50, 66, 75 and 100% of swimming time duration are also shown. The average v values for the three conditions were different from each other, with 97.5%MLSS slowest and 102.5%MLSS fastest (Figure 2.1). All swimmers completed the swims at 97.5 and 100%MLSS. However, eight out of the ten swimmers were not able to maintain the predetermined v during the 30 min of the 102.5%MLSS swim, reaching voluntary exhaustion at 19.3 ± 4.9 min of exercise.

Figure 2.1 presents $\dot{V}O_2$, $\dot{E}$, C and [La-] values as a function of velocity during the three swimming conditions. [La-] values were similar at 97.5 and 100%MLSS, however, the values were higher at 102.5%MLSS. $\dot{V}O_{2\text{relative}}$ and $\dot{E}$

increased significantly as a function of v throughout the studied intensities. C increased as a function of v between 97.5 and 102.5%MLSS.

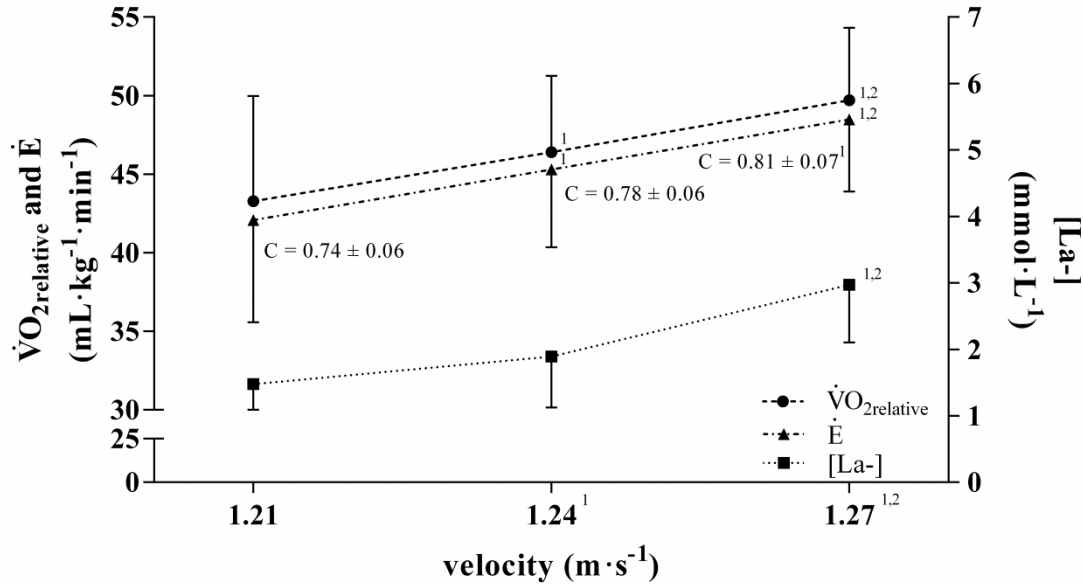


Figure 2.1. Mean $\pm$ SEM-SD of oxygen uptake corrected for body mass ($\dot{V}O_{2relative}$), total energy expenditure ($\dot{E}$), energy cost of locomotion (C) and blood lactate concentration ($[La^-]$) values at velocities corresponding to 97.5, 100 and 102.5% (slowest to highest velocity, respectively) of the maximal lactate steady state (MLSS) plotted as a function of swimming velocity (v).

^{1,2} Values significantly different to 97.5 and 100%MLSS, respectively ($p < 0.05$).

The bioenergetic and biomechanical parameters are presented in Table 2.1. The resting values of all parameters were not different among the three swimming conditions. Regarding the hypothesis decomposition, the interaction effect, i.e., significance level ($p < 0.05$) between the intensity and its time effects, only occurred with the VE and OUE.

The measured $\dot{V}O_2$ throughout the swims increased significantly as a function of v . Secondary to the increased $\dot{V}O_2$, C increased as function of v between below (97.5%MLSS) and above (102.5%MLSS) 100%MLSS and $\dot{E}$ also increased as a function of v during the three swimming intensities. The HR values increased as a function of v and were significantly higher at 102.5%MLSS compared to 97.5%MLSS.

Table 2.1. Bioenergetic and biomechanical parameters associated with the velocity at 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS) for the 8 normalized time moments of the swims. Statistical analyses were described by intensity and/or time effect or interaction effect (N=10).

Parameters/Effect	Intensity	Time Moments							
		rest	4min	25%	33%	50%	66%	75%	100%
						a,b	a		a
VO₂[#] (L.min⁻¹)	97.5%MLSS	0.44 (0.15)	2.68 (0.28)	2.63 (0.29)	2.61 (0.28)	2.58 (0.28)	2.59 (0.30)	2.65 (0.28)	2.63 (0.28)
	100%MLSS¹	0.36 (0.05)	2.88 (0.23)	2.88 (0.22)	2.81 (0.21)	2.78 (0.19)	2.80 (0.22)	2.81 (0.17)	2.80 (0.21)
	102.5%MLSS^{1,2}	0.39 (0.06)	3.05 (0.21)	3.05 (0.19)	3.06 (0.22)	3.02 (0.21)	3.00 (0.22)	3.03 (0.21)	3.01(0.20)
VE[†] (L.min⁻¹)	97.5%MLSS	14.7 (5.0)	62.4 (8.1)	63.6 (9.6)	63.3 (8.7)	62.9 (8.9)	64.7 (9.5)	66.2 (10.0)	64.5 (9.3)
	100%MLSS	12.1 (1.8)	68.6 (8.2) ¹	70.7 (8.2) ¹	69.1 (8.4) ¹	68.4 (7.1) ¹	71.5 (7.6) ¹	69.5 (8.3)	70.3 (10.5) ¹
	102.5%MLSS	14.6 (4.5)	75.7 (6.7) ^{1,2}	76.3 (5.8) ^{1,2}	76.5 (7.2) ^{1,2}	78.4 (9.6) ^{1,2}	79.8 (8.6) ^{1,2}	80.5 (9.3) ^{1,2}	82.9 (9.4) ^{1,2,a,b,c}
OUE[†] (mL O₂.L⁻¹.VE)	97.5%MLSS	31.0 (5.7)	43.3 (3.5)	41.8 (4.2)	41.5 (3.8)	41.3 (3.5)	40.4 (3.2) ^a	40.4 (4.1) ^a	41.1 (4.2) ^a
	100%MLSS	30.0 (2.9)	42.3 (3.2)	41.0 (3.5)	41.1 (3.7)	40.9 (4.3)	39.6 (4.7) ^a	40.9 (4.3)	40.4 (4.8)
	102.5%MLSS	28.3 (5.8)	40.5 (3.3) ¹	40.2 (3.2)	40.2 (3.0)	38.8 (4.1) ¹	37.9 (3.9) ^{1,a,b,c}	38.0 (4.0) ^{1,2,a,b,c}	36.6 (4.2) ^{1,2,a,b,c,d}
				a	a	a	a,b	a,b,c	a,b,c,d
HR[#] (bpm)	97.5%MLSS	77.8 (11.7)	160.4 (16.3)	165.2 (15.9)	166.6 (14.9)	168.4 (15.4)	168.4 (16.2)	170.4 (14.7)	170.6 (14.7)
	100%MLSS	73.0 (11.5)	168.9 (7.7)	173.3 (9.8)	173.8 (11.2)	173.0 (9.6)	174.7 (10.2)	175.0 (10.9)	176.3 (10.5)
	102.5%MLSS¹	74.1 (11.6)	173.0 (8.8)	176.8 (10.0)	178.8 (10.2)	180.3 (9.7)	181.7 (9.3)	182.1 (9.2)	182.2 (11.1)
						a,b			
C[#] (kJ.m⁻¹)	97.5%MLSS	0.17 (0.04)	0.75 (0.06)	0.74 (0.07)	0.73 (0.06)	0.72 (0.05)	0.73 (0.06)	0.74 (0.06)	0.73 (0.06)
	100%MLSS	0.16 (0.04)	0.79 (0.06)	0.79 (0.06)	0.77 (0.06)	0.76 (0.06)	0.77 (0.07)	0.77 (0.06)	0.77 (0.07)
	102.5%MLSS¹	0.14 (0.03)	0.82 (0.06)	0.82 (0.07)	0.82 (0.07)	0.81 (0.06)	0.81 (0.07)	0.81 (0.07)	0.81 (0.07)
						a,b			
Ė[#] (mL.kg⁻¹.min⁻¹)	97.5%MLSS	9.4 (2.2)	42.8 (6.9)	42.3 (7.0)	41.9 (7.0)	41.4 (6.9)	41.7 (6.9)	42.5 (6.5)	42.0 (6.3)
	100%MLSS¹	9.2 (2.8)	46.0 (5.4)	46.3 (5.6)	45.3 (5.9)	44.5 (5.0)	45.2 (5.2)	45.0 (4.0)	44.8 (4.8)
	102.5%MLSS^{1,2}	8.3 (1.7)	48.7 (5.0)	48.9 (4.6)	49.1 (5.5)	48.2 (4.9)	48.0 (4.3)	48.4 (4.5)	48.1 (4.5)
							a	a	a,c,d
SR[#] (cycles.min⁻¹)	97.5%MLSS	-----	33.4 (3.3)	33.8 (3.4)	33.4 (3.3)	33.6 (3.4)	33.7 (3.2)	34.1 (3.6)	34.2 (3.5)
	100%MLSS¹	-----	34.0 (3.3)	34.5 (3.0)	34.5 (3.1)	34.4 (3.2)	34.8 (3.6)	34.6 (3.8)	35.2 (3.8)
	102.5%MLSS^{1,2}	-----	35.4 (3.3)	36.1 (3.3)	36.2 (3.1)	36.0 (3.3)	36.7 (2.8)	37.3 (3.3)	37.2 (3.3)
								a	a,c,d
SL[#] (m.cycle⁻¹)	97.5%MLSS	-----	2.18 (0.14)	2.16 (0.14)	2.18 (0.15)	2.17 (0.14)	2.16 (0.13)	2.14 (0.15)	2.13 (0.15)
	100%MLSS	-----	2.20 (0.13)	2.16 (0.12)	2.17 (0.14)	2.17 (0.13)	2.15 (0.15)	2.16 (0.16)	2.13 (0.16)
	102.5%MLSS^{1,2}	-----	2.16 (0.12)	2.12 (0.14)	2.11 (0.14)	2.12 (0.14)	2.08 (0.14)	2.05 (0.13)	2.06 (0.14)
								a	a,c,d
SI[†] (m².s⁻¹.cycle⁻¹)	97.5%MLSS	-----	2.63 (0.20)	2.60 (0.20)	2.63 (0.23)	2.62 (0.18)	2.61 (0.19)	2.58 (0.21)	2.57 (0.20)
	100%MLSS	-----	2.72 (0.19)	2.68 (0.21)	2.69 (0.22)	2.69 (0.19)	2.66 (0.21)	2.67 (0.21)	2.63 (0.21)
	102.5%MLSS	-----	2.73 (0.18)	2.68 (0.22)	2.67 (0.24)	2.68 (0.22)	2.63 (0.25)	2.59 (0.21)	2.60 (0.22)

[#] Intensity effect; ^{*} time effect; [†] interaction effect; ^{1,2} Values significantly different to 97.5 and 100%MLSS, respectively; ^{a,b,c,d} Values significantly different to the 4th min, 25, 33 and 50%, respectively (*p* < 0.05);

VE increased as a function of v at all-time points, less at 75% of exercise duration for the 97.5%MLSS to 100%MLSS. However, VE was higher at the 100% of 102.5%MLSS comparing to the 4th min, 25 and 33% of exercise. The OUE values were lower at the 4th min, 50, 66, 75 and 100% comparing 97.5 and 102.5%MLSS. Moreover, OUE decreased as a function of time at the 66, 75 and 100% of 97.5%MLSS compared to the 4th min of exercise, at the 66% of 100%MLSS compared to the 4th min of exercise; and at 66, 75 and 100% of 102.5%MLSS compared to the 4th min, 25 and 33% of exercise, and 100% comparing 50% of exercise. The differences for VE described above have to acknowledge that there was a statistical interaction between swimming v (97.5, 100 and 102.5%MLSS) and the time points (4th min., 25, 33, 50, 66, 75 and 100%) of measurements and for OUE.

Figure 2.2 presents the changes in SR, SL and SI values as a function of velocity during the three swimming intensities. SR values increased as a function of v . However, SL were lower at 102.5%MLSS compared to 97.5 and 100%MLSS. The SI values were not different among the three velocities.

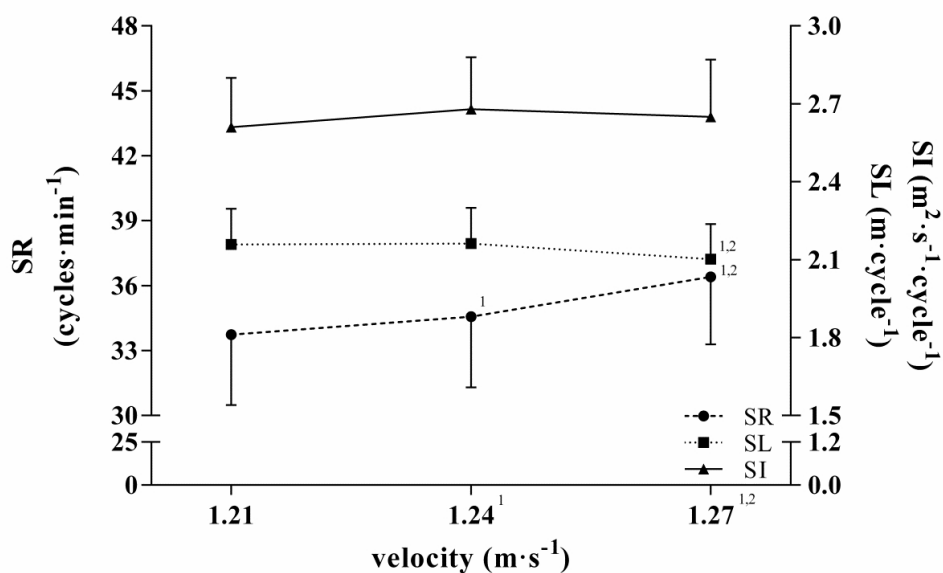


Figure 2.2. Mean $\pm$ SEMI-SD of stroke rate (SR), stroke length (SL) and stroke index (SI) values at velocities corresponding to 97.5, 100 and 102.5% (slowest to highest velocity, respectively) of the maximal lactate steady state (MLSS) plotted as a function of velocity.

^{1,2} Values significantly different to 97.5 and 100%MLSS, respectively ($p < 0.05$).

Regarding the time effect, the $\dot{V}O_2$ values were lower at the 50, 66 and 100% compared to 4th min, and at the 50% compared to 25% of exercise. Subsequent to the decreased $\dot{V}O_2$, C and $\dot{E}$ were lower at the 50% time compared to the 4th min and the 25% time of exercise. The HR values increased at the all swim times compared to the 4th min, as well as at 66, 75 and 100% of exercise compared to the 25%, at 75% and 100% comparing 33%, and comparing 100% than at 50% time point. SR values increased at 66, 75 and 100% compared to the 4th min, and at 100% compared to the 33 and 50% of exercise. Whereas, SL and SI were lower at 75 and 100% time compared to the 4th min of exercise, and at 100% compared to the 33 and 50% of exercise.

Discussion

This study analyzed the intensity and time-dependent variation of bioenergetic and biomechanical factors in swimming at intensities below, at, and above the MLSS. The MLSS is considered by some (Beneke & von Duvillard, 1996; Beneke, 2003; Faude et al., 2009) as the gold-standard method for the evaluation of aerobic capacity. The main findings of the present study were: (a) $\dot{V}O_2$, C and $\dot{E}$ were constant throughout the test time duration at each one of the three studied swimming intensities (97.5, 100 and 102.5%MLSS); (b) at 97.5%MLSS, bioenergetic factors did not change as a function of time. However, biomechanical factors (increased SR and decreased SL) and HR increased with time at all the three studied intensities; (c) at 102.5%MLSS, although the $\dot{V}O_2$, $\dot{E}$ and C were constant as a function of time, VE and HR increased as time elapsed. With a constant $\dot{V}O_2$ and an increasing VE, OUE decreased; (d) at 102.5%MLSS there was an increase in [La-] as a function of time, suggesting that the production exceeded its removal and this was associated with voluntary exhaustion; (e) as the $\dot{V}O_2$ was constant, the C and $\dot{E}$ were also constant during the three swimming conditions, despite [La-] increases during 102.5%MLSS.

In the present study, gas exchange values ($\dot{V}O_2$ and $\dot{V}E$) were directly measured breath-by-breath as a function of time for intensities below, at, and above 100%MLSS in swimming. However, previous researchers used measurements during the recovery period to assess $\dot{V}O_2$ and $\dot{V}E$ values during prolonged continuous swimming (Baron et al., 2005; Dekerle et al., 2005a). Despite the $\dot{V}O_2$ values for 100%MLSS in women were lower in the present study ($2.83 \text{ L}\cdot\text{min}^{-1}$) compared to those previously reported for men during submaximal exercise using that method ($4.94 \text{ L}\cdot\text{min}^{-1}$) (Dekerle et al., 2005a), the MLSS in the present study observed for women occurred at 85% (4% SD) of $\dot{V}O_{2\text{max}}$, which is similar to that reported in a previous study for men (86% $\dot{V}O_{2\text{peak}}$) (Dekerle et al., 2005a) based on the measurements of recovery period. In this sense, the lower $\dot{V}O_2$ values in the present study could be likely explained by differences in the sex of the subjects studied, such as lower muscle mass, and differences in pulmonary structure (Hopkins & Harms, 2004; Sheel et al., 2004). Indeed, it is well established in literature lower $\dot{V}O_2$ values for female athletes compared to their male counterparts (Rodriguez & Mader, 2011).

The increase in $\dot{V}E$ values as function of time was greater at the highest velocity studied (102.5%MLSS), but remained stable at the lower velocities. This finding is in accordance with a previous study (Baron et al., 2003), who reported similar values ($\sim 71.6 \text{ L}\cdot\text{min}^{-1}$) for cycling at 100%MLSS. The time-dependent increase in $\dot{V}E$ likely occurs as a respiratory compensation secondary to the build-up of [La-] in blood (metabolic acidosis) as seen in the present study, and likely due to the C of swimming at that velocity exceeding the aerobic supply capacity. The physiological system adjusts cardiopulmonary variables to match the oxygen delivery to the exercise intensity/velocity, i.e. the ratio between $\dot{V}O_2$ and $\dot{V}E$. The ratio of $\dot{V}O_2/\dot{V}E$ has been described as an index of ventilatory efficiency (OUE) (Baba et al., 1996), which has also been reported to vary among different athletes (Pelarigo et al., 2014).

Although the OUE values in this study decreased as a function of time at all exercise intensities, at the lowest studied velocity, the mild decrease in OUE

may be explained by a slight reduction in $\dot{V}O_2$ with a constant $\dot{V}E$. The reduction in $\dot{V}O_2$ as a function of time may be explained by biomechanical adjustments to promote gross efficiency, with swimmers improving propelling efficiency and/or decreasing drag (Pelarigo et al., 2011; Toussaint & Hollander, 1994). At the fastest velocity (102.5%MLSS), OUE showed a greater, and significant decay compared to the lower velocities. Also at 102.5%MLSS, the decrease of OUE with time is likely explained by the respiratory compensation for metabolic acidosis, increasing $\dot{V}E$ when $\dot{V}O_2$ remained constant (Baba et al., 1996). Alternatively, there may be an increased pulmonary dead space due to the reduction in tidal volume, and resultant increase in breathing frequency to meet the increased $\dot{V}E$ needs (Baba et al., 1996). If the pulmonary dead space significantly increased during exercise, the $\dot{V}E$ would have to be increased to provide the same alveolar ventilation at a higher energy cost to the respiratory muscles (Harms et al., 2000). The present study did not show differences in OUE as a function of time or intensity at or below 100%MLSS. For the higher velocity (102.5%MLSS), the reduced OUE became significant at 33% of exercise time duration, and it continued to decrease for all the remaining time moments up to 100%. Thus, it is likely that both respiratory compensation for metabolic acidosis and increased pulmonary dead space were responsible for the reduction in OUE, which might be associated with biomechanical adaptations and to exhaustion. The reduced OUE is also likely responsible for eight out of ten of the subjects' not completing the 30 min swim at 102.5%MLSS.

Supporting the role of respiratory compensation for metabolic acidosis at 102.5%MLSS is the reduced arterial CO_2 (P_aCO_2) values estimated from end-tidal P_aCO_2 (ETP_aCO_2). The ETP_aCO_2 is a physiological marker used to suggest changes in pH and hydrogen carbonate (HCO_3^-), both involved in the buffering system and control of metabolic acidosis. Although ETP_aCO_2 values were similar at all velocities, at 102.5%MLSS it showed a tendency to have lower values (mean = 37.60 mmHg) than at the two lower velocities (97.5%MLSS - mean = 38.92 mmHg; $p = 0.103$ and 100%MLSS - mean = 38.99 mmHg; $p = 0.083$). Furthermore, the ETP_aCO_2 values decreased as a function of time in the

102.5%MLSS swim from the start of the exercise (4th min, 25 and 33%) to its end (66, 75 and 100%) for all swimming speeds ($F_{6,54} = 10.328$, $p < 0.001$, $\eta_p^2 = 0.499$). Thus, the reductions in $\text{ETP}_{\text{aCO}_2}$ as a function of time at all velocities, and particularly for the 102.5%MLSS velocity confirm the respiratory compensation, and thus support its role in the reduced OUE.

Lower values of $[\text{La-}]$ at 100%MLSS (1.89 mmol.L⁻¹) were observed in the present study compared to swimming literature (2.8 – 3.3 mmol.L⁻¹) (Dekerle et al., 2005a; Fernandes et al., 2011; Pelarigo et al., 2011), and reports from other sports (2 – 8 mmol.L⁻¹) (Beneke et al., 2000; Figueira et al., 2008). Part of this difference in the $[\text{La-}]$ values is due to the lower $[\text{La-}]$ values commonly observed for women compared to men in endurance exercise (Crewther et al., 2006; Greco et al., 2007), which are likely explained by their lower body mass and lean muscle mass (Crewther et al., 2006). A further potential difference between men and women is the higher testosterone concentration in men (Deschenes & Kraemer, 2002), which could suggest a different metabolic balance between carbohydrates and fat throughout prolonged exercises (Greco et al., 2007; Tarnopolsky et al., 1995). The low values of $[\text{La-}]$ for women found in the present study may also be due to the high adaptation of aerobic metabolism during exertion caused by the high level of training of the women studied. Indeed, such endurance athletes likely present higher phenotypic expression of oxidative muscle fibers compared to sprint athletes (Tanaka & Swensen, 1998), fibers which consumes lactate (Gladden, 2008), supporting a physiological steady state at intensities near the $\dot{V}\text{O}_{2\text{max}}$ and to support the total energy expenditure required in high swimming intensities. This also explains the typical low final $[\text{La-}]$ values observed in middle-distance and endurance swimmers reported in the present study.

The C has been reported as the ratio of $\dot{E}$ and v, defined as the major determinant of swimming performance (di Prampero et al., 2011), where $\dot{E}$ is derived from both aerobic and anaerobic energy sources (Fernandes et al., 2006). In the present study C was measured by direct methods during submaximal constant swimming for MLSS assessment. Therefore, the

measured $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$) allow calculation of the respiratory exchange quotient, and thus determining the caloric equivalent of $\dot{V}O_2$. The $\dot{E}$ measured in this study increased around 7.5% as a function of v . Meanwhile, the C increased around 5% as a function of v during the three swimming velocities, both variables increasing with the speed as a linear function of v , although variables presented different regression slopes', as demonstrated before (Fernandes et al., 2006). On the other hand, these values are in contrast with previous studies where C increases with the velocity as a nonlinear function (Capelli et al., 1998; Holmer, 1992). This difference could be explained by the fact that in the present study a narrow framework of submaximal efforts were studied, in contrast with previous reported literature that aimed to a nonlinear function, but used very low to maximal swimming velocities (Capelli et al., 1998), intensity differences attained up to 100%, contrasting with the increases around 7.5% between intensities in our study. The present findings showed that the swimmers were able to maintain similar swimming economy as a function of v , even though the swimming intensities varied between a physiological steady state and voluntary exhaustion.

Comparing velocities at similar percentages of $v\dot{V}O_{2max}$ in front crawl swimming, values of C of $37.9 \text{ mL}\cdot\text{m}^{-1}$ ($0.79 \text{ kJ}\cdot\text{m}^{-1}$) and $41 \text{ mL}\cdot\text{m}^{-1}$ ($0.86 \text{ kJ}\cdot\text{m}^{-1}$) for high level female swimmers at mean intensity values of 88% and 95% of maximum 400 m speed, respectively, have previously been reported (Chatard et al., 1991). The 400 m race in swimming has been highly associated with the minimum velocity that elicits $\dot{V}O_{2max}$ (Costill et al., 1985). Although there were methodological differences and the exercise mode used in these studies, the mean values of C were similar (0.78 and $0.81 \text{ kJ}\cdot\text{m}^{-1}$ at 100 and 102.5%MLSS, respectively).

HR presented similar adjustments as a function of time among the three swimming conditions in the present study, drifting up around 10 bpm from the 4th min to the end of the test. The increased HR observed in prolonged exercise, as in the present study, defined as "cardiovascular drift" (Fritzsche et al., 1999), is likely explained by an increase in sympathetic nervous system

activity and circulating norepinephrine concentrations, as well as other mechanisms to maintain cardiac output (Baron et al., 2008). There was only a difference in HR between 97.5 and 102.5%MLSS, as values during steady state were similar. The mean HR value at 100%MLSS was of 91.6% (SD 3.6%) of HR at $\text{VO}_{2\text{max}}$ in the present study, values which were similar to the previously reported in literature (Dekerle et al., 2005a; Dekerle et al., 2005b).

Concerning the biomechanical factors (v , SR, SL and SI), the v values at 100%MLSS for females reported in this study are in accordance with those reported in previous studies (Baron et al., 2005; Dekerle et al., 2005b; Pelarigo et al., 2011), in spite of the fact that most of the swimmers examined in the previous studies were male. These similarities of the female and male data are most likely due to the high technical and training level of the swimmers we studied, compared to those of the men studied by other. This assertion is strengthened by the v at 100%MLSS expressed as a percentage of $v\text{VO}_{2\text{max}}$ observed in the present study. Indeed, our results showed higher percentage of the $v\text{VO}_{2\text{max}}$ ($91.8 \pm 4.6\%$) compared to previous reports in swimming ($88.9 \pm 3.3\%$) (Dekerle et al., 2005a), cycling ($78.2 \pm 4.9\%$), and running ($75.9 \pm 5.1\%$) (Figueira et al., 2008).

Swimming v is obtained by the product of SR and SL (Craig & Pendergast, 1979). It has also been shown that fatigue may interfere with the stroking parameters adopted by the swimmers to maintain a given velocity (Pelarigo et al., 2011). In the present study, swimmers did not sustain their SL at 102.5%MLSS compared to 97.5 and 100%MLSS, and thus they had to increase their SR to maintain their paced velocity. However, the SI values were not different among the three swimming velocities. Indeed, the decline in SL as a function of v to result in a decrease in SI, suggesting the importance of maintaining biomechanical efficiency with exercise intensity. These findings are in agreement with previous studies, who reported decreases in SL and increases in SR in all-out distance trials (Craig & Pendergast, 1979) and with time at imposed paces (Dekerle et al., 2005a; Figueiredo et al., 2014; Pelarigo et al., 2011). In addition, SR values in this study increased in the final periods of

the swims (66, 75 and 100% of the exercise time duration) compared to the beginning of the swims (4th min, 33 and 50%). Conversely, SL and SI were lower in the final periods of the swims (75 and 100%) compared with the beginning of the swims (4th min, 33 and 50%). Our results suggest that, at the beginning of the three swimming velocities exertions, an important adaptation occurred to the swimming intensity, as previously shown (Figueiredo et al., 2014), the differences of which were clearly evidenced when swimming at 102.5%MLSS. Previous study (Dekerle et al., 2005a) reported that, at 100%MLSS, there was a slightly decrease of SL (-3.3%) and increase of SR (3.6%) (non-significant in absolute values), from the beginning to the end of exercise, respectively. Similar trends SL and SR were found in the present study during 100%MLSS exercise. Moreover, above 100%MLSS (102.5%MLSS) fatigue likely developed as a function of time and was associated with the SL decrease (-4%) and the SR increase (4.3%) from the beginning to the end of exercise. The biomechanical data show that for all three swimming conditions, technical adjustments are needed to maintain velocity as a function of intensity and time; interestingly these changes did not affect $\dot{V}_E$ and C, which were constant as a function of time during each swimming intensity.

Our results suggest that, at intensities up to the maximal lactate steady state (MLSS), bioenergetic and biomechanical factors are constant as a function of time. However, above the MLSS (102.5%MLSS) there is hyperventilation, most likely caused by respiratory compensation for metabolic acidosis, thus decreasing of oxygen uptake efficiency. Increased dead space may also play a role in the reduced OUE. The changes in bioenergetic parameters are associated with the biomechanical changes, and together they are associated with the inability of most swimmers to complete the 30 min swim at 102.5%MLSS most likely attributable to fatigue.

Perspective

During the last decades, scientists have extensively investigated the maximal exercise intensity where a physiological steady state can be maintained over

time (MLSS). This intensity is commonly used as the aerobic capacity training target, and considered the main determinant factor for the improvement of swimmers' aerobic endurance performance. Meanwhile, consequences of small changes around this intensity, very common on a training session, are not well-known concerning the relevant biophysical modifications and their possible consequences on performance structure. The present study provides evidences that only 2.5% changes of swimming intensity above MLSS alter key physiological parameters ($\dot{V}E$ and $[La-]$) by hyperventilation and metabolic unsteady state installation, compromising the ventilatory efficiency (OUE), and consequently, the biomechanical control throughout time. These biophysical modifications were able to lead most swimmers to fatigue and consequently, to voluntary exhaustion. These results highlight fundamental aspects for the control, evaluation and prescription of aerobic capacity training, as well as some biophysical modifications occurred throughout time by induced fatigue, altering the aerobic endurance performance potential of competitive swimmers.

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Chapter 3

Oxygen uptake kinetics and energy system's contribution around maximal lactate steady state swimming intensity

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Abstract

Purpose: Our purpose was to examine the oxygen uptake (VO_2) kinetics and the energy systems' contribution at 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS) swimming intensity. **Methods:** Ten elite female swimmers performed three-to-five 30 min submaximal constant swimming bouts at imposed paces for the determination of the swimming velocity (v) at 100%MLSS based on the v associated at the individual anaerobic threshold. VO_2 kinetics (cardiodynamic, primary and slow component phases) and the aerobic and anaerobic energy contributions were assessed during the continuous exercises, which the former was studied for the beginning and second phase of exercise. **Results:** Subjects showed similar time delay (TD) (mean = 11.5 - 14.3 s) and time constant (τ_p) (mean = 13.8 - 16.3 s) as a function of v , but increased amplitude of the primary component for 97.5% ($35.7 \pm 7.3 \text{ mL.kg.min}^{-1}$) compared to 100 and 102.5%MLSS (41.0 ± 7.0 and $41.3 \pm 5.4 \text{ mL.kg.min}^{-1}$, respectively), but τ_p decreased (mean = 9.6 - 10.8 s) during the second phase of exercise. Despite the slow component did not occur for all swimmers at all swim intensities, when observed it tended to increase as a function of v . Moreover, total energy contribution was almost exclusively aerobic (98-99%) at 97.5, 100 and 102.5%MLSS. **Conclusions:** We suggest that elite endurance swimmers with a fast TD and τ_p values may be able to adjust faster the physiological requirements to minimize the A_s occurrence, parameter associated with the fatigue delay and increase in exhaustion time during performance.

Key words: aerobic capacity, gas exchange, slow component, intensity domains

Introduction

An important aspect of aerobic endurance performance is the ability to sustain the highest percentage of maximal oxygen uptake ($\%VO_{2max}$) as long as possible. In this sense, coaches and swimmers have used the $\%VO_{2max}$ in different submaximal intensities to control, prescribe and improve sports training (Bosquet et al., 2002). Additionally, scientists have shown that the VO_2 kinetics analysis may help to understand the physiological adjustments produced over time by the athletes in several sports, allowing them to maintain a high $\%VO_{2max}$ in a physiological steady state during aerobic endurance performance (Gaesser & Poole, 1996; Poole et al., 1988; Poole & Richardson, 1997).

Meanwhile, the scientific community has mainly described the VO_2 kinetics in three different intensity domains during continuous exercise. First, the moderate domain is described as the exercise intensities in which a steady state for VO_2 is achieved within 3 min of constant exercise (Burnley & Jones, 2007). Subsequently, the heavy domain is described as the exercise intensities in which VO_2 slow component should be evident, causing a delay on the achievement of the VO_2 steady state during exercise (Gaesser & Poole, 1996). Last, the severe domain is described as the exercise intensities in which VO_2 is elevated compared to rest values and continue to increase over time, leading to attain the VO_{2max} (Whipp & Wasserman, 1972; Whipp & Ward, 1990).

Maximal lactate steady state (MLSS) is considered one of the main relevant parameters for prescription and improvement of aerobic endurance performance, once it has been assumed as the limit intensity at which, during prolonged and submaximal exercise, the metabolic energy is produced mainly by the aerobic metabolism of pyruvate and glycolysis (Beneke, 2003; Heck et al., 1985). Moreover, MLSS is identified as the maximal intensity that can be maintained over time without the lactate production exceeding removal more than 1 mmol.L^{-1} , and considered the direct and gold-standard method for the evaluation of aerobic capacity (Beneke & von Duvillard, 1996; Billat et al., 2003; Faude et al., 2009).

Once maximal velocity where a steady state is found represents a fundamental physiological border, subtle changes in this intensity could likely modify VO_2 kinetics response. For instance, when the exercise is performed at intensities slightly below MLSS, a physiological steady state is sustained for both blood lactate concentration [La-] and VO_2 as a function of time (Baron et al., 2005; Whipp & Wasserman, 1972; Whipp & Ward, 1990). On the other hand, at intensities above the MLSS, a significant increase in [La-] and VO_2 is likely to be observed throughout time (Beneke, 2003; Billat et al., 2003; Poole et al., 1988; Whipp & Ward, 1990), leading to fatigue and voluntary exhaustion (Pelarigo et al., 2011; Poole et al., 1988; Poole & Richardson, 1997). Moreover, the swimming MLSS determination needs a short time of interruption for the analysis of [La-] during the 10th minute of exercise, and then, a resumption of exercise to complete the test. Thus, it seems to be fundamental to examine the behavior of VO_2 kinetics not only the beginning of exercise, but too after the resumption of exercise throughout exercise to better understanding of the entire process of the swimmer physiological response along the exercise.

VO_2 kinetics has been studied in different sports over the last decades (Gaesser & Poole, 1996; Sousa et al., 2014; Whipp & Wasserman, 1972), and there are relevant number of researches based on [La-] and gas exchange at intensities related to MLSS (Baron et al., 2005; Beneke, 2003; Pelarigo et al., 2011). However, no study has evaluated VO_2 kinetics at (and around) the MLSS intensity. Thus, our purpose was to examine VO_2 kinetics and the energy systems' contribution at 97.5, 100 and 102.5%MLSS in swimming. It was hypothesized that at 97.5%MLSS, VO_2 kinetics adjustments may not be so evident such as 100 and 102.5%MLSS. It was further hypothesized that even at the 100%MLSS intensity, swimmers may also have to adjust VO_2 kinetics during the exercise, once this intensity would lead to voluntary exhaustion over time. On the other hand, at the intensity of 102.5%MLSS, VO_2 kinetics may be compromised by fatigue, requiring faster time adjustments for time delay and time constant, and higher VO_2 amplitudes either for primary or slow components compared to lower exercise intensities. We further intended to assess VO_2 kinetics of the second phase of exercise, starting after the

collection of [La-] and resumption of exercise (from 10th min to the exercise end - final exercise), hypothesizing that these parameters could be faster than without previous exercise. Moreover, as MLSS may be maintained for long time period without continuous [La-] accumulation, as well as a submaximal exercise, the energy supply should be mainly supported through the aerobic system for the swimming intensities of $\pm 2.5\%$ around MLSS.

Material and Methods

Ten elite female swimmers volunteered and gave written informed consent to participate in the present study, which was approved by the local ethics committee and performed according to the Declaration of Helsinki. The swimmers were (mean $\pm$ SD) 17.6 $\pm$ 1.9 years of age, 1.70 $\pm$ 0.05 m height, 61.3 $\pm$ 5.8 kg body mass, 15.5 $\pm$ 2.9% body fat mass, and 54.9 $\pm$ 6.7 mL.kg.min⁻¹ $\dot{V}O_{2max}$, specialized in middle- and long-distance swimming events. The subjects had, at the least, seven years of experience as competitive swimmers and their mean performance over a 400m freestyle swim was 88.0 $\pm$ 3.4% of the short course world record.

The test sessions were performed in a 25 m indoor swimming pool. Air humidity was maintained nominally between 40-60%, and pool water temperature between 27-28°C. Swimmers were advised to refrain from intense training at least 24 h before the experimental sessions. The tests were conducted within a seven day period, at the same time of the day (± 2 h), minimizing the circadian rhythm effects. Previously to the test sessions, swimmers performed a 1000 m warm-up at low/moderate intensity. The tests were performed in front crawl, with in-water starts and open turns, without relevant underwater glides. A 24 h interval was imposed between all tests.

Initially, swimmers performed an intermittent incremental protocol until voluntary exhaustion to find the velocity (v) corresponding to the individual anaerobic threshold (IAnT). The distance covered in each step was 200 m, with v increases of 0.05 m.s⁻¹ and 30 s rest intervals between each swim (Fernandes et al., 2006). According to these authors, the predetermined v of the last step

was defined as the currently best expected performance for the subjects' 400 m front crawl, and then used to define all the v steps for the incremental test. The IAnT was assessed by the relationship between $[La^-]$ and v using a curve fitting method, and considered the interception point between linear and exponential regressions to determine the accurate v where $[La^-]$ increased exponentially (Fernandes et al., 2006; Machado et al., 2006).

Subsequently, each swimmer performed three-to-five 30 min submaximal constant swimming bouts at imposed paces to determine the highest v where a MLSS was achieved (100%MLSS). The first trial was performed at the v corresponding to IAnT; and, if a steady state or a decrease in $[La^-]$ was observed, further subsequent trials with 2.5% higher velocities were performed until no $[La^-]$ steady state could be maintained (Pelarigo et al., 2011). Following this study, if the first trial resulted in a clearly identifiable increase of the $[La^-]$, and/or could not be sustained due to exhaustion, further trials were conducted with reduced velocities. MLSS was defined as the $[La^-]$ that increased by no more than 1 mmol.l^{-1} between the 10th and 30th min of the test (Heck et al., 1985).

Earlobe capillary blood samples (5 μL) were collected: (a) at rest and in the first 30 s after each step of the incremental test, immediately after exhaustion, and at each 2 min of recovery (until the $[La^-]$ recovery peak was found); and (b) at rest, 10 and 30th min (or voluntary exhaustion) of each continuous bout (Lactate Pro, Arkray, Inc., Kyoto, Japan).

The v was set and maintained using a visual underwater pacer (GBK-Pacer, GBK Electronics, Aveiro, Portugal), with lights located each 2.5 m apart by a light strip on the bottom of the pool. Swimmers followed the flashing lights to maintain the predetermined velocities and were instructed to keep their heads above each visual signal. Exhaustion was defined when the swimmers remained 5 m behind the lights.

VO_2 was measured by a telemetric portable gas analyzer (K4b², Cosmed, Italy) in both tests, connected to the swimmer by a low hydrodynamic resistance

respiratory snorkel and valve system (New AquaTrainer[®], Cosmed, Italy). This system has been previously validated (Baldari et al., 2013) and used in similar studies (Sousa et al., 2014). The device was calibrated for minute ventilation (VE) with a calibrated syringe (3 L) and the O₂ and CO₂ analyzers with standard calibration gases (16% O₂ and 5% CO₂) before each test. In all tests, VO₂ data were analyzed and errant breaths occurred by swallow water and/or saliva, sighs and coughs were excluded. Afterwards, VO₂ values were measured in mean $\pm$ 3 SD and outside values were removed. Subsequently, the breath-by-breath data were linearly interpolated to provide five-by-five s values, and smoothed using three breath averages (Fernandes et al., 2012; Sousa et al., 2014). Heart rate (HR) was monitored and registered continuously by a HR monitor system (Polar Vantage NV, Polar electro Oy, Kempele, Finland) and transferred in real time, through a telemetric signal, to the K4b² device. The HR values were also averaged every 5 s intervals.

The average VO₂ values were analyzed by a nonlinear least squares algorithm to fit the data through MatLab 7.0 Software (MathWorks, Natick, MA). The mathematical model consisted of two (cardiodynamic and primary components) or three (cardiodynamic, primary and slow components) exponential models. An F-Test ($p < 0.05$) was used to evaluate whether the two or three exponentials models provided the best fit to each data set. The VO₂ kinetics was described as a single-exponential (Equations 3.1 and 3.2) and biexponential (Equation 3.3) functions of time by the following equations:

$$\text{VO}_2(t) = \text{VO}_{2 \text{ baseline}} + A_c [1 - e^{-(t/\tau_c)}] \quad 3.1$$

phase I (cardiodynamic component)

$$+ A_p [1 - e^{-(t - \text{TD}_p)/\tau_p}] \quad 3.2$$

phase II (primary component)

$$+ A_s [1 - e^{-(t - \text{TD}_s)/\tau_s}] \quad 3.3$$

phase III (slow component)

where $\dot{V}O_2(t)$ represents the absolute $\dot{V}O_2$ at time, $\dot{V}O_{2\text{ baseline}}$ is the $\dot{V}O_2$ in resting baseline period, A_c and τ_c are the amplitude and the time constant of the cardiodynamic component; A_p , TD_p and τ_p are the amplitude, the time delay and the time constant of the primary component; A_s , TD_s and τ_s are the amplitude, the time delay and the time constant of the slow component. The mean response time (MRT) was applied to represent the overall pulmonary $\dot{V}O_2$ kinetics response, which was determined as the sum of TD_p and τ_p (Sousa et al., 2014). The $\dot{V}O_2$ kinetics was assessed during the beginning of exercise until the break (at the 10th min) of swim for collection of [La-] (initial exercise), and the second phase of exercise, starting after the collection of [La-] and resumption of exercise (final exercise).

The energy systems' contribution has been assessed by the total energy expenditure ($\dot{E}$). The $\dot{E}$ was obtained by the addition of the aerobic energy expenditure calculated by the difference between the exercise $\dot{V}O_2$ ($\dot{V}O_{2\text{ exercise}}$) and baseline $\dot{V}O_2$ ($\dot{V}O_{2\text{ baseline}}$) ($\text{mL.kg}^{-1}.\text{min}^{-1}$), and by the anaerobic energy expenditure that was calculated by the net [La-] values transformed into O_2 equivalents using the constant value of $2.7 \text{ mL}O_2.\text{kg}^{-1}.\text{mM}^{-1}$ (di Prampero, 1981; Sousa et al., 2014) during continuous exercises.

Data are presented as mean and standard deviation ($\pm$ SD). Normality and sphericity of data were checked with the Shapiro-Wilk's W and Mauchley Sphericity tests. When the assumption of sphericity was not attained, Greenhouse-Geisser or the Huynh-Feld adjusted univariate tests for repeated measures were used. The partial Eta square (η_p^2) was used to measure the effect size, defined as small, medium and large for values of 0.01, 0.06 and 0.14, respectively (Stevens, 2002). The comparisons of $\dot{V}O_2$ kinetics (cardiodynamic and primary components) and energy systems' contribution (aerobic and anaerobic energy expenditure) were performed using multivariate ANOVA and examined by the intensity and previous exercise effects. The v and [La-] values were performed using the univariate ANOVA. All analyses were conducted for repeated measures, complemented with the Bonferroni correction post-hoc test with a significance level of $p < 0.05$.

Results

All swimmers performed 30 min when swimming at 97.5 and 100%MLSS, but eight swimmers were not able to maintain the predetermined v during 30 min at 102.5%MLSS, reaching voluntary exhaustion at 19.3 ± 4.9 min. The average v and %VO_{2max} values were different in between the three swim intensities, with 97.5%MLSS slowest and lowest, and 102.5%MLSS fastest and highest ($F_{2,18} = 2560.200$, $p < 0.001$, $\eta_p^2 = 0.996$; $F_{2,18} = 15.538$, $p < 0.001$, $\eta_p^2 = 0.633$, respectively) (Table 3.1). [La-] and HR values for the three swim intensities are also shown in Table 3.1 with a higher values at 102.5%MLSS compared to 97.5 and 100%MLSS for [La-] ($F_{2,18} = 18.123$, $p < 0.001$, $\eta_p^2 = 0.668$), and at 102.5%MLSS compared to 97.5%MLSS for HR ($F_{2,18} = 7.222$, $p < 0.005$, $\eta_p^2 = 0.445$).

Table 3.1. Mean (SD) values of swimming velocity (v), blood lactate concentration ([La-]), heart rate (HR), and percentage of maximal oxygen uptake (%VO_{2max}) are shown at 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS) (N=10).

	97.5%MLSS	100%MLSS	102.5%MLSS
v (m.s ⁻¹)	1.21 (0.07)	1.24 (0.07) ¹	1.27 (0.07) ^{1,2}
[La-] (mmol.L ⁻¹)	1.48 (0.39)	1.89 (0.77)	2.97 (0.87) ^{1,2}
HR (beats.min ⁻¹)	167 (15)	174 (10)	179 (9) ¹
%VO _{2max} (%)	79 (9)	85 (4) ¹	91 (5) ^{1,2}

^{1,2} Values different from 97.5 and 100%MLSS, respectively ($p < 0.05$).

VO₂ kinetics parameters are presented in Table 3.2. A_p tended to increase with the swimming intensity (v) during the initial exercise, but differences were only noticed comparing 100 and 102.5%MLSS to 97.5%MLSS ($F_{2,18} = 8.249$, $p < 0.05$, $\eta_p^2 = 0.478$). Meanwhile, A_p was similar at final exercise for the three swim conditions ($F_{2,18} = 1.167$, $p = 0.334$, $\eta_p^2 = 0.115$). On the other hand, A_p decreased as a function of previous exercise for the three swims bouts. TD_p , τ_p and MRT were similar as function of v at initial exercise and final exercise during the three swimming conditions. However, when analyzed the swim bouts as a function of previous exercise, TD_p decreased for the 97.5%MLSS, but the

values remained similar for 100 and 102.5%MLSS; τ_p decreased for all swim intensities, and MRT decreased for the 97.5 and 102.5%MLSS, but remained similar for 100%MLSS.

The both measured $\text{VO}_{2\text{baseline}}$ at initial exercise ($F_{2,18} = 2.389$, $p = 0.120$, $\dot{\eta}_p^2 = 0.210$) and final exercise ($F_{2,18} = 1.034$, $p = 0.376$, $\dot{\eta}_p^2 = 0.103$) were similar in between the three swim conditions, but $\text{VO}_{2\text{baseline}}$ increased as a function of previous exercise (initial to final exercise) for all continuous intensities ($F_{1,9} = 68.311$, $p < 0.001$, $\dot{\eta}_p^2 = 0.884$). A_c was similar as a function of v for both initial exercise ($F_{2,18} = 0.134$, $p = 0.876$, $\dot{\eta}_p^2 = 0.015$) and final exercise ($F_{2,18} = 1.974$, $p = 0.168$, $\dot{\eta}_p^2 = 0.180$). Moreover, at 97.5%MLSS, A_c was lower comparing initial and final exercise, but values remained similar for 100 and 102.5%MLSS.

Table 3.2. Mean (SD) values of oxygen uptake (VO_2) kinetics parameters at velocities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS) for the beginning of exercise until the break of swim for blood collection (initial exercise), and the second phase of the exercise, starting after blood collection (final exercise) (N=10).

	97.5%MLSS		100%MLSS		102.5%MLSS	
	Initial exercise	Final exercise	Initial exercise	Final exercise	Initial exercise	Final exercise
$\text{VO}_{2\text{baseline}}$ ($\text{mL.kg}^{-1}.\text{min}^{-1}$)	7.2 (2.1)	16.0 (5.3) ^a	6.0 (1.0)	17.4 (5.7) ^a	6.4 (0.8)	18.8 (5.8) ^a
A_c ($\text{mL.kg}^{-1}.\text{min}^{-1}$)	16.4 (5.9)	10.4 (4.9) ^a	16.1 (7.1)	14.2 (5.4)	15.1 (6.5)	14.9 (5.7)
A_p ($\text{mL.kg}^{-1}.\text{min}^{-1}$)	35.7 (7.3)	26.3 (7.4) ^a	41.0 (7.0) ¹	28.3 (5.2) ^a	41.3 (5.4) ¹	29.8 (5.5) ^a
TD_p (s)	14.3 (5.5)	12.0 (5.3) ^a	12.4 (8.1)	11.9 (4.9)	11.5 (6.8)	11.1 (4.7)
τ_p (s)	16.3 (5.4)	10.8 (4.7) ^a	13.8 (4.5)	9.7 (4.5) ^a	16.0 (5.8)	9.6 (5.3) ^a
MRT (s)	30.6 (5.2)	22.8 (5.4) ^a	26.2 (6.8)	21.6 (4.6)	27.4 (8.5)	20.7 (5.2) ^a

Statistical analyses were described by intensity and previous exercise effect;

¹ Values different from 97.5%MLSS for initial exercise;

^a Values different from initial exercise ($p < 0.05$);

A_s of VO_2 kinetics was observed for all tested swimming intensities and testing phases (initial and final exercise) only in two out of ten subjects. In one subject A_s was never observed. The A_s only occurred for 6 swimmers during initial exercise and 8 swimmers during final exercise at 97.5%MLSS, for 6 swimmers during initial exercise and 7 swimmers during final exercise at 100%MLSS, and for 9 swimmers during initial exercise and 5 swimmers during final exercise at 102.5%MLSS. The A_s values are presented in Table 3.3. It was perceived that A_s tended to increase with swimming intensity during initial exercise, but keeping constant during final exercise whatever the intensity considered; however no statistical analysis was applied, once the occurrence of the A_s was apparently chaotic among swimmers both considering swimming intensities and phases of testing (initial and final exercise).

Table 3.3. Individual and mean (SD) values of the amplitude of slow component (A_s) at velocities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS) for the beginning of exercise until the break of swim for blood collection (initial exercise), and the second phase of the exercise, starting after blood collection (final exercise) (N=10).

swimmer	A_s (mL.kg ⁻¹ .min ⁻¹)					
	97.5%MLSS		100%MLSS		102.5%MLSS	
	Initial exercise	Final exercise	Initial exercise	Final exercise	Initial exercise	Final exercise
1	1.7	2.9	2.3	3.8	4.5	1.6
2	2.3	0.7	4.4	-----	3.7	-----
3	1.1	-----	2.6	-----	4.4	-----
4	-----	-----	-----	-----	-----	-----
5	4.2	0.9	2.8	0.8	2.9	-----
6	-----	0.8	-----	0.8	1.9	2.2
7	-----	1.2	-----	0.9	7.2	1.1
8	-----	1.7	2.8	1.1	4.5	-----
9	2.5	1.3	2.6	1.5	6.1	0.8
10	1.4	-----	-----	1.5	5.1	1.8
Mean (SD)	2.2 (1.1)	1.4 (0.8)	2.9 (0.8)	1.5 (1.1)	4.5 (1.6)	1.5 (0.6)

The relative energy contribution for each one of the three swim intensity bouts is shown in Figure 3.1. The aerobic energy contribution decreased ($F_{2,18} = 15.254$, $p < 0.001$, $\eta_p^2 = 0.629$) and the anaerobic energy increased ($F_{2,18} = 15.254$, $p < 0.001$, $\eta_p^2 = 0.629$) at 102.5%MLSS compared to 97.5 and 100%MLSS.

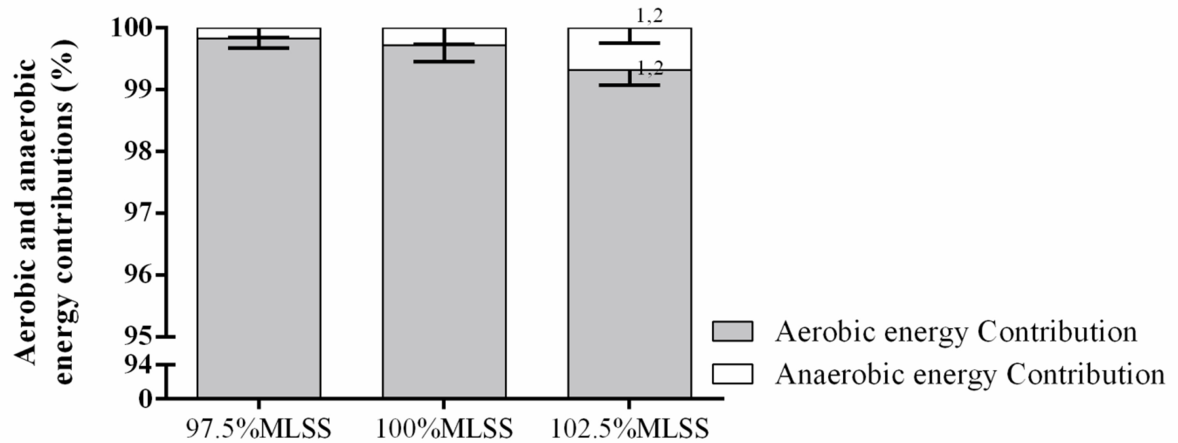


Figure 3.1. Mean $\pm$ SD of aerobic and anaerobic energy contribution values at velocities corresponding to 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS).

Discussion

In sports science, VO_2 kinetics have aided the understanding of physiological adjustments over time (Gaesser & Poole, 1996; Poole et al., 1988; Poole & Richardson, 1997), such as muscle metabolism and systemic oxygen transport (Xu & Rhodes, 1999). Moreover, one of the most relevant exercise intensities in swimming for aerobic training, prescription and evaluation is the v at which MLSS is obtained, being considered the direct and gold-standard method for the evaluation of aerobic capacity (Beneke & von Duvillard, 1996; Beneke, 2003; Billat et al., 2003; Faude et al., 2009; Pelarigo et al., 2011). Thus, both aspects (VO_2 kinetics and MLSS) are decisive for the understanding of energy supply and oxidative metabolism supporting muscular exercise. As a consequence, our purpose was to examine the amplitude and time adjustments of VO_2 kinetics during swims at intensities of 97.5, 100 and 102.5%MLSS, exploring the effects of small prescriptions variations on swimming oxidative physiology.

The main findings were: (a) A_p tended to increase with swimming v for the initial phase of exercise, despite differences were only noticed comparing 100 and 102.5%MLSS to 97.5%MLSS. Meanwhile, A_p was similar at the final phase of exercise during the three swim conditions. However, A_p decreased as a function of previous exercise for the three swim intensities; (b) TD_p , τ_p and MRT were similar irrespective of v both at initial and final exercise; (c) regarding the effect of previous exercise comparing initial and final exercise for the three swimming intensities, TD_p decreased for the 97.5%MLSS, but was similar for 100 and 102.5%MLSS, τ_p decreased for all swim intensities, and MRT decreased for the 97.5 and 102.5%MLSS, but was similar for 100%MLSS; (d) although A_s was not evident for all swimmers during the three swimming conditions, it tended to increase with intensity during initial exercise, remaining constant during final exercise; (e) A_c was similar both for the initial and final exercise comparing the three swim intensities, but was lower during final exercise compared to initial exercise at 97.5%MLSS, and was similar at 100 and 102.5%MLSS; (f) aerobic and anaerobic energy contributions were different at 102.5%MLSS compared to lower swim velocities; (g) at the three swim intensities, the aerobic contribution values were higher than 98% of the total energy input.

The VO_2 values in the present study were directly measured breath-by-breath throughout time for the three swim intensities. Subsequently, the VO_2 data were fitted through mathematical modelling as previously applied in swimming for maximal and submaximal exercises (Fernandes et al., 2012; Pessoa Filho et al., 2012; Reis et al., 2012a, 2012b; Reis et al., 2010; Sousa et al., 2014). Some studies have reported VO_2 kinetics at intensities near the maximal v where a steady state in swimming is found (MLSS) (Pessoa Filho et al., 2012; Reis et al., 2012a, 2012b), however we are unaware of a study that has evaluated and compared VO_2 kinetics at or around the MLSS in swimming. Most of previous studies reported in sports science (Fernandes et al., 2012; Gaesser & Poole, 1996; Jones & Burnley, 2009; Pessoa Filho et al., 2012; Reis et al., 2012a, 2012b; Reis et al., 2010; Sousa et al., 2014) have studied VO_2 kinetics at maximal and submaximal intensities, demonstrating the fundamental role of VO_2 kinetics to understand the physiological mechanisms underpinning the

dynamics of the aerobic response at different exercise intensities. Thus, the understanding of the VO_2 kinetics throughout time may aid the evaluation of aerobic capacity and prescription of specific training sets during these fundamental training intensities around MLSS.

The 100%MLSS $\dot{V}$ values reported in this study are in accordance with those reported in previous ones (Baron et al., 2005; Dekerle et al., 2005b; Pelarigo et al., 2011), in spite of the fact that most of the swimmers examined in the previous studies were male when compared with the female subjects of the present study. Despite higher $\dot{V}$ values at a given relative intensity are expected to be higher for male than female counterparts of similar training level (Greco et al., 2007), the sex similitude comparing our results with literature could likely be explained by a higher technical and biomechanical proficiency of our female swimmers when compared to the male swimmers of the previous studies. Indeed, the $\%\text{VO}_{2\text{max}}$ at 100%MLSS ($85 \pm 4\%$) observed in the present study for women is similar to previously reported data for men ($86.1\% \text{VO}_{2\text{peak}}$) (Dekerle et al., 2005a), suggesting similar levels of aerobic capacity development, even the $\text{VO}_{2\text{max}}/\text{VO}_{2\text{peak}}$ being higher in the previous study (mean= $\sim 83 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) when compared with our results ($54.9 \pm 6.7 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). Meanwhile, the mean HR value at 100%MLSS was $174 \pm 10 \text{ beats}\cdot\text{min}^{-1}$ in the present study, values which were similar to the previous reported in literature (Dekerle et al., 2005a; Dekerle et al., 2005b), as expected by the comparable age of samples.

Moreover, the $[\text{La-}]$ at 100%MLSS ($1.89 \pm 0.77 \text{ mmol}\cdot\text{L}^{-1}$) in the present study were lower when compared to swimming literature ($2.8 - 3.3 \text{ mmol}\cdot\text{L}^{-1}$) (Dekerle et al., 2005a; Figueiredo et al., 2014; Pelarigo et al., 2011). These lower $[\text{La-}]$ values may be explained by sex differences for similar levels of aerobic capacity development, with expected lower values for women due to lower body mass and lean muscle mass compared to men (Crewther et al., 2006). Furthermore, women have showed lower testosterone concentration compared to men (Deschenes & Kraemer, 2002) during aerobic endurance exercise (Crewther et al., 2006; Greco et al., 2007), suggesting different metabolic contributions

between carbohydrates and fat during long-distance exercise (Greco et al., 2007; Tarnopolsky et al., 1995), and supporting comparable lower [La-].

Since the early research on VO_2 kinetics (Margaria et al., 1933) until up to date, the time constant (τ) has been studied in sports science in the attempt to comprehend the physiological adjustments during the non-steady state period at the beginning of exercise due to the increase of metabolic demand. In the present study, the τ_p values were similar between intensity levels for the initial exercise phase (mean = 15.4 ± 5.2 s) and final exercise phase (mean = 10.0 ± 4.7 s), but the values decreased with previous exercise for the three swim conditions. This is particularly relevant for training practice, underlining the influence of previous exercise on the subsequent metabolic dynamics. In all studied exercise intensities, the τ_p in the present study showed similar values compared than those previously reported in swimming (~15-20 s) (Pessoa Filho et al., 2012; Reis et al., 2012a, 2012b), cycling (Berger & Jones, 2007; Koppo et al., 2004), rowing (Ingham et al., 2007), and running (Borrani et al., 2001; Carter et al., 2000). Thus, those values reported for intensities up to and above the MLSS seem to behave similarly as expected, based on the previous knowledge on the VO_2 kinetics during different intensity domains for well-trained athletes. Indeed, a faster attainment of a steady state and a reduction in the oxygen deficit are associated to the fatigue delay and increase in exhaustion time, being well trained athletes able to perform at higher intensities with lower requirements of anaerobic energy during the transition from rest to exercise (Burnley & Jones, 2007). Hence, the lower τ_p values reported in this study when compared to previously published ones regarding physiological adaptations induced by aerobic endurance training confirm the highly endurance training status and specialization (endurance athletes) of our swimmers (Burnley & Jones, 2007; Carter et al., 2000).

Partially in contrast with previous literature that showed the existence of the A_s at these exercise intensities (Burnley & Jones, 2007; Gaesser & Poole, 1996; Poole & Richardson, 1997), in the present study it has shown to occur chaotically during the three swimming conditions, with very diverse individual

occurrence profiles; however, observing the sample data a tendency to A_s increase as a function of intensity was observed (2.2 ± 1.1 , 2.9 ± 0.8 and 4.5 ± 1.6 mL.kg⁻¹.min⁻¹, respectively for 97.5, 100 and 102.5%MLSS), but only during initial exercise, not during the final phase after metabolic adaptation already occurs.. Besides, only two swimmers showed A_s occurrence in all trials both at the initial and final exercise phases, and one swimmer did not show any A_s during all the swimming efforts and phases. It is worthy to emphasize the curiosity of that particular swimmer being a national record holder (800 and 1500m) and the best endurance swimmer of the sample. These partially contradictory findings could be explained, at least in part, by the specific physiological adaptations occurred through the highly endurance training status for our swimmers, such as faster τ_p (Carter et al., 2000), possible increase in the mitochondrial content of the cell (Holloszy & Coyle, 1984), beyond also possible alterations in the mitochondrial sensitivity to the respiration regulators (Dudley et al., 1987), and the fact of these endurance athletes might have mainly type I muscle fibers (Holloszy & Coyle, 1984). Thus, our endurance swimmers with fast $\dot{V}O_2$ kinetics would be able to adjust faster the physiological requirements for aerobic performance during the high intensity aerobic exercises, minimizing the A_s demand. In addition, the appearance of the A_s is normally explained by a phenomena that may be attenuated in our very specialized sample, namely the recruitment of type II fibers with fatigue (Poole et al., 1991), after which the magnitude of A_s has been correlated with the rise of [La-] (Gaesser & Poole, 1996; Holloszy & Coyle, 1984). Thereby, the absence of significant A_s in the present study may be likely explained by the high-level of endurance training of the sample (Billat et al., 1998).

Moreover, to reinforce the predominance of aerobic energy system during the three swim conditions around MLSS, the present study determined the total energy contribution at each one of the studied exercise intensities. At all swimming intensities up to and above MLSS, the aerobic energy contribution was higher than 98% of the total energy contribution; however there were significant differences between the highest and the lower v regarding aerobic and anaerobic energy contributions. This study was the first study to show the

energy contribution during intensities at and around MLSS directly measured breath-by-breath in swimming, which highlights that even at intensities above MLSS; the total energy contribution was mainly and almost exclusively controlled by the oxidative bioenergetics system.

Conclusion

The present study showed that well-trained endurance swimmers with a fast component of VO_2 kinetics and low $[\text{La-}]$ may be able to adjust faster the physiological requirements during intensities up to and slightly above MLSS to minimize the appearance of the slow component and reduce the oxygen deficit, both parameters are associated to the fatigue delay and the increase in exhaustion time, key factors to endurance performance. Moreover, the data shows that the aerobic energy contribution at intensities up to and slightly above MLSS plays a fundamental role controlling almost exclusively the required energy supply.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Ethical standards

The Institutional Review Board of the University of Porto, Faculty of Sport, approved the study design. All subjects gave their informed consent prior to their inclusion in the study. The procedures were in accordance to the Declaration of Helsinki in respect to Human research.

Chapter 4

Comparison of different methods for the swimming aerobic capacity evaluation

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Abstract

This study aimed to compare velocity (v) and bioenergetic (gas exchange and energetic parameters) factors using different methods applied for the swimming aerobic capacity evaluation. Ten elite female swimmers (17.6 ± 1.9 yrs., 1.70 ± 0.05 m, 61.3 ± 5.8 kg and $15.5 \pm 2.9\%$ body fat mass) performed an intermittent incremental velocity protocol until voluntary exhaustion to determine the v associated to the individual anaerobic threshold (IAnT), ventilatory threshold (VT), heart rate threshold (HRT), lactate threshold fixed in 3.5 mmol.L^{-1} (LT_{3.5}) and maximal oxygen uptake ($\text{VO}_{2\text{max}}$). In addition, swimmers performed two-to-three 30 min submaximal constant tests at imposed paces for the assessment of the v at maximal lactate steady state (MLSS). The v , gas exchange, heart rate and blood lactate concentration variables were monitored in all tests. The average values of all parameters at the v corresponding to MLSS, IAnT, VT and HRT were similar ($p < 0.05$), with high agreement values ($r^2 > 0.400$). However, v and bioenergetic factors at LT_{3.5} were higher compared to the other methods. It is suggested that IAnT, VT and HRT methods are better predictors of the intensity corresponding to MLSS for elite endurance swimmers compared to the LT_{3.5}.

Key words: maximal lactate steady state, endurance, oxygen uptake, blood lactate, training, testing

Introduction

The ability to sustain the highest percentage of maximal oxygen uptake ($\text{VO}_{2\text{max}}$) during long-distance events has been defined as aerobic capacity. This intensity is associated with maximal lactate steady state (MLSS) and anaerobic threshold (AnT), and is considered a main physiological variable related to endurance performance (Bosquet et al., 2002). Moreover, aerobic capacity is often normalized and expressed in terms of $\text{VO}_{2\text{max}}$, distinguishing athletes by the relative values of $\text{VO}_{2\text{max}}$ ($\%\text{VO}_{2\text{max}}$) (Bassett & Howley, 2000).

In swimming, like in others sports, the evaluation of the aerobic capacity is paramount to control and prescribe endurance intensity training. There are several methods to determine the aerobic capacity based on ventilatory, metabolic and cardiac parameters (Bosquet et al., 2002). The MLSS intensity has been considered an essential parameter to individually define the training load and to optimize swim training and performance, and is inclusively, also considered as the gold-standard method for the evaluation of aerobic capacity (Beneke & von Duvillard, 1996; Faude et al., 2009).

The MLSS test consists of determining the highest intensity that can be maintained over time without continuous accumulation of blood lactate concentration ($[\text{La-}]$) (Beneke, 1995; Beneke et al., 2000). MLSS requires several days of tests to be determined without submission to relevant training loads, and the protocol consists on repetitions of 30 min at constant speed while assessing the $[\text{La-}]$ throughout the exercise. Indeed, the MLSS determination involves complex and time-consuming procedures. Therefore, scientists, coaches, and athletes have used several methods to predict the intensity associated with the MLSS, and some of them are considered to be easy-to-apply, less time-consuming and non-invasive protocols. However, monitoring swimming training process requires reliable methods to provide not only training intensity, but also reliable bioenergetic (gas exchange and energetic parameters) and biomechanical (stroke rate and stroke length) specific information. Thereby, the choice of a reliable and useful method to predict

MLSS has probably become one of the most important topics for the diagnosis of endurance performance in sports sciences (Faude et al., 2009).

According to Toussaint and Hollander (1994), swimming performance is described as the result of the transformation of metabolic power into mechanical power with a given energetic efficiency. Since the mechanical power requirements to overcome drag forces are theoretically dependent on the cube of swimming velocity (v) (Toussaint & Hollander, 1994), differences on the velocities provided by these methods could underestimate or overestimate the physiologic load associated to the MLSS. Thus, slightly higher or lower values of v may cause serious differences (cubic related) in the mechanical power requirements, involving different adjustments on the total energy expenditure, energy cost, propulsive force, and/or propelling efficiency.

Thus, the present study aimed to compare the methods most commonly used for the aerobic capacity evaluation in swimming based on v and bioenergetic factors. It was hypothesized that significant differences in these parameters among the MLSS and concurrent methods may exist, once two different exercise modes are involved (i.e. continuous and intermittent exercise). Moreover, it was also hypothesized that v and bioenergetic responses during the individual anaerobic threshold (IAN_T) and ventilatory threshold (VT) could likely be better predictors of MLSS than heart rate threshold (HRT) and lactate threshold of fixed 3.5 mmol.L⁻¹ (LT_{3.5}) methods, once IAN_T and VT are determined by individual manner through physiological responses (Fernandes et al., 2011; Roels et al., 2005), while HRT and LT_{3.5} are determined by indirect markers (heart rate) or fixed metabolic parameters, respectively.

Methods

Ten elite female swimmers (17.6 ± 1.9 years of age, 1.70 ± 0.05 m of height, 61.3 ± 5.8 kg of body mass, $15.5 \pm 2.9\%$ body fat mass, and 54.9 ± 6.7 mL.kg⁻¹.min⁻¹ of VO_{2max}), who were specialized in middle- and long-distance events, volunteered to participate in this study. Swimmers had at the least seven years of experience as competitive swimmers with a mean performance over a 400 m

freestyle swim corresponding to $88.0 \pm 3.4\%$ of the 25 m pool 2014 world record. The study protocol was approved by the local ethics committee and was performed according to the Declaration of Helsinki. Signed informed consent was collected from all subjects/parents before the experiment started.

A 25 m indoor swimming pool was used to perform the test sessions. The water temperature was maintained between 27-28 °C and air humidity was nominally between 40-60%. Swimmers were advised to refrain from intense training sessions at least 24 h before the experimental sessions. The swimmers were tested in front-crawl stroke, but using in-water starts and open turns without underwater gliding. All tests were conducted within a four day period, at the same time of the day (± 2 h) to minimize the effect of circadian rhythm. Swimmers performed in all test sessions a 1000 m individualized warm-up at low/moderate aerobic intensity. A segmental body composition analyser was used to assess body mass and fat measurements (Tanita, TBF 305, Tokyo, Japan).

First, swimmers performed a front crawl intermittent incremental velocity protocol until voluntary exhaustion, consisting in seven 200 m stages with $0.05 \text{ m}\cdot\text{s}^{-1}$ velocity increments between each step, and 30 s rest intervals in-between. The predetermined v of the last step was defined through the best time for the subjects' 400 m front crawl time estimated at the testing period (Fernandes et al., 2006). Subsequently, swimmers performed two-to-five 30 min submaximal constant swimming tests at imposed paces to determine the MLSS. The first trial was performed at the IAnT swimming v , and if a steady state or a decrease in $[\text{La-}]$ was observed during the test, further subsequent trials with 2.5% higher velocities were performed until no $[\text{La-}]$ steady state could be maintained. If the first trial resulted in a clearly identifiable increase of the $[\text{La-}]$ and/or the swimmer was not able to complete the 30 min of exercise, further trials were conducted with lower velocities. The v at MLSS was defined as the highest swimming speed at which the $[\text{La-}]$ increased no more than $1 \text{ mmol}\cdot\text{L}^{-1}$ between the 10th and the 30th min (Beneke, 2003), and the corresponding $[\text{La-}]$

value was assumed as the average value of the 10th and 30th min. A 24 h rest was imposed between tests.

Earlobe capillary blood samples were collected: (a) at the incremental test at rest and during the first 30 s after intermediate step, and immediately after and at each 2 min of the recovery from the last step, until the [La-] recovery peak was found; (b) at rest, and at the 10th and 30th min (or voluntary exhaustion) of each bout of the continuous test. The [La-] were assessed through a portable lactate analyser (Lactate Pro, Arkray, Inc., Kyoto, Japan).

The v was set and maintained using a visual underwater pacer (GBK-Pacer, GBK Electronics, Aveiro, Portugal), with a light strip on the bottom of the pool with lights located 2.5 m apart. The swimmers were instructed to keep their head above each visual signal down the pool length, following the flashing lights to maintain the predetermined velocities. Exhaustion and end of the test was defined when the swimmers remained 5 m behind the lights.

The incremental test was performed to determine the v values assessed to each one of the contrasting methods most commonly used for the evaluation of aerobic capacity and $\text{VO}_{2\text{max}}$. All the corresponding values of gas exchange, energetic and heart rate (HR) parameters were determined through interpolation based on a polynomial regression model calculated between the incremental velocities and their corresponding parameters (Neter et al., 1985). This incremental protocol has been previously used to determine maximal ($\text{VO}_{2\text{max}}$) (Fernandes et al., 2006) and submaximal physiological variables (VT) in swimming (Roels et al., 2005).

The IAnT was calculated by mathematical modelling on a fit curve between [La-] and v plotted values (Fernandes et al., 2006). The VT was determined using the v -slope method and its corresponding values of pulmonary ventilation (VE) divided by VO_2 , and then was defined as a disproportional increase of VE (Svedahl & MacIntosh, 2003). The HRT was calculated by the slope of the HR and v curve (Cellini et al., 1986), assuming that the deflection point

corresponded to the v at HRT. The $LT_{3.5}$ was determined by the fixed 3.5 mmol.L⁻¹ value of [La-] and its corresponding v (Heck et al., 1985).

The bioenergetic factors were divided into gas exchange and energetic parameters. $\dot{V}O_2$ and $\dot{V}E$ were measured both during continuous and intermittent exercises by a telemetric portable gas analyser (K4b², Cosmed, Italy), connected to the swimmer by the newest respiratory snorkel and valve system (New AquaTrainer[®], Cosmed, Italy). The equipment presented low hydrodynamic resistance and has been previously validated (Baldari et al., 2013) and used in similar studies (Sousa et al., 2014). The oximeter was calibrated for $\dot{V}E$ with a calibrated syringe and O_2 and CO_2 analysers with standard calibration gases before each test. During all tests, gas exchange values were measured breath-by-breath; subsequently, gas exchange values were smoothed using a three breath moving average and averaged every 5 s (Fernandes et al., 2012). HR was monitored and registered continuously through a monitor system (Polar Vantage NV, Polar electro Oy, Kempele, Finland) and simultaneously transferred through a telemetric signal to the portable oximeter. The HR values were averaged every 5 s.

$\dot{V}O_{2max}$ was considered to be reached according to main physiological criteria : (a) occurrence of a plateau in $\dot{V}O_2$ regarding an increase of v , where $\dot{V}O_2$ does not increase more than 2.1 mL.kg⁻¹.min⁻¹ in the last min of the step; (b) [La-] value higher than 8 mmol.L⁻¹; (c) elevated values of respiratory exchange ratio ($r \geq 1.0$); (d) HR value higher than 90% of theoretical maximum (220-age); and (e) an exhaustive perceived exertion, determined visually and case-by-case.

The energetic parameters studied were the total energy expenditure ($\dot{E}$), obtained by adding the aerobic and anaerobic energy parts. The aerobic energy expenditure was calculated by taking the difference between the exercise and baseline $\dot{V}O_2$, and the anaerobic energy expenditure was obtained by the net [La-] values transformed into O_2 equivalents through the constant value of 2.7 mL O_2 .kg⁻¹.mmol⁻¹. Energy cost (C) was also determined, as the ratio of $\dot{E}$ and its respective v values (Fernandes et al., 2006; Sousa et al., 2014).

Data are presented as mean and standard deviation ($\pm$ SD). Shapiro-Wilk's test was used to examine the normality of the data distribution. The effective hypothesis decomposition was conducted by the Mauchley Sphericity test. When the assumption of sphericity was not attained, Greenhouse-Geisser or the Huynh-Feldt univariate adjusted tests for repeated measures were used. The partial Eta square (η_p^2) was used to measure the effect size, which was defined as small, medium, and large for values of 0.01, 0.06 and 0.14, respectively (Stevens, 2002). The gas exchange ($\dot{V}O_2$ and $\dot{V}E$) and energetic ($\dot{E}$ and C) statistical analysis were performed using multivariate ANOVA. The v and $[La-]$ values were tested using univariate ANOVA. All analyses were conducted for repeated measures, complemented with the Bonferroni correction post-hoc test through data analysis software system STATISTICA, version 12 (StatSoft, 2013).

Furthermore, Passing & Bablok regression analyses (MedCalc Statistical Software version 12.7.2 – MedCalc Software bvba, Ostend, Belgium; <http://www.medcalc.org>; 2013) were performed to compare the MLSS and the other main methods used for the evaluation of aerobic capacity concerning v , $[La-]$, $\dot{V}O_2$, $\dot{V}E$, $\dot{E}$ and C . In addition, regression equations were used to determine systematic differences (Intercept A), proportional differences (Slope B) and the random differences (Residual Standard Deviation). The corresponding 95% confidence intervals (95% CI) to determine the degree of association between the methods was applied. The Pearson's coefficient of determination (R^2) was used. The significance level of $\alpha = 0.05$ was assumed for all comparisons.

Results

The average of v ($1.35 \pm 0.06 \text{ m.s}^{-1}$), $[La-]$ ($6.47 \pm 2.51 \text{ mmol.L}^{-1}$), HR ($189.6 \pm 7.5 \text{ beats.min}^{-1}$), and $\dot{V}O_2$ ($54.9 \pm 6.7 \text{ mL.kg}^{-1}.\text{min}^{-1}$) values corresponding to the $\dot{V}O_{2\text{max}}$ intensity were higher compared to MLSS, IAnT, VT and HRT ($p < 0.05$). However, v , HR and $\dot{V}O_2$ values were similar when $\dot{V}O_{2\text{max}}$ was compared to LT_{3.5} ($p < 0.05$). The values of v and bioenergetic factors obtained during MLSS,

IAnt, VT, HRT and LT_{3.5} are presented in Table 4.1. The average values of all parameters obtained for MLSS, IAnt, VT and HRT were similar. On the other hand, the LT_{3.5} compared with all other methods showed higher values of v and all bioenergetic parameters.

Table 4.1. Mean (SD) values of swimming velocity (v), blood lactate concentration ([La-]), gas exchange and energetic parameters at the maximal lactate steady state (MLSS), individual anaerobic threshold (IAnt), ventilatory threshold (VT), heart rate threshold (HRT) and lactate threshold fixed in 3.5 mmol.L⁻¹ (LT_{3.5}) (N=10).

	MLSS	IAnt	VT	HRT	LT _{3.5}
v (m.s ⁻¹)	1.24 (0.07)	1.24 (0.06)	1.23 (0.05)	1.24 (0.06)	1.32 (0.06) ^{1,2,3,4}
% vVO _{2max} (%)	91.8 (4.6)	91.5 (3.7)	90.7 (2.7)	91.6 (2.6)	97.7 (3.2) ^{1,2,3,4}
[La-] (mmol.L ⁻¹)	1.90 (0.77)	1.49 (0.41)	1.55 (0.54)	1.81 (0.71)	3.50 (0.00) ^{1,2,3,4}
VO ₂ (mL.kg ⁻¹ .min ⁻¹)	46.4 (4.9)	45.9 (5.1)	45.1 (5.3)	45.9 (4.5)	52.3 (6.3) ^{1,2,3,4}
% VO _{2max} (%)	84.7 (3.8)	83.8 (5.6)	82.3 (4.9)	83.9 (4.2)	95.4 (5.0) ^{1,2,3,4}
VE (L.min ⁻¹)	69.7 (7.8)	66.2 (8.5)	64.9 (8.1)	67.1 (9.9)	83.0 (9.2) ^{1,2,3,4}
HR (beats.min ⁻¹)	173.6 (9.7)	172.3 (7.5)	170.1 (8.3)	172.1 (8.0)	185.1 (9.1) ^{1,2,3,4}
Ė (mL.kg ⁻¹ .min ⁻¹)	40.3 (5.1)	40.0 (4.6)	39.1 (4.9)	40.1 (4.1)	47.9 (5.5) ^{1,2,3,4}
%Ė VO _{2max} (%)	79.3 (5.9)	78.8 (7.2)	76.9 (6.3)	78.9 (4.7)	94.3 (6.9) ^{1,2,3,4}
C (kJ.m ⁻¹)	0.69 (0.06)	0.69 (0.06)	0.68 (0.06)	0.69 (0.06)	0.76 (0.05) ^{1,2,3,4}
%C VO _{2max} (%)	85.8 (5.8)	85.4 (5.5)	84.2 (5.7)	85.5 (3.9)	94.8 (4.6) ^{1,2,3,4}

v: swimming velocity; % vVO_{2max}: velocity expressed as a percentage of maximal oxygen uptake; [La-]: blood lactate concentration; VO₂: oxygen uptake; % VO_{2max}: oxygen uptake expressed as a percentage of maximal oxygen uptake; VE: pulmonary ventilation; HR: heart rate; Ė: total energy expenditure; %Ė VO_{2max}: total energy expenditure expressed as percentage of maximal oxygen uptake; C: energy cost; %C VO_{2max}: energy cost expressed as a percentage of maximal oxygen uptake.

^{1,2,3,4} Statistically different from MLSS, IAnt, VT and HRT, respectively ($p < 0.05$).

The Passing & Bablok regression analysis and R^2 values for v and bioenergetic factors obtained for MLSS vs IAnT, VT, HRT and $LT_{3.5}$, and the Slope B, Intercept A and Residual Standard Deviation values with their corresponding 95 % confidence intervals (95% CI) are presented in Table 4.2.

Table 4.2. Agreement values of swimming velocity (v) and bioenergetic factors obtained between maximal lactate steady state (MLSS) and individual anaerobic threshold (IAnT), ventilatory threshold (VT), heart rate threshold (HRT) and lactate threshold fixed in 3.5 mmol.L⁻¹ (LT_{3.5}). Pearson's Coefficient of determination (R^2) and regression equation variables are presented (N=10) ($p < 0.05$).

MLSS vs IAnT				
Parameters	R^2	Slope B	Intercept A	Residual Standard Deviation
v (m.s ⁻¹)	0.520*	0.752 (0.393 to 1.621)	0.301 (-0.781 to 0.747)	0.035 (-0.069 to 0.069)
[La-] (mmol.L ⁻¹)	0.166	0.316 (-0.035 to 1.151)	0.912 (-0.589 to 1.482)	0.388 (-0.760 to 0.760)
VO ₂ (mL.kg ⁻¹ .min ⁻¹)	0.787*	1.142 (0.695 to 1.501)	-6.192 (-22.889 to 13.564)	1.925 (-3.774 to 3.774)
VE (L.min ⁻¹)	0.491*	0.944 (0.245 to 1.523)	0.057 (-41.572 to 51.579)	4.792 (-9.392 to 9.392)
HR (bpm)	0.532*	0.679 (0.256 to 1.438)	54.323 (-78.875 to 128.247)	4.611 (-9.037 to 9.037)
$\dot{E}$ (mL.kg ⁻¹ .min ⁻¹)	0.802*	0.901 (0.492 to 1.253)	4.089 (-9.543 to 19.750)	1.704 (-3.340 to 3.340)
C (kJ.m ⁻¹)	0.592*	0.677 (0.425 to 1.736)	0.212 (-0.521 to 0.378)	0.032 (-0.063 to 0.063)
MLSS vs VT				
Parameters	R^2	Slope B	Intercept A	Residual Standard Deviation
v (m.s ⁻¹)	0.734*	0.630 (0.358 to 1.026)	0.439 (-0.049 to 0.780)	0.022 (-0.044 to 0.044)
[La-] (mmol.L ⁻¹)	0.080	0.754 (-0.040 to 1.520)	0.342 (-1.016 to 1.452)	0.601 (-1.177 to 1.177)
VO ₂ (mL.kg ⁻¹ .min ⁻¹)	0.736*	1.148 (0.478 to 1.573)	-8.189 (-27.611 to 22.629)	2.041 (-4.000 to 4.000)
VE (L.min ⁻¹)	0.354	0.575 (0.062 to 1.098)	27.160 (-9.546 to 62.481)	6.382 (-12.509 to 12.509)
HR (bpm)	0.555*	0.917 (0.436 to 1.876)	11.254 (-152.552 to 95.282)	4.830 (-9.467 to 9.467)
$\dot{E}$ (mL.kg ⁻¹ .min ⁻¹)	0.761*	0.777 (0.419 to 1.297)	7.107 (-12.233 to 22.303)	2.106 (-4.127 to 4.127)
C (kJ.m ⁻¹)	0.494*	0.924 (0.381 to 1.884)	0.017 (-0.649 to 0.409)	0.039 (-0.076 to 0.076)
MLSS vs HRT				
Parameters	R^2	Slope B	Intercept A	Residual Standard Deviation
v (m.s ⁻¹)	0.304	0.667 (0.000 to 1.567)	0.405 (-0.732 to 1.265)	0.044 (-0.087 to 0.087)
[La-] (mmol.L ⁻¹)	0.225	0.531 (0.147 to 2.624)	0.628 (-2.771 to 1.303)	0.613 (-1.202 to 1.202)
VO ₂ (mL.kg ⁻¹ .min ⁻¹)	0.857*	0.916 (0.636 to 1.250)	3.303 (-11.411 to 16.164)	1.353 (-2.653 to 2.653)
VE (L.min ⁻¹)	0.405*	1.239 (0.652 to 3.549)	-21.540 (-171.820 to 21.213)	5.805 (-11.377 to 11.377)
HR (bpm)	0.400*	0.726 (0.209 to 1.544)	45.217 (-97.874 to 136.757)	5.659 (-11.091 to 11.091)
$\dot{E}$ (mL.kg ⁻¹ .min ⁻¹)	0.780*	0.833 (0.593 to 1.091)	6.496 (-3.446 to 15.470)	1.644 (-3.222 to 3.222)
C (kJ.m ⁻¹)	0.732*	0.927 (0.577 to 1.952)	0.056 (-0.679 to 0.280)	0.024 (-0.048 to 0.048)
MLSS vs LT _{3.5}				
Parameters	R^2	Slope B	Intercept A	Residual Standard Deviation
v (m.s ⁻¹)	0.602*	0.928 (0.472 to 1.915)	0.171 (-1.065 to 0.729)	0.034 (-0.066 to 0.066)
[La-] (mmol.L ⁻¹)	-----	-----	-----	-----
VO ₂ (mL.kg ⁻¹ .min ⁻¹)	0.672*	1.007 (0.530 to 1.759)	4.333 (-28.070 to 26.612)	2.886 (-5.656 to 5.656)
VE (L.min ⁻¹)	0.036	0.925 (-0.209 to 5.367)	17.117 (-292.037 to 100.706)	8.320 (-16.307 to 16.307)
HR (bpm)	0.533*	0.831 (0.266 to 1.578)	39.388 (-89.579 to 137.637)	5.333 (-10.452 to 10.452)
$\dot{E}$ (mL.kg ⁻¹ .min ⁻¹)	0.506*	0.749 (0.371 to 1.774)	17.588 (-22.999 to 31.793)	3.260 (-6.390 to 6.390)
C (kJ.m ⁻¹)	0.353	0.785 (0.204 to 2.640)	0.224 (-1.085 to 0.614)	0.039 (-0.076 to 0.076)

Regarding R^2 values, the v values obtained for MLSS vs IAnT ($R^2 = 0.520$), VT ($R^2 = 0.734$) and $LT_{3.5}$ ($R^2 = 0.602$) were highly correlated, but poorly correlated for MLSS vs HRT ($R^2 = 0.225$). Meanwhile, $[La^-]$ values were poorly correlated between MLSS and the remaining methods ($R^2 < 0.225$). Highly correlated $\dot{V}O_2$ ($R^2 > 0.672$), HR ($R^2 > 0.400$) and $\dot{E}$ values ($R^2 > 0.506$) were observed for all comparisons between the methods ($p < 0.05$). Also, highly correlated $\dot{V}CO_2$ and $\dot{V}E$ values were observed between MLSS vs IAnT ($R^2 > 0.401$) and HRT ($R^2 > 0.405$). Finally, C values were highly correlated between MLSS vs IAnT ($R^2 = 0.592$), VT ($R^2 = 0.494$) and HRT ($R^2 = 0.732$). The Passing & Bablok regression analysis of the v and $\dot{V}O_2$ values obtained during MLSS vs IAnT, VT, HRT, and $LT_{3.5}$ are depicted in Figure 4.1 and Figure 4.2, respectively.

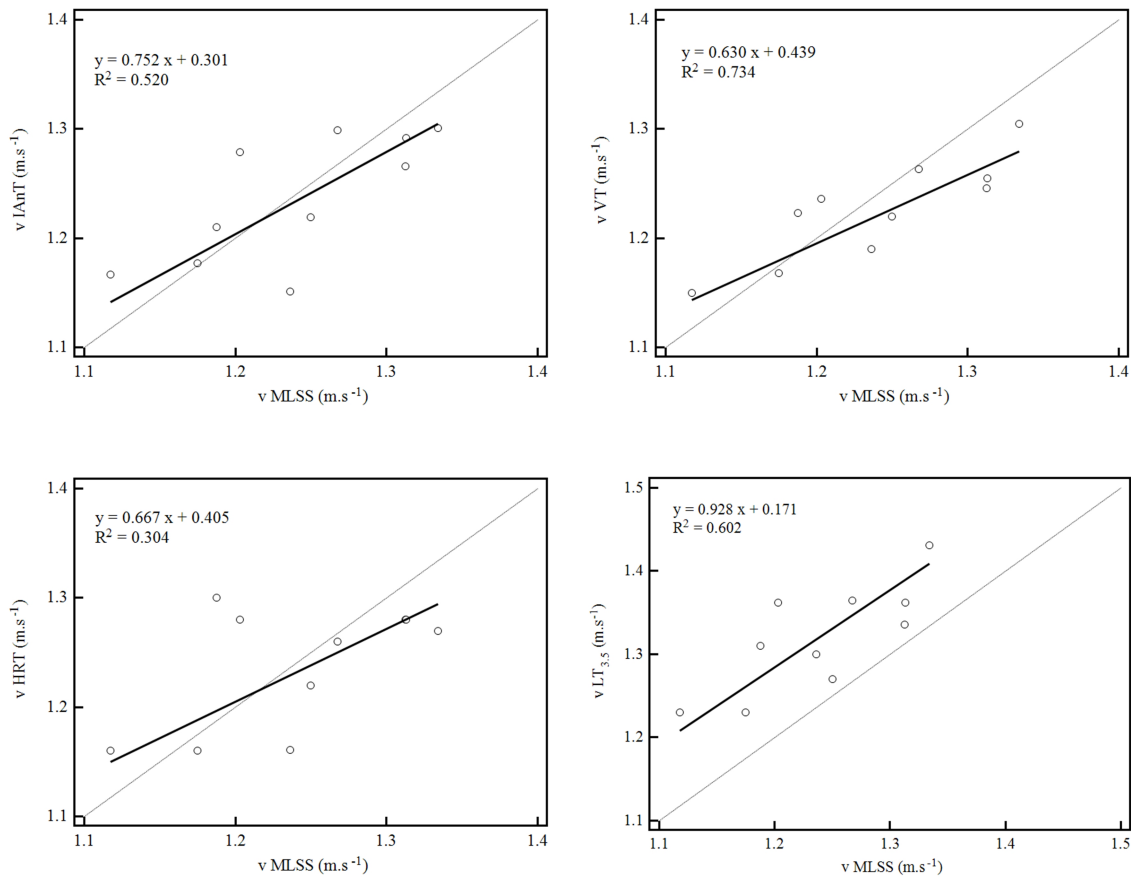


Figure 4.1. Passing & Bablok regression analysis of the swimming velocity (v) values obtained during maximal lactate steady state (MLSS) and individual anaerobic threshold (IAnT) (upper left panel), ventilatory threshold (VT) (upper right panel), heart rate threshold (HRT) (lower left panel), and lactate threshold fixed in 3.5 mmol.L⁻¹ ($LT_{3.5}$) (lower right panel) (N=10).

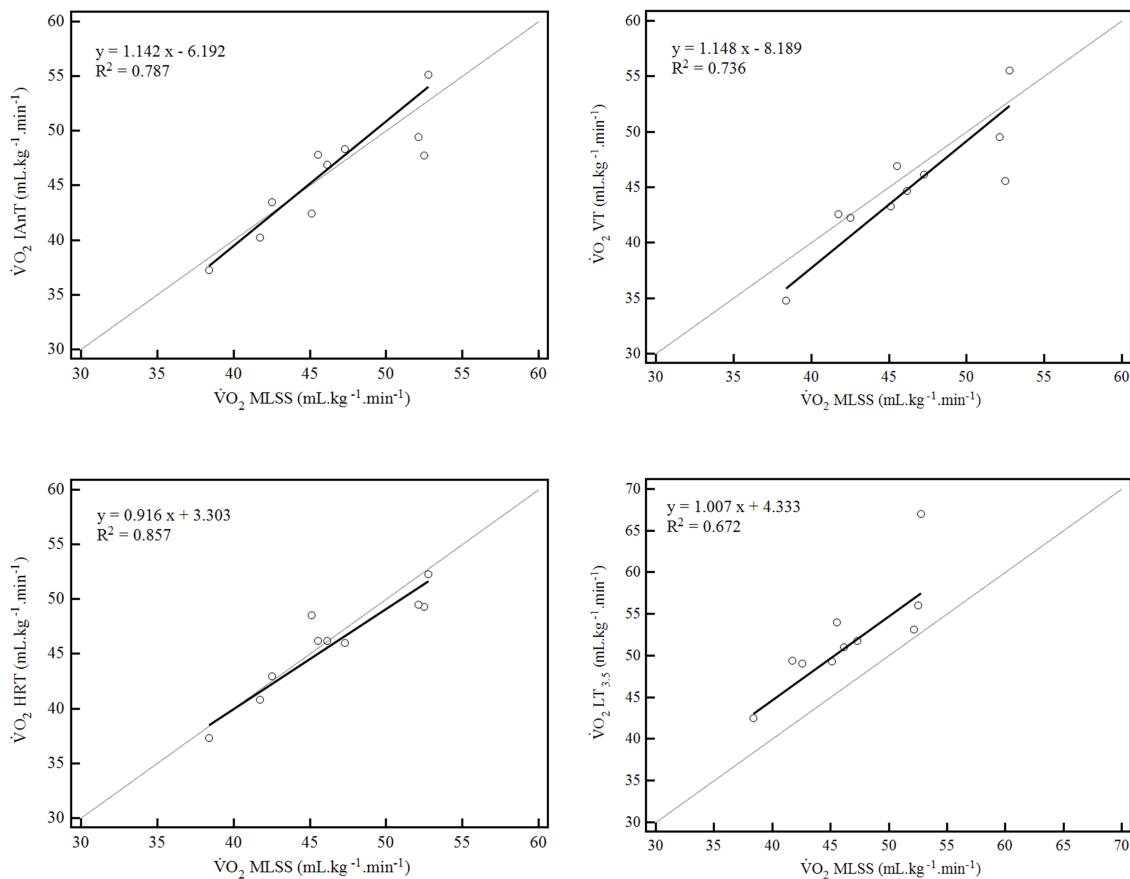


Figure 4.2. Passing & Bablok regression analysis of the oxygen uptake ($\dot{V}O_2$) values obtained during maximal lactate steady state (MLSS) and individual anaerobic threshold (IAnT) (upper left panel), ventilatory threshold (VT) (upper right panel), heart rate threshold (HRT) (lower left panel), and lactate threshold fixed in 3.5 mmol.L⁻¹ (LT_{3.5}) (lower right panel) (N=10).

Discussion

Up until now, scientists and coaches have extensively searched for reliable and feasible evaluation tests to control and prescribe sports training load. In sports science, the MLSS is considered the gold-standard method to determine the maximal intensity where a physiological steady state is found, and it has been applied in several sports such as cycling, running, rowing and swimming (Beneke & von Duvillard, 1996; Beneke, 2003; Figueiredo et al., 2014; Pelarigo et al., 2011). On the other hand, the MLSS determination is time consuming and difficult when compared to the other methods applied for the evaluation of aerobic capacity.

This is the first study that compared bioenergetic factors obtained at MLSS to the remaining mostly used methods applied for the evaluation of aerobic capacity. The main findings were: (a) the MLSS presented similar values compared to the IAnT, VT and HRT concerning v and bioenergetic factors; (b) the $LT_{3.5}$ provided significantly higher values than all other methods concerning v and the bioenergetic factors studied, and; (c) highly correlated values were obtained through regression analysis between MLSS vs IAnT, VT and HRT. Thus, the hypothesis that IAnT and VT could likely be better predictors of the MLSS when compared to the HRT and $LT_{3.5}$ was partially confirmed, since the hypothesis only differed regarding v and $[La^-]$ values of the HRT that showed a similar mean values compared to MLSS, but poorly correlated.

Once v is considered, IAnT, VT and HRT tests showed similar values when compared to the gold-standard method (MLSS). However, only IAnT and VT presented high agreement in the regression analysis. In accordance with our findings, similar results have been found in swimming between MLSS ($1.09 \text{ m}\cdot\text{s}^{-1}$) and IAnT ($1.09 \text{ m}\cdot\text{s}^{-1}$) (Fernandes et al., 2011), and HRT and AnT (Cellini et al., 1986); in cycling between VT and MLSS (Van Schuylenbergh et al., 2004), and AnT and MLSS (Aunola & Rusko, 1992); and in running between MLSS and AnT (Smith & Jones, 2001). Contrary, Beneke (1995) found significant differences between IAnT and MLSS in rowing ergometer. Although the HRT and MLSS mean v showed to be similar in the present study, the methods were poorly correlated ($R^2 = 0.304$). The findings are in agreement with literature, which point out that the HRT is not reliable and valid to precisely predict the MLSS (Jones & Doust, 1997; Van Schuylenbergh et al., 2004).

The VT v showed similar values and was highly correlated when compared to MLSS, IAnT and HRT. Accordingly, previous studies found similar VT and MLSS/IAnT values in cycling (Van Schuylenbergh et al., 2004; Wasserman et al., 1973). Moreover, Leti et al. (2012) observed similar values between VT and MLSS in running. Contrary, Dekerle et al. (2003) and Laplaud et al. (2006) observed a higher v at VT compared with MLSS in male cyclists. However, there are no literature reporting significant differences between IAnT/VT and

MLSS in swimming and also the relationship of v at VT and MLSS/IAnt in this particular mode of locomotion.

On the other hand, the present study verified that the v at $LT_{3.5}$ was significantly higher (~6.5%) when compared to MLSS, IAnt, VT and HRT. Moreover, the $[La-]$ values found from those methods were lower than 3.5 mmol.L^{-1} . These results are in accordance with swimming related studies, which have reported lower $[La-]$ and v obtained during the MLSS and/or IAnt compared to the fixed values of $[La-]$ (Fernandes et al., 2011; Pyne et al., 2001). Furthermore, similar results have been found in rowing (Beneke, 1995; Beneke et al., 2001) and running (Figueira et al., 2008). Meanwhile, MLSS and $LT_{3.5}$ were highly correlated ($R^2 = 0.602$), showing that $LT_{3.5}$ has some potential for qualitative evaluation of training progresses, but not for the training intensity prescription.

Our swimmers showed lower $[La-]$ values at MLSS ($1.90 \pm 0.77 \text{ mmol.L}^{-1}$) when compared with the literature, that showed higher $[La-]$ ($2.8 - 3.3 \text{ mmol.L}^{-1}$) in swimming (Dekerle et al., 2003; Fernandes et al., 2011; Figueiredo et al., 2014; Pelarigo et al., 2011), and in others sports ($2 - 8 \text{ mmol.L}^{-1}$) (Beneke et al., 2000; Figueira et al., 2008). Moreover, the $[La-]$ values obtained at IAnt, VT and HRT presented no differences when compared to MLSS (1.49, 1.55 and 1.81 mmol.L^{-1} , respectively). These findings may be explained by the fact that almost all subjects recruited for previous studies were male and/or non-long-distance trained swimmers. Indeed, literature has shown lower $[La-]$ values for female compared the male subjects in endurance exercise (Crewther et al., 2006; Greco et al., 2007) that might be explained by lower lean muscle mass (Crewther et al., 2006) and testosterone levels (Deschenes & Kraemer, 2002), suggesting a different metabolic balance between carbohydrates and fat throughout prolonged exercises (Greco et al., 2007; Tarnopolsky et al., 1990). Thus, endurance athletes have shown a high adaptation to sustain the highest prevalence of aerobic metabolism during the exertion in physiological state steady, as expressed by the typical low $[La-]$ values observed in the swimmers examined in this study.

In swimming, gas exchange response is considered a complex procedure for examining acute physiological responses during exercise. Most of previous studies examined the direct gas exchange parameters during short and middle-distance swimming events. Although some studies showed gas exchange response based on recovery period measurements during the MLSS and long-distance events (Baron et al., 2005; Dekerle et al., 2005a), no previous study seems to exist that examines gas exchange response directly measured breath-by-breath through gas analysers during prolonged continuous swimming exercise. Therefore, this is the first study examining exchange gas parameters directly and breath-by-breath measured during prolonged distances in swimming, and also to compare their responses with those associated with the most common indirect methods applied for the evaluation of aerobic capacity.

VO_2 , in the present study, showed similar values when MLSS, IAnT, VT and HRT were compared, but $\text{LT}_{3.5}$ showed higher values compared to the previous mentioned tests; nevertheless, all methods were highly correlated to the MLSS for VO_2 values. Moreover, no differences were found between MLSS, IAnT, VT and HRT in the $\% \text{VO}_{2\text{max}}$ values ($\sim 85\% \text{VO}_{2\text{max}}$). Dekerle et al. (2005a) also found mean values of $\sim 86\% \text{VO}_{2\text{max}}$ in well-trained swimmers, despite the measurements assessed based on recovery period. However, previous studies showed lower $\% \text{VO}_{2\text{max}}$ values (70-75%) for the MLSS compared to our study (Baron et al., 2003; Baron et al., 2008; Beneke, 2003), probably justified due to the specific physiological adaptations that occur in endurance athletes, who typically experience higher $\% \text{VO}_{2\text{max}}$ in a maximal steady state physiologic condition. Meanwhile, $\text{LT}_{3.5}$ showed higher $\% \text{VO}_{2\text{max}}$ values ($\sim 95\%$); values of this magnitude are normally associated with the maximal efforts of 800 and 1500m events, where $[\text{La-}]$ are normally higher than MLSS/IAnT intensity (Sousa et al., 2014).

During exercise, VE increases as much by the increase of tidal volume as by the breathing rate. Indeed, VE values during maximal efforts may exceed more than 20 times that of rest levels (Guenette & Sheel, 2007). In the present study, VE values were similar between MLSS, IAnT, VT and HRT, but these methods showed lower values compared to the $\text{LT}_{3.5}$. Moreover, only IAnT and HRT

were highly correlated when compared to the MLSS. The $\dot{V}E$ values in the present study were lower at MLSS and $\dot{V}O_{2max}$ intensities (~ 70 and $92 \text{ L}\cdot\text{min}^{-1}$, respectively) compared with those verified by Baron et al. (2008), who showed higher $\dot{V}E$ values at MLSS and $\dot{V}O_{2max}$ (~ 75 and $121 \text{ L}\cdot\text{min}^{-1}$, respectively). The lower $\dot{V}E$ values in the present study may be due to significant sex differences regarding the expiratory exercise physiology, since most of previously studied subjects were male, despite that still may be explained by the effect of exercise mode (swimming vs cycling). Female athletes typically have lower expiratory flow rates and smaller lung volumes relative to male athletes, even when the measured values are adjusted by height (Sheel et al., 2004). These specific differences in the respiratory structure may likely influence the gas exchange and the ventilatory response during exercise (Guenette & Sheel, 2007), explaining the lower $\dot{V}E$ values found in our swimmers.

Once the maximal cardiac output is considered a limiting factor for $\dot{V}O_{2max}$, we assessed one of the components that determine this parameter, namely the maximal HR attained at $\dot{V}O_{2max}$ (HR_{max}). The HR_{max} showed higher values when compared to the HR values of MLSS, IAnT, VT and HRT, even though the MLSS represented approximately 92% $\dot{V}O_{2max}$. The HR at MLSS was lower than HR_{max} (~ 174 and $190 \text{ beats}\cdot\text{min}^{-1}$, respectively), which is in accordance with Dekerle et al. (2005a), who also showed lower HR values at MLSS than HR_{max} (~ 178 and $184 \text{ beats}\cdot\text{min}^{-1}$, respectively). Otherwise, the HR_{max} was not different from HR values at $LT_{3.5}$. Furthermore, the HR values were similar between all methods, except for $LT_{3.5}$. On the other hand, all methods were highly correlated to the MLSS following regression analysis on HR.

The swimming economy is considered a major swimming performance determinant (di Prampero et al., 2011), and it was addressed in the present study through the C, the ratio of total energy expenditure ($\dot{E}$) and v. The results in the present study showed similar values between MLSS, IAnT, VT and HRT ($\sim 0.69 \text{ kJ}\cdot\text{m}^{-1}$), but the C for $LT_{3.5}$ was higher ($\sim 0.76 \text{ kJ}\cdot\text{m}^{-1}$). As previously reported following the regression analysis, a similar pattern was found with high agreement ($R^2 = 0.494 - 0.732$) for IAnT, VT and HRT compared to the MLSS regarding C. The C values at $v\dot{V}O_{2max}$ in the present study were higher ($0.81 \pm$

0.06 kJ.m⁻¹) than for the others tests, except for LT_{3.5}. These findings are in accordance with literature for similar submaximal intensities (Zamparo et al., 2005a) and maximal aerobic power intensities (Chatard et al., 1991). Moreover, Chatard et al. (1991) found similar C values (~0.69 kJ.m⁻¹) at intensities around 85% vVO_{2max} in long-distance swimmers, which is in very close agreement with the present findings for MLSS (~0.69 kJ.m⁻¹). However, it is important to highlight that the swimmers of the present study performed the MLSS at a much higher (~92%) %vVO_{2max} than those referred by Chatard et al. (1991) with a similar C. This particular finding may be likely due to the different specific aerobic adaptations to endurance training, being our swimmers more economical at velocities near the vVO_{2max}. Moreover, those specific adaptations seem to be paramount in training evaluation/prescriptions, allowing to shift the lactate/velocity curve to the right, and making possible for swimmers to keep higher velocities in a physiological steady state at intensities near the vVO_{2max}. Furthermore, swimming performance is defined as the result of the conversion of the swimmers metabolic power to mechanical power with a given energetic efficiency. In accordance, the rate of the $\dot{E}$ increases with the cube of the swimming v (Toussaint & Hollander, 1994). In the present study, the $\dot{E}$ values were similar between MLSS, IAnT, VT and HRT, where corresponding v values were also similar. However, those methods showed lower values compared with LT_{3.5} for both parameters. The v and $\dot{E}$ values in this study (~6 and 16%, respectively) observed between MLSS and LT_{3.5} did not present a cubic relationship as previously proposed in literature. Those differences on v and mechanical power might contribute to the development of an excessive training load under priming over-reaching and/or overtraining caused by successive intense training sessions over prolonged periods, and/or interfere on the biomechanical adjustments used by the swimmers at exercise intensities above MLSS (Pelarigo et al., 2011).

Conclusions

The results suggest that compared to $LT_{3.5}$, v and bioenergetic responses at IAnT, VT and HRT methods are better predictors of the intensity corresponding to the MLSS for the evaluation of aerobic capacity. However, it is important to note that swimming velocity at HRT was poorly correlated with MLSS, which requires caution applying this method for swimming intensity training prescription. Despite the gold-standard method (MLSS) is determined through a continuous exercise mode and the other methods are assessed through intermittent exercise mode, this difference did not compromise the similarity of the swimming v and bioenergetic responses provided by the methods.

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Chapter 5

Are different methods for the aerobic capacity evaluation providing coherent biomechanical parameters?

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Abstract

Introduction: Monitoring the swimming training process requires reliable methods for the aerobic capacity evaluation. There are different methods available in literature, eventually providing similar feedback regarding swimming velocity and blood [La-]. Nevertheless, a given swimming velocity can be achieved through different stroke rate and stroke length relationship. Indeed, different adjustments in the biomechanical parameters can interfere with swimming efficiency, which is a major determining factor of swimming performance. Thus, for training prescription, it is important to determine the best individual swimming velocity for the aerobic capacity potentiation, but also the biomechanical determining factors characteristic of that particular intensity. Therefore, this study aimed to compare swimming biomechanical parameters and velocity (v) obtained by the gold-standard method, i.e. the maximal lactate steady state test (MLSS), and those obtained from the main and most common methods employed to evaluate aerobic capacity in swimming training.

Methods: Five elite female swimmers (17.2 ± 2.3 yrs., 1.68 ± 0.04 m, 61.4 ± 5.0 kg) performed in different days: 1) an intermittent incremental protocol until voluntary exhaustion to determine the v associated to the individual lactate threshold (IAnT), ventilatory threshold (VT), heart rate threshold (HRT), lactate threshold of fixed 3.5 mmol.L^{-1} (LT_{3.5}) and maximal oxygen uptake ($\text{VO}_{2\text{max}}$) (Fernandes et al., 2006); 2) two to three 30min sub-maximal continuous tests to determine the v associated to the MLSS (Pelarigo et al., 2011). Swimming velocity, blood lactate concentration ([La-]), stroke rate (SR), stroke length, (SL) and stroke index (SI) were controlled during all the tests. ANOVA repeated measures and regression analysis were performed to test differences between the methods ($p < 0.05$). **Results:** The findings revealed that v at the LT_{3.5} test was higher ($1.32 \pm 0.08 \text{ m.s}^{-1}$) compared to MLSS, IAnT, VT and HRT (1.24 ± 0.09 , 1.24 ± 0.06 , 1.23 ± 0.06 and $1.25 \pm 0.06 \text{ m.s}^{-1}$, respectively). SR was higher during the LT_{3.5} ($35.8 \pm 2.2 \text{ cycles.min}^{-1}$) compared to IAnT, VT and HRT (32.2 ± 1.5 , 31.8 ± 1.0 and $32.3 \pm 1.6 \text{ cycles.min}^{-1}$, respectively). However, SR was similar compared to MLSS ($34.1 \pm 3.0 \text{ cycles.min}^{-1}$). SL at the MLSS ($2.18 \pm 0.10 \text{ m.cycle}^{-1}$) and LT_{3.5} ($2.22 \pm 0.11 \text{ m.cycle}^{-1}$) were lower compared to

IAnT, VT and HRT (2.31 ± 0.09 , 2.32 ± 0.08 and 2.31 ± 0.09 m.cycle⁻¹, respectively). SI was lower during the MLSS (2.71 ± 0.23) compared to IAnT, VT, HRT and LT_{3.5} (2.87 ± 0.21 , 2.86 ± 0.21 , 2.89 ± 0.20 and 2.93 ± 0.27 , respectively). The percentage of SR and SL at MLSS regarding to the VO_{2max} were 89.4 ± 7.0 and $103.2 \pm 8.1\%$, respectively. Furthermore, high correlation values were obtained between MLSS/IAnT and MLSS/VT ($p < 0.05$). **Conclusions:** These findings suggest that IAnT and VT may be better predictors of the gold-standard method for the aerobic capacity evaluation compared to LT_{3.5} and HRT. **Acknowledgments:** This research was supported by grants from the Capes Foundation, Ministry of Education of Brazil (BEX: 0536/10-5).

Key words: biomechanical parameters, aerobic capacity evaluation, swimming training.

Introduction

To attain the best performance in swimming, technique is as important as the physiological support of exercise. Generally, the increase of v is obtained by an increase of propelling efficiency and/or by a decrease of drag forces (Toussaint & Hollander, 1994). Therefore, the level of swim technique can be expressed by the capacity to reduce hydrodynamic drag (Hollander et al., 1986; Kolmogorov & Duplishcheva, 1992) and to enhance the propulsive force (Rouard et al., 1996; Schleihau et al., 1988).

The most important methods, i.e. reliable and useful methods, to evaluate and prescribe the swim aerobic training intensity have been used by researchers and coaches, and are commonly considered as methods of physiologic evaluation. However, the swim performance at a given physiologic intensity is not only highly dependent on the physiological aspects, but is also related to the biomechanical parameters such as the combination of stroke rate (SR) and stroke length (SL) for a given intensity or velocity (Craig & Pendergast, 1979).

Thereby, the purpose of the study was to compare the biomechanical parameters and the v obtained by the gold-standard method, i.e. the maximal lactate steady state test (MLSS), to the other main methods employed to evaluate aerobic capacity in swimming.

Methods

Five elite female endurance swimmers (17.2 ± 2.3 yrs., 1.68 ± 0.04 m, 61.4 ± 5.0 kg and $15.3 \pm 3.1\%$ body fat mass) volunteered for this study, and signed an informed consent before participation. The swimmers had at least seven years of experience as competitive swimmers and a mean performance over a 400 m freestyle swim of $87.9 \pm 3.1\%$ of the short course world record. Tests were performed in a 25 m indoor swimming pool. The swimmers used in-water starts and open turns without underwater gliding. All the tests were conducted in three to four days, at the same time of the day (± 2 h) to minimise the effect of circadian variation during the tests (Atkinson & Reilly, 1996). The swimmers

were advised to avoid high intense training during the 24 h before experimental sessions. A 1000 m warm-up at moderate aerobic intensity was performed.

Swimmers performed a front crawl intermittent incremental swimming protocol ($n \times 200$ m, increments of $0.05 \text{ m}\cdot\text{s}^{-1}$ and 30 s rest intervals between each step) until voluntary exhaustion (Cardoso et al., 2003; Fernandes et al., 2006). Subsequently, they performed two to three 30 min submaximal constant tests at imposed paces for the assessment of swimming v associated to the MLSS (Pelarigo et al., 2011). The MLSS v was defined as the highest velocity at which the [La-] did not increase more than $1 \text{ mmol}\cdot\text{L}^{-1}$ between the 10th and 30th swim minute.

Earlobe capillary blood samples were collected: 1) at rest, at the end of each intermediate step of the incremental test during the 30 s interval, and immediately after and at each 2 min of recovery the last step, until the [La-] recovery peak was found; 2) at rest, at the 10th and 30th min (or voluntary exhaustion) of each continuous swimming test to assess [La-]. The corresponding [La-] was calculated as the average of the two [La-] values obtained at the 10th and the 30th minutes (Heck et al., 1985). Capillary [La-] was assessed through a portable lactate analyzer (Lactate Pro, Arkray, Inc.).

The control of swimming v was performed using a visual underwater pacer on the bottom of the pool (GBK-Pacer, GBK Electronics, Aveiro, Portugal) to control the predetermined imposed v . It was considered that exhaustion was reached, and also the end of the test, when the swimmers remained 5 m behind the light, incapable to follow the prescribed pace.

The incremental test was performed to determine the v values prescribed by the main methods commonly used for the evaluation of aerobic capacity and maximal oxygen uptake ($\text{VO}_{2\text{max}}$). Consequently, all the corresponding values of biomechanical parameters were determined through interpolation based on a polynomial regression model calculated between the incremental velocities and their corresponding parameters (Neter et al., 1985).

The IAnT was calculated through the mathematical modelling method proposed by (Machado et al., 2006). The $LT_{3.5}$ was determined through the fixed 3.5mmol.L^{-1} value of $[La^-]$ and its corresponding v (Heck et al., 1985). The VT was determined using the v slope method and its respective values of pulmonary ventilation ($\dot{V}E$) divided by the oxygen uptake ($\dot{V}E.\dot{V}O_2^{-1}$), defining a disproportional increase of ventilation concerning the increase at speed of locomotion during an incremental exercise test (Svedahl & MacIntosh, 2003). The HRT was calculated through the curve slope method calculated between v and heart rate (Cellini et al., 1986), assuming that the inflection point of the curve corresponds to the HRTv.

The biomechanical parameters were measured by an overwater video camera operating at a frequency of 50 Hz, allowing to analyze two stroke cycles in the middle of the pool. The SR was determined by the number of cycles per unit of time (cycles.min^{-1}), the SL (m.cycle^{-1}) by the ratio of v (m.s^{-1}) and the SR, and the SI was the product of v and SL. The biomechanical parameters were assessed in each 50 m of each intensity of the incremental test, and averaged for the entire step. The MLSS test was split into seven time moments corresponding to the 4th min, 25, 33, 50, 66, 75, and 100% of the total MLSS duration; biomechanical parameters were assessed during the last 1 min of each test phase to calculate the mean. The mean values of all test phases were obtained and assumed as the parameter's values.

Data are presented as mean ($\pm SD$) and their corresponding 95% confidence intervals ([95%CI]). All the statistical assumptions were checked before the analysis. The one-way ANOVA for repeated measures was conducted to compare the swimming v and biomechanical parameters between aerobic capacity assessment methods, complemented with Bonferroni correction and post-hoc test. The partial Eta square (η_p^2) was used to measure the effect size, in which was defined as small, medium and large for values of 0.01, 0.06 and 0.14, respectively (Stevens, 2002). The regression analysis was performed using Passing & Bablok regression (MedCalc Statistical Software, Belgium) to compare the MLSS with other methods regarding the v and biomechanical

parameters, and their corresponding 95% confidence intervals (95% CI) to determine the degree of association between the methods. The Pearson's coefficient of determination (R^2) was used. It was accepted a 5% significance level ($p < 0.05$).

Results

Results showed close relationship (high R^2 values) and non-statistical significant differences between the v values obtained for the critical intensity to aerobic capacity training considering MLSS, IAnT, VT and HRT assessment methods. The $LT_{3.5}v$ was higher compared to all other methods ($F_{4,16} = 7.106$, $p = 0.002$, $n_p^2 = 0.640$). The SR values were similar comparing the MLSS to the other methods. Contrary, the $LT_{3.5}$ was higher than IAnT, VT and HRT values ($F_{4,16} = 8.069$, $p = 0.001$, $n_p^2 = 0.669$). The SL values were similar comparing the MLSS to the $LT_{3.5}$; however, these methods showed lower values compared to IAnT, VT and HRT ($F_{4,16} = 10.020$, $p = 0.000$, $n_p^2 = 0.715$). The SI at MLSS was lower comparing to the corresponding values obtained by the other methods ($F_{4,16} = 8.122$, $p = 0.001$, $n_p^2 = 0.670$).

The percentage of SR values at maximal oxygen uptake ($\%SRVO_{2max}$), was similar among the MLSS, IAnT, VT and HRT. On the other hand, the corresponding value obtained for $LT_{3.5}$ was higher than IAnT, VT and HRT values ($F_{4,16} = 8.693$, $p = 0.001$, $n_p^2 = 0.685$). The percentage of SL values at maximal oxygen uptake ($\%SLVO_{2max}$) showed similar values between MLSS and $LT_{3.5}$, whereas these methods showed lower $\%SLVO_{2max}$ compared to IAnT, VT and HRT corresponding values ($F_{4,16} = 9.300$, $p = 0.000$, $n_p^2 = 0.699$) (Table 5.1).

Table 5.1. The velocity and biomechanical parameters compared between the main methods for the aerobic capacity evaluation in swimming (N=5).

	MLSS	IAnT	VT	HRT	LT _{3.5}
v (m.s ⁻¹)	1.24 (0.09) [1.13 to 1.35]	1.24 (0.06) [1.17 to 1.31]	1.23 (0.06) [1.16 to 1.30]	1.25 (0.06) [1.18 to 1.32]	1.32 (0.08) ^{1,2,3,4} [1.22 to 1.42]
SR (cycles.min ⁻¹)	34.1 (3.0) [30.4 to 37.9]	32.2 (1.5) [30.3 to 34.0]	31.8 (1.0) [30.6 to 33.0]	32.3 (1.6) [30.4 to 34.3]	35.8 (2.2) ^{2,3,4} [33.1 to 38.5]
SL (m.cycle ⁻¹)	2.18 (0.10) ^{2,3,4} [2.07 to 2.30]	2.31 (0.09) [2.20 to 2.43]	2.32 (0.08) [2.23 to 2.42]	2.31 (0.09) [2.20 to 2.43]	2.22 (0.11) ^{2,3,4} [2.08 to 2.36]
SI	2.71 (0.23) ^{2,3,4,5} [2.42 to 3.00]	2.87 (0.21) [2.60 to 3.13]	2.86 (0.21) [2.60 to 3.13]	2.89 (0.20) [2.64 to 3.14]	2.93 (0.27) [2.60 to 3.26]
%SRVO _{2max} (%)	89.4 (7.0) [80.7 to 98.0]	84.2 (2.2) [81.4 to 86.9]	83.3 (2.7) [79.9 to 86.6]	84.7 (4.8) [78.7 to 90.7]	93.7 (3.7) ^{2,3,4} [89.1 to 98.2]
%SLVO _{2max} (%)	103.2 (8.1) ^{2,3,4} [93.1 to 113.2]	109.1 (5.1) [102.7 to 115.4]	109.6 (5.7) [102.6 to 116.6]	109.2 (5.7) [102.1 to 116.2]	104.5 (3.8) ^{2,3,4} [99.8 to 109.2]

^{1,2,3,4,5} Statistical different from MLSS, IAnT, VT, HRT and LT_{3.5}, respectively (p < 0.05).

The R² values and the Passing & Bablok regression equation parameters (Slope B and Intercept A) of the v and biomechanical parameters measured between MLSS and IAnT, MLSS and VT, MLSS and HRT, and MLSS and LT_{3.5} are presented in Table 5.2.

Table 5.2. Agreement values of velocity (v) and biomechanical parameters obtained between maximal lactate steady state (MLSS) and individual anaerobic threshold (IAnT) (upper left panel), ventilatory threshold (VT) (upper right panel), heart rate threshold (HRT) (lower left panel), and lactate threshold fixed in 3.5 mmol.L⁻¹ (LT_{3.5}) assessed by Passing & Bablok regression analysis. Coefficient of determination (R^2) and regression equation variables are presented.

MLSS vs IAnT			
Parameters	R^2	Slope B	Intercept A
v (m.s ⁻¹)	0.940*	0.620 (0.144 to 1.160)	0.474 (-0.232 to 1.039)
SR (cycles.min ⁻¹)	0.674	0.316 (-0.000 to 11.981)	21.119 (-382.509 to 31.468)
SL (m.cycle ⁻¹)	0.487	0.859	0.462
SI	0.915*	0.908 (-0.195 to 2.804)	0.384 (-4.700 to 3.366)
% SR VO _{2max} (%)	0.866*	0.333	0.550
% SL VO _{2max} (%)	0.939*	0.604 (-0.333 to 3.000)	0.463 (-1.990 to 1.410)
MLSS vs VT			
Parameters	R^2	Slope B	Intercept A
v (m.s ⁻¹)	0.876*	0.558 (-0.048 to 2.363)	0.527 (-1.733 to 1.280)
SR (cycles.min ⁻¹)	0.930*	0.316 (-0.000 to 11.981)	21.119 (-382.509 to 31.468)
SL (m.cycle ⁻¹)	0.486	0.783	0.631
SI	0.892*	0.908 (-0.195 to 2.804)	0.384 (-4.700 to 3.366)
% SR VO _{2max} (%)	0.542	0.222	0.636
% SL VO _{2max} (%)	0.876*	0.682	0.382
MLSS vs HRT			
Parameters	R^2	Slope B	Intercept A
v (m.s ⁻¹)	0.364	0.551	0.544
SR (cycles.min ⁻¹)	0.284	0.783	4.413
SL (m.cycle ⁻¹)	0.533	0.979	0.193
SI	0.583	-0.365	1.192
% SR VO _{2max} (%)	0.235	0.800	0.104
% SL VO _{2max} (%)	0.918*	0.697 (-0.333 to 2.000)	0.369 (-0.960 to 1.420)
MLSS vs LT _{3.5}			
Parameters	R^2	Slope B	Intercept A
v (m.s ⁻¹)	0.759*	0.876 (-0.644 to 3.260)	0.251 (-2.805 to 2.075)
SR (cycles.min ⁻¹)	0.307	0.361 (-0.597 to 77.283)	24.666 (-2636.999 to 53.991)
SL (m.cycle ⁻¹)	0.155	1.432	-0.824
SI	0.728	1.124	-0.149
% SR VO _{2max} (%)	0.092	0.481	0.499
% SL VO _{2max} (%)	0.618	0.432 (-0.667 to 7.000)	0.600 (-6.130 to 1.690)

* $p < 0.05$;

Highly correlated ($p < 0.05$) v values were obtained between MLSS-IAnT, MLSS-VT and MLSS-LT_{3.5}. Also highly correlated SR values were observed of MLSS-VT, and the SI between MLSS-IAnT and MLSS-VT. Again, highly correlated %SRVO_{2max} values were obtained between MLSS-IAnT, and SLVO_{2max} between MLSS-IAnT, MLSS-VT and MLSS-HRT. The Passing & Bablok regression analysis of the v values obtained between MLSS and IAnT, MLSS and VT, MLSS and HRT, and MLSS and LT_{3.5} are shown in Figure 5.1.

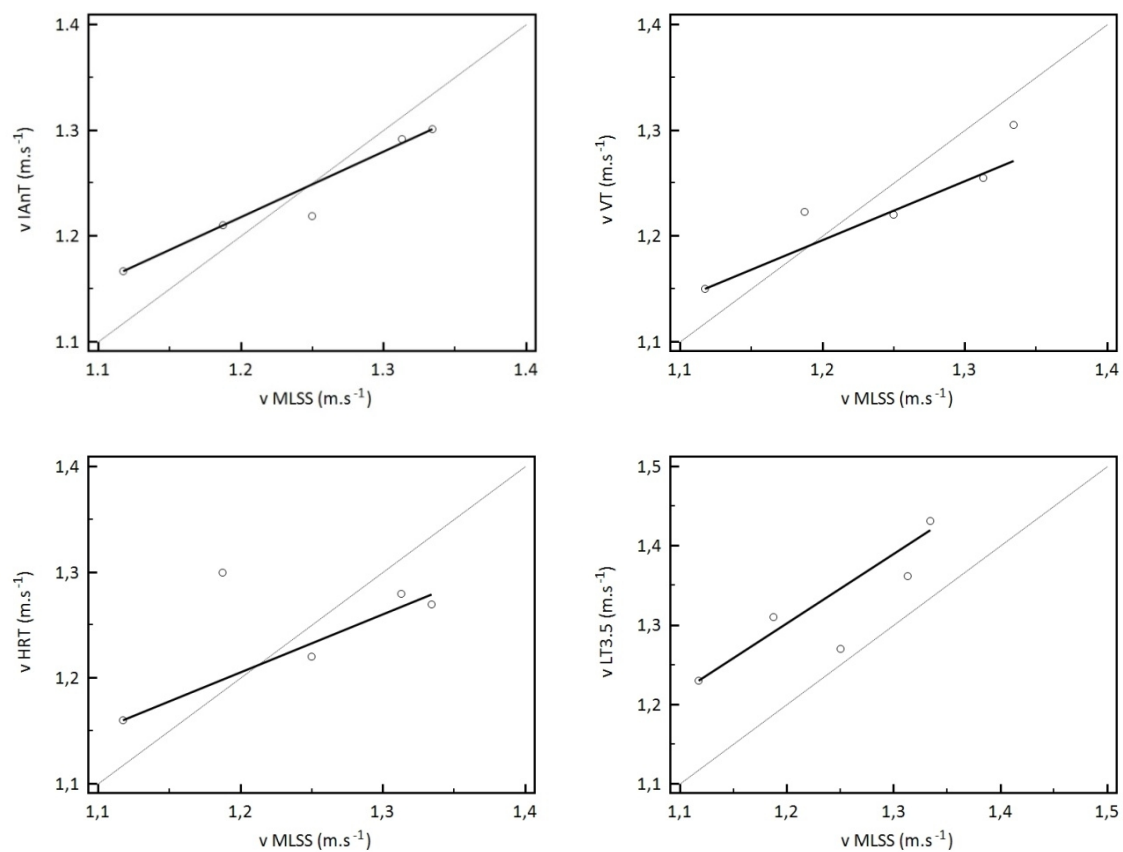


Figure 5.1. Passing-Bablok regression analysis of velocity (v) values obtained during maximal lactate steady state (MLSS) and individual anaerobic threshold (IAnT) (upper left panel), ventilatory threshold (VT) (upper right panel), heart rate threshold (HRT) (lower left panel), and lactate threshold fixed in 3.5 mmol.L⁻¹ (LT_{3.5}) (lower right panel) methods (N=5).

Discussion

This study aimed to compare the v and biomechanical parameters regarding the main evaluation methods used by researchers and coaches around the world to control and prescribe the aerobic capacity training in swimming. We compared the most well-known methods with the MLSS, considered as the gold-standard method for the aerobic capacity evaluation. The main findings suggest that the IAnT and VT tests are the better predictors of the MLSS test concerning the swimming intensity (v). However, the analysis of the biomechanical parameters showed that only the SR values obtained during the VT test were statistical significant and highly correlated to the MLSS test, suggesting that this might be the test with closest output regarding the chosen gold standard.

The IAnT and VT tests did not present significant differences with the MLSS test regarding the velocity, as well as high agreement were obtained using regression analysis. These results were similar to those reported in literature, in which they did not find significant differences between the IAnT ($1.10 \text{ m}\cdot\text{s}^{-1}$) and MLSS ($1.09 \text{ m}\cdot\text{s}^{-1}$) in swimming (Fernandes et al., 2011), and between the VT (302 W) and MLSS (311 W) in cycling (Van Schuylenbergh et al., 2004).

The MLSS and HRT intensities were similar (1.24 and $1.25 \text{ m}\cdot\text{s}^{-1}$, respectively). However, when the regression analysis was considered, the variables presented lower correlation ($R^2 = 0.364$), corroborating the literature that considers the HRT as not possible capable to precisely predict MLSS (Van Schuylenbergh et al., 2004). Conversely, the comparison of MLSS to $\text{LT}_{3.5}$ intensities showed significantly different swimming velocities (1.24 and $1.32 \text{ m}\cdot\text{s}^{-1}$, respectively), such as previously stated in the literature (Fernandes et al., 2011). However, these methods presented high correlation using regression analysis ($R^2 = 0.759$), showing that $\text{LT}_{3.5}$ has some potential for quantitative evaluation, but not for training prescription.

The SR presented similar values comparing the MLSS to the other methods, although the $\text{LT}_{3.5}$ was higher compared to IAnT, VT and HRT methods. However, a high agreement was only obtained between MLSS and VT tests (R^2

= 0.930). The SR obtained during the MLSS presented in this study corroborate the values obtained at the maximal speed of 30 min, method that have been used as predictor of the MLSS (Greco et al., 2007).

Concerning the SL, the MLSS presented similar values compared to $LT_{3.5}$, while the MLSS was lower than IAnT, VT and HRT. These SL values obtained during the MLSS corroborate the literature (Oliveira et al., 2012a). However, none of the studied methods demonstrated high correlation compared to the gold-standard method during the regression analysis. It seems that the SL may be more sensible to specificities between continuous/rectangular and intermittent/incremental exercise, in which the characteristic pauses of the intermittent exercise may improve the lactate removal and the restoration of creatine phosphate (Billat, 2001), allowing the swimmers to maintain higher SL values for a given intensity compared to the MLSS test.

Additionally, the SI value obtained during the MLSS was lower compared to the other methods, whereas the IAnT and VT presented high correlations values ($R^2 = 0.915$ and $R^2 = 0.892$, respectively) with the MLSS. Moreover, once the SI has been considered as an index of swimming efficiency, differences observed between continuous and intermittent tests may suggest that intermittent protocols may allow higher values of swimming efficiency.

Thereby, these findings suggest that IAnT and VT tests may be the better predictors of the gold-standard method for the aerobic capacity training intensity evaluation, when compared to the $LT_{3.5}$ and HRT. However, the biomechanical parameters seem to present different adjustments determined by the exercise mode (continuous vs intermittent). Thus, researchers and coaches should be careful in the prescription and control of training intensity, since different combinations of swim technique may occur between the continuous and intermittent exercise.

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Chapter 6

Relationship between the oxygen uptake efficiency plateau and the individual anaerobic threshold in endurance swimmers

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Abstract

Introduction: The oxygen uptake efficiency slope (OUES) has been proposed as a valid index for the objective estimation of cardiopulmonary function during submaximal laboratory testing (Baba et al., 1996). OUES is strongly correlated with maximal oxygen uptake ($\text{VO}_{2\text{max}}$) and has been observed to reach its highest and leveling off values (plateau - OUEP) near the anaerobic threshold (AnT) in patients with cardiorespiratory disease and normal subjects (Sun et al., 2012). However, OUES and OUEP have never been studied in highly trained athletes, particularly swimmers. The purpose of this study was to compare the velocity and oxygen uptake efficiency (OUE) values obtained during OUEP and individual anaerobic threshold (IAnt) in well trained swimmers. **Methods:** Eight female endurance swimmers (17.5 ± 1.9 yrs., 1.71 ± 0.06 m, 62.1 ± 6.2 kg) performed an intermittent incremental swimming step test (7 x 200 m, with increments of $0.05 \text{ m}\cdot\text{s}^{-1}$ and 30 s intervals). OUES was calculated by the ratio of oxygen uptake and minute ventilation. The IAnt was determined by the velocity vs. lactate curve modeling method. ANOVA for repeated measures and regression analysis were performed to test differences between methods ($p < 0.05$). **Results:** Similar velocity (1.20 ± 0.05 vs. $1.22 \pm 0.05 \text{ m}\cdot\text{s}^{-1}$) and OUE values (43.9 ± 5.83 vs. $42.9 \pm 5.8 \text{ mL VO}_2\cdot\text{L VE}^{-1}$) were obtained during OUEP and IAnt calculated intensities, respectively. Regarding the Passing & Bablok regression analysis and the Pearson's coefficient of determination, velocity (Intercept A= -0.096, Slope B= 1.071, $R^2 = 0.638$, $p < 0.017$) and OUE values (Intercept A= -5.360, Slope B= 1.154, $R^2 = 0.875$, $p < 0.001$) obtained both at the OUEP and at the IAnt were highly correlated. **Conclusion:** These findings suggest that OUEP has a practical application in swimming as a non-invasive submaximal index closely related to the IAnt in well-trained female endurance swimmers. **Acknowledgments:** This research was supported by grants from the Capes Foundation, Ministry of Education of Brazil (BEX: 0536/10-5), and Project PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577).

Key words: Oxygen uptake efficiency, velocity at individual anaerobic threshold, swimming.

Introduction

Several methods have been used to assess aerobic endurance, while the measurement of maximal oxygen uptake ($\text{VO}_{2\text{max}}$) is the most objective and widely used. Besides $\text{VO}_{2\text{max}}$, other parameters, such as the anaerobic threshold (AnT) and swimming economy are recognized to be important in the prediction of performance, especially in long-distance events (Bosquet et al., 2002).

The oxygen uptake efficiency slope (OUES), expressing the ratio between oxygen uptake to minute ventilation, is considered to be a valid sub-maximal index for the measurement of cardiorespiratory fitness during laboratory testing (Baba et al., 1996). The assessment of this index requires no maximal exercise and is significantly correlated with relevant exercise parameters, such as the peak and maximal oxygen uptake and the ventilatory threshold (Akkerman et al., 2010). Furthermore, OUES seems to be influenced by anthropometric variables, but not by the duration of the testing procedure (Baba et al., 1996). Studies conducted with health subjects and patients with cardiorespiratory disease showed that OUE values reach a plateau (OUEP) near the AnT. Interestingly, OUEP is considered to be more reproducible and less variable compared to OUES (Sun et al., 2012).

Meanwhile, the AT detected through blood lactate concentration values (lAnT) is presented as one of the most valid and reliable testing procedures in swimming to monitor training adaptations, evaluate the aerobic profile and prescribe training intensity (Morais et al., 2006; Pyne et al., 2001). Complementary, the velocity corresponding to the lAnT is more strongly correlated with distance performance than $\text{VO}_{2\text{max}}$ (Bassett & Howley, 2000).

To date, no study has attempted to examine the relationship between OUEP and lAnT during field conditions in well trained swimmers. Thereby, the purpose of this study was to compare the swimming velocities and OUE values obtained during the OUEP and lAnT intensities in well trained swimmers.

Methods

Eight female endurance swimmers (age 17.5 ± 1.9 yrs., height 1.71 ± 0.06 m, body mass 62.1 ± 6.2 kg and percentage of body fat $16.4 \pm 2.6\%$) volunteered to participate in the study, giving their written informed consent before participation. In addition, swimmers below the age of 18 yrs. provided written parental consent. The participants had at least seven years of experience as competitive swimmers and their best 400 m front-crawl performance corresponded to $87.4 \pm 3.5\%$ of the 2013 25 m pool world record.

The testing sessions were performed in a 25 m indoor swimming pool, after a standard warm-up of 1000 m at moderate self-paced swim and under the same pool conditions ($27\text{-}28^{\circ}\text{C}$). Swimmers were instructed to refrain from intense training sessions at least 24 h before testing.

Swimmers performed an intermittent and incremental front-crawl protocol, with increments of $0.05\text{ m}\cdot\text{s}^{-1}$ and 30 s rest intervals between each 200 m steps to assess IAnT and detect the swimming velocities associated with the OUEP. The predetermined velocity of the last step was calculated considering the best performance of the 400 m front-crawl race minus seven increments of velocity (Cardoso et al., 2003; Fernandes et al., 2006). Swimmers were advised to use in-water starts and open turns, without underwater gliding.

The swimming velocity (SV) was set and controlled using a visual underwater pacer with flashing lights on the bottom of the pool (GBK-Pacer, GBK Electronics, Aveiro, Portugal) (Fernandes et al., 2011); the lights were located 2.5 m apart along the bottom of the 25 m pool.

The VO_2 and VE were measured by a telemetric portable gas analyzer (K4 b², Cosmed, Italy), connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system (New AquaTrainer®, Cosmed, Italy), previously validated (Baldari et al., 2013). The equipment was calibrated before each test for VE with a 3 L calibrated syringe and the O_2 and CO_2 analyzers with standard calibration gases. The values of gas exchange were measured

breath-by-breath during the test and averaged every 5 s. Heart rate (HR) was recorded continuously (Polar Electro, Kempele, Finland) throughout the test.

Blood lactate collection (BLa) was performed in the first 30 s after each step, at the earlobe using a portable lactate analyzer (Lactate Pro, Akray, Japan). The IAnT was determined by the velocity vs. lactate curve modeling method. The lactate increase inflexion point was considered to be the interception point between linear and exponential regressions to determine the exact velocity where BLa increased exponentially (Machado et al., 2006). The OUES was calculated by the ratio of oxygen uptake and minute ventilation. The OUE plateau (OUEP) was considered as the highest consecutive measurements of oxygen uptake (VO_2) / minute ventilation (VE) values briefly stabilized near the AT, before declining due to hyperventilation stimulated by the excess $[\text{H}^+]$ and metabolic acidosis (Sun et al., 2012). In the case a swimmer did not attain the maximal velocity and/or exhaustion with the pre-defined steps, one more step was used.

Data are presented as mean ($\pm\text{SD}$). Standard statistical assumptions were checked before the analysis. ANOVA one-way for repeated measures and Passing & Bablok regression analysis (MedCalc Statistical Software, Belgium) were conducted to compare SV and OUE values obtained during OUEP and IAnT calculated intensities, complemented with Bonferroni correction and post-hoc test. The Pearson's determination coefficient (R^2) was used. Statistical significance level was set at $p \leq 0.05$.

Results

Table 6.1 presents the mean (*SD*) SV and OUE values obtained at the OUEP and IAnT intensities.

Table 6.1. Mean (SD) values for swimming velocity (SV) and oxygen uptake efficiency (OUE) values obtained during the oxygen uptake efficiency plateau (OUEP) and individual anaerobic threshold (IAnT) intensities (N=8).

	SV (m.s ⁻¹)	OUE (mL VO ₂ . L VE ⁻¹)
OUEP	1.20 (0.05)	43.9 (5.8)
IAnT	1.22 (0.05)	42.9 (5.8)

According to Table 6.1, similar velocity ($F_{1,7} = 2.635$, $p < 0.149$, $\eta_p^2 = 0.273$) and OUE values ($F_{1,7} = 1.913$, $p < 0.209$, $\eta_p^2 = 0.215$) were observed both for OUEP and IAnT calculated intensities. Table 6.2 presents the mean (SD) sub-maximal BLa, HR and VO₂ values corresponding to the IAnT.

Table 6.2. Mean (SD) values for the sub-maximal physiological variables corresponding to the individual anaerobic threshold (IAnT) (N=8).

BLa (mmol.L ⁻¹)	HR (b.min ⁻¹)	VO ₂ (mL.min ⁻¹ .kg ⁻¹)
1.50 (0.47)	171.76 (5.62)	44.42 (4.27)

The Passing & Bablok analysis and the Pearson's determination coefficient showed that swimming velocity and OUE mean values obtained through the OUEP and IAnT intensities were highly correlated ($p \leq 0.05$) (Table 3). Figure 6.1 and Figure 6.2 present the Passing-Bablok regression analysis and Bland-Altman plot, respectively, determined between OUES and IAnT intensities concerning the SV (Left Panel) and OUE (Right Panel) values.

In **Table 6.3**, the coefficient of determination (R^2), p value and regression equation variables for the comparison between the OUEP and IAnT intensities for SV and OUE values are presented.

Table 6.3. Comparison between the oxygen uptake efficiency plateau (OUEP) and individual anaerobic threshold (IAnT) intensities for swimming velocity (SV) and oxygen uptake efficiency (OUE) values.

OUEP vs. IAnT				
Parameters	R ²	p value	Slope B	Intercept A
SV (m.s ⁻¹)	0.638*	0.017	1.071 (0.339 to 2.128)	-0.096 (-1.404 to 0.786)
OUE (mL O ₂ . L VE ⁻¹)	0.875*	0.001	1.155 (0.673 to 2.351)	-5.360 (-56.188 to 14.909)

* $p < 0.05$.

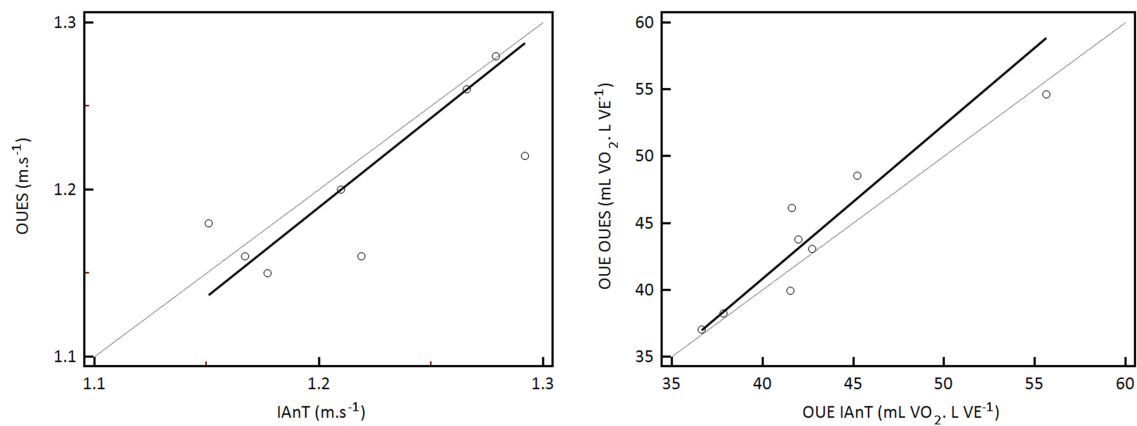


Figure 6.1. Passing-Bablok regression analysis obtained during oxygen uptake efficiency slope (OUES) and individual anaerobic threshold (IAnT) intensities regarding the swimming velocity (SV) (left panel) and the oxygen uptake efficiency (OUE) values (right panel) (N=8).

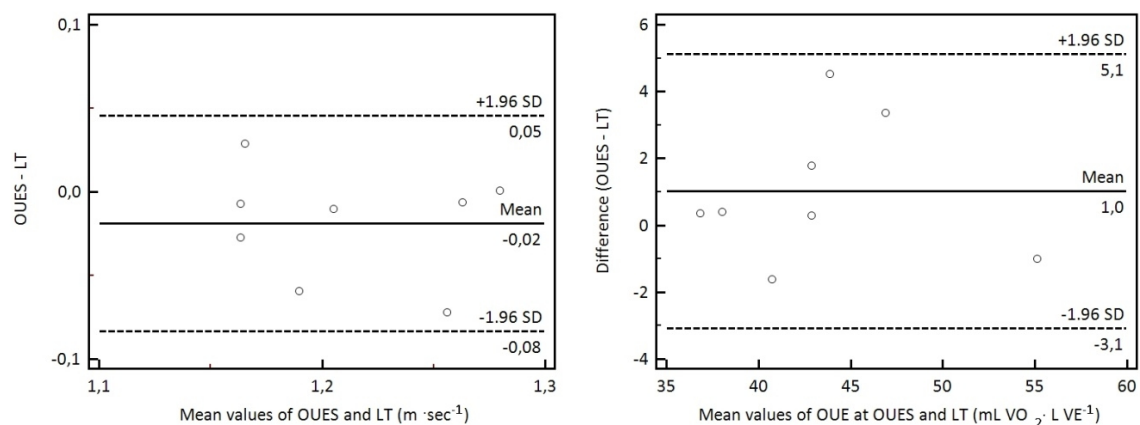


Figure 6.2. Bland-Altman plot of the oxygen uptake efficiency slope (OUES) and individual anaerobic threshold (IAnT) intensities regarding the swimming velocity (SV) (left panel) and the oxygen uptake efficiency (OUE) values (right panel) (N=8).

Discussion

The current study presents sub-maximal OUE values obtained in well-trained female endurance swimmers, as well as comparison between OUEP and IAnT intensities regarding both OUE and SV. The main findings indicate that SV as well as OUE values attained during OUEP and IAnT intensities are highly correlated and not significantly different, suggesting that they both refer to the same biophysical state of the swimmer.

Caution must be taken when comparing SV, BLA and HR mean values corresponding to the IAnT of our participants with those from other studies, due to the inconsistency regarding the methodology applied for the IAnT determination in swimming. Approaches usually include SV and HR values at: (i) the fixed 4 mmol·L⁻¹ BLA, (ii) at the final step of the incremental test, (iii) during different testing procedures (i.e., 2 to 7 x 200 m step tests) or, (iv) include the mathematical approach to determine the individual IAnT (Altimari et al., 2007; Anderson et al., 2006; Fernandes et al., 2010; Pyne et al., 2006). Nevertheless, Pyne et al. (2001) and Thanopoulos (2010) presented higher BLA values at the IAnT than those reported in this study (3.6 and 5.5 mmol·L⁻¹ in world-ranked male/female and national level female swimmers, respectively). Similarly, in the latter study the SV values corresponding to the IAnT were

higher than those presented here (1.45 vs. 1.22 m·s⁻¹). At least partially, differences might be attributed to the performance level of the swimmers.

Sub-maximal OUE values presented in this study are in accordance with those reported by Akkerman et al. (2010), despite the differences in the conditions used for exercise testing (cycle ergometer vs. free swimming) and the chronological age of the participants (12.9 ± 2.6 vs. 17.5 ± 1.9 yrs.). Sun et al. (2012) showed that OUES is significantly influenced by age and body size.

To our knowledge, this is the first attempt to examine the practical application of the OUEP method by correlating and comparing OUE and SV values obtained during OUEP and a widely accepted field test, such as the IAnT, in well-trained swimmers. From a practical point of view, OUEP may be used to assess IAnT without using intrusive procedures. Furthermore, once OUES indicates ventilatory efficiency with regard to VO₂ (Akkerman et al., 2010), the leveling off values of OUES at the intensity correspondent to the IAnT, implies that, at this particular intensity, a deleterious effect of exercise intensity is observed over the respiratory dynamics. OUES may be also used as a potential sub-maximal index of swimming economy, since the latter is considered to be an efficiency index, expressing the VO₂ required to maintain a given swimming velocity. Since distance swimming performance is significantly influenced by the VO_{2max} and the AT, the results obtained during this study can provide valuable information for designing training programs in swimmers. Future work should focus on examining the efficacy of the OUES and OUEP indexes in determining adaptations after a training period.

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Chapter 7

Biophysics of the elite endurance swimmer: a case study during aerobic capacity evaluation using different methods

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Abstract

Introduction: In swimming research, the characterization of various parameters is generally accomplished by its reduction to the mean and standard deviation. This procedure allows analyzing the tendencies and/or the variability of a group. However, in doing so, individual characteristics of an elite swimmer may be hidden by the group tendency. Thereby, the purpose of this case study was to analyze one elite endurance swimmer comparing biomechanical and physiological parameters among the main methods used for the aerobic capacity evaluation. **Methods:** The elite female endurance swimmer (18 yrs., 1.64 m, 56 kg, 91.3% 400m freestyle WR) performed in different days: 1) an intermittent incremental protocol until voluntary exhaustion to determine the velocity (v) associated at the individual anaerobic threshold (IA_{NT}), the ventilatory threshold (VT), the heart rate threshold (HRT), the lactate threshold of fixed 3.5mmol.L⁻¹ (LT_{3.5}), maximal oxygen uptake ($\dot{V}O_{2max}$), and minimal v that elicits $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$); 2) three 30min sub-maximal continuous tests to determine the v and oxygen uptake ($\dot{V}O_2$) kinetics associated at the maximal lactate steady state test (100%MLSS), above (102.5%MLSS) and below (97.5%MLSS) this intensity. Blood lactate collection (BL_a), v , ventilatory, energetic and biomechanical parameters were controlled in all tests. **Results:** The results showed a close relationship among the 100%MLSS, IA_{NT} and VT regarding the v , ventilatory, energetic and biomechanical parameters. Meanwhile, LT_{3.5} and $v\dot{V}O_{2max}$ presented higher values in all these parameters. Key points were noticed: 1) the oxygen uptake efficiency values (OUE) presented an uncommon stability and linear relationship with the v until $\dot{V}O_{2max}$, while the remaining swimmers showed decreased values of OUE, largely determined by metabolic acidosis and pulmonary dead space (Sun et al., 2012). Thus, this maintenance of OUE may be explained by the low BL_a observed in swimmer's $v\dot{V}O_{2max}$ (4.4mmol.L⁻¹); 2) $\dot{V}O_2$ slow component was not observed in both intensities of 100%MLSS and 102.5%MLSS; 3) the 100%MLSS v was very high (92.6% $v\dot{V}O_{2max}$) implying low $\dot{V}O_2$ values (77.5% $\dot{V}O_{2max}$). **Conclusion:** Thereby, the analysis of individual characteristics of specific athletes, particularly elite swimmers, rather than rely upon mean sample values, may be

decisive to understand the specific intervention required and to improve performance. **Acknowledgments:** This research was supported by grants from the Capes Foundation, Ministry of Education of Brazil (BEX: 0536/10-5), and Project PTDC/DES/101224/2008 (FCOMP-01-0124-FEDER-009577).

Key words: oxygen uptake, biomechanical parameters, aerobic capacity evaluation, swimming training.

Introduction

In sports science, the characterization of the transversal or longitudinal behavior of most performance relevant parameters, such as the maximal oxygen uptake ($\text{VO}_{2\text{max}}$), has been generally accomplished by its reduction to the mean and standard deviation analysis. This allows one to study the tendencies and/or the variability of a group. However, in doing so, the individual characteristics of an outlier swimmer may be hidden by the group tendency: and this swimmer may be extremely relevant; as a record holder, for instance.

On the other hand, when an elite athlete that show expressive results at national and International levels is analyzed as a case study, it might be possible to highlight biophysical specificities that may inform his hone training process, as well as the pathway to be followed by lower performance level swimmers. Thereby, the purpose of this case study was to analyze an elite endurance swimmer comparing biomechanical and physiological parameters among the most-known methods used for the aerobic capacity evaluation, emphasizing the particular adaptations that may help the achievement of best results.

Methods

One elite female endurance swimmer (18 yrs., 1.64 m, 56 kg and 12% body fat mass) volunteered to participate in the present study, signing a form of informed consent before participation. At the time experiments, the personal best 400 m freestyle swim was 91.2% of the 25 m pool world record. The test sessions were performed in a 25 m indoor swimming pools within a five days period, and at the same time of the day (± 2 h) to minimize the effect of circadian rhythm variation on the test (Atkinson & Reilly, 1996). The swimmer warmed up at moderate aerobic intensity at 1000 m swim, and was advised to refrain from intense training sessions at least 24 h before the experimental sessions. Tests were performed in front crawl, using in-water starts, and open turns without underwater gliding.

Initially, the swimmer performed a front crawl intermittent incremental v protocol until voluntary exhaustion, with repeated ($\sim 7\times$) distances of 200 m, increments of $0.05 \text{ m}\cdot\text{s}^{-1}$ and 30 s rest intervals between each step. The predetermined v of the last step was defined by the best time at the 400 m front crawl race and to define all the v steps (Fernandes et al., 2006). The intermittent incremental protocol was realized to determine the v output provided by the main methods used for the aerobic capacity and power – $\text{VO}_{2\text{max}}$ - evaluation. All the corresponding values of gas exchange, energetic and biomechanical parameters were also determined. Interpolation procedures were used for this purpose, based on a polynomial regression model and calculated between the incremental velocities and the correspondent relevant parameters (Neter et al., 1985).

The IAnT was assessed through the mathematical curve fitting method between lactate and v values (Machado et al., 2006). The $\text{LT}_{3.5}$ was determined by the fixed $3.5 \text{ mmol}\cdot\text{L}^{-1}$ value of BLA and its correspondent v (Heck et al., 1985). The VT was determined using the v slope method and its respective values of pulmonary ventilation (VE), defining a disproportional increase of VE concerning the increase of locomotion speed during the incremental test (Svedahl & MacIntosh, 2003). The HRT was determined by the curve slope method calculated between v and heart rate (Cellini et al., 1986), assuming that the curve inflection point corresponds to the HRT_v .

Subsequently, the swimmer performed three 30 min submaximal constant swimming tests at imposed paces for determination of the v associated to the maximal lactate steady state (100%MLSS). The first trial was performed at the IAnT_v , and a negative delta in BLA was observed (97.5%MLSS). Further, two subsequent trials with 2.5% higher velocities were performed to find the 100%MLSS $_v$ and above the 100%MLSS $_v$ (102.5%MLSS), in which at the 102.5%MLSS (Pelarigo et al., 2011), the swimmer was not able to maintain the v and attained exhaustion at 27th min of test. The 100%MLSS $_v$ was defined as the highest intensity in which the BLA did not increase more than $1 \text{ mmol}\cdot\text{L}^{-1}$.

between the 10th and 30th minute of swim (Heck et al., 1985). The MLSS test is considered the gold-standard direct method for the aerobic capacity evaluation.

Earlobe capillary blood samples were collected: 1) at rest, at the end of each intermediate step of the incremental test during the 30 s interval, and immediately after and at each 2 min of recovery the last step, until the BLA recovery peak was found; 2) at rest, at the 10th and 30th min (or voluntary exhaustion) of each continuous swimming test to assess BLA. Capillary BLA was assessed through a portable lactate analyzer (Lactate Pro, Arkray, Inc.). All the blood samples collection lasted around 30s.

Gas exchange were measured by a telemetric portable gas analyzer (K4 b², Cosmed, Italy) attached a newest respiratory snorkel and valve system (New AquaTrainer[®], Cosmed, Italy), with a low hydrodynamic resistance (Baldari et al., 2013), that was connected to the swimmer in all the tests. The oximeter was calibrated before each test. The heart rate (HR) was monitored and registered continuously by a heart rate monitor system (Polar Vantage NV, Polar electro Oy, Kempele, Finland) and real-time transferred through a telemetric signal to the portable oximeter.

The control of swimming v was obtained using a visual underwater pacer on the bottom of the pool (GBK-Pacer, GBK Eletronics, Aveiro, Portugal) with lights located each 2.5 m. The swimmer's head should be above each visual signal. Exhaustion was assumed and the test ended when the swimmer remained 5 m behind the light.

In all each tests, the $\dot{V}O_2$ data were analyzed and the occurring errant breaths caused by coughing, swallowing, and sighing were excluded from the local mean. Afterwards, the gas exchange values were characterized as mean $\pm$ 3SD, and the values outside this amplitude were removed. To all swimmers' data, the breath-by-breath data were subsequently averaged to provide 5 s mean values. In the incremental test, the gas exchange parameters values obtained in the last minute of each step were retained and the mean value considered to be the representative of that step. The continuous test was split

into seven time moments corresponding to the 4th min, 25%, 33%, 50%, 66%, 75%, and 100% of the total test duration. Again, the 1 min period before each time moment was retained to calculate the mean values of that moment in the time duration of the test. The $\dot{V}O_{2max}$ was considered to be reached in accordance to conventional physiological criteria (Howley et al., 1995).

The energetic parameters were described by the total energy expenditure ($\dot{E}$) and the energy cost (C). In the 100%MLSS, those parameters were calculated at the 10th and 30th min, the same time moments used for BLA, and in the incremental test they were calculated at the final 1 min of each step of exercise. The $\dot{E}$ values were obtained through the addition of the aerobic and the anaerobic energy expenditure. The aerobic energy expenditure was considered to be expressed by the difference between the exercise oxygen uptake ($\dot{V}O_{2exercise}$) and the baseline oxygen uptake ($\dot{V}O_{2baseline}$) ($mL \cdot kg^{-1} \cdot min^{-1}$); the anaerobic energy expenditure was obtained by the BLA net values transformed into O_2 equivalents through the constant multiplicative value of $2.7 mL O_2 \cdot kg^{-1} \cdot mM^{-1}$ (Barbosa et al., 2008). C was determined as the ratio of $\dot{E}$ and its respective v (di Prampero, 1986).

The $\dot{V}O_2$ kinetics was described as a single-exponential (Equations 7.1 and 7.2) or bi-exponential (Equation 7.3) function of time by the following equation:

$$\dot{V}O_2(t) = \dot{V}O_{2baseline} + A_c [1 - e^{-(t/\tau_c)}] \quad 7.1$$

phase I (cardiodynamic component)

$$\dot{V}O_2(t) = \dot{V}O_{2baseline} + A_p [1 - e^{-(t-TD_p)/\tau_p}] \quad 7.2$$

phase II (primary component)

$$\dot{V}O_2(t) = \dot{V}O_{2baseline} + A_p [1 - e^{-(t-TD_p)/\tau_p}] + A_s [1 - e^{-(t-TD_s)/\tau_s}] \quad 7.3$$

phase III (slow component)

where $\dot{V}O_2(t)$ represents the absolute $\dot{V}O_2$ at the considered time moment, $\dot{V}O_{2baseline}$ is the resting $\dot{V}O_2$, A_c and τ_c are the amplitude and the time constant of the cardiodynamic component; A_1 , TD_1 and τ_1 are the amplitude, the time delay and the time constant of primary component, respectively; A_s , TD_s and τ_s are the amplitude, the time delay and the time constant of slow component,

respectively. The cardiodynamic component terminated at the start of primary component (TD_p), the primary component terminated at the start of slow component (TD_s). The $\dot{V}O_2$ kinetics was calculated at the first 10 min and the last 20 min (or exhaustion time) of exercise.

The biomechanical parameters were assessed through a dry land video camera operating at a frequency of 50 Hz, allowing to analyze two stroke cycles in the middle of the swimming pool. The stroke rate (SR) was determined by the number of cycles per unit of time ($\text{cycles}\cdot\text{min}^{-1}$), the stroke length (SL) by the ratio of v ($\text{m}\cdot\text{min}^{-1}$) and SR, and the stroke index (SI) was the product of v ($\text{m}\cdot\text{s}^{-1}$) and SL. These parameters were analyzed in each 50 m of each step of incremental test, and averaged for the entire step. At the 100%MLSS, the biomechanical parameters were obtained at each one of the seven time moments corresponding to the 4th min, 25, 33, 50, 66, 75, and 100% of the total test duration, during the last 1 min of each time moment. The mean value of each parameter at all-time moments was assumed as representative of the test.

Results

The results showed a narrow relationship among the 100%MLSS, IAnT and VT methods, with similar values of v , gas exchange and energetic parameters. However, the biomechanical parameters showed to be different when 100%MLSS was compared to the all other pace assessment methods under evaluation. The $LT_{3.5}$ overestimated most of the variables compared to the 100%MLSS and the other methods, providing closest values to the characteristic of $\dot{V}O_{2\max}$ intensity. The indirect HRT test underestimated the most of the variables which were characterized in the 100%MLSS. The 100%MLSS corresponded to high percent values of the v correspondent to maximal oxygen uptake ($\%v\dot{V}O_{2\max}$). However, the respective $\dot{V}O_2$ values did not attain high percent of maximal oxygen uptake ($\%\dot{V}O_{2\max}$) compared to intensity values (Table 7.1).

Table 7.1. Global swim analysis evolving velocity (v), gas exchange, energetic and biomechanical parameters compared to the most-known methods for the aerobic capacity evaluation in an elite female endurance swimmer.

	100%MLSS	IAnT	LT _{3.5}	VT	HRT	VO _{2max}
v (m.s ⁻¹)	1.33	1.30	1.43	1.29	1.27	1.44
%vVO _{2max} (%)	93%	90%	99%	90%	88%	100%
BLa (mmol.L ⁻¹)	1.8	1.5	3.5	1.6	1.4	4.4
VO ₂ (mL.kg ⁻¹ .min ⁻¹)	53	55	67	54	52	68
%VO _{2max} (%)	78%	81%	99%	80%	77%	100%
VCO ₂ (L.min ⁻¹)	2.61	2.65	3.45	2.61	2.48	3.59
VE (L.min ⁻¹)	73.4	70.3	85.7	69.4	66.7	89.7
R	0.89	0.86	0.92	0.86	0.85	0.94
HR (beats.min ⁻¹)	193	186	202	185	181	203
%HR VO _{2max} (%)	95%	92%	99%	91%	89%	100%
$\dot{E}$ (mL.kg ⁻¹ .min ⁻¹)	46.2	48.0	61.1	47.2	45.0	62.3
C (kJ.m ⁻¹)	0.68	0.73	0.83	0.72	0.70	0.84
SR (cycles.min ⁻¹)	34.6	31.9	37.3	31.7	31.0	38.0
SL (m.cycle ⁻¹)	2.31	2.44	2.30	2.45	2.46	2.28
SI	3.09	3.18	3.29	3.17	3.12	3.28
time/100m (min)	1'14"96	1'16"86	1'09"88	1'17"34	1'18"74	1'09"44

VO₂ kinetics at 97.5%, 100% and 102.5% MLSS are presented in Table 2. VO₂ kinetics values were obtained during the first 10 min (10 min) of exercise, and during the last 20 min of exercise (20 min) or voluntary exhaustion. There was a tendency to increase the VO₂ with the increase of intensity. The swimmer did not present slow component in any intensity.

Table 7.2. Oxygen uptake ($\dot{V}O_2$) kinetics at maximal lactate steady state test (100%MLSS), above (102.5%MLSS) and below (97.5%MLSS) this intensity at the first 10 min (10 min) and the last 20 min (20 min) of exercise in an elite female endurance swimmer.

	97.5%MLSS		100%MLSS		102.5%MLSS	
	10 min	20 min	10 min	20 min	10 min	20 min
$\dot{V}O_{2\text{baseline}}$ (mL.kg.min ⁻¹)	7.0	12.4	5.2	19.9	7.0	17.9
A_p (mL.kg.min ⁻¹)	43.2	36.5	48.8	31.9	51.4	36.8
TD_p (s)	9.9	8.1	28.4	9.8	5.9	7.1
τ_p (s)	14.9	15.2	7.9	9.8	18.6	13.0

Regarding the oxygen uptake efficiency values (OUE) (Figure 1), the swimmer showed a relatively wobbling profile during the incremental test, but with a tendency to keep constant values. It is interesting to note the sudden increase of OUE at the 6th step, which was coincident with the intensity of the IAnT, followed by a persistent tendency to reduced values (Left Panel). When the behavior of OUE values around the 100%MLSS was analyzed, the swimmer presented decreased values at the 102.5%MLSS after 33% of test duration, whereas at the other intensities tested, the OUE values maintained stable throughout time (Right Panel).

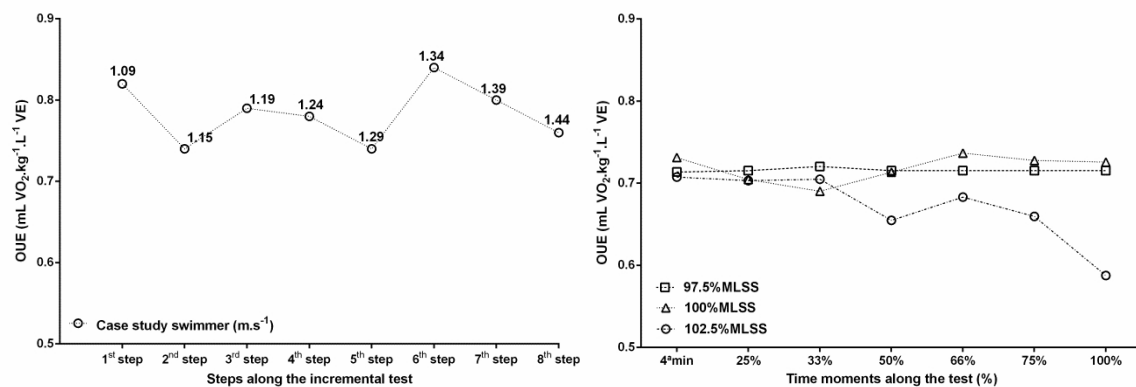


Figure 7.1. The oxygen uptake efficiency (OUE) values throughout an incremental test until voluntary exhaustion in the case study swimmer (Left Panel); and the OUE values at 97.5%, 100% and 102.5% of the maximal lactate steady state (MLSS) in the case study swimmer (Right Panel).

Discussion

The purpose of this study was to investigate the most well-known and used methods for the aerobic capacity evaluation, comparing among them the gas exchange, energetic and biomechanical parameters in an elite female endurance swimmer.

The swimmer showed specific physiological adaptations normally presented by endurance athletes, such as the MLSS intensity at a high %vVO_{2max} (93%) compared to a relative lower oxygen uptake - %VO_{2max} (78%), supporting the observed high OUE at this particular intensity. Accordingly, low values of BLa at MLSS and vVO_{2max} (1.8 and 4.4 mmol.L⁻¹, respectively) were observed, reinforcing the high adaptation to the prevalence of aerobic metabolism sustaining exertion. This phenomena is usually reported in the literature in which these kind of athletes exhibit a lactate to velocity curve shifted to the right (Holfelder et al., 2013), allowing them to keep high velocities in a physiological steady state at intensities near the vVO_{2max}. Indeed, such endurance athletes present higher phenotypic expression of oxidative muscle fibers compared to sprint athletes (Tanaka & Swensen, 1998), and fibers which consumes lactate (Gladden, 2008), allowing to support the total energy expenditure required in high swimming intensities, explaining the typical low final BLa values observed in swimmers like the one analyzed in this study.

In the present study, the investigated swimmer presented a VO_{2max} of 68 mL.kg⁻¹.min⁻¹, slightly higher than the 65 mL.kg⁻¹.min⁻¹ found as representative of female endurance swimmers (Rodriguez & Mader, 2011). Commonly, endurance specialists are characterized by a very high VO_{2max} values, determining a predominance of the aerobic energy pathways, and an elevated capacity to sustain metabolic balance intensities. Moreover, in this type of athletes, such the swimmer in study, VO₂ correspondent to 100%MLSS reaches values close to maximal, and a steady state occur at a higher level of muscle and lactate concentrations (Rodriguez & Mader, 2011).

The swimming economy, described in this paper as energy cost (C), is defined by the ratio of the total energy expenditure ($\dot{E}$) and v . It has been considered as the major determinant of swimming performance (di Prampero et al., 2011). In this study, the investigated swimmer presented C and $\dot{E}$ values at MLSS, expressed as percentages of $\text{VO}_{2\text{max}}$ of 81% and 74.2%, respectively. When the C value of the preferable intensity to train aerobic capacity is compared among different assessment methods, the lower values were observed for the 100%MLSS. This was so once 100%MLSS was also the method that prescribed higher v values compared to the LT, VT and HRT methods (C = 7.4, 5.9 and 2.9%, respectively). This suggests that the exercise mode (continuous or intermittent) may contribute differently to the adjustments of swimming efficiency, with continuous exercise showing to be more economical. The C (0.68 and 0.84 $\text{kJ}\cdot\text{m}^{-1}$) and $\dot{E}$ (46.2 and 62.3 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) values at 100%MLSS and $\text{VO}_{2\text{max}}$, respectively, corroborating the literature concerning the similar sub-maximal intensities (Zamparo et al., 2005a) and the maximal aerobic power intensities (Chatard et al., 1991).

Regarding the biomechanical parameters, the swimmer demonstrated different adjustments between the 100%MLSS and other methods. In the 100%MLSS test, the SR was higher and the SL was lower compared to LT, VT and HRT methods, and the SR was lower and SL was similar compared to the $\text{LT}_{3.5}$ method. These biomechanical adjustments seem to follow the differences observed in C and $\dot{E}$ between the exercise mode (continuous and intermittent), in which the increased intensity of intermittent exercise has been attributed to factors such as lactate removal and restoration of creatine phosphate (Billat, 2001). These aspects may influence differences in technical adjustments occurred between continuous and intermittent exercise. Furthermore, as the continuous exercise is affected by the muscular fatigue established throughout exercise duration (Sahlin et al., 1990), athletes tend to adopt the most economical mechanical adjustments to keep a given intensity (Baron et al., 2005; Zamparo et al., 2001).

Usually, researchers define the 100%MLSS as the upper boundary of heavy and/or lower boundary of severe intensity domains (Burnley & Jones, 2007; Xu & Rhodes, 1999). At or above this 100%MLSS intensity, the $\dot{V}O_2$ slow component is assumed to be evident (Burnley & Jones, 2007). However, in this case study, the swimmer did not show any $\dot{V}O_2$ slow component, either at 100%MLSS or above this intensity, explained in part by the low BL_a. Indeed, endurance athletes present high percentage of oxidative muscle fibers, lactate consumers, as previously described, not requiring additional and progressive anaerobic contributions to the energy expenditure, one of determining factors to develop $\dot{V}O_2$ slow component (Cannon et al., 2011).

One of the more interesting issues raised about this swimmer and its specific physiological adaptations is perceived through OUE values, indicator of ventilatory efficiency (Sun et al., 2002). The case study swimmer presented a stable and almost linear OUE values variation with increasing velocity until exhaustion, while the mean tendency of national level swimmers decreased the OUE values, due to factors as the metabolic acidosis and pulmonary dead space (Baba et al., 1996). It is important to underline that the case study did not show high values of BL_a to keep high velocities near the $v \dot{V}O_{2max}$ in a physiological steady state. Moreover, the OUE showed similar values in all the three continuous intensities around the 100%MLSS until 33% (± 10 min) of all tests, do not been affected by both metabolic acidosis and physiologic pulmonary dead space, status indicators of the systemic and pulmonary perfusion (Baba et al., 1996). However, just after 33% of the total time duration, the unbalance exercise (102.5%MLSS) clearly showed the decrease of ventilatory efficiency (OUE), leading to exhaustion.

Thereby, the analysis of individual characteristics of specific athletes, particularly elite swimmers, rather than rely upon mean sample values, may be decisive to understand the specific individual characteristics and required intervention, and to improve performance.

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Chapter 8

General Discussion

Training load is determined not only by swimming v and duration, but also by its biomechanics (particularly by drag and propulsive efficiency), which determines the C , and consequently, the energetic responses of a subject. Accordingly, the general purpose of this Thesis was to clearly establish the biophysical performance determinant profile of the aerobic capacity of a swimmer, being divided in two purposes: the first main purpose was to understand the physiological, bioenergetic and biomechanical factors occurred at intensities 5% around the MLSS intensity, i.e. the load defined by the gold-standard method used for the evaluation of aerobic capacity, the MLSS. Research questions behind this purpose were: will a 5% changes of intensity around MLSS lead to significantly different ventilatory, metabolic, energetic and biomechanical responses of a swimmer? Is this much relevant to precisely target the MLSS intensity or 5% flexibility may at least be allowed for training prescription or tolerated considering training response of the swimmer? Exploring this extended characterization, one decisive question arises: do the concurrent main methods used for the aerobic capacity evaluation provide similar outcomes? Despite similar (or not) swimming v , do they suggest a similar physiological, energetic, and biomechanical profile? So, the second main purpose was to compare these biophysical parameters between the MLSS and concurrent main methods used for the evaluation and prescription of the aerobic capacity training in swimming.

The main findings provided by the studies included in this Thesis were:

- (I) The mean v increased among each intensity level between 97.5, 100 and 102.5%MLSS. As expected with the intensity increase, $[La^-]$, $\dot{V}O_2$, $\dot{V}E$, C , $\dot{E}$ and SR also increased, but $[La^-]$ increases were only significant at 102.5%MLSS compared to 97.5 and 100%MLSS, and C at 102.5%MLSS when compared to 97.5%MLSS. SL was similar at 97.5 and 100%MLSS,

but the values decreased at 102.5%MLSS. In addition, almost all studied physiological and energetic factors were constant throughout time at each one of the three studied continuous swimming intensities (97.5, 100 and 102.5%MLSS). However, at 102.5%MLSS, VE and HR increased as time elapsed. With a constant $\dot{V}O_2$ and an increasing VE, ventilatory efficiency (OUE) decreased over time. Moreover, at 102.5%MLSS there was an increase in [La-] as a function of time, supporting that the production exceeded removal, which was associated with voluntary exhaustion for eight out of ten swimmers before 30 min of test duration. Meanwhile, at 97.5 and 100%MLSS, bioenergetic factors did not change as a function of time, but biomechanical factors (increased SR and decreased SL), as well as HR (increased values) were significantly changed as a function of time, not only at 102.5 and 100%, but also at 97.5%MLSS;

- (II) Regarding $\dot{V}O_2$ kinetics around MLSS, A_p increased at 102.5%MLSS when compared to 97.5%MLSS. TD_p , τ_p and MRT were similar for the three swimming conditions. Although A_s was not evident for all swimmers during the three swimming intensities, it tended to increase with intensity. Moreover, anaerobic energy contribution was higher at 102.5%MLSS compared to the lower swim velocities and the aerobic system contributions were higher than 98% of the total energy input at the three studied intensities;
- (III) MLSS presented similar values compared to the IAnT, VT and HRT concerning v and bioenergetic factors. On the contrary, $LT_{3.5}$ provided higher values of v and the bioenergetic factors than all other methods. Moreover, highly correlated values between MLSS vs IAnT, VT and HRT were obtained. Meanwhile, the biomechanical parameters analysis,

particularly considering SR, showed that IAnT and VT tests were the best predictors of the gold-standard method (MLSS);

- (IV) The biophysical analysis of the case-study (national record holder swimmer) at intensities around MLSS, and at the intensities provided by the concurrent methods for the evaluation of aerobic capacity, showed specific physiological adaptations allowing to maintain high velocities in a physiological steady state at intensities near the $\dot{V}O_{2max}$. Also, the case-study did not show any $\dot{V}O_2$ slow component at 97.5, 100 or 102.5%MLSS, which may be explained, at least in part, by the higher ventilatory efficiency observed as the v increase. Moreover, the swimmer showed different biomechanical adjustments between MLSS (continuous exercise) and concurrent methods (intermittent exercise), most probably caused by the muscular fatigue established throughout time during continuous exercise, and thus, imposing the most economical biomechanical adjustments to keep a given intensity, what do not necessarily happens during intermittent exercise.
- (V) The v and OUE values attained during OUEP and IAnT intensities were similar and highly correlated, suggesting that both parameters referred to the same biophysical state of the swimmers. However, to prove these evidences also applicable to the gold-standard method (MLSS), further comparisons between MLSS and these methods (OUEP and IAnT) were done in this Thesis. OUE was similar among the methods, showing that OUEP could also be used to assess MLSS, as well as IAnT.

Thus, the overall finding of this Thesis confirmed the intended and induced differences in swimming v between 97.5, 100 and 102.5%MLSS. Secondary to v difference, most bioenergetic factors also increased as a function of intensity, as well as SR among the biomechanical studied parameters. Meanwhile, SL was similar at 97.5 and 100%MLSS, but decreased at 102.5%MLSS,

highlighting a special behavior of this parameter when swimming above MLSS. In addition, at intensities up to MLSS, bioenergetic and biomechanical factors were maintained constant throughout time. However, when the exercise was performed at intensity above MLSS, despite almost bioenergetic parameters were also maintained constant throughout time, an increase of [La-] and VE was observed, and thus, biomechanical factors and ventilatory efficiency (OUE) became compromised, leading swimmers to fatigue and/or voluntary exhaustion over time. Moreover, although the biomechanical factors showed differences between MLSS and concurrent methods (with the exception of SR), most bioenergetic factors obtained for IAnT, VT and HRT methods showed that these are feasible and reliable methods to predict the maximal physiological steady state (MLSS).

In continuation we will discuss the results of the seven studies included in this Thesis. We will do this following an as much integrated manner as possible. We will consider at a time each relevant studied parameter obtained from the studies that analyzed intensities at and around MLSS, and subsequently, we will discuss this parameter from the studies that examined the relationship between the gold-standard method (MLSS) and the concurrent main methods (IAnT, VT, HRT and LT_{3.5}) for the aerobic capacity evaluation which were object of study in this Thesis.

Swimming velocity (v)

As expected (and induced), the mean v values observed for the three studied swim intensities were different among each other, being 97.5%MLSS the slowest and 102.5%MLSS the fastest (**Chapters 2 and 3**). More relevant is that the absolute v values ($\text{m}\cdot\text{s}^{-1}$) at each one of these intensities were lower compared to the $v\text{VO}_{2\text{max}}$, presenting relative values ($\%v\text{VO}_{2\text{max}}$) of $89.4 \pm 4.6\%$, $91.8 \pm 4.6\%$, and $94.0 \pm 4.7\%$, respectively (Figure 8.1 – upper and lower panels) (**Chapter 3**).

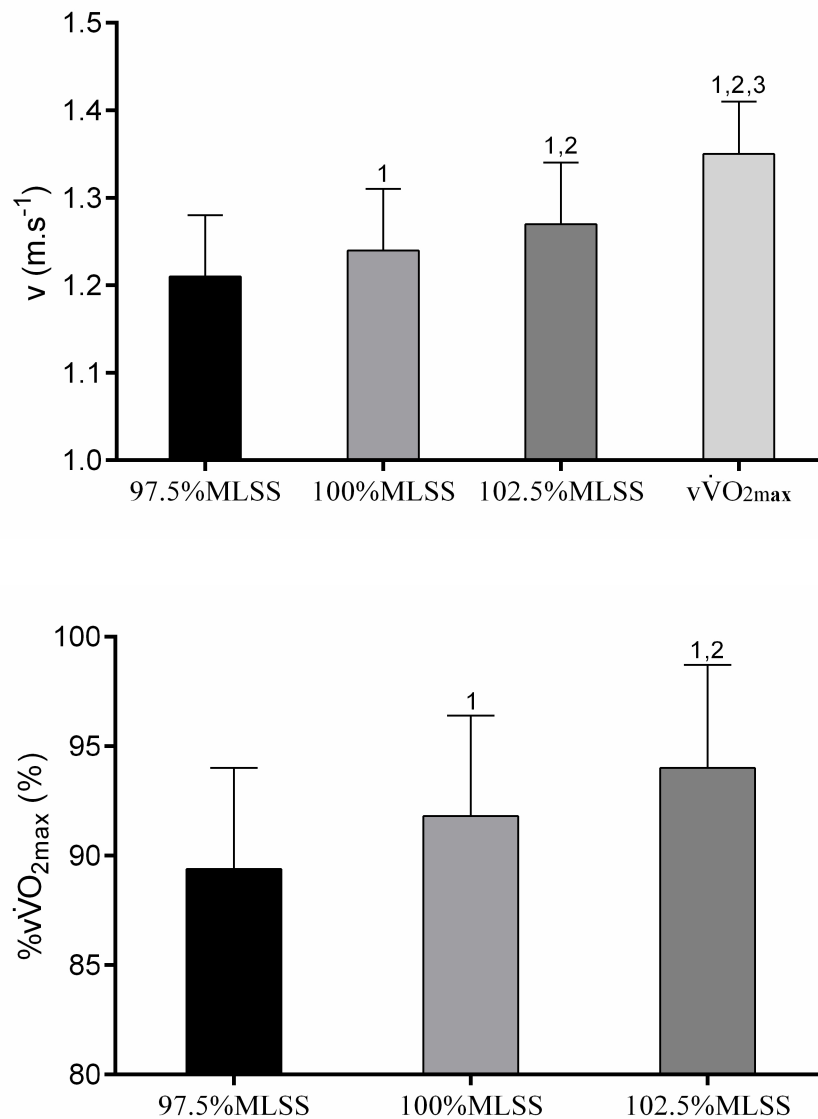


Figure 8.1. Mean $\pm$ SD of velocity (v) at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS), and minimal velocity that elicits maximal oxygen uptake ($v\dot{V}\text{O}_{2\text{max}}$) (upper panel); Mean $\pm$ SD of velocity expressed as a percentage of the minimal velocity that elicits maximal oxygen uptake (% $v\dot{V}\text{O}_{2\text{max}}$) at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS) (lower panel).

^{1,2,3} Values different from 97.5, 100 and 102.5%MLSS, respectively ($p < 0.05$).

Swimming literature also showed expectably higher $v\dot{V}\text{O}_{2\text{max}}$, $v\dot{V}\text{O}_{2\text{peak}}$ and S400 values when compared to submaximal exercise intensities up to MLSS (Baron et al., 2005; Dekerle et al., 2005a; Espada et al., 2014; Pelarigo et al., 2011). Nevertheless, our results mean that MLSS intensity is, for these highly

aerobically trained swimmers, a lower but pretty close intensity to $v\dot{V}O_{2max}$, and that there is a narrow window for further definition of more than one intensity training zone between aerobic capacity (MLSS) and aerobic power ($v\dot{V}O_{2max}$), as some literature tries to suggest (Brickley et al., 2002; Dekerle et al., 2003; Dekerle et al., 2005b; di Prampero et al., 2008; Poole et al., 1988). Indeed, trying to find any well-defined intermediate intensity in between these two intensity zones, it seems more methodologically induced than reality based. We particularly refer to the hypothetical possibility of the critical velocity (CV) to fall in this intensity spectra area, possibility that we are more inclined to suspect as a consequence of the methodology used for CV assessment than emerging from a real intensity incongruence between MLSS and CV. We accept, however, that this is rather controversial, and that our results were not yet elaborated to answer to this question.

Baron et al. (2005), Dekerle et al. (2005a) and Pelarigo et al. (2011) showed slightly lower v for MLSS (mean = $\sim 1.22 \text{ m}\cdot\text{s}^{-1}$) and $\%v\dot{V}O_{2max}$ ($\%v\dot{V}O_{2peak}$ or $\%S400$ – mean = $\sim 88\%$) values when compared to ours results of v ($1.24 \text{ m}\cdot\text{s}^{-1}$) and $\%v\dot{V}O_{2max}$ ($\sim 92\%$) for 100%MLSS. In this sense, Espada et al. (2014) showed higher v ($1.30 \text{ m}\cdot\text{s}^{-1}$) and slightly lower $\%v\dot{V}O_{2max}$ (90%) values compared to our results.

Once those authors studied mostly male swimmers, the higher v and $\%v\dot{V}O_{2max}$ that we found for female swimmers compared with most of all previous studies might be explained by: (i) the different methods used by previous reports for $v\dot{V}O_{2peak}$ (or S400) assessment – overestimating the real $v\dot{V}O_{2max}$ (here, the distinction between the concepts of $v\dot{V}O_{2max}$ and $v\dot{V}O_{2peak}$ may also play a decisive role) or (ii) by aerobic endurance specialization of our swimmers, allowing higher v at MLSS for a lower $v\dot{V}O_{2max}$ ($1.35 \text{ m}\cdot\text{s}^{-1}$) compared to male counterparts in most of the previous studies (1.37 , 1.37 and $1.41 \text{ m}\cdot\text{s}^{-1}$), expressing the ability to use a larger fraction of $v\dot{V}O_{2max}$ at the MISS.

The absolute v values that we found for MLSS, and those obtained for IAnT, VT and HRT tests were similar (**Chapters 4 and 5**) (Figure 8.2 – upper panel). In addition, IAnT, VT and HRT showed similar $\%v\dot{V}O_{2max}$ ($\sim 91\%$) when compared

to MLSS (~92%). Furthermore, it is worthy to underline that all the previous methods (MLSS, IAnT, VT, and HRT), including MLSS, showed lower v values compared to $v\dot{V}O_{2\max}$ values (Figure 8.2 – lower panel), as expected when aerobic capacity and aerobic power are compared.

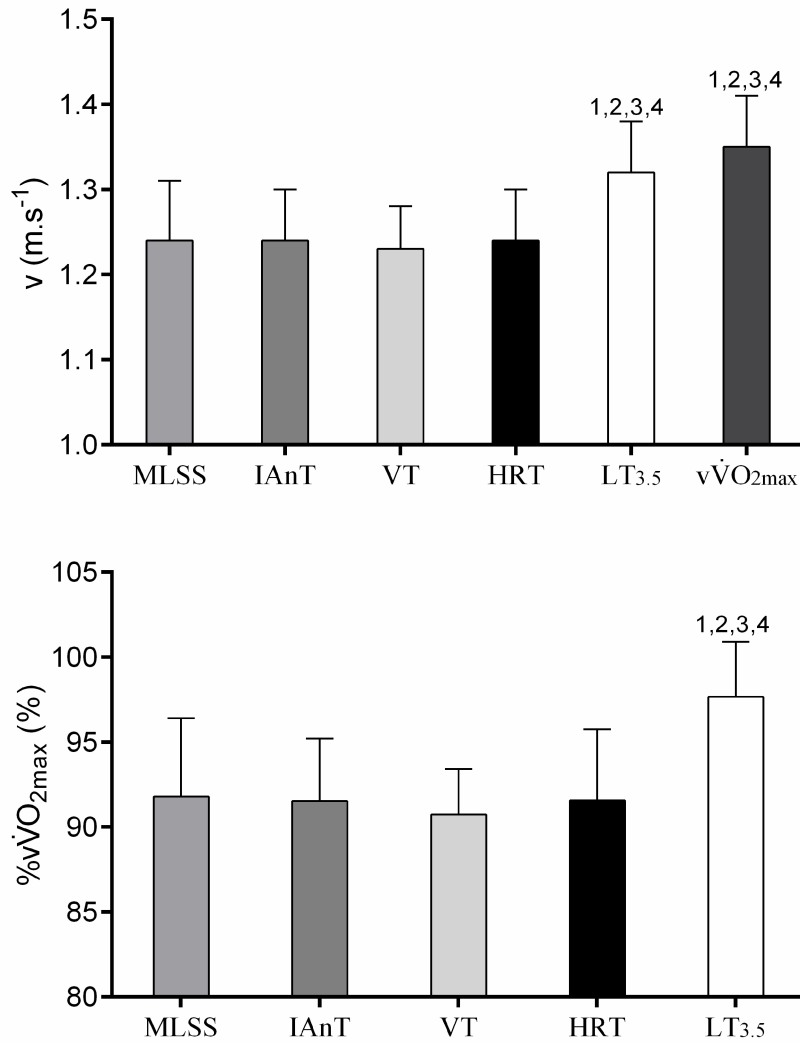


Figure 8.2. Mean $\pm$ SD of velocity (v) at maximal lactate steady state (MLSS), individual anaerobic threshold (IAnT), ventilatory threshold (VT), heart rate threshold (HRT), lactate threshold fixed in 3.5 mmol.L^{-1} ($LT_{3.5}$), and minimal v that elicits maximal oxygen uptake ($v\dot{V}O_{2\max}$) (upper panel); Mean $\pm$ SD of v expressed as a percentage of maximal oxygen uptake ($\%v\dot{V}O_{2\max}$) at intensities of the MLSS, IAnT, VT, HRT, $LT_{3.5}$ (lower panel).

^{1,2,3,4} Values different from 97.5, 100 and 102.5%MLSS, respectively ($p < 0.05$)

Some studies showed similar v values comparing MLSS ($1.09 \text{ m}\cdot\text{s}^{-1}$) and IAnT ($1.09 \text{ m}\cdot\text{s}^{-1}$) (Fernandes et al., 2011), and HRT and AnT (Cellini et al., 1986) in swimming; VT and MLSS (Van Schuylenbergh et al., 2004), and AnT and MLSS (Aunola & Rusko, 1992) in cycling; and MLSS and AnT (Smith & Jones, 2001) in running. On the other hand, Beneke (1995) showed differences in power output between IAnT and MLSS obtained in rowing ergometer. Despite the HRT and MLSS mean v showed similar values in our studies, the methods were poorly correlated ($R^2 = 0.304$). These findings are in accordance with Jones and Doust (1997) and Van Schuylenbergh et al. (2004), who showed that the HRT is not reliable and valid to precisely predict the MLSS. Indeed, in order to allow the recognition that a method is able to successfully replace one other is, at least, necessary that both produce similar mean values and also that both change coherently among subjects, imposing high correlation values.

The swimming v obtained through the VT method showed similar values to MLSS, IAnT and HRT (Figure 8.1 – upper panel), being highly correlated with MLSS (**Chapters 4 and 5**). The literature has shown conflicting findings concerning the comparison of these methods. In accordance with our studies, Espada et al. (2014) showed similar v values between VT ($1.31 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$) and MLSS ($1.30 \pm 0.04 \text{ m}\cdot\text{s}^{-1}$) in swimming. Moreover, Leti et al. (2012) showed that VT and MLSS were similar in terms of running v , as well as similar values were found between AnT/VT and MLSS in cycling (Van Schuylenbergh et al., 2004; Wasserman et al., 1973; Yamamoto et al., 1991). On the contrary, Dekerle et al. (2003) and Laplaud et al. (2006) showed higher VT power output values when compared to MLSS in male cyclists. However, despite some comparisons are available, there are no data in literature reporting differences among IAnT, VT and MLSS in swimming. Therefore, literature has shown a relevant variability and lack of consistency among sports concerning the convergence of the outcomes provided by these methods, reinforcing the importance of specific selected tests to diagnose the aerobic fitness and to individualize the sports training prescription.

In the past decades, $LT_{3.5}$ and LT_4 were considered to be strongly associated to the intensity of the gold-standard method used for the evaluation of aerobic capacity, i.e. MLSS (Heck et al., 1985; Mader et al., 1978; Olbrecht et al., 1985; Wakayoshi et al., 1993). However, studies have shown that the $[La-]$ and v values observed for $LT_{3.5}$ and LT_4 overestimated paired data obtained through MLSS and IAnT tests in swimming (Fernandes et al., 2011), running (Figueira et al., 2008), and rowing (Beneke, 1995; Beneke et al., 2001). Still, some studies showed that fixed $[La-]$ values may underestimate the $[La-]$ values for MLSS in cycling (Beneke et al., 2001; Figueira et al., 2008) or may be similar to $[La-]$ at MLSS in swimming (Greco et al., 2007; Pelarigo et al., 2011), and at IAnT in rowing (Stegmann & Kindermann, 1982). This means that $[La-]$ values at MLSS or IAnT seems to be unsystematic among subjects and sports, imposing that fixed $[La-]$ value tests, like $LT_{3.5}$ and LT_4 should be used with caution for training evaluation and prescription (Bosquet et al., 2002; Stegmann et al., 1981; Stegmann & Kindermann, 1982). Accordingly to the majority of the recent data in several modes of locomotion, our studies verified that the v at $LT_{3.5}$ (and consequently at LT_4) was higher (~6.5%) when compared to the other methods, particularly MLSS (**Chapters 4 and 5**) (Figure 8.2 – upper panel), as well as were higher $\%v\dot{V}O_{2max}$ values for $LT_{3.5}$ when compared to all other methods (Figure 8.2 – lower panel). This shows that, despite the previously highlighted limitations, $LT_{3.5}$ has some potential for qualitative evaluation of training progresses ($R^2 = 0.602$), but not for training intensity prescription.

Summarizing, our results showed that some of the concurrent testing methods (IAnT, VT and HRT) may better predict the intensity of the MLSS assessed through the MLSS, when compared with other procedures extensively applied for the swimming aerobic capacity evaluation (like $LT_{3.5}$ and, consequently, LT_4). Meanwhile, we may state that the MLSS seems to be very sensitive to small changes in intensity, like 2.5% (increasing v), imposing anticipated exercise ending in eight out of ten swimmers. This was underlined by the observed increases in the C (cf. **Chapter 2**), but particularly, by the observed changes on the biomechanical parameters (increased SR, and reduced SL).

Oxygen uptake ($\dot{V}O_2$)

In the present Thesis, gas exchange values ($\dot{V}O_2$ and $\dot{V}E$) were directly measured breath-by-breath as a function of time for swimming intensities below, at, and above MLSS (**Chapters 2 and 3**). The $\dot{V}O_2$ values in our study increased with intensity, showing a 7.7% increase between 97.5 and 100%MLSS, and 7.3% between 100 and 102.5%MLSS (Figure 8.3). Despite the difference in percent increase of $\dot{V}O_2$ values between the two 2.5% intensity increases was very small, it might suggest that the excess of energy supply was not only supported by oxidative process, but partially also by anaerobic energetic pathways above the MLSS intensity. This, inclusively, may be emphasized if we consider the expected non-linear variation of energy expenditure with v . Indeed, in accordance with swimming literature, $\dot{V}O_2$ values increases with v , once higher v values are associated with an elevated C imposed by drag and associated power output - $P = D * v$ (Capelli et al., 1998; Di Prampero et al., 1974; Pendergast et al., 2003; Pendergast et al., 1977).

All the previous researches conducted during prolonged continuous swimming (MLSS) have used measurements during the recovery period to assess $\dot{V}O_2$ and $\dot{V}E$ values (Baron et al., 2005; Dekerle et al., 2005a). In theory, this method (perhaps with the exception of the backward extrapolation approach) should underestimate $\dot{V}O_2$ values measured during exercise, once $\dot{V}O_2$ off-transient kinetics seem to be very fast (Sousa et al., 2011), underpinning the use of the backward extrapolation method to estimate exercise values. Despite expectedly underestimated, the previous available $\dot{V}O_2$ values at MLSS - 4.94 L.min⁻¹ (Dekerle et al., 2005a) – were markedly higher than ours values (2.83 L.min⁻¹; 46.4 mL.kg⁻¹.min⁻¹). However, the results from Dekerle et al. (2005a) were obtained for men (69.6 mL.kg⁻¹.min⁻¹), while our sample was only composed by female (46.4 mL.kg⁻¹.min⁻¹) swimmers.

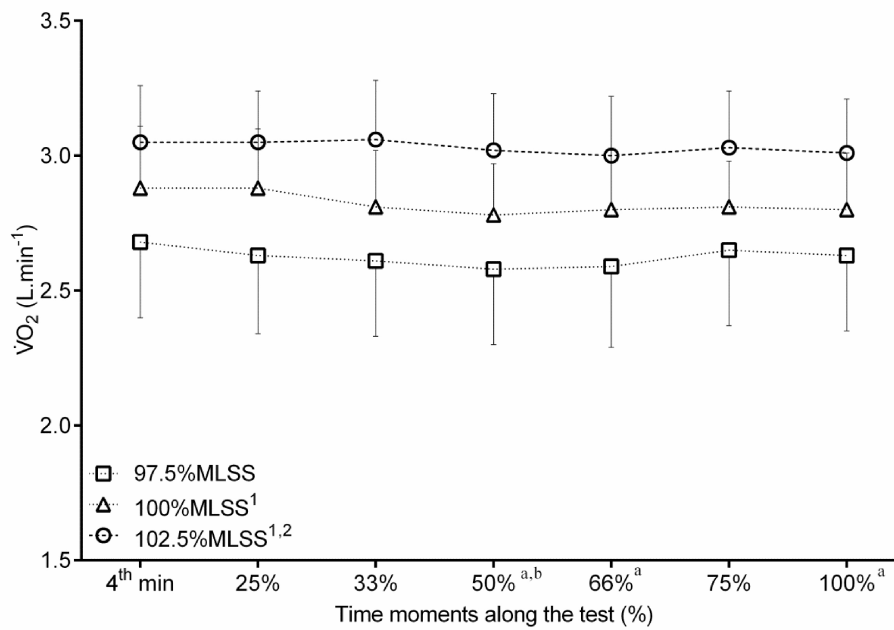


Figure 8.3. Mean $\pm$ SD values of oxygen uptake (VO_2) throughout time at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS). The statistical outcomes are described both by intensity and time effect, once there was not a significant interaction effect.

^{1,2} Values different from 97.5 and 100%MLSS, respectively ($p < 0.05$);

^{a,b,c,d} Values different from 4th min, 25%, 33% and 50%, respectively ($p < 0.05$).

Thus, the lower VO_2 values in our results are likely explained by sex differences, related to the lower muscle mass of females and, consequently, lower mitochondrial content and total oxygen extraction from the blood by the tissues, expressing lower $\text{VO}_{2\text{max}}$ and submaximal VO_2 values when compared to male counterparts (Charkoudian & Joyner, 2004; Cortright & Koves, 2000; Hopkins & Harms, 2004; Pate & Kriska, 1984; Scalzo et al., 2014). This higher $\text{VO}_{2\text{max}}$ values could be likely explained by the men's cardiac work, with higher systolic volume as a consequence of larger body size, and then, circulating more oxygen-carrying hemoglobin than the women athletes (Wernstedt et al., 2002). Lower female VO_2 values compared to their male counterparts were also observed in swimming (Bentley et al., 2005; Costill et al., 1985; Fernandes et al., 2005; Fernandes et al., 2008; Pendergast et al., 1977). These studies reported similar $\text{VO}_{2\text{max}}$ values than ours ($54.9 \pm 6.7 \text{ mL.kg}^{-1}.\text{min}^{-1}$) for high level female middle- and long-distance swimmers, which reinforces the training and

specialization levels of our swimmers (**Chapter 2**). In our study, the MLSS for women occurred at 84.7% (3.8% SD) of $\dot{V}O_{2\max}$, value similar to the previous reports for men swimmers (86.1% $\dot{V}O_{2\text{peak}}$) (Dekerle et al., 2005a). It is worthy to underline that this male percentage was relative to $\dot{V}O_{2\text{peak}}$ and ours to $\dot{V}O_{2\max}$, but $\dot{V}O_{2\text{peak}}$ was obtained using recovery values.

$\dot{V}O_2$ at MLSS, IAnT, VT and HRT showed similar values ($\sim 46 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) in our study, but $\dot{V}O_2$ values at $LT_{3.5}$ were higher ($\sim 52 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). Still, $\dot{V}O_2$ values for all methods were highly correlated to those obtained through the MLSS (**Chapter 4**). These $\dot{V}O_2$ differences between $LT_{3.5}$ and other methods ($\sim 14\%$) could be associated to higher C and drag, once $LT_{3.5}$ v showed to be $\sim 6.5\%$ higher than the one extracted from the other methods.

In addition, MLSS, IAnT, VT and HRT tests showed $\dot{V}O_2$ values around 85% of $\dot{V}O_{2\max}$. As previous stated, these values corroborated with the results measured by the recovery period in the study conducted by Dekerle et al. (2005a), that showed similar % $\dot{V}O_{2\max}$ values ($\sim 86\%$) for the MLSS in well-trained swimmers. Meanwhile, previous studies in cycle-ergometer showed lower % $\dot{V}O_{2\max}$ values (70-75%) for the MLSS (Baron et al., 2003; Baron et al., 2008) when compared with our study. These differences concerning % $\dot{V}O_{2\max}$ could be likely explained by the training level and specialization of the subjects (higher % $\dot{V}O_{2\max}$ values in a physiological steady state for long-distance swimmers), by the effect of the sport modality (swimming vs cycle ergometer), and finally by the specific physiological adaptations occurred in aerobic endurance athletes. The latter phenomena is commonly explained by researchers in which those particular athletes exhibit a lactate/velocity curve shifted to the right (Holfelder et al., 2013), allowing subjects to keep high velocities in a physiological steady state at intensities near to the $v\dot{V}O_{2\max}$. Moreover, aerobic endurance athletes usually present higher phenotypic expression of oxidative muscle fibers compared to sprint athletes (Tanaka & Swensen, 1998), fibers which consumes lactate (Gladden, 2008), allowing to support the $\dot{E}$ required in high swimming intensities, and explaining the typical low final [La-] values observed in our study.

On the other hand, and as expected from other markers (v and $[La-]$), $LT_{3.5}$ showed higher $\%VO_{2max}$ (~95%) when compared to the other methods for the evaluation of swimming aerobic capacity (**Chapter 4**). These values have normally been associated with maximal efforts of 800 and 1500 m events, where VO_2 and $[La-]$ levels are normally higher than for the aerobic capacity exercise (Sousa et al., 2014). Furthermore, our case-study, i.e. an elite endurance swimmer and middle to long-distances national record holder, showed low VO_2 (78% VO_{2max}) and high v values (93% vVO_{2max}) in maximal physiological steady state (100%MLSS), values pretty close to maximal ones (**Chapter 7**). These characteristics could be explained by the predominance of the aerobic energy pathways, as well as an elevated capacity to sustain metabolic steady state intensities (Rodriguez & Mader, 2011), as previously discussed about this phenomena in the latter paragraph.

Thus, VO_2 values here reported for the three swimming intensities highlighted important information about the VO_2 responses during progressively intense rectangular efforts up to physiological steady state and above. In fact, previously literature has shown that VO_2 values tend to increase throughout time until voluntary exhaustion at intensities above MLSS (Barbosa et al., 2009; Burnley & Jones, 2007; Pringle & Jones, 2002; Xu & Rhodes, 1999). However, the VO_2 values found from our elite endurance swimmers showed a constant behavior of VO_2 throughout time at 102.5%MLSS (**Chapter 2**), despite a slow component was observed on VO_2 on-transient kinetics until the 10th min of exercise for some of the swimmers (**Chapter 3**). This highlights the importance of being aware to the range of intensities between the MISS and VO_{2max} , particularly on the possible combined adaptive effect of different physiologic parameters, but also considering the decisive role of the biomechanical factors on the overall biophysical scene characterizing each particular intensity zone. In this domain, further investigation is clearly needed.

Meanwhile, from the comparisons of the gold-standard method (MLSS) and the concurrent methods for the aerobic capacity evaluation, another important question emerged: do the exercise modes (continuous vs intermittent) influence

the final outcome regarding VO_2 adaptation to this particular intensity? Indeed our results pointed out new insights on this issue suggesting that some feasible and reliable methods for v at MLSS estimation (IA_nT, VT and HRT tests) based on intermittent exercise, showed similar VO_2 responses when compared to the gold-standard method (MLSS) determined by continuous exercise (**Chapter 4**).

Oxygen uptake kinetics

Subsequently to the previous analysis of measured VO_2 values over time at 97.5, 100 and 102.5%MLSS, VO_2 data were also fitted through mathematical modelling for VO_2 kinetics analysis. This type of analysis is exemplified in Figure 8.4 for a 30 min continuous test (MLSS) with a pause during the 10th min for blood collection. These analyses were previously applied for maximal and submaximal exercises in swimming (Fernandes et al., 2012; Pessoa Filho et al., 2012; Reis et al., 2012a, 2012b; Reis et al., 2010; Sousa et al., 2014), and they were used in this study to evaluate and compare VO_2 kinetics at and around MLSS (**Chapter 3**).

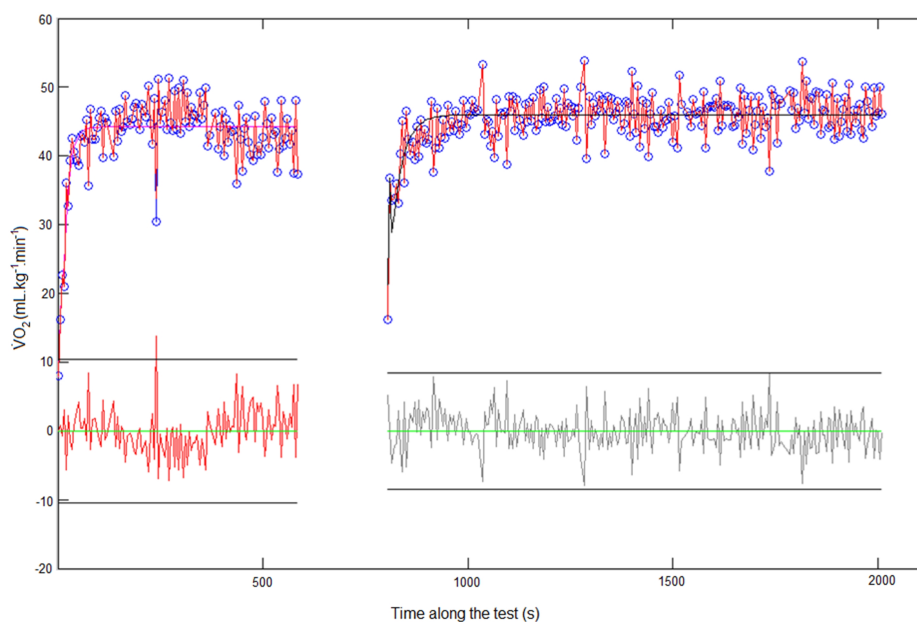


Figure 8.4. Example of oxygen uptake (VO_2) kinetics fitted by mathematical modeling along the maximal lactate steady state test (MLSS), with a pause during the 10th min for blood collection. Residuals are also shown.

The τ_p showed similar values for the initial exercise phase – until the 10th min (mean = 15.4 ± 5.2 s) - and final exercise phase – from exercise resume to the end (mean = 10.0 ± 4.7 s), independently of swimming intensity, but decreased with previous exercise (comparing the 10th min with exercise end) at all studied intensities (97.5, 100 and 102.5%MLSS). For all intensities, τ_p was similar in our study when compared to those previously reported in swimming (~15-20 s) (Pessoa Filho et al., 2012; Reis et al., 2012a, 2012b), cycling (Berger & Jones, 2007; Koppo et al., 2004), rowing (Ingham et al., 2007), and running (Borrani et al., 2001; Carter et al., 2000). Therefore, our τ_p values for intensities up to and above MLSS seem to respond similarly with those previously reported during different intensity domains for well-trained athletes.

Usually, a faster steady state attainment and an oxygen deficit reduction are related to fatigue delay and increased exhaustion time (Burnley & Jones, 2007; Carter et al., 2000; Jones & Burnley, 2009). Well-trained athletes who showed these previous characteristics may be able to perform at higher intensities with lower anaerobic energy/glycolysis requirements during the transition from rest to exercise (Burnley & Jones, 2007). Our results confirm this reasoning, once they were obtained from highly specialized middle- and long-distance swimmers, obtaining τ_p values similar to those reported in the literature concerning physiological adaptations induced by aerobic endurance training (Burnley & Jones, 2007; Carter et al., 2000).

The results observed for A_s at 97.5, 100 and 102.5%MLSS (**Chapter 3**) were partially in contrast with previous literature. Indeed, previous works reported A_s occurrence at corresponding intensities domains (Burnley & Jones, 2007; Gaesser & Poole, 1996; Poole & Richardson, 1997), particularly at the higher intensities. On the contrary, our results have shown A_s to chaotically occur or not (A_s appearance), during the three swimming studied intensities, but with a tendency to increase with the increase of exercise intensity (2.2 ± 1.1 , 2.9 ± 0.8 and 4.5 ± 1.6 mL.kg⁻¹.min⁻¹, respectively). When occurred, it happened usually observed during the initial phase (the first 10th min of exercise), not during the final phase of the exercise. In addition, only two swimmers showed A_s

occurrence in the three swimming conditions and in both exercise phases, and one swimmer did not show any A_s during all the swimming efforts. It is worthy to emphasize the curiosity of that particular swimmer being a national record holder (800 and 1500m) and the best endurance swimmer of the sample (**Chapter 7**). Our partially contradictory findings could be explained by the specific physiological adaptations that may have occurred by highly aerobic endurance training status of subjects (like our swimmers), such as faster τ_p (Carter et al., 2000), increase in the mitochondrial content of the cell (Holloszy & Coyle, 1984), alterations in the mitochondrial sensitivity to the respiration regulators (Dudley et al., 1987), and the fact that these endurance athletes might have mainly type I muscle fibers (Holloszy & Coyle, 1984). Thus, our endurance swimmers with fast TD and τ_p , would be able to adjust faster the physiological requirements for aerobic performance, and thus, minimize the A_s during high intensity exercises. In addition, the A_s appearance is mainly explained by the type II fibers recruitment with fatigue (Poole et al., 1991), and by its magnitude, that is correlated with [La-] rise (Gaesser & Poole, 1996; Holloszy & Coyle, 1984); all the previous aspects that characterize A_s appearance are contrary to our endurance swimmers characteristics. Thereby, the absence of significant A_s in our study may be likely explained by the high-level aerobic endurance training of our swimmers (Billat et al., 1998), or may stress out the possibility of this type of athlete to be less susceptible to A_s occurrence.

Minute ventilation (VE)

As expected with increases of intensity, VE also increases to maintain blood gas homeostasis during exercise, which may be compromised in some subjects when ventilatory demands exceed the capacity of the lung and chest wall to generate flow and volume, resulting in a high breathing work and probably diaphragm fatigue caused by expiratory flow limitation (Guenette & Sheel, 2007). Those factors could lead to impaired exercise performance caused by the competitive relationship between respiratory and locomotion muscles for blood flow (Guenette & Sheel, 2007; Harms et al., 1997; Harms et al., 2000). In

accordance with previous aspects related to the increases of intensity, VE values increased, in our study, as a function of intensity: 9% between 97.5 and 100%MLSS, and 12.7% between 100 and 102.5%MLSS. In addition, VE remained constant at 97.5 and 100%MLSS, but increased at 102.5%MLSS as a function of time (Figure 8.5) (**Chapter 2**). In agreement with our results, Baron et al. (2003) showed similar VE values ($\sim 71.6 \text{ L}\cdot\text{min}^{-1}$) for cycling at 100%MLSS. The increased VE seems to be time-dependent, which likely occurs due to a respiratory compensation secondary to the build-up of [La-] in blood (metabolic acidosis) and C of swimming, at velocities exceeding the aerobic supply capacity of our swimmers.

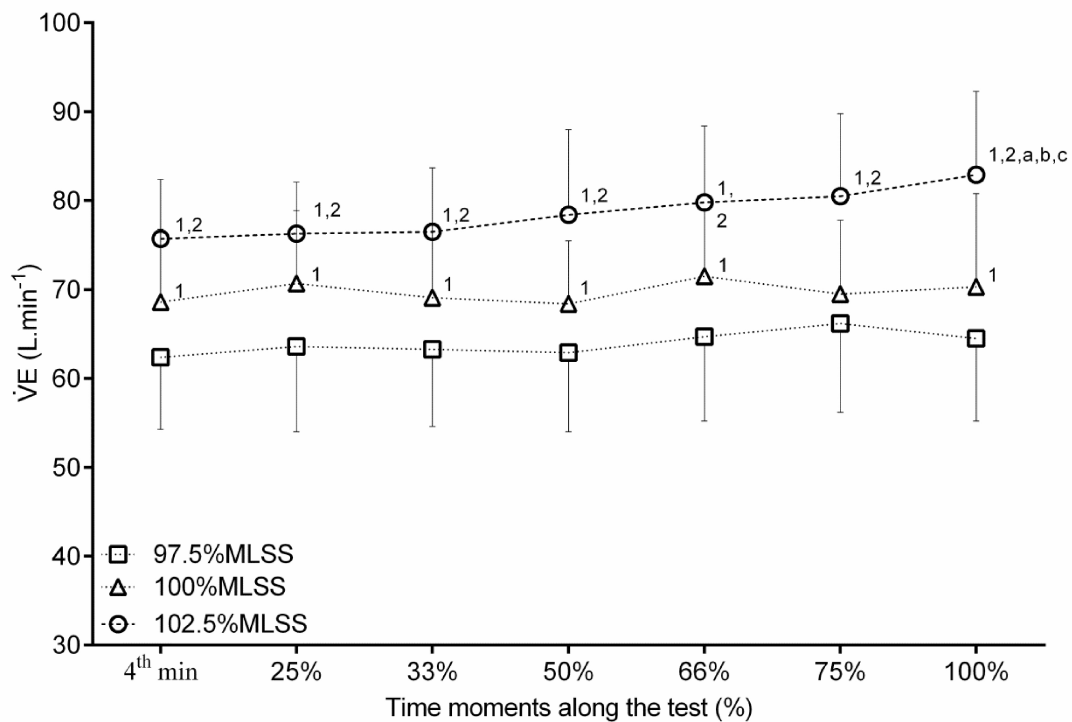


Figure 8.5. Mean $\pm$ SD values of minute ventilation (VE) throughout time at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS).

^{1,2} Values different from 97.5 and 100%MLSS, respectively ($p < 0.05$);

^{a,b,c} Values different from 4th min, 25% and 33%, respectively ($p < 0.05$).

Meanwhile, VE showed higher values at LT_{3.5} when compared to MLSS, IAnT, VT and HRT, but the latter mentioned methods were similar between each other (**Chapter 4**). In addition, VE showed lower values at MLSS and VO_{2max} intensities (~70 and 92 L.min⁻¹, respectively) in this study when compared to those reported by Baron et al. (2008) (~75 and 121 L.min⁻¹, respectively), even though these authors used recovery period measurements. These lower VE values could likely be explained by sex differences presented by the expiratory exercise physiology, since most of subjects previously studied were male. Additionally, female athletes typically have lower expiratory flow rates and smaller lung volumes compared to male athletes, even when values are normalized by height (Sheel et al., 2004). These specific differences in respiratory structure may likely influence gas exchange and ventilatory response during exercise (Guenette & Sheel, 2007), explained by lower VE values found in our study (**Chapter 4**). These findings reinforce two main conclusions: (i) 102.5%MLSS is an exercise intensity not allowing a physiological steady state, and (ii) LT_{3.5} refers to an exercise intensity higher than the one pointed out by the remaining methods studied in this Thesis.

Oxygen uptake efficiency (OUE)

The ratio of VO₂ and VE is described as an indicator of ventilatory efficiency (OUE) (Baba et al., 1996; Sun et al., 2002). The OUE values found in this study were lower at 102.5%MLSS compared to 97.5 and 100%MLSS during the final stage of exercise (between 75 and 100% time duration), but at 50% of the test duration the OUE at 102.5%MLSS was already lower than at 97.5%MLSS, pointing out that exercise intensity compromises OUE, particularly as a function of exercise time duration. Indeed, this values decreased as a function of time at 97.5%MLSS, but particularly at the higher intensities studied, especially 102.5%MLSS, where a steeper decrease was observed from 66% of the total exercise duration (Figure 8.6) (**Chapter 2**).

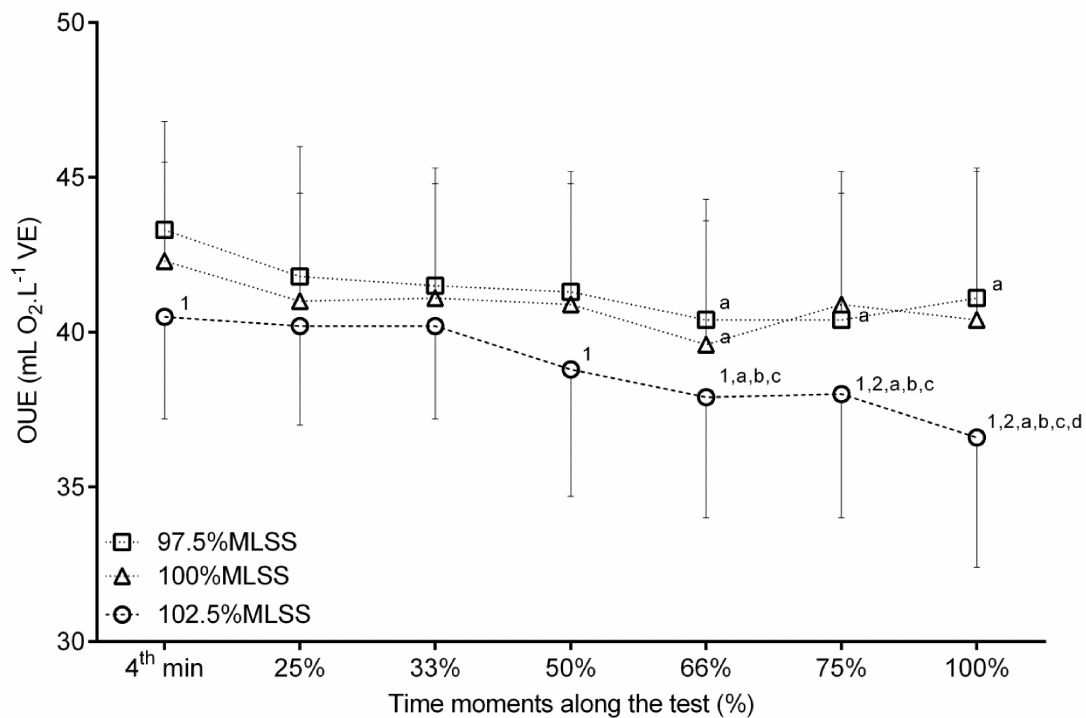


Figure 8.6. Mean $\pm$ SD values of oxygen uptake efficiency (OUE) throughout time at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS).

^{1,2} Values different from 97.5 and 100%MLSS, respectively ($p < 0.05$);

^{a,b,c,d} Values different from 4th min, 25%, 33% and 50%, respectively ($p < 0.05$).

At 97.5%MLSS, the mild decrease in OUE could be explained by a slight decreased VO_2 accompanied by a constant VE. Meanwhile, the decreased VO_2 as a function of time at this submaximal intensity could be explained by biomechanical adjustments (Pelarigo et al., 2011) to reduce C and energy expenditure, with swimmers tending to improve propelling efficiency and/or decreasing drag (Figueiredo et al., 2013b; Pendergast et al., 2005; Toussaint & Beek, 1992; Toussaint & Hollander, 1994). At the 102.5%MLSS, OUE showed a greatest decrease throughout time compared to 97.5 and 100%MLSS, probably explained by the respiratory compensation for metabolic acidosis, with increased VE despite the constant VO_2 (Baba et al., 1996). Here the reduced SL and SI, and the increased SR pointed out a different biomechanical adaptation, with a deleterious effect on efficiency and/or drag increase (**Chapter 2**). Moreover, it may happened an increased pulmonary dead space due to the

reduction in tidal volume, and the resultant increase in breathing frequency to meet the increased VE needs (Baba et al., 1996). If the pulmonary dead space increased during exercise, the VE would have to be increased to provide the same alveolar ventilation at a higher C of the respiratory muscles (Harms et al., 2000).

In our study, OUE values were similar as a function of time at 97.5 and 100%MLSS. However, at 102.5%MLSS, OUE values were lower than at both 97.5 and 100%MLSS and decreased after 66% of the total exercise duration until the end of exercise. This could be explained by both the respiratory compensation for metabolic acidosis and increased pulmonary dead space. This might also be associated with biomechanical control and voluntary exhaustion. The reduced OUE is also likely responsible for the fact that eight out of ten of the swimmers were not able to complete the total 30 min of exercise at 102.5%MLSS.

The behavior of VE and OUE values found in our results suggests that at exercises up to MLSS intensity, these variables had similar responses as those also observed with [La-] until the MISS, once both variables were constant over time until this intensity zone. However, as expected, when the exercise was performed above MLSS, swimmers needed to increase VE by hyperventilation with decrease of OUE, and increased [La-], most probably caused by respiratory compensation for metabolic acidosis, and thus, leading most of swimmers to do not finish the 30 min swim at 102.5%MLSS, due to fatigue. It suggests that both plateau losses (OUE and [La-]) might be used as markers of the same phenomena – the end of MISS, marking the aerobic capacity limit intensity (the MISS).

Moreover, we further aimed to examine the practical application of the OUEP, comparing it with the IAnT, both determined by an intermittent progressive incremental test. For this purpose, we observed similar OUE and v values obtained during OUEP ($43.9 \pm 5.8 \text{ mL VO}_2 \cdot \text{L}^{-1} \text{ VE}$ at $v = 1.20 \pm 0.05 \text{ m} \cdot \text{s}^{-1}$) and IAnT ($42.9 \pm 5.8 \text{ mL VO}_2 \cdot \text{L}^{-1} \text{ VE}$ at $v = 1.22 \pm 0.05 \text{ m} \cdot \text{s}^{-1}$) (**Chapter 6**). However, to attain the fully understanding of the OUE analyses, comparisons between the

gold-standard method (MLSS) and the previous reported methods (OUEP and IAnT) were also conducted. It was observed that the OUE values for MLSS (mean = $40.9 \pm 4.1 \text{ mL VO}_2 \cdot \text{L}^{-1} \text{ VE}$) (**Chapter 2**) were similar when compared to OUEP and IAnT, showing that OUEP loss can contribute to explain both MLSS, as well as IAnT. OUES indicates an index of ventilatory efficiency associated with VO_2 (Akkerman et al., 2010), leveling off at the intensity corresponding to the IAnT. This implies that, at this particular intensity, a deleterious effect of exercise intensity is observed over the respiratory dynamics, affecting all the oxidative metabolic response of the swimmer. Since middle- and long-distance swimming performance is significantly influenced by the $\text{VO}_{2\text{max}}$ and the AnT, the results obtained during this study can provide valuable information for designing training programs for swimmers (**Chapter 6**).

Carbon dioxide production (VCO_2)

Although none of the studies included in this Thesis have addressed questions about VCO_2 response, we believe that it might be relevant to discuss this parameter in this general discussion. It is well established that VCO_2 increases with exercise intensity, what was also observed in our results, with 97.5% implying the lowest and 102.5%MLSS the highest values. In addition, VCO_2 showed similar values at MLSS, IAnT and HRT, but VT and $\text{LT}_{3.5}$ showed lower and higher values, respectively, when compared with the MLSS. Highly correlated values for VCO_2 at IAnT, HRT and $\text{LT}_{3.5}$ regarding to MLSS were found.

Only one study was found in swimming literature that showed VCO_2 values during MLSS. Our results showed lower VCO_2 values at MLSS and $\text{VO}_{2\text{max}}$ intensities (~ 2.5 and $3 \text{ L} \cdot \text{min}^{-1}$, respectively) when compared to the values (~ 2.7 and $4.7 \text{ L} \cdot \text{min}^{-1}$, respectively) reported by Baron et al. (2008). These differences could probably be explained by the same reasons previously discussed about VE, such as sex differences. Additionally, respiratory structure differences might likely influence gas exchange and ventilatory response during exercise

(Guenette & Sheel, 2007), explained by the lower $\dot{V}E$ and $\dot{V}CO_2$ values observed in our study.

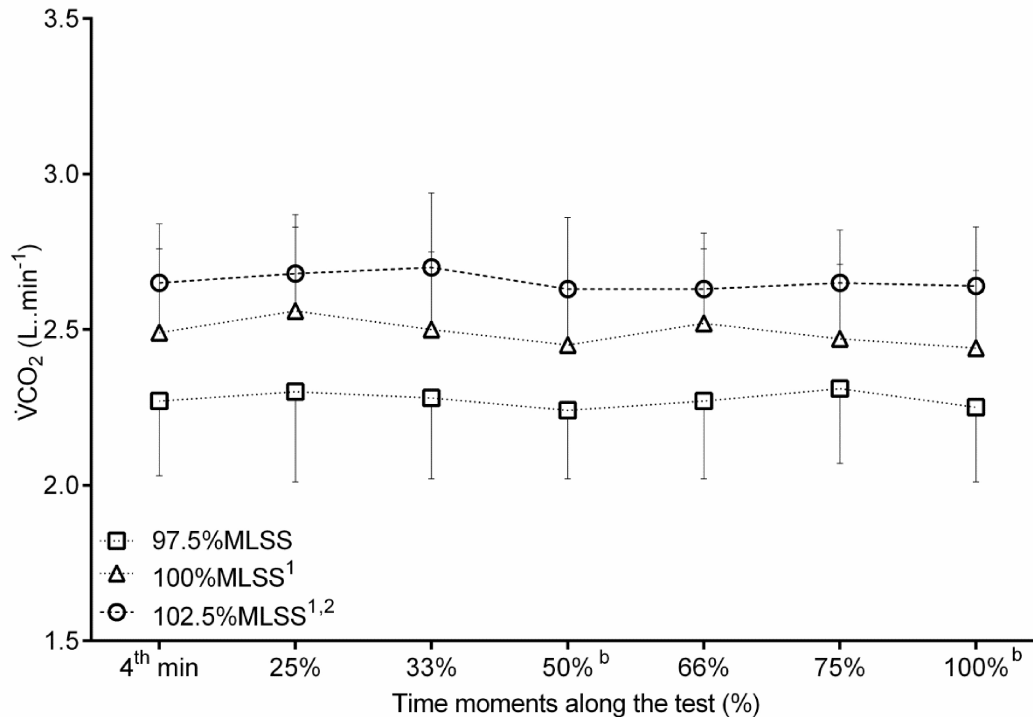


Figure 8.7. Mean $\pm$ SD values of carbon dioxide production ($\dot{V}CO_2$) throughout time at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS).

^{1,2} Values different from 97.5 and 100%MLSS, respectively ($p < 0.05$);

^b Values different from 25% ($p < 0.05$).

Blood lactate concentration ([La-])

The [La-] showed higher values at 102.5%MLSS (2.97 ± 0.87 mmol.L⁻¹) compared to 97.5 and 100%MLSS (1.48 ± 0.39 and 1.89 ± 0.77 mmol.L⁻¹, respectively) (**Chapter 2 and 3**). Our swimmers showed lower [La-] values at 100%MLSS (**Chapters 2, 3, 4 and 7**) when compared to those found in the swimming literature (2.8 to 4.5 mmol.L⁻¹) (Baron et al., 2005; Dekerle et al., 2005a; Espada et al., 2014; Fernandes et al., 2011; Figueiredo et al., 2014; Greco et al., 2013; Pelarigo et al., 2011), and previous studies from other sports (2 to 8 mmol.L⁻¹), such as cycling (Barbosa et al., 2009; Beneke et al., 2000; Denadai et al., 2004; Figueira et al., 2008; Hauser et al., 2014), running (Billat

et al., 2004; Dittrich et al., 2013; Dittrich et al., 2014; Leti et al., 2012) and rowing (Beneke, 1995; Klusiewicz, 2005).

Moreover, the [La-] values obtained at IAnT, VT and HRT did not show differences when compared to MLSS (1.49, 1.55 and 1.81 mmol.L⁻¹, respectively) (**Chapter 4**), being also lower than those mostly reported in literature for these particular tests (Fernandes et al., 2011; Hofmann et al., 1994; Ribeiro et al., 2014; Yamamoto et al., 1991), and naturally, lower than 3.5 mmol.L⁻¹ used as a fixed value at LT_{3.5}. These lower [La-] values could be explained by differences of sex and specialization of the subjects. Indeed, almost all subjects participating in the previous studies were male and/or non-long-distance trained swimmers. Part of this difference in the [La-] values is likely due to the lower [La-] values commonly observed for women compared to men in long-distance exercise (Crewther et al., 2006; Greco et al., 2007). In addition, lower [La-] values found for our female swimmers might be explained by lower lean muscle mass (Crewther et al., 2006) and testosterone levels (Deschenes & Kraemer, 2002). This could suggest a different metabolic balance between carbohydrates and fat throughout prolonged exercises (Greco et al., 2007; Tarnopolsky et al., 1990). Indeed, such endurance athletes are characterized by a higher phenotypic expression of oxidative muscle fibers compared to sprint athletes (Tanaka & Swensen, 1998), fibers which consumes lactate (Gladden, 2008), supporting a physiological steady state at intensities near the $\dot{V}O_{2max}$.

Despite the possible explanations for the observed low [La-] values, it is relevant to emphasize the unusually low [La-] values observed, and the two possible concurrent conclusions obtainable out of them: (i) swimming is requiring a high aerobic profile of the athletes or (ii) swimmers are being trained far much on the aerobic domain, than actually is required by the typical competitive exercise duration. Considering typical energy contribution results for swimming Olympic and World Championship events (Pyne & Sharp, 2014) and general Physiology outcomes (Gastin, 2001), we dare to risk that our swimmers

might be submitted to an unusual aerobic training load, most suitable, for instance, for open-water competitions.

Heart rate (HR)

When a swimmer starts to swim from rest to a given exercise intensity, the cardiorespiratory system needs to adapt the energy demand imposed by exercise, and then, requiring an increase in cardiac output and oxygen distribution from blood to tissues. Once the cardiac output is the product of stroke volume and HR, increases in cardiac output during increments of exercise intensity are associated with HR increase. Thus, as expected with the increase of intensity, our HR values increased between 97.5 and 102.5%MLSS. No differences were observed between 97.5 and 100% and between 100 and 102.5%, reinforcing the low discriminative capacity of HR for exercise intensity, inclusively at exercise domains below $\dot{V}O_{2max}$ (Maglischo, 2003; Peyrebrune & Hardy, 1992). In addition, HR showed similar adjustments as a function of time at 97.5, 100 and 102.5%MLSS, drifting up around 10 bpm from the 4th min to the end of the test (Figure 8.8) (**Chapters 2 and 3**). The increased HR observed in prolonged exercise is defined as “cardiovascular drift” (Fritzsche et al., 1999), likely explained by an increase in sympathetic nervous system activity and circulating norepinephrine concentrations, as well as other mechanisms to maintain cardiac output (Baron et al., 2008). Dekerle et al. (2005a) and Dekerle et al. (2005b) showed HR values around 178 beats.min⁻¹, as well as Oliveira et al. (2012a) also showed HR values of 170 ± 10 beats.min⁻¹ during 100%MLSS in swimming. Similar intermediate HR values (174 ± 10 beats.min⁻¹) found in our study at 100%MLSS.

Furthermore, we compared the gold-standard method (MLSS) and concurrent methods (IAnT, VT, HRT and LT_{3.5}) for the aerobic capacity evaluation. HR showed similar values among MLSS, IAnT, VT and HRT (mean = 170.1 to 173.6 beats.min⁻¹), but lower values compared to LT_{3.5} (mean = 185.1 beats.min⁻¹). In addition, all concurrent methods were highly correlated to the MLSS. The HR observed during the $\dot{v}O_{2max}$ (HR_{max}) (mean = 189.6 beats.min⁻¹

¹⁾ was higher compared to the HR of MLSS, IAnT, VT and HRT, but was similar compared to LT_{3.5}. Our findings are in accordance with Dekerle et al. (2005a), who also showed lower HR values at MLSS than HR_{max} (~178 and 184 beats.min⁻¹, respectively).

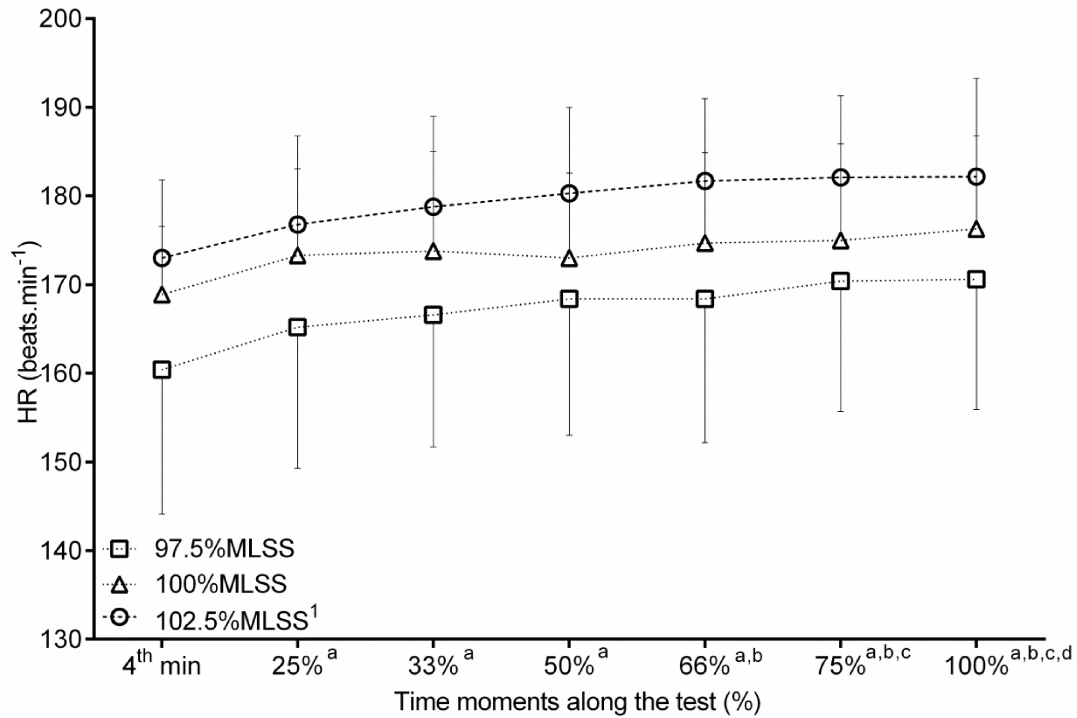


Figure 8.8. Mean $\pm$ SD values of heart rate (HR) throughout time at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS). The statistical outcomes are described both by intensity and time effect, once there was not a significant interaction effect.

¹ Values different from 97.5%MLSS ($p < 0.05$);

^{a,b,c,d} Values different from 4th min, 25%, 33% and 50%, respectively ($p < 0.05$).

Total energy expenditure ($\dot{E}$) and energy cost (C)

Swimming performance is defined as emerging from the conversion of the swimmer's metabolic power ($\dot{E}$) to mechanical power with a given energetic efficiency. In addition, C is defined as the $\dot{E}$ required to displace the body over a given unit of distance (Barbosa et al., 2010; di Prampero et al., 2011; Schmidt-Nielsen, 1972). Once mechanical power is the product of drag force times v , and drag varies with the square function of v , $\dot{E}$ increases with the cube of the

swimming velocity (Toussaint & Hollander, 1994). Thus, $\dot{E}$ and C differs widely according to exercise intensity (and, consequently, duration) and, expectedly, the contribution of the aerobic and anaerobic energy systems will also change (di Prampero et al., 2011).

In this Thesis, we used two methods to assess $\dot{E}$ and, consequently, C. The first was based on direct methods during submaximal constant swimming (97.5, 100 and 102.5%MLSS) using $\dot{V}O_2$ and $\dot{V}CO_2$ to calculate the respiratory exchange quotient, and thus determining the caloric equivalent of $\dot{V}O_2$. This method allows to analyze both the $\dot{E}$ and C dynamics throughout the entire exercise duration (**Chapter 2**). In this chapter, $\dot{E}$ and C increased around 7.5 and 5% as a function of v, respectively. However, changes of C with intensity were only significant between 97.5 and 102.5%MLSS. In addition, these variables ($\dot{E}$ and C) were pretty constant throughout time at the three swimming intensities, and increased as a linear function of v, although variables presented different regression slopes, as demonstrated before (Fernandes et al., 2006). On the other hand, these values are in contrast with previous studies where C increases with the velocity as a nonlinear function (Capelli et al., 1998; di Prampero et al., 2011; Holmer, 1992). This might be explained by the fact that, in this study (**Chapter 2**), a narrow framework of submaximal efforts were studied, in contrast with previously reported literature that showed a nonlinear function, but using a wide range of swimming velocities, from very low to maximal intensities. Indeed in some of the previous studies, velocity changed up to 100% (Capelli et al., 1998), contrasting with the ~7.5% of increase in this study. The present findings showed that the swimmers were able to maintain a similar swimming economy profile as a function of v, even though the swimming intensities varied between the MISS and voluntary exhaustion.

The second method was based on a traditional model to assess $\dot{E}$ and C through $\dot{V}O_2$ and [La-] values (**Chapter 4**). The results of this chapter showed similar $\dot{E}$ and C values between MLSS, IAnT, VT and HRT (~40 mL.kg⁻¹.min⁻¹ and ~0.69 kJ.m⁻¹, respectively), but LT_{3.5} implied higher $\dot{E}$ and C (~48 mL.kg⁻¹.min⁻¹ and ~0.76 kJ.m⁻¹) when compared to the other methods, as expected by

the higher corresponding v values. Our findings demonstrate the importance to prescribe very precisely the aerobic endurance training intensities and to control rigorously the biomechanical profile of swimming technique, because depending on the methods used for the aerobic fitness evaluation, the v may likely represent much higher $\dot{E}$ requirements, and consequently, higher C . Those differences on v and mechanical power in the present study might contribute to the development of an excessive training load under priming over-reaching and/or overtraining caused by successive intense training sessions over prolonged periods (Halsen & Jeukendrup, 2004; Lakier Smith, 2003; Maglischo, 2003; Urhausen & Kindermann, 2002), and/or interfere on the biomechanical adjustments used by the swimmers at exercise intensities above MLSS (Pelarigo et al., 2011). In addition, our findings are in accordance with literature for similar submaximal intensities (Zamparo et al., 2005a) and maximal aerobic power intensities (Chatard et al., 1991). Moreover, Chatard et al. (1991) found similar C values ($\sim 0.69 \text{ kJ.m}^{-1}$) at intensities around 85% $v\text{VO}_{2\text{max}}$ in long-distance swimmers, which is in a very close agreement with the present findings for MLSS ($\sim 0.69 \text{ kJ.m}^{-1}$).

Thus, both methods have contributed to the $\dot{E}$ and C analysis in this Thesis. The first method (based on caloric equivalent of VO_2) provided the possibility of examining the behavior of C throughout time, whereas the second and most used method in swimming (based on VO_2 and $[\text{La-}]$) provided similar methodology as applied previously by swimming literature, and consequently, easier data comparison. Moreover, to better understand the consistency of $\dot{E}$ and C estimation provided by these methods, a comparison between them was conducted in this Thesis. The first method showed higher $\dot{E}$ and C values when compared to the second method at 97.5 (36.1 ± 7.2 and $42.1 \pm 6.7 \text{ mL.kg}^{-1}.\text{min}^{-1}$; 0.74 ± 0.06 and $0.63 \pm 0.06 \text{ kJ.m}^{-1}$, respectively), 100 (40.3 ± 5.1 and $45.3 \pm 5.0 \text{ mL.kg}^{-1}.\text{min}^{-1}$; 0.78 ± 0.06 and $0.69 \pm 0.06 \text{ kJ.m}^{-1}$, respectively) and 102.5%MLSS (43.6 ± 4.9 and $48.4 \pm 4.7 \text{ mL.kg}^{-1}.\text{min}^{-1}$; 0.81 ± 0.07 and $0.73 \pm 0.06 \text{ kJ.m}^{-1}$, respectively) ($p < 0.05$) (Figure 8.9). Differences for $\dot{E}$ and C were around 18% (97.5%MLSS), 12% (100%MLSS) and 11% (102.5%MLSS). These differences between methods could be likely explained

by the intrinsic procedures and assumptions of each method, once the first only consider $\dot{V}E$ and respiratory parameters ($\dot{V}CO_2$ analysis, as well as $\dot{V}O_2$), whereas the second method uses $\dot{V}O_2$ and metabolic ($[La-]$) analysis, assuming a $[La-]$ to $\dot{V}O_2$ transformation constant. In addition, the former method uses the respiratory quotient analysis to calculate the different energy substrates (such as fat, carbohydrate and protein) by the estimated values for each fuel contribution (Elia & Livesey, 1992), whereas the latter method do not consider separately these different energy substrates. Those aspects could partially explain the different $\dot{E}$ and C values observed in our results by both methods.

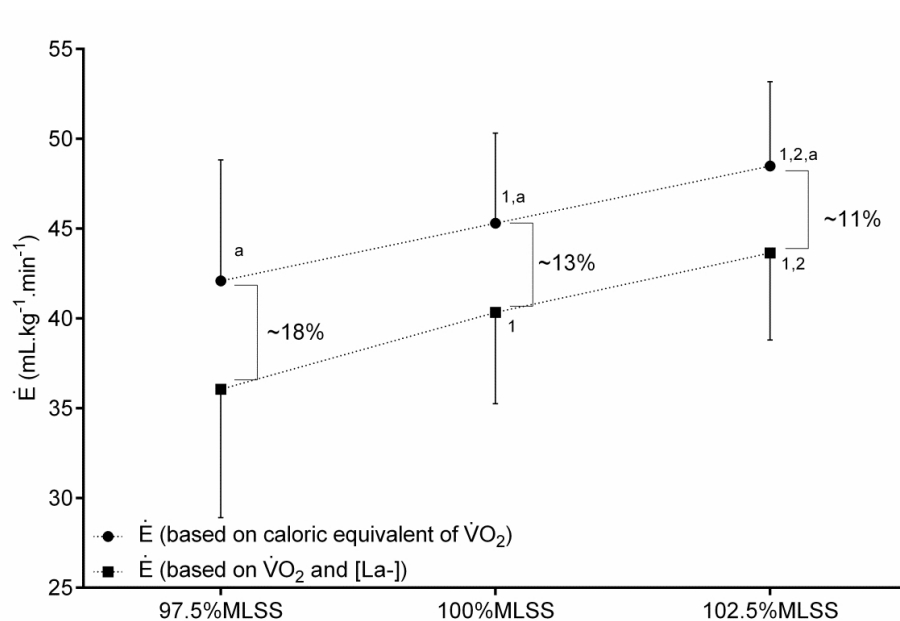


Figure 8.9. Mean $\pm$ SD values of total energy expenditure ($\dot{E}$) (upper panel) and energy cost (C) (lower panel) assessed by the caloric equivalent of oxygen uptake ($\dot{V}O_2$), and by the $\dot{V}O_2$ and blood lactate concentration ($[La-]$) at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS). Percentage differences (%) are presented for each exercise intensity.

^{1,2} Values different from 97.5 and 100%MLSS ($p < 0.05$);

^a Values different from C (based on $\dot{V}O_2$ and $[La-]$) ($p < 0.05$).

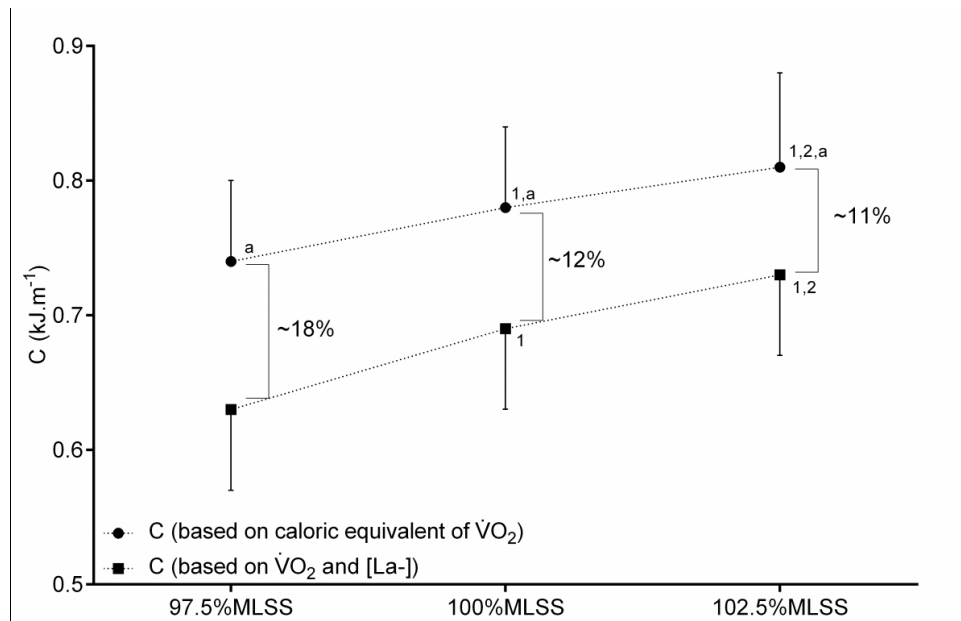


Figure 8.9. Mean $\pm$ SD values of total energy expenditure ($\dot{E}$) (upper panel) and energy cost (C) (lower panel) assessed by the caloric equivalent of oxygen uptake ($\dot{V}O_2$), and by the $\dot{V}O_2$ and blood lactate concentration ($[La^-]$) at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS). Percentage differences (%) are presented for each exercise intensity.

^{1,2} Values different from 97.5 and 100%MLSS ($p < 0.05$);

^a Values different from C (based on $\dot{V}O_2$ and $[La^-]$) ($p < 0.05$).

Energy system's contribution (aerobic and anaerobic energy systems)

In **Chapter 3** we aimed to determine the total energy contribution through the aerobic and anaerobic energy systems at 97.5, 100 and 102.5%MLSS. The anaerobic and aerobic energy contributions showed, respectively, higher and lower values at 102.5%MLSS when compared to 97.5 and 100%MLSS. Nevertheless, the aerobic system was contributing more than 98% of the total $\dot{E}$ for the three swimming intensities. This study was the first showing aerobic and anaerobic energy contribution fractions at exercise intensities at and around MLSS directly measured breath-by-breath in swimming, once most of studies have studied the energy system's contribution during maximal efforts (Gastin, 2001; Sousa et al., 2014). These findings highlight that, even at intensities above MLSS, the total energy contribution was mainly and almost exclusively controlled by the oxidative system.

Biomechanical parameters (Stroke rate - SR, stroke length - SL and stroke index - SI)

Several researchers have shown that swimming intensity and fatigue may interfere with the stroking parameters adopted by the swimmers throughout time (Dekerle et al., 2005a; Oliveira et al., 2012a; Oliveira et al., 2012b; Pelarigo et al., 2011). In our study, increasing swimming intensity from 97.5 to 102.5%MLSS, determined a SL decrease, and a compensatory SR increase, the later also perceptible comparing 97.5 and 100%MLSS (Figure 8.10) (**Chapter 2**). These results are in agreement with previous literature, which reported decreases in SL and increases in SR in all-out trials of different distances / intensities (Craig & Pendergast, 1979; Craig et al., 1985; Keskinen & Komi, 1993). Interestingly, SI was not affected when swimming intensities were compared, probably because the gap between studied v values was not so evident, and also because swimmers are used to maintain the focus on biomechanical efficiency with exercise intensity increases during training.

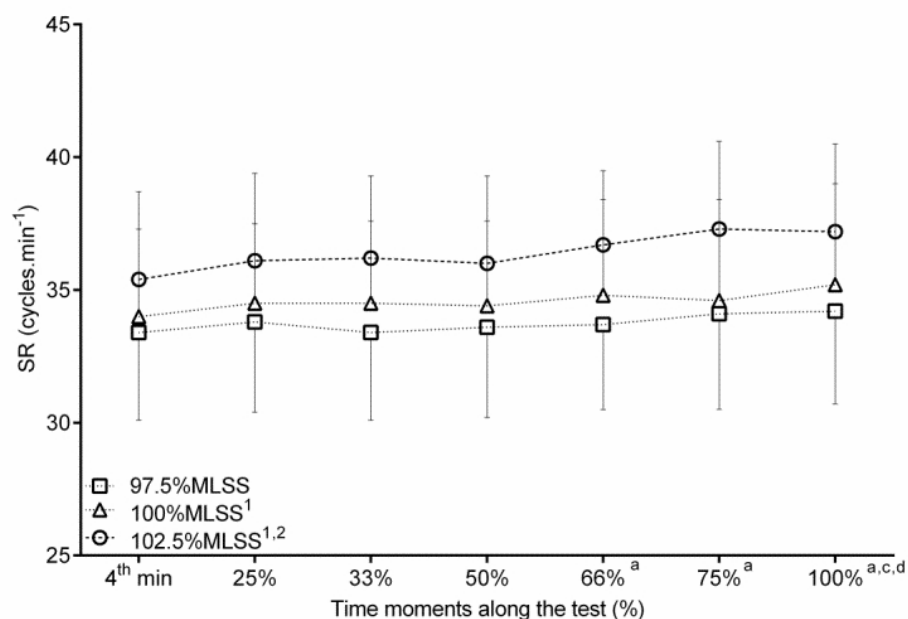


Figure 8.10. Mean $\pm$ SD values of stroke rate (SR) (upper panel), stroke length (SL) (middle panel), and stroke index (SI) (lower panel) throughout time at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS).

^{1,2} Values different from 97.5 and 100%MLSS ($p < 0.05$);

^{a,c,d} Values different from 4th min, 33% and 50%, respectively ($p < 0.05$).

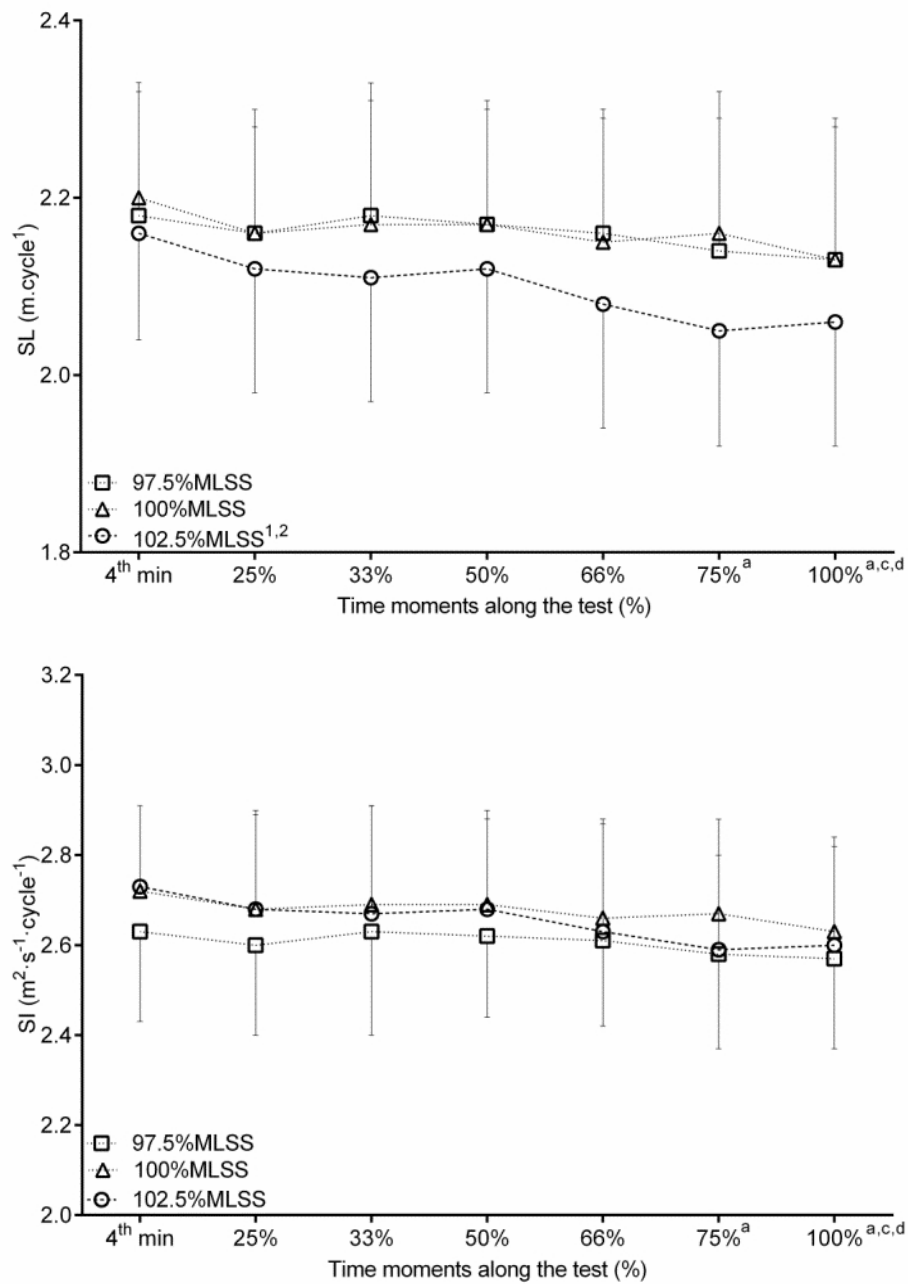


Figure 8.10. Mean $\pm$ SD values of stroke rate (SR) (upper panel), stroke length (SL) (middle panel), and stroke index (SI) (lower panel) throughout time at intensities of 97.5, 100 and 102.5% of the maximal lactate steady state (MLSS).

^{1,2} Values different from 97.5 and 100%MLSS ($p < 0.05$);

^{a,c,d} Values different from 4th min, 33% and 50%, respectively ($p < 0.05$).

Our results were also in agreement with previous reports describing SL and SI drops, and SR increases with exertion time at imposed paces (Dekerle et al., 2005a; Figueiredo et al., 2014; Pelarigo et al., 2011). Indeed, in our study SR values increased during the final time moments of the swims (66, 75 and 100% of the total exercise duration) compared to the beginning of the swims (4th min, 33 and 50%). Conversely, SL and SI were lower at the ending parts of the swims (75 and 100%) compared with the initial time intervals (4th min, 33 and 50%) (Figure 8.10). Dekerle et al. (2005a) reported that, at 100%MLSS, there was a slightly decrease of SL (-3.3%) and increase of SR (3.6%) (non-significant in absolute values), from the beginning to the end of exercise. Similar trends were found in our study during 100%MLSS exercise. These results suggest that, from the beginning of the three swimming intensities, important adaptations occur at each particular v , as shown by the SR and SL adjustments throughout time in **Appendix I**; These differences were clearly evidenced when swimming at 102.5%MLSS. In fact, at this intensity, fatigue likely developed as a function of time, being associated to a SL decrease (-4%) and a SR increase (4.3%) from the beginning to the end of exercise.

Meanwhile, SR showed similar values when MLSS and concurrent methods were compared, despite the LT_{3.5} provided again higher values compared to MLSS, IAnT, VT and HRT methods (**Chapter 5**). However, only MLSS and VT tests obtained high values of agreement ($R^2 = 0.930$) out of the correlation study. Our results of SR obtained during MLSS corroborated with results found at the maximal speed of a 30 min test (T30) showed by Greco et al. (2007), a method considered to be a simpler and easy to implement predictor of the MLSS (Olbrecht et al., 1985). Meanwhile, our SL values obtained during MLSS were also similar to previous literature (Oliveira et al., 2012a). However SL values were similar between MLSS and LT_{3.5}, but were lower compared to IAnT, VT and HRT (**Chapter 5**). Nevertheless, IAnT, VT, HRT and LT_{3.5} were high correlated to MLSS. Our results suggest that SL could be more sensible to specificities of continuous/rectangular vs intermittent/incremental exercise, in which the pauses may favor lactate removal and creatine phosphate resynthesis (Billat, 2001), allowing the swimmers to maintain higher SL values

for a given intensity compared to MLSS test. Furthermore, SI was lower at the MLSS and $LT_{3.5}$ when compared to IAnT, VT and HRT methods, despite IAnT and VT showed high correlations values ($R^2 = 0.915$ and $R^2 = 0.892$, respectively) with MLSS (**Chapter 5**). Moreover, once the SI has been considered as an index of swimming efficiency, differences observed between continuous and intermittent tests may suggest that intermittent protocols may allow the preservation of higher swimming efficiency values.

Chapter 9

Conclusions

The findings obtained in the collection of studies of this Thesis highlight the importance of assessing biophysical factors for evaluation of aerobic endurance performance potential, underpinning the improvement of the swimmer's aerobic capacity. Thus, the conclusions of this Thesis are:

- (I) At intensities up to the MLSS (97.5 and 100%MLSS), bioenergetic and biomechanical factors are constant as a function of time. However, when the exercise is performed at intensity above MLSS (102.5%MLSS), despite most bioenergetic factors are constant throughout time, non-metabolic steady state, hyperventilation and decreased ventilatory efficiency (OUE) led most swimmers to do not complete the 30 min swim at 102.5%MLSS due to fatigue.
- (II) Changes in bioenergetic parameters are associated with biomechanical changes, and together they are associated with the inability of most swimmers to complete the 30 min swim at 102.5%MLSS due to fatigue.
- (III) So, fatigue should be considered as a multifactorial phenomenon, requiring a biophysic approach at least involving physiologic and biomechanical parameters.
- (IV) Swimmers with a fast TD and τ_p values and low [La-] may be able to adjust faster the physiological requirements during intensities up to (97.5 and 100%MLSS) and above (102.5%MLSS) MLSS to minimize the appearance of the slow component and reduce the oxygen deficit, both parameters associated to the fatigue delay and increase in exhaustion time, key factors to aerobic endurance performance.
- (V) The aerobic energy contribution at intensities up to (97.5 and 100%MLSS) and above (102.5%MLSS) MLSS plays a fundamental role controlling almost exclusively (above 98%) the athletes' energy supply in this intensity zone.

- (VI) IAnT, VT and HRT are the best methods to predict the bioenergetic factors and intensity corresponding to the gold-standard method (i.e. MLSS) for the evaluation of aerobic capacity. However, HRT requires caution when applied for swimming intensity training prescription, because the method showed poor agreement with MLSS.
- (VII) IAnT and VT are the best methods to predict the biomechanical parameters, particularly considering SR, corresponding to the gold-standard method (i.e. MLSS) for the evaluation of aerobic capacity.
- (VIII) Different exercise modes (continuous and intermittent exercises) do not compromise the bioenergetic responses and intensity, but these compromise some of the biomechanical responses for the evaluation of relevant parameters to characterize aerobic capacity.
- (IX) The OUE and intensity associated to the OUEP predict both IAnT and MLSS for the evaluation of swimming aerobic capacity.
- (X) The analysis of specific characteristics of specific athletes, particularly elite swimmers, rather than rely upon mean sample values, is decisive to understand the required specific individual intervention to improve performance.
- (XI) The exercise prescription process around MLSS is quite sensitive to the appropriateness of diagnosing specific and personalized exercise intensities, particularly when ideal swimming v is overestimated.

The findings of the studies presented in this Thesis may contribute to better understand the importance and the feasibility of precisely define different biophysical dimensions of the optimal load for the aerobic capacity training. This was done emphasizing, on one hand, the effect on the magnitude of swimmer's response to small modifications on the prescribed load and, on the other, underlining the appropriateness – or lack of it – of the outcomes provided by different methods to assess the optimal training load. Furthermore, this Thesis highlights the importance of training oriented research, particularly the one related to load analysis, to consider the interplay between physiological, bioenergetic and biomechanical outcomes for a better understanding of complex performance.

Chapter 10

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Appendix I

Kinematical analysis along maximal lactate steady state swimming intensity

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Abstract

The purpose of this study was to conduct a kinematical analysis during swimming at the intensity corresponding to maximal lactate steady state (MLSS). Thirteen long distance swimmers performed, in different days, an intermittent incremental protocol of $n \times 200$ m until exhaustion and two to four 30-min submaximal constant speed bouts to determine the MLSS. The video analysis, using APAS System (Ariel Dynamics Inc., USA), allowed determining the following relevant swimming determinants (in five moments of the 30-min test: 0, 25, 50, 75, and 100%): stroke rate, stroke length, trunk incline, intracyclic velocity variation, propelling efficiency, index of coordination and the time allotted to propulsion per distance unit. An ANOVA for repeated measures was used to compare the parameters mean values along each moment of analysis. Stroke rate tended to increase and stroke length to decrease along the test; a tendency to decrease was also found for intracyclic velocity variation and propelling efficiency whereas the index of coordination and the propulsive impulse remained stable during the MLSS test. It can be concluded that the MLSS is not only an intensity to maintain without a significant increase of blood lactate concentration, but a concomitant stability for some biomechanical parameters exists (after an initial adaptation). However, efficiency indicators seem to be more sensitive to changes occurring during swimming at this threshold intensity.

Key words: Swimming, front crawl, biomechanics, aerobic capacity, lactate.

Introduction

Swimming is an individual and cyclic sport influenced by several determinant factors (Barbosa et al., 2010). From these, biomechanical and energetic related parameters are the most relevant, whose developments allow significantly enhancing performance and achieving high-standard competitive levels. The useful mechanical power in swimming is that to overcome drag force ($\dot{W}_d = D \times v$) and, since metabolic power ($\dot{E}$) is related to this component of total mechanical power through the drag efficiency ($\eta_d = \dot{W}_d / \dot{E}$), swimming velocity is then determined by. di Prampero et al. (2011) and Zamparo et al. (2011):

$$v = \dot{E} \cdot (\eta_d / D) \quad A.1$$

This equation indicates that swimming velocity will be higher the highest the propelling efficiency and/or the metabolic power are, and the lower the hydrodynamic drag is.

Parameters representing each one of the above mentioned areas should be frequently monitored, aiming to develop better training processes and, therefore, increasing performance. Indeed, tests are used as part of elite training programs to assess the likely outcome of the swimmers competitive performance (Anderson et al., 2008). From these, one of the most well-known is the Maximal Lactate Steady State (MLSS) test, which aims to assess the highest workload that can be maintained over time with stable blood lactate concentration values ($[La^-]$), i.e., without a continuous blood lactate accumulation. The MLSS test is considered the gold-standard protocol for assessing swimmers' individual anaerobic threshold (Beneke & von Duvillard, 1996) and, therefore, to evaluate and prescribe individualized aerobic training.

Complementarily, the definition of training loads should focus not only on volume, intensity and frequency of training, but also on technical constraints, which would enable to control the swimmers' technique. Changes in the stroke parameters partly depend on the aerobic potential (particularly on aerobic capacity) and the extent to which the anaerobic metabolism is involved in total energy release also has a decisive role (Pelayo et al., 2007).

Moreover, long distance swimming (open water and long distance triathlons) has become increasingly popular and the strategies to maintain a constant velocity during these events, aiming to maintain the metabolic equilibrium, are important to promote specific adaptations (i.e. oxidative capacity) (Pelayo et al., 2007). Nonetheless, it possibly requires a biomechanical adjustment, as peripheral fatigue may evolve during these long duration events.

In fact, it has been reported that the anaerobic threshold seems also to influence the behavior of some biomechanical variables, as concomitant changes on some selected kinematical and coordinative parameters and [La-] during incremental and constant load tests have been reported (Figueiredo et al., 2013a; Keskinen & Komi, 1993; Psycharakis et al., 2008; Wakayoshi et al., 1995). This supports the idea that, in swimming, biomechanical changes could be related to metabolic effects and that the anaerobic threshold represents not only a physiological transition but also a biomechanical and coordinative boundary, coincident with a stroke length (SL) drop, and an increase in the stroke rate (SR) and index of coordination (IdC) (Figueiredo et al., 2013a; Oliveira et al., 2012b). Specifically when swimming at MLSS, it was found stability in the SL, SF and IdC in national level swimmers (Dekerle et al., 2005a; Pelarigo et al., 2011), but it was suggested that this could be different depending on the swimmers level as contradictory results were reported (Pelarigo et al., 2011). In fact, this analysis should go further, as swimming performance is influenced by other relevant factors, particularly the hydrodynamic drag and propulsive forces (Toussaint, 2011). As it has been evidenced that biomechanical skills in swimming are of far greater importance for metabolic economy than in running and cycling, and that elite swimmers adopt different combinations of stroke parameters than their less proficient counterparts, we aimed to analyze the behavior of relevant kinematical parameters when swimming at MLSS intensity. This analysis will contribute to the understanding of the main factors that influence the maintenance of the highest swimming intensity that could be supported by the aerobic energy system without a significant rise of the [La-].

Methods

Thirteen long distance swimmers voluntarily participated in the present study. Their main physical and training background characteristics were: 27.8 ± 10.9 years of age, 1.76 ± 0.56 m of height, 1.77 ± 0.64 m of arm span, 68.8 ± 5.6 kg of body mass, 22.22 ± 1.65 of body mass index and 5.8 ± 4.8 years of swimming competitive experience. The criterion for swimmers' participation was a performance of 360 s (or less) in the 400 m freestyle event. The local ethics committee approved the experimental procedures and all swimmers signed a written consent form in which the protocol was detailed explained. All test sessions took place in a 25 m indoor pool, 1.90 m deep, with a water temperature of 27.5°C. A standardized warm-up, consisting primarily of 1000 m of aerobic swimming of low-to-moderate intensity, was conducted before each protocol. Using in-water starts and flip turns, each participant performed a front crawl intermittent incremental protocol of $n \times 200$ m until exhaustion with increments of $0.05 \text{ m}\cdot\text{s}^{-1}$ between steps and 30 s rest intervals to assess the swimming velocity corresponding to individual anaerobic threshold (Fernandes et al., 2006). The individual anaerobic threshold was determined by [La-]/velocity curve modelling method, as describe previously (Fernandes et al., 2011). After a 48 h rest interval, a MLSS test – a long distance continuous intensity test proposed by Stegmann and Kindermann (1982) and Heck et al. (1985) – was conducted in front crawl, with swimmers performing two to four 30 min bouts at different velocities with 24 h rest in-between. The swimming velocity for the first trial was established based on the individual velocity corresponding to anaerobic threshold obtained in the intermittent incremental protocol. The velocity increments (or declines) between bouts corresponded to 2.5% of the initial 30 min velocity (Pelarigo et al., 2011) and the velocity corresponding to MLSS ($v@MLSS$) was defined as the highest swimming velocity during which [La-] increased $1 \text{ mmol}\cdot\text{L}^{-1}$ during the final 20 min of the test (Baron et al., 2005; Dekerle et al., 2005a; Heck et al., 1985; Hein et al., 1989). The [La-] corresponding to MLSS ([La-] MLSS) was obtained through the mean of [La-] measured at the 10th and 30th min (blood samples were also taken at rest). During both incremental and continuous tests, velocity was

controlled through a visual pacer (TAR. 1.1, GBK, Electronics, Aveiro, Portugal), with flashing lights on the bottom of the pool, helping swimmers to keep up the predetermined velocity. Swimmers were videotaped in the sagittal plane using a dual-media set-up (Sony® DCR-HC42E, Nagoya, Japan) that recorded the mid-pool stroke cycles, placed 0.30 m above and below the water surface at the lateral wall of the pool, 6.78 m from the plane of movement, and 12.5 m from the starting wall. The images of both cameras were recorded independently and swimmers were monitored when passing through a specific pre-calibrated space using a calibration frame (6.3 m²). Synchronization of the images was obtained using a pair of lights, fixed to the calibration volume, visible in the field of view of each camera (de Jesus et al., 2012). The Ariel Performance Analysis System software (Ariel Dynamics, USA) was used to analyze the kinematical parameters along the MLSS test. Nine anatomical points, (the right hip – femoral condyle - and both sides' finger tips, fist, elbow and shoulder) were digitized manually and frame by frame at a frequency of 50 Hz. After a bi-dimensional reconstruction using DLT procedure (Abdel-Aziz & Karara, 1971), a low pass filter of 5 Hz was used (Winter, 1990). The duration of the MLSS test was normalized to 100% and split into five parts (0, 25, 50, 75, and 100% of the 30-min test) of its total duration for the analysis of the variables along the test (0% was only considered at 75 m because swimmers did not instantly catch up with the right pace and only mid-pool non-breathing stroke cycles were considered).

The kinematical analysis consisted on the assessment of the stroke kinematics (mean velocity, SF and SL) and the absolute trunk inclination with horizontal plane (TI, as the value of the angle between the shoulder and the hip segment and the horizontal at the end of insweep of the upper limbs action, as proposed by Zamparo et al. (2009). For the efficiency estimation, it were selected the intracyclic velocity variation (IVV, computed as the hip's instantaneous velocity coefficient of variation) and the upper limb's propelling efficiency (η_p , by assessing the underwater phase only, as proposed by Zamparo et al. (2005b) and indicated in Equation A.2.

$$\eta_p = [(v \times 0.9) / 2\pi \times SF \times l] (2 / \pi) \quad A.2$$

being l the average shoulder to hand distance (the length in the vertical axis between the shoulder and the hand during the insweep phase). The velocity was multiplied by 0.9 to take into account that ~10% of forward propulsion in front crawl is produced by the lower limbs action (Zamparo et al., 2005b). To assess the motor control, the IdC was evaluated, measuring the lag time between the propulsive phases of each upper limb and expressing it as the percentage of the overall duration of the stroke cycle (Chollet et al., 2000). Following these authors, the propulsive phase begins with the start of the hand's backward movement until the moment where it exits from the water (pull and push phases) and the non-propulsive phase initiates with the hand water release and ends at the beginning of the propulsive phase (recovery, entry and catch phases), existing three coordination modes: (i) catch-up, when a lag time occurred between the propulsive phases of the two upper limbs ($IdC < 0\%$); (ii) opposition, when the propulsive phase of one upper limb started when the other ended its propulsive phase ($IdC = 0\%$); and (iii) superposition, when the propulsive phases of the upper limbs are overlapped ($IdC > 0\%$). In addition, the change in the duration of the propulsive impulse, which seems to be useful to estimate the time allotted by the swimmer to propulsion per lap ($T_{prop}/distance$), was estimated as indicated in Equation A.3 (Alberty et al., 2009):

$$T_{prop}/distance = T_{cycle} \cdot (100\% + 2 \cdot IdC) D/SL \quad A.3$$

where D/SL corresponds to the number of stroke cycles needed to cover the distance and IdC is the Index of Coordination.

Mean and SD were used as measures of centrality and dispersion of the studied variables. The normal Gaussian distribution of the data was verified by the Shapiro- Wilk's test and the compound symmetry (or sphericity) was checked using the Mauchley test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure when the epsilon correction factor was < 0.75 or according to

the Huyn–Feld procedure when the epsilon correction factor was >0.75 (Vincent, 1999). A one-way ANOVA for repeated measures was used to compare the mean values for each variable at each point of analysis (0, 25, 50, 75 and 100% of the MLSS). When a significant Fvalue was achieved, Bonferroni post-hoc procedure was performed to locate the pairwise differences. All statistical analysis was performed using STATA 12.1 (Stata-Corp, USA) and the level of statistical significance was set at $P < 0.05$. Effect size was computed with Cohen's f . It was considered a (Cohen, 1988): (i) small effect size if $0 \leq |f| \leq 0.10$; (ii) medium effect size if $0.10 < |f| \leq 0.25$ and; (iii) large effect size if $|f| > 0.25$.

Results

As it was expected, velocity remained stable along the test ($F_{(4,48)} = 0.12$, $p = 0.98$, $f < 0.01$), with a mean value of $1.06 \pm 0.14 \text{ m.s}^{-1}$, corroborated by the constant values of [La-]MLSS between the 10th and 30th min (3.25 ± 1.08 vs. $3.38 \pm 1.18 \text{ mmol.L}^{-1}$, respectively). However, adaptations occurred concomitantly in the SF ($F_{(4,48)} = 14.57$, $p < 0.001$, $f = 0.23$) and SL ($F_{(4,48)} = 3.12$, $p = 0.02$, $f = 0.10$) between the first and the last moment of the 30 min test (Figure A.1).

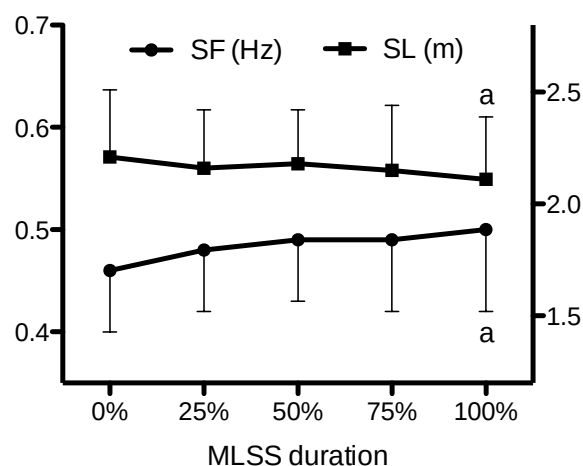


Figure A.1 Evolution through maximal lactate steady state (MLSS) test of the mean $\pm$ SD values of the stroke frequency (SF) and stroke length (SL).

^a Significantly different from 0% ($p < 0.05$).

Efficiency parameters changed as well, with the η_p decreasing from the 0 and 25% to the 100% of the test ($F_{(4,48)} = 3.91$, $p = 0.008$, $f = 0.14$) and the IVV diminishing from the first three moments to the last stage of the effort ($F_{(4,48)} = 3.14$, $p = 0.02$, $f = 0.26$) (Table 1). Conversely, the TI remained stable along the test ($F_{(4,48)} = 0.51$, $P = 0.73$, $f < 0.01$) and no significant effect of time on IdC ($F_{(4,48)} = 1.11$, $p = 0.36$, $f = 0.03$) and Tprop values ($F_{(4,48)} = 0.10$, $p = 0.98$, $f < 0.01$) was observed (Table A.1). All swimmers adopted the catch-up arm coordination mode.

Table A.1 Evolution through the maximal lactate steady state (MLSS) test of the mean (SD) values of the trunk incline (TI), upper limb propelling efficiency (η_p), intracycle velocity variation (IVV), index of coordination (IdC), and the time allotted for propulsion per pool length (Tprop).

	0%	25%	50%	75%	100%
TI (°)	10.8 (3.8)	10.5 (3.9)	10.3 (3.4)	10.0 (3.9)	10.1 (3.8)
η_p	0.36 (0.05)	0.36 (0.04)	0.35 (0.04)	0.34 (0.04)	0.34 (0.05) ^{a,b}
IVV	0.24 (0.06)	0.23 (0.05)	0.24 (0.04)	0.22 (0.05)	0.20 (0.05) ^{a,b,c}
IdC (%)	-16.8 (5.8)	-15.9 (4.7)	-16.0 (5.2)	-15.6 (5.8)	-15.2 (5.0)
Tprop (s)	16.7 (4.4)	17.0 (4.3)	16.7 (4.3)	16.8 (4.0)	16.7 (3.3)

^{a,b,c} Significantly different with 0, 25, and 50%, respectively ($p < 0.05$).

Discussion

The aim of this study was to analyze the behavior of relevant kinematical parameters when swimming at the MLSS intensity. Efficiency related parameters (IVV and η_p) and general biomechanical parameters (SF and SL) changed, but TI, IdC and Tprop remained stable along this typically aerobic effort. Moreover, the observed [La-] MLSS values were similar to those reported by Dekerle et al. (2005a) and Pelarigo et al. (2011) (3.30 and 3.28 mmol.L⁻¹, respectively), notwithstanding the differences obtained in the velocity attained at the MLSS (1.22 vs 1.06 m.s⁻¹). The obtained [La-] values also evidenced, as

proposed previously (Fernandes et al., 2011; Stegmann & Kindermann, 1982), that individual assessments should be used rather than averaged fixed values.

Regarding the stroking parameters, the SF and the SL values remained stable, with the exception of the 0% moment where the SF was lower and the SL higher. These results are in agreement with Dekerle et al. (2005a) and Pelarigo et al. (2011) who also reported a stability in SF and SL (but only started their analysis at 12.5% and 10th min of the test, respectively), suggesting that when beginning at MLSS intensity there is an important phase of adaptation to the imposed pace, enforcing a constancy of the required propulsion to overcome the corresponding drag impulse. However, by changing the magnitude of the generated propulsion, swimmers have some freedom in combining SF and SL. Afterwards SF and SL remained stable, but as seen before for 400 m front crawl at an intensity corresponding to the anaerobic threshold (Keskinen & Komi, 1993) and in MLSS (Dekerle et al., 2005a) studies, SF increased and SL decreased slightly and non-significantly in terms of absolute values. In addition, after a 2 km test (simulating a long-distance competition by maintaining a 10 km race pace) significant differences in SF and SL were reported (Zamparo et al., 2005b). Above this intensity, at 102.5-105% (Dekerle et al., 2005a; Pelarigo et al., 2011), or at the velocity of maximal oxygen consumption (Marinho et al., 2006), greater changes in SF and SL were reported, probably due to the higher technical constraints at the heavy intensity domain (above moderate exercise). This fact suggests that the maintenance of the muscular homeostasis (evidenced by the [La-] stability) might be relevant for stable stroke parameters behavior; nevertheless some peripheral fatigue may start to evolve (as observed for long distance swimming; Invernizzi et al., 2014). In addition, differences in technical skill of the swimmers could emphasize these possible changes, as it was observed that subjects with higher technical skill would be able to maintain higher SL values for longer (Chollet et al., 1997; Craig et al., 1985).

Furthermore, the TI values remained stable during the MLSS test, which might indicate that swimmers were able to maintain their swimming technique along

the exercise without experiencing additional drag form, since the frontal area (highly related to the TI) is expected to be maintained (Zamparo et al., 2009). Regarding the efficiency parameters, a decrease in IVV and η_p was observed along the MLSS, in spite of the observed stability in other parameters. Nevertheless, it is known that IVV and η_p are related with the stroking parameters (Figueiredo et al., 2011; Figueiredo et al., 2013b), probably changing along the exercise due to modifications in the SF and SL. Thus, IVV and η_p seem to be more sensitive to time rather than the general stroke parameters (SF and SL), although these latter presents a tendency (in terms of absolute values) to a decrease in SL and an increase of the SF from the 1st quarter of the test till the end. In fact, η_p should not show a different trend from SL, as the ratio v/SF (equation 2) is indeed SL and all other parameters (but I) are constant. It also should be considered the fact that these variables are macro kinematical parameters, representing every adaptation that occur in face of the constraints imposed on action, resulting in the final velocity.

The task constraint of even pace should also be discussed as it could have highly influenced the initial moments of the test, rather than the eventual muscular fatigue. In fact, it is believed that the pacing selected by athletes is largely dependent on the anticipated exercise duration and on the presence of an experientially developed performance template as studies investigating pacing during prolonged exercise have observed a fast start in the beginning of race (Roelands et al., 2013). Although [La-] stability was observed, swimmers could have experienced some increase in the rate of perceived exertion, profile of mood state (fatigue) and muscular pain, as observed by Invernizzi et al. (2014) for long distance swimming. In addition, the tendency to increase the SF in the final of the test may be due to a neuromuscular reserve, as evidenced for cycling exercise (Marcora & Staiano, 2010).

Complementarily, it is known that the lower limbs action in front crawl swimming has a contribution of about 15% to overall propulsion in maximal efforts, which is considered to be low (Deschodt et al., 1999) and expected to be even lower in long distance swimming. However, as upper limb action efficiency decreased,

the role of the lower limbs action may be critical and should be taken into consideration in futures studies on this topic. The observed changes on propelling efficiency, concomitant with the SF increase, did not changed the required T_{prop} to overcome the drag impulse that was expected to occur due to the constant pace, without energetical increments. Alberty et al. (2009) showed that swimmers have freedom to choose the combination of SF, IdC and, consequently, T_{prop} . Although changes were observed in SF in the beginning of the MLSS test, they were not sufficient to impose changes on the IdC , even being a control parameter. This non-relation between SF and IdC was already reported, but during a time to exhaustion test (Alberty et al., 2009). A catch-up mode was adopted during MLSS test, remaining stable throughout, as previously observed by Pelarigo et al. (2011).

Conclusion

In summary, MLSS intensity in swimming is maintained with a concomitant stability of $[La^-]$ and some biomechanical parameters (after an initial adaptation). However, efficiency indicators seem to be more sensitive to possible changes occurring through time at this intensity and should be further considered. Thus, MLSS is a useful and practical swimming intensity to be maintained for a long period of time, but some constraints in technique can occur.