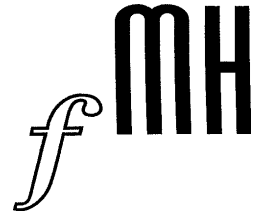




Universidade de Lisboa
Faculdade de Motricidade Humana



Oxygen Uptake Kinetics and Bioenergetics Profile at Maximal and Supramaximal Intensities in Swimming

Tiago André Freire de Almeida

Orientador: Prof. Doutor Francisco José Bessone Ferreira Alves
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Tese especialmente elaborada para obtenção do grau de Doutor em
Motricidade Humana na especialidade de Fisiologia do Exercício

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2020

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e aos meus manos Miguel e Joaquim,
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Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Alves F (2020) $\dot{V}O_2$ kinetics and energy contribution in simulated maximal performance during short and middle distance-trials in swimming. *European Journal of Applied Physiology*. doi: 10.1007/s00421-020-04348-y

Almeida T, Espada M, Pessôa Filho D, Reis J, Simionato A, Siqueira L, Sancassani A, Alves F (2019) Tempo limite à velocidade aeróbia máxima em nadadores. In: *Edições Desafio Singular (ed) Proceedings of the XLII Technical and Scientific Congress of the Portuguese Association of Swimming Technicians*. *Motricidade* 15(S4):22-23. doi: 10.6063/motricidade.18397

Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019) Is $\dot{V}O_2$ kinetics influenced by swimming intensity in maximal and supramaximal velocities in young female swimmers? In: *Proceedings of the International Seminar of Physical Education, Leisure and Health, Castelo Branco, Portugal*. *Journal of Human Sport and Exercise* 14(4proc):1566-1569. doi: 10.14198/jhse.2019.14.Proc4.82

Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019) Physiological responses at maximal aerobic swimming pacing in different distance-trials. In: *Proceedings of the International Seminar of Physical Education, Leisure and Health, Castelo Branco, Portugal*. *Journal of Human Sport and Exercise* 14(4proc):1686-1689. doi: 10.14198/jhse.2019.14.Proc4.82

Almeida T, Pessôa Filho D, Simionato A, Espada M, Reis J, Alves F (2018) High intensity interval training in swimming – effects of different intensities. In: Murphy M, Boreham C, De Vito G, Tsolakidis E (eds) *23rd Annual Congress of the ECSS – Book of Abstracts, European College of Sport Science, Dublin, p. 270*

Almeida T, Pessôa Filho D, Simionato A, Espada M, Reis J, Alves F (2018) Comparação da resposta do consumo de oxigénio entre duas tarefas de treino intervalado em natação – 8 x 100 vs 4 x 200 metros. In: *Edições Desafio Singular*

(ed) Proceedings of the XLI Technical and Scientific Congress of the Portuguese Association of Swimming Technicians. *Motricidade* 14(2-3):148. doi: 10.6063/motricidade.14332

Almeida T, Pessoa Filho D, Simionato A, Silva J, Pestana D, Espada M, Reis J, Alves F (2016) Oxygen uptake response at supramaximal swimming intensities – study of 50, 100 and 200 meters time trials. In: Baca A, Wessner B, Dikemüller R, Tschan H, Hofmann M, Kornfeind P, Tsolakidis E (eds) 21st Annual Congress of the ECSS – Book of Abstracts. European College of Sport Science, Vienna, p. 341

Complementary Studies:

Pessoa Filho DM, Massini DA, Siqueira LO, Santos LG, Vasconcelos CM, Almeida TF, Espada MA, Reis JF, Alves FB, DiMenna FJ (2020) A rapidly incremented tethered-swimming maximal protocol for cardiorespiratory assessment of swimmers. *Journal of Visualized Experiments* (155): e60630. doi: 10.3791/60630

Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *Journal of Strength and Conditioning Research* 29(10):2836-43. doi: 10.1519/JSC.0000000000000504

Ramos C, Reis J, Almeida T, Alves F, Wolterbeek H, Almeida S (2015) Estimating the inhaled dose of pollutants during indoor physical activity. *Science of the Total Environment* 527-528:111-118. doi: 10.1016/j.scitotenv.2015.04.120

Abstract

The aim of this work was to investigate and describe the swimmers oxygen uptake kinetics ($\dot{V}O_2K$) and bioenergetic profiles at different maximal and supramaximal intensities in order to provide new insights about the impact that competitive and training efforts have on swimmers physiology. For that purpose, several physiological parameters were measured throughout the different tests performed by the swimmers before, during and after exercise, such as $\dot{V}O_2$, heart rate, blood lactate concentration and rate of perceived exertion (RPE). All tests were conducted using a breath-by-breath apparatus connected to a swimming snorkel for pulmonary gas sampling and an underwater visual pacer displayed at the bottom of the pool for velocity control. The $\dot{V}O_2K$ parameters were calculated through mono or bi-exponential modelling and by a new growth rate method. For the analysis of the bioenergetic profiles we considered: the aerobic system determined as the time integral of the net $\dot{V}O_2$ during exercise; the anaerobic lactic system calculated by the net $[La^-]$ at the end of exercise; and the anaerobic alactic system determined by the analyses of the fast component of the $\dot{V}O_2$ recovery curve. Four main studies embody the fundamental part of this thesis. They were designed to: 1) characterize swimming competitive events; 2) test the tolerance to the maximal aerobic velocity (MAV) at continuous vs. interval training (IT) sets; 3) test two different work-intervals (medium and long) in IT sets performed at the MAV; and 4) test the impact of different intensities applied on similar IT sets, testing also the effects of short and medium work-intervals. For each study, swimmers first performed a discontinuous incremental test in order to access the second ventilatory threshold (VT_2), maximal oxygen uptake (Peak- $\dot{V}O_2$) and maximal aerobic velocity (MAV). This allowed to set the reference markers for the application of the remaining tests that were performed at maximal and supramaximal intensities, varying according to intensity (constant vs. maximal trials) and total distance performed (continuous vs. intermittent). In study 1, three simulated swimming events (50, 100 and 200 meters maximal trials) showed a tendency, as the distance of the event increases and the exercise intensity decreases, of a slower $\dot{V}O_2K$ response but higher oxidative responses, while the aerobic participation increased and the anaerobic decreased,

presenting a cross-over in the 100 meters event. Study 2 showed that athletes could hold the MAV intensity for ~256 seconds, with less proficient swimmers getting higher times to exhaustion (TLim). Furthermore, performing this intensity intermittently (100 meters bouts with 15 seconds breaks) lead to significantly longer TLim and consequently swimmers spent a considerable longer time near the $\dot{V}O_2$ maximal values. Study 3 showed that, independently of performing medium or long work-intervals (100 vs. 200 meters bouts), the physiological impact on swimmers is similar and capable to tax the aerobic mechanism to its maximal values. When normalized for the same overall distance (first 800 meters) the RPE showed that swimmers could easily perform the shorter work-interval getting the same physiological benefits than with longer work-interval. Study 4 showed that, whilst training with short distance bouts (50-m), 5 to 10% of increase in the intensity could rise the oxidative rate ~6 to 13% higher, and improve ~20 to 46% the tolerance to swimming in the severe domain (i.e., above VT_2). In addition, the results recommend an increase of, at least, 5% of the intensity to an IT set performed with 50 meters bouts to match the results obtained with 100 meters bouts. Overall, the studies demonstrated that higher oxidative rates, amplitudes of the $\dot{V}O_2K$, MAV's and aerobic and total anaerobic participations seemed to be associated with better swimming performances. At MAV, the IT sets seemed to bring more benefits for the aerobic capacity development than the continuous workout and increasing the intensity of a short work-interval IT set above MAV is advisable for a more taxing effect on the aerobic metabolism. When comparing work-intervals it seems that a significant improvement occurs from increasing the sets repetition from 50 to 100 meters bouts, however no further physiological benefits occur from the 100 to the 200 meters bouts. Our investigation confirms that the analysis of the $\dot{V}O_2K$ parameters as well as profiling swimmers bioenergetics, especially in the intensities associated with training and competitive events, are important aspects for a true understanding of human sports performance.

Keywords: Oxygen Uptake Kinetics; Bioenergetics; Swimming; Maximal Aerobic Velocity; Interval Training

Resumo

A presente tese procurou investigar e descrever a cinética do consumo de oxigénio ($\dot{V}O_2K$) e o perfil bioenergético de nadadores em intensidades máximas e supramáximas, com o objetivo de aprofundar o conhecimento do impacto que esforços tipicamente desempenhados em competição e treino têm nas suas respostas fisiológicas. Para tal, vários parâmetros fisiológicos foram medidos ao longo dos diferentes testes realizados pelos nadadores antes, durante e após o exercício, tais como o $\dot{V}O_2$, frequência cardíaca, concentração de lactato sanguíneo e percepção subjetiva de esforço (RPE). Durante as sessões de testes foi sempre utilizado um analisador de gases acoplado ao atleta através de um *snorkel* para uma análise “breath-by-breath” dos gases expirados ao longo de todo o percurso de nado e um *pacer* subaquático foi utilizado para o controlo das intensidades. Os parâmetros da $\dot{V}O_2K$ foram determinados através de modelos mono e bi-exponenciais tendo sido apresentado um novo modelo de análise através da taxa de crescimento do $\dot{V}O_2$. Para a análise do perfil bioenergético dos nadadores foram considerados: o sistema aeróbio, determinado pela integral da resposta do $\dot{V}O_2$ durante o exercício; o sistema anaeróbio láctico, determinado pela diferença da concentração de lactato pós exercício; e o sistema anaeróbio aláctico, calculado através da análise da componente rápida da curva de recuperação do $\dot{V}O_2$ pós exercício. Os quatro estudos principais que incorporam a parte fundamental desta tese foram desenhados de forma a: 1) caracterizar eventos competitivos de natação; 2) testar a tolerância à velocidade aeróbia máxima (MAV) em esforços contínuos e intervalados (IT); 3) testar duas tarefas de IT com diferentes intervalos de esforço (médios e longos) à MAV; e 4) testar o impacto que diferentes intensidades provocam em IT semelhantes, testando também o efeito de intervalos de esforços de curta e média duração. Os nadadores começaram por desempenhar um teste incremental descontínuo para a avaliação do segundo limiar ventilatório (VT_2), consumo máximo de oxigénio (Peak- $\dot{V}O_2$) e da MAV. Este teste permitiu definir os valores de referência para a aplicação e avaliação dos testes remanescentes, realizados a intensidades máximas e supramáximas, variando de acordo com a intensidade (constante vs. máxima) e distância total realizada (contínua vs. intermitente). No estudo 1, três eventos máximos simulados (50, 100 e 200 metros) mostraram uma tendência, à medida que a distância do evento aumenta e a intensidade do exercício diminui, de uma resposta mais lenta da $\dot{V}O_2K$, mas respostas oxidativas superiores, enquanto a contribuição aeróbia

aumentou e a anaeróbia diminuiu, apresentando um *cross-over* no teste dos 100 metros. O estudo 2 mostrou uma tolerância à MAV (TLim) de ~ 256 segundos, com os nadadores com MAV mais lentos a obterem tempos superiores de TLim. Realizar esta intensidade intermitentemente (séries de 100 metros com intervalos de 15 segundos) levou a um TLim significativamente mais longo e, conseqüentemente, os nadadores passaram um tempo consideravelmente superior perto dos seus valores máximos de $\dot{V}O_2$, quando comparado com o teste contínuo. O estudo 3 mostrou que, independentemente da divisão de uma tarefa de IT em intervalos de esforços médios ou longos (repetições de 100 vs. 200 metros), o impacto fisiológico sobre os nadadores é semelhante e capaz de elevar o mecanismo aeróbio aos valores máximos. Quando normalizado para a mesma distância total (primeiros 800 metros) a RPE mostrou que os nadadores executam o IT com repetições mais curtas mais facilmente, obtendo os mesmos benefícios fisiológicos quando comparado com repetições mais longas. O estudo 4 mostrou que, ao treinar com repetições de curta duração (50 metros), 5 a 10% de aumento da intensidade poderá aumentar a taxa oxidativa em ~6 a 13%, e aumentar a tolerância ao esforço no domínio severo em ~ 20 a 46% (i.e., acima do VT_2). Os resultados recomendam também um aumento de, pelo menos, 5% da intensidade para se obterem respostas fisiológicas semelhantes àquelas obtidas em IT com repetições de 100 metros. No geral, os estudos demonstraram que maiores taxas oxidativas, amplitudes da $\dot{V}O_{2K}$, MAV e participações aeróbias e anaeróbias totais parecem estar associadas a melhores desempenhos desportivos. À MAV as tarefas de treino intervalado parecem trazer mais benefícios para o desenvolvimento da capacidade aeróbia do que o treino contínuo, e o aumento da intensidade acima da MAV, em IT com repetições curtas, é aconselhável para um efeito mais significativo sobre o metabolismo aeróbio. Em tarefas de IT, parece existir uma melhoria significativa nas respostas fisiológicas dos nadadores com o aumento das repetições de 50 para 100 metros, no entanto parece que não existem mais melhorias ao aumentar as repetições para 200 metros. A nossa investigação confirma a análise dos parâmetros $\dot{V}O_{2K}$, bem como a caracterização dos perfis bioenergéticos de nadadores, especialmente nas intensidades associadas ao treino e eventos competitivos, como aspetos importantes para uma verdadeira compreensão do desempenho desportivo humano.

Palavras-chave: Cinética do Consumo de Oxigénio; Bioenergética; Velocidade Aeróbia Máxima; Treino Intervalado; Natação

Resumo Desenvolvido

Do movimento mais simples ao evento desportivo mais exigente, uma certa quantidade de energia será necessária para suprir a demanda energética imposta pelo esforço. Para esse efeito, três sistemas energéticos distintos, mas estreitamente interligados, operam em conjunto para satisfazer as necessidades energéticas do músculo, sendo que a capacidade/velocidade à qual um atleta será capaz de acionar os seus sistemas energéticos em resposta ao início do esforço irá certamente tornar o seu exercício mais eficiente, contribuindo para melhores desempenhos desportivos. Quão bem os parâmetros fisiológicos respondem ao exercício é um dos principais campos de estudo das Ciências do Desporto. A este respeito, a cinética do consumo de oxigénio ($\dot{V}O_2K$) que se foca na análise da resposta dinâmica do consumo de oxigénio pelas células musculares tem sido considerado como um aspeto importante de estudo no campo da fisiologia do exercício, uma vez que permite uma melhor compreensão da bioenergética humana e do desempenho desportivo.

A natação é uma modalidade desportiva consideravelmente diferente das praticadas no meio terrestre devido aos condicionamentos externos que geram cenários diferentes a níveis metabólicos e biomecânicos. Fatores como a posição horizontal, a predominância dos membros superiores e os condicionamentos do meio aquático no débito cardíaco têm sido apontados como características que poderão influenciar o comportamento da cinética do $\dot{V}O_2$, tornando-a mais lenta, embora em nadadores bem treinados, provavelmente por adaptações específicas, este facto possa não se verificar.

Em natação, os constrangimentos metodológicos impostos pelo ambiente aquático têm dificultado o trabalho dos investigadores ao longo do tempo, o que coloca uma lacuna no conhecimento que já se encontra mais consolidado nas modalidades desportivas terrestres. A maioria dos estudos de natação centram-se em intensidades submáximas, no entanto ~86% dos eventos competitivos de natação são realizados em intensidades máximas e supramáximas.

A presente tese procurou investigar e descrever a $\dot{V}O_2K$ e o perfil bioenergético de nadadores em intensidades máximas e supramáximas, com o objetivo de aprofundar o conhecimento do impacto que esforços tipicamente

desempenhados em competição e treino têm nas suas respostas fisiológicas. Para tal, vários parâmetros fisiológicos foram medidos ao longo dos diferentes testes realizados pelos nadadores antes, durante e após o exercício, tais como o $\dot{V}O_2$, frequência cardíaca, concentração de lactato sanguíneo e percepção subjetiva de esforço (RPE). Durante as sessões de testes foi sempre utilizado um analisador de gases (K4b², Cosmed, Itália) acoplado ao atleta através de um *snorkel* (new-AquaTrainer[®], Cosmed, Itália) para uma análise “breath-by-breath” dos gases expirados ao longo de todo o percurso de nado e um *pacer* subaquático (Pacer2Swim[®], KulzerTEC, Portugal) foi utilizado para o controlo das intensidades. Os parâmetros da $\dot{V}O_2K$ (atraso temporal (TD), constante temporal (τ) e amplitude (A)) foram determinados através de modelos mono e bi-exponenciais tendo sido apresentado um novo modelo de análise através da taxa de crescimento do $\dot{V}O_2$ (calculando a média das derivadas em ordem ao tempo do $\dot{V}O_2$ entre o 20^o e 30^o segundo do início do exercício). Para a análise do perfil bioenergético dos nadadores foram considerados: o sistema aeróbio, determinado pela integral da resposta do $\dot{V}O_2$ durante o exercício; o sistema anaeróbio láctico, determinado pela diferença da concentração de lactato pós exercício, relativamente ao lactato de repouso; e o sistema anaeróbio aláctico, calculado através da análise do $\dot{V}O_2$ pós exercício, como o produto entre a amplitude e a constante temporal da componente rápida da curva de recuperação do $\dot{V}O_2$. Os quatro estudos principais que incorporam a parte fundamental desta tese foram desenhados de forma a: 1) caracterizar eventos competitivos de natação (50, 100 e 200 metros); 2) testar a tolerância à velocidade aeróbia máxima (MAV) em esforços contínuos e intervalados (IT); 3) testar duas tarefas de IT com diferentes intervalos de esforço (médios e longos) à MAV; e 4) testar o impacto que diferentes intensidades provocam em IT semelhantes, testando também o efeito de intervalos de esforços de curta e média duração. Primeiramente, os 28 nadadores (14 de cada sexo), que se voluntariaram para participar no estudo, começaram por desempenhar um teste incremental descontínuo máximo composto por 6 patamares de 250 metros e uma última repetição de 200 metros à máxima intensidade na técnica de crol para a avaliação do segundo limiar ventilatório (VT_2), consumo máximo de

oxigénio (Peak- $\dot{V}O_2$) e da MAV. Este teste permitiu definir os valores de referência para a aplicação e avaliação dos testes remanescentes, realizados a intensidades máximas e supramáximas, variando de acordo com a intensidade (constante vs. máxima) e distância total realizada (contínua vs. intermitente), sempre na técnica de crol.

No estudo 1, três eventos máximos simulados (50, 100 e 200 metros) mostraram uma tendência, à medida que a distância do evento aumenta e a intensidade do exercício diminui, de uma resposta mais lenta da $\dot{V}O_{2K}$ (~9s vs. 12s vs. 17s de constante temporal nos 50, 100 e 200-m, respetivamente), mas respostas oxidativas superiores, enquanto a contribuição aeróbia aumentou e a anaeróbia diminuiu (~34.4%, 54% e 71%, para o sistema aeróbio, e ~66%, 46% e 29% para o sistema anaeróbio, respetivamente para os testes dos 50, 100 e 200-m), apresentando um *cross-over* no teste dos 100 metros.

O estudo 2 mostrou uma tolerância à MAV (TLim) de ~ 256 segundos, com os nadadores com MAV mais lentas a obterem tempos superiores de TLim. Realizar esta intensidade intermitentemente (séries de 100 metros com intervalos de 15 segundos) levou a um TLim significativamente mais longo (mais ~757 segundos) e, conseqüentemente, os nadadores passaram um tempo consideravelmente superior perto dos seus valores máximos de $\dot{V}O_2$ (mais ~312 segundos acima do VT_2), quando comparado com o teste contínuo.

O estudo 3 mostrou que, independentemente da divisão de uma tarefa de IT em intervalos de esforços médios ou longos (repetições de 100 vs. 200 metros), o impacto fisiológico sobre os nadadores é semelhante (sem diferenças significativas ao nível dos parâmetros fisiológicos ou de desempenho da tarefa) e capaz de elevar o mecanismo aeróbio aos valores máximos. Quando normalizado para a mesma distância total (primeiros 800 metros) a RPE do IT composto por repetições de 200 metros foi significativamente mais elevada, mostrando que os nadadores executam o IT com repetições mais curtas mais facilmente, obtendo os mesmos benefícios fisiológicos quando comparado com repetições mais longas.

O estudo 4 mostrou que, ao treinar com repetições de curta duração (50-m), 5 a 10% de aumento da intensidade poderá aumentar a taxa oxidativa em ~6 a 13%,

e aumentar a tolerância ao esforço no domínio severo em ~ 20 a 46% (i.e., acima do VT_2). Os resultados recomendam também um aumento de, pelo menos, 5% da intensidade para se obterem respostas fisiológicas semelhantes às aquelas obtidas em IT com repetições de 100 metros.

No geral, os estudos demonstraram que maiores taxas oxidativas, amplitudes da $\dot{V}O_2K$, MAV e participações aeróbias e anaeróbias totais parecem estar associadas a melhores desempenhos desportivos. À MAV, as tarefas de treino intervalado parecem trazer mais benefícios para o desenvolvimento da capacidade aeróbia do que o treino contínuo, e o aumento da intensidade de acima da MAV, em IT com repetições curtas, é aconselhável para um efeito mais significativo sobre o metabolismo aeróbio. Em tarefas de IT, parece existir uma melhoria significativa nas respostas fisiológicas dos nadadores com o aumento das repetições de 50 para 100 metros, no entanto parece que não existem mais melhorias ao aumentar as repetições para 200 metros. A nossa investigação confirma a análise dos parâmetros $\dot{V}O_2K$, bem como a caracterização dos perfis bioenergéticos de nadadores, especialmente nas intensidades associadas ao treino e eventos competitivos, como aspetos importantes para uma verdadeira compreensão do desempenho desportivo humano.

Palavras-chave: Cinética do Consumo de Oxigénio; Bioenergética; Velocidade Aeróbia Máxima; Treino Intervalado; Natação

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Abbreviations and Symbols

%	Percentage
%MAV	Percentage velocity to the MAV
%Peak- $\dot{V}O_2$	Percentage to the Peak- $\dot{V}O_2$
τ	Time constant
[La ⁻]	Blood lactate concentration
~	Aproximadamente
Δ [La ⁻]	Difference between rest and maximal [La ⁻]
$\Delta\dot{V}O_2/t$	$\dot{V}O_2$ growth rate
A	Amplitude
ADP	Adenosine Diphosphate
Aer	Aerobic
AnaAlac	Anaerobic alactic
AnaLac	Anaerobic lactic
ANOVA	Analysis of variance
A _p	Amplitude of the primary phase
A _{sc}	Amplitude of the slow component
ASR	Anaerobic speed reserve
ATP	Adenosine triphosphate
b	Heart beats
CO ₂	carbon dioxide
C _{sw}	Energy cost of swimming
dt	Time variation
DXA	Dual-energy x-ray absorptiometry
E	Net metabolic power
e.g.	For example
EE $\dot{V}O_2$	End-exercise $\dot{V}O_2$
et al	And colaborators
HIT	High-intensity interval training
HIT100	HIT composed by 100 meters bouts
HIT50	HIT composed by 50 meters bouts
HR	Heart rate
i.e.	This is
ISD	Individual snorkel delay
IT	Interval training
IT100	IT set composed by 100 meters bouts
IT200	IT set composed by 200 meters bouts
K4b ²	Portable breath-by-breath gas analyser
Kg	Kilogram
Km	Kilometers
L	Litter
LED	Light Emitting Diode
LO ₂	Litters of Oxygen
m	Meter
MAOD	Maximal Accumulate Oxygen Deficit
MAV	Maximal aerobic velocity
min	Minute

ml	Millilitre
mlO ₂	Mililiters of Oxygen
MLSS	Maximal Lactate Steady State
mmol	Milimol
MRT	Mean Response Time
MSS	Maximum sprinting speed
MT	Maximal trials
M \dot{V} O _{2peak}	Mean \dot{V} O _{2peak} during an IT set
N	Sample size
NISR	Near-infrared spectroscopy
η_p	Propelling efficiency
O ₂	Oxygen
O _{2InitialDef}	Oxygen deficit at the onset of exercise
off-K	Oxygen uptake off kinetics
p	Probability value
PB	Personal best
PB100	PB in the 100 meters freestyle event
PB200	PB in the 200 meters freestyle event
PB400	PB in the 400 meters freestyle event
PB50	PB in the 50 meters freestyle event
PB800	PB in the 800 meters freestyle event
PCr	Phosphocreatine
Peak- \dot{V} O ₂	Maximal oxygen uptake at the incremental test
PETCO ₂	End-tidal CO ₂ pressure
PETO ₂	End-tidal O ₂ pressure
P _i	Inorganic phosphate
Q _t	Blood flow
r	Pearson correlation coefficient
RPE	Rate of perceived exertion
RST	Repeated sprint training
s	Second
SD	Standard deviation
SIT	Sprint interval training
SPSS	Statistical Package for the Social Sciences
t	Time
TD	Time delay
td ₁	Time delay of the primary phase
td ₂	Time delay of the slow component
td _p	Time delay of the primary phase
Td _{sc}	Time delay of the slow component
TLim	Time limit
ul	Microliter
v	Velocity
V Δ 50	speed half way between $v\dot{V}$ O _{2max} and MLSS
V _{crit}	critical velocity
VE/ \dot{V} CO ₂	Respiratory equivalent for CO ₂
VE/ \dot{V} O ₂	Respiratory equivalent for O ₂
\dot{V} O ₂	Oxygen uptake

$\dot{V}O_{2(t)}$	$\dot{V}O_2$ at a given time
$\dot{V}O_{2base}$	$\dot{V}O_2$ at rest
$\dot{V}O_{2K}$	Oxygen uptake kinetics
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	$\dot{V}O_2$ maximal rise in the maximal trials
$\dot{V}O_{2peak100}$	$\dot{V}O_2$ maximal rise in the 100 meters maximal trial test
$\dot{V}O_{2peak200}$	$\dot{V}O_2$ maximal rise in the 200 meters maximal trial test
$\dot{V}O_{2peak50}$	$\dot{V}O_2$ maximal rise in the 50 meters maximal trial test
$\dot{V}O_{2pre}$	Projected $\dot{V}O_2$
VT_1	First ventilatory threshold
VT_2	Second ventilatory threshold
$v\dot{V}O_{2max}$	Velocity at $\dot{V}O_{2max}$
vVT_2	Velocity at the second ventilatory threshold
W_d	Hydrodynamic resistance
τ_1	Time constant of the primary phase
τ_2	Time constant of the slow component
τ_p	Time constant of the primary phase
τ_{sc}	Time constant of the slow component

Chapter I. Introduction

From the simple action of leafing through this thesis to running a marathon, a certain amount of energy will be required by our muscles in order to allow any single movement. In the transition from rest to movement, the pulmonary, cardiovascular and muscular systems will increase the oxygen supply to muscle mitochondria, allowing aerobic respiration and energy production to increase in turn (Jones and Poole, 2005). During daily activities the human body has to adjust to various increments and variations in the energy demands imposed by the different intensities of the exercises that it performs. In sport, these changes and transitions in energy needs are very frequent and marked. Therefore, the individual's ability to adapt quickly to these changes will influence their sporting success, as they will be able to meet the energy demands of each exercise more quickly, slowing down some of the processes that will eventually lead to fatigue (Jones and Poole, 2005). How well an individual copes with the exercise energetic demands will depend, in part, upon the rate at which oxygen uptake ($\dot{V}O_2$) rises in the transition from rest, or from a previous less demanding level of exercise, to the imposed exercise (Jones and Poole, 2005).

The study of the oxygen uptake kinetics ($\dot{V}O_{2K}$), that focuses on the analysis of the dynamic response of the oxygen consumption by the muscles cells which involves a complex coordination between neuromuscular, cardiovascular and respiratory systems (Hughson, 2009), allows a better understanding of the human bioenergetics and performance as it has been considered in the last few decades as an important aspect of study in the exercise's physiology field (Jones and Burnley, 2009).

Several studies have associated fast kinetics of oxygen uptake with improved fitness status and, consequently, better sporting performance (Burnley and Jones, 2007; Jones and Burnley, 2009). Studies in cycling, running, rowing and swimming exercises showed that fast $\dot{V}O_2$ kinetics led to better performances, associating them with better fitness conditions (Alves et al., 2009; Espada et al., 2015; Ingham et al., 2007; Koppo et al., 2004; Reis et al., 2012a,b).

For any kind of exercise, three distinct but closely integrated systems operate together to satisfy the energy requirements of the muscle, being each system more or less solicited according to the level of the effort's intensity (Gastin, 2001). If at submaximal intensities, where the aerobic energy sources are primarily used, the measure of $\dot{V}O_2$ can reflect with an almost accurate precision the total amount of energy of the effort, at maximal or supramaximal intensities (as the shorter swimming competitive distances) the energy expenditure necessarily implies the contribution of anaerobic sources of energy, the more so the shorter the race duration (Zamparo et al, 2011). This way, understanding the role of the participation of the anaerobic alactic and lactic systems is critical in order to comprehend the performance of the maximal and supramaximal efforts, being also important to measure other biomarkers of fatigue that could provide a broader understanding of the human physiology.

While the $\dot{V}O_2K$ and bioenergetics studies have been growing over the last few decades in the terrestrial sports modalities, in swimming there is a considerable lower number of studies focusing on these study areas. The fact that swimming studies imposes higher methodologic challenges for the data collection, due to the aquatic environment, compared to the traditional laboratory-controlled setting, could explain why this is a reality. Notwithstanding, the number of studies in swimming have been rising considerably in the last decade (Almeida et al., 2019a,b; Campos et al., 2017; Espada et al., 2015; Hellard et al., 2018; Peyrebrune et al., 2014; Pessôa Filho et al., 2012 and *in press*; Reis et al., 2012a,b and 2017; Ribeiro et al., 2015; Rodríguez and Mader, 2011; Sousa et al., 2011, 2013, 2014 and 2017) which contributed for new insights about this widely practiced sport.

The fact that swimming is a sport considerably different from those practiced in the terrestrial environment, since in the aquatic environment a whole set of constraints arise which can influence the "normal" response of $\dot{V}O_2$, due to external conditions that generate different scenarios at metabolic and biomechanical levels, reinforces the relevance to continue to deepen this specific

area of study and justifies the choice for studying the swimming sport in this thesis.

Even though some recent studies have focused on the energetic contributions and $\dot{V}O_2K$ in higher levels of effort, the majority of studies were performed at submaximal and constant intensities which do not reflect the reality of the swimmers efforts in competition. Therefore, this thesis proposes to continue to bring new insights of the swimmers physiological responses at the maximal and supramaximal intensities, which reflects ~86% of the indoor swimming events. Furthermore, the training process, that is widely recognised as one of the main factors that contributes for athletes' performances improvement, which in swimming have been considerably neglected by scientific studies (mainly those regarding the $\dot{V}O_2$ responses topic), will have a place in this work, in order to deepen the understanding about the physiological responses of the swimmers at different training protocols and how that could lead to better sports performances.

1.1 Aims and Outline of this thesis

Based on over approximately 135.000 meters swam by the swimmers that volunteered to participate in this study, we have tried to perform a broad investigation of the reality of the swimming performance either in the competitive level, but also regarding the training process, as one of the main factors that could make the difference in sports performance.

The general purpose of this thesis is to investigate and describe the swimmers $\dot{V}O_2$ responses and bioenergetics profiles at different maximal and supramaximal intensities that could be related to the reality of competitive efforts. Also, the maximal aerobic velocity, intensity associated with the maximal oxygen consumption and widely used for training intensity prescription, will be tested for swimmers tolerance, as well as the physiological responses at different kinds of interval training will be studied, through the comparison of several kinds of training protocols that are usually used by coaches in their training routines.

In **Chapter II** a brief literature review will be presented, which will focus on the four main topics of this thesis: 1) the $\dot{V}O_2K$ characteristics in the different domains of exercise, with a special focus on those tested in this work; 2) the energy systems interaction and the relative contributions for maximal exercises; 3) the maximal aerobic velocity and the significance of the time to exhaustion at this intensity; and 4) the importance of interval training for athletes development and the physiological responses of athletes at this kind of training with a special focus on the high-intensity interval training.

Chapter III presents the methodology used in the design of the studies that comprises the fundamental part of this thesis. This chapter contains a description of the athletes that participated in our studies as well as the procedures that were conducted in order to perform the different testing sessions and the data analysis. A more specific methodology will be presented latter in each study.

The Chapters IV to VII will present the four studies that compose the main part of this thesis and presents the results of the field study that was performed.

In **Chapter IV** simulated swimming events of 50, 100 and 200 meters were studied for characterizing the $\dot{V}O_2K$ and profile the swimmers bioenergetics at these competitive distances, in order to provide a close insight of the swimmers efforts in a similar procedure to a real swimming competitive situation.

The **Chapter V** characterizes the swimmers' tolerance at the maximal aerobic velocity when performing two different time limit tests, comparing a continuous versus an intermittent situation, in order to characterize the physiological responses at both sets and understand which could be better to the aerobic capacity's development.

The **Chapter VI**, directs the thesis definitely for the interval training field comparing two similar intermittent sets at the maximal aerobic velocity, however with different work-intervals (100 vs. 200 meters bouts), trying to understand how different work intervals will impact the swimmers physiological responses.

The **Chapter VII** presents the last study of this thesis and, contrarily to the previous study, swimmers performed similar intermittent sets composed by 50 meters repetitions, but at different intensities (100 to 110% of the maximal aerobic velocity), in order to analyse the impact that different intensities could promote on swimmers physiological responses. Also, a comparison of the impact of using 50 versus 100 meters bouts at the maximal aerobic velocity on swimmers physiological responses will be presented.

The **Chapters VIII and IX** resume and discuss the main findings and conclusions of the studies that were presented in this thesis.

The **Chapter X** presents the main appendixes referred along the work. From those, two short studies are focusing on the relationship between $\dot{V}O_2K$ and exercise intensity in order to complement the findings of the studies presented in the fundamental part of this thesis. In the appendix I, what is tested is if the $\dot{V}O_2K$ and specifically the time constant of the primary phase is influenced by the swimming velocity at maximal and supramaximal intensities, while in the appendix II the physiological responses of different distance swimming trials at the same maximal aerobic velocity are analysed.

References of Chapter I

- Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019a) Is $\dot{V}O_2$ kinetics influenced by swimming intensity in maximal and supramaximal velocities in young female swimmers? In: Proceedings of the International Seminar of Physical Education, Leisure and Health; Castelo Branco, Portugal. *Journal of Human Sport and Exercise* 14(4proc):1566-1569
- Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019b) Physiological responses at maximal aerobic swimming pacing in different distance-trials. In: Proceedings of the International Seminar of Physical Education, Leisure and Health; Castelo Branco, Portugal. *Journal of Human Sport and Exercise* 14(4proc):1686-1689
- Alves F, Reis L, Vleck V, Bruno P, Millet G (2009) Oxygen uptake kinetics in heavy intensity exercise and endurance performance in swimmers. *Med Sci Sport Exerc* 41:978
- Burnley M, Jones A (2007) Oxygen uptake kinetics as a determinant of sports performance. *Eur J Sport Sci* 7(2):63-79
- Campos EZ, Kalva-Filho C, Gobbi R, Barbieri R, Almeida NP, Papoti M (2017) Anaerobic contribution determined in swimming distances: Relation with performance. *Front Physiol* 8:1-6
- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843
- Gastin PB (2001) Energy system interaction and relative contribution during maximal exercise. *Sports Med* 31(10):725-741
- Hellard P, Pla R, Rodríguez FA, Simbana D, Pyne DB (2018) Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *Int J Sports Physiol Perform* 13(8):1011-1120
- Hughson RL (2009) Oxygen uptake kinetics: historical perspective and future directions. *Appl Physiol Nutr Metab* 34(5):840-850
- Ingham SA, Carter H, Whyte G, Doust JH (2007) Comparison of the oxygen uptake kinetics of club and Olympic champion rowers. *Med Sci Sports Exerc* 39(5):865-871.

- Jones A, Burnley M (2009) Oxygen uptake kinetics: An underappreciated determinant of exercise performance. *Int J Sports Physiol and Perform* 4(4):524-532
- Jones AM, Poole DC (2005) Introduction to oxygen uptake kinetics and historical development of the discipline. In: Jones AM, Poole DC (Eds), *Oxygen uptake kinetics in sport, exercise and medicine*. Routledge, London, pp 3-37
- Koppo K, Bouckaert J, Jones A (2004) Effects of training status and exercise intensity on phase II $\dot{V}O_2$ kinetics. *Med Sci Sports Exerc* 36(2):225-232
- Pessôa Filho D, Alves F, Reis J, Greco, C, Denadai, B (2012) $\dot{V}O_2$ kinetics during heavy and severe exercise in swimming. *Int J Sports Med* 33(09):744-748.
- Pessôa Filho D, Massini D, Siqueira L, Santos LG, Vasconcelos CM, Almeida TF, Espada MA, Reis J, Alves F, DiMenna F (in press) A rapidly incremented tethered-swimming maximal protocol for cardiorespiratory assessment of swimmers. *J Vis Exp*
- Peyrebrune MC, Toubekis AG, Lakomy HK, Nevill ME (2014) Estimating the energy contribution during single and repeated sprint swimming. *Scand J Med Sci* 24 (2):369-376
- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012a) Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *Eur J Appl Physiol* 112(5):1689-1697
- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012b) Oxygen uptake kinetics and middle distance swimming performance. *J Sci Med Sport* 15:58-63
- Reis J, Millet GP, Bruno P, Vleck V, Alves F (2017) Sex and exercise intensity do not influence oxygen uptake kinetics in submaximal swimming. *Front Physio* 8:72
- Ribeiro J, Figueiredo P, Sousa A, Monteiro J, Pelarigo J, Vilas-Boas JP, Toussaint, HM, Fernandes R (2015) $\dot{V}O_2$ kinetics and metabolic contributions during full and upper body extreme swimming intensity. *Eur J Appl Physiol* 115(5):1117-1124
- Rodríguez FA, Mader A (2011) Energy systems in swimming. In: Seifert L, Chollet D, Mujika I (eds) *World Book of Swimming: From Science to Performance*. Nova Science Publishers, Hauppauge, New York, pp 225–240
- Sousa A, Borrani F, Rodríguez FA (2017) Oxygen uptake kinetics is slower in swimming than in arm cranking and cycling during heavy intensity. *Front Physio* 8:639
- Sousa A, Figueiredo P, Oliveira N, Oliveira J, Silva A, Keskinen KL, Rodríguez FA, Machado L, Vilas-Boas JP, Fernandes R (2011) $\dot{V}O_2$ Kinetics in 200-m race-pace front

crawl swimming. *Int J Sports Med* 32(10):765-770

Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190

Sousa A, Vilas-Boas J, Fernandes R (2014) $\dot{V}O_2$ kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at $\dot{V}O_{2max}$. *Biomed Res Int* 2014:675363

Zamparo P, Capelli C, Pendergast D (2011) Energetics of swimming: a historical perspective. *Eur J Appl Physiol* 111(3):367-378

Chapter II. Literature Review

2.1 Oxygen consumption evaluation and Peak- $\dot{V}O_2$ concept

In sports, the energetic demands required by the beginning of each exercise suddenly creates an unbalanced state between the energy that is already available in the muscles cells for exercise, from that which is demanded by the level and duration of the effort. From the three energy systems capable of converting the energy contained in the food we eat into adenosine triphosphate (ATP), the substrate required to energize all muscular contractions, DiMenna and Jones (2009) considered the aerobic system, that involves the re-synthesis of ATP via the oxidative phosphorylation, as the predominant one.

The onset of any physical exercise triggers the cardiorespiratory and muscular systems allowing a pronounced supply of oxygen to the muscle mitochondria in order to promote the aerobic respiration and the energy production necessary to supply the energetic demands of each exercise (Jones and Poole, 2005; Xu and Rhodes, 1999). The ability/velocity at which an individual can respond to these energetic demands will, certainly, influence their performance and sporting success, which lauds the importance that is been given to the evaluation of oxygen uptake ($\dot{V}O_2$) as a determinant aspect of human performance in the contemporary research in sports science, since it allows a better understanding of the human bioenergetics (Jones and Burnley, 2009).

According to DiMenna and Jones (2009), the $\dot{V}O_2$ as a field of study probably started in the late 1700s, when Priestly and Scheele, independently, discovered a gas we know comprises 20.93% of the ambient air. This “imminent respirable” gas Lavoisier named as oxygen (O_2) and measured its consumption through the decrease of the O_2 available in a chamber when an animal was sealed within. Several years latter a German physiologist, Adolf Eugen Fick (1870), presented a principle that can be used to measure the blood flow through any organ that adds substances to, or removes substances from, the blood through the following relationship:

$$Q = M / (V - A) \quad \text{(Equation 1)}$$

Where Q is the volume of blood flowing through an organ in a minute, M the number of moles of a substance added to the blood by an organ in one minute, and V and A are the venous and arterial concentrations of that substance. Fick's work led to the currently used Fick equation for the consumption of oxygen by the tissues (Jones and Poole, 2005):

$$\dot{V}O_2 = \dot{Q}_t \cdot (CaO_2 - CvO_2) \quad (\text{Equation 2})$$

Where \dot{Q}_t represents tissue blood flow (which depend upon cardiac output) and CaO_2 and CvO_2 represent arterial and venous O_2 contents. The difference between CaO_2 and CvO_2 reflects the amount of oxygen extracted from the arterial blood by the tissue to support the oxidative phosphorylation in the cells mitochondria (Jones and Poole, 2005).

According to DiMenna and Jones (2009), a huge advance in the gas exchange analysis occurred when in 1911 the British scientist Claude Douglas and co-workers studied the acute effects of altitude exposure on ventilation and respiration, using a bag-collection method to measure $\dot{V}O_2$ and CO_2 at rest and during muscular work, during chosen periods of data collection determination of the average of the $\dot{V}O_2$ values. Douglas' new *Method for determining the total respiratory exchange in man* (1911) allowed future researchers to improve the knowledge about the sports physiology especially in terrestrials' modalities as running and cycling exercise, being his *Douglas Bags* still considered as the gold standard for the $\dot{V}O_2$ assessment.

In swimming, this system presented several limitations, especially when it comes to the handling of the bags, due to its permeability to the external air and to its posterior retrospective analysis determination of the relative CO_2 and O_2 concentrations, also difficult to conduct when the swimmers swim up and down the pool and turn at each end, since the hoses and valves pose some limitations to the swimmers' technique and collection times. Therefore, and in order to overcome such difficulty, several investigators applied this method by collecting consecutive samples of expired air at the end of the swim (namely for the first 8,

20 or 40s of the recovery period), with the $\dot{V}O_2$ recovery onset obtained by backward extrapolating the O_2 recovery curve (Sousa et al., 2014a)

In 1913 Jules Amar analysing samples of expired air assessed the effect of cycling-ergometer, while in 1922 Hill and Meyerhof discovered that the contracting muscle of a frog yielded fast production of heat on the initial contractions and a slow production later (Sousa et al, 2014a). One year later, the work from Hill and Lupton, in 1923, testing the $\dot{V}O_2$ in several running intensities, lead to the proposal of the concept of maximal oxygen uptake ($\dot{V}O_{2max}$) in humans during exercise. The authors found that the rate of oxygen intake per minute due to the exercise increases as the speed increases, reaching a maximum for speeds beyond about 260 meters per minute, however when the speed was increased beyond this limit, no further increase in oxygen uptake was observed, even though the requirement of the body for oxygen is far higher (figure 1), suggesting that the heart, lungs, circulation, and the diffusion of oxygen to the active muscle-fibres attained their maximum activity speeds, thereby defining the limits of the cardiorespiratory system.

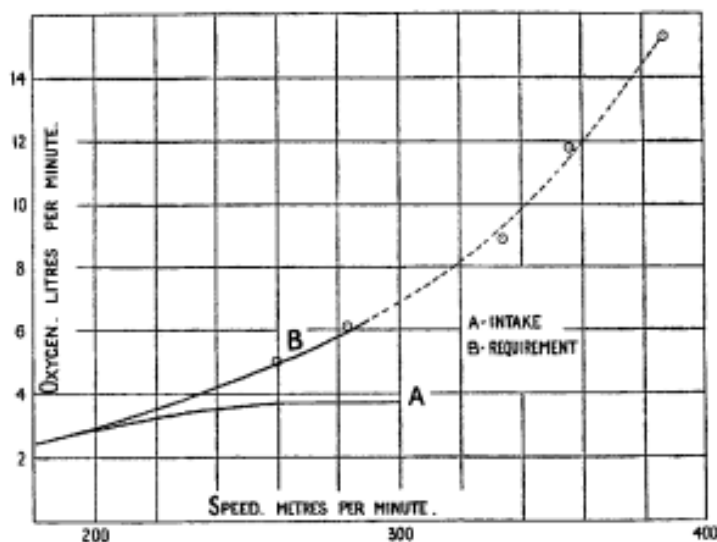


Figure 1. Relationship between oxygen intake (curve A), or oxygen requirement (curve B), and speed, in running at various speeds. (Hill and Lupton, 1923)

Accordingly to Xu and Rodes (1999), the control mechanism for exercise $\dot{V}O_2$ kinetics, two opposing hypotheses have been proposed. One of them suggests

that the rate of the increase in $\dot{V}O_2$ at the onset of exercise is limited by the capacity of oxygen delivery to active muscle. The other suggests that the ability of the oxygen utilisation in exercising muscle acts as the rate-limiting step. For Jones and Carter (2000), it is currently accepted that $\dot{V}O_{2max}$ is limited by the rate at which oxygen can be supplied to the muscles and not by the muscle's ability to extract oxygen from the blood it receives. Notwithstanding, this is still an open issue.

The concept that the measurement of a plateau of $\dot{V}O_{2max}$ is a quantifiable and reproducible parameter of the cardiorespiratory system's ability to maximally deliver oxygen has been repeated sufficiently that it has achieved near universal acceptance (Hawkins et al., 2007). However, in spite of the clarity of the concept of a plateau observed in maximal graded tests on a treadmill or cycle ergometer, Howley et al. (1995) proposed a variety of secondary criteria to characterize the oxygen uptake measured in the last minutes of the incremental test, in order to confirm the effort as maximal, since the authors stated that it is not uncommon for some subjects not to clearly demonstrate a plateau in $\dot{V}O_2$. These secondary criteria include the occurrence at the end of the exercise of: high levels of blood lactate concentration (i.e., $\geq 8\text{mM}$) elevated respiratory exchange ratio (i.e., > 1.00 , 1.10 , or 1.15) and the achievement of an elevated percentage of the maximal heart rate estimated for the age of the subjects (≤ 10 beats/min or 5% of the maximum age-predicted 220-age) (Howley et al., 1995; Midley et al., 2009; Poole et al., 2008).

The usage of incremental maximal test (continuous or discontinuous protocols) has been widely used for $\dot{V}O_{2max}$ determination since the first contributions of Hill's work, however, recently, some authors have been alerting for the possible misuse of the concept when this variable is simply obtained from an incremental maximal test if a clear $\dot{V}O_2$ plateau is not observed.

For Poole and Jones (2017), the literature has been giving to these "so called secondary criteria" to validate $\dot{V}O_{2max}$, a broad range of maximal values for each of these variables which could lead to misevaluations, especially in sedentary or

patient populations. Therefore, the authors suggest the application of a secondary subsequent exhausting constant work rate test at a higher work rate than that achieved at the end of the incremental test (i.e., above ~10%), since it allows a sufficient duration for the kinetics to achieve the same or a greater $\dot{V}O_2$, if possible.

Previous studies performed this reliable test in running at intensities above ~3 to ~10% of the intensity associated to the $\dot{V}O_{2max}$ achieved in an incremental test, however none presented higher values of $\dot{V}O_2$ than those that were previously found in the corresponding traditional incremental tests (Hawkins et al., 2007; Midgley et al., 2006 and 2009; Weatherwax et al., 2016). In swimming, studies that performed constant exhaustive tests at 100% (Fernandes et al., 2003) or at 105% of the velocity associated to the $\dot{V}O_{2max}$ (Sousa et al., 2014b), did not present, also, differences from the previous $\dot{V}O_{2max}$ values obtained first at the corresponding incremental tests. In this thesis, although several maximal and supramaximal tests were performed by the swimmers, which could reinforce the maximal uptake values obtained in the incremental tests, we opted, for caution, to use the term Peak $\dot{V}O_2$ (Peak- $\dot{V}O_2$), instead of the more traditional $\dot{V}O_{2max}$ term.

According to DiMenna and Jones (2009) the modern concept of the $\dot{V}O_2$ responding by an exponential function was first presented by the Henry's model in 1951 suggesting a linear first-order $\dot{V}O_2$ control. However, few years later, Henry and DeMoor (1956) rebuilt the initial model including a two-exponential equation, since, apparently, the time to reach a steady state in the $\dot{V}O_2$ increases with increasing work rates, suggesting a secondary raise on the $\dot{V}O_2$ values above some intensities.

The emergence of new technologies in the 1960s dramatically changed open-circuit spirometry as computers and fast-responding O_2 and CO_2 analysers were developed, involving the measurement of flow volume at a mouthpiece through which inhalation and exhalation takes place allowing a breath-by-breath analysis, which allowed the improvement of the study of the $\dot{V}O_2$ kinetics (DiMenna and Jones 2009). The concept of $\dot{V}O_2$ kinetics, as we know today, was well described

by Whipp and Wasserman in 1972.

2.2 Oxygen uptake kinetics

The study of $\dot{V}O_2$ kinetics comprises the description and analysis of the dynamic response of oxygen consumption by the muscles cells in response to the start of any exercise and is being considered as a crucial aspect of study in the modern sports sciences field since it allows a better understanding of the human bioenergetics and a real understanding of the physiological determinants of athletic performance (Jones and Burnley, 2009). This response, that involves a complex coordination between neuromuscular, cardiovascular and respiratory systems (Hughson, 2009), determines the instantaneous rate of aerobic and anaerobic energy transfer, the mixture and amount of substrate utilized and the tolerance of the exercise (Burnley and Jones, 2007). Since the amount of work that can be done anaerobically is limited, the rate at which the $\dot{V}O_2$ adjusts to the exercises' energetic demands will increase the contribution of the oxidative metabolism to energy turnover, influencing the O_2 deficit incurred and thus the extent to which muscle and systemic homeostasis is perturbed, having the potential to delay some of the processes that eventually will lead to fatigue and by this way enhance the performance (Jones and Burnley, 2009).

Several studies have linked fast kinetics of oxygen uptake with improved fitness status and, therefore, with better sports performance (Burnley and Jones, 2007; Espada et al., 2015; Jones and Burnley, 2009; Pessôa Filho et al., 2012; Reis et al., 2012a,b). Studies about running, cycling and rowing exercises clearly demonstrated that fast $\dot{V}O_2$ kinetics leads to better performances, associating them with better fitness conditions (Ingham et al., 2007; Koppo et al., 2004). Hence, if the individual is able to use the aerobic energy mechanism more quickly, he/she will be able to delay the fatigue process, tolerating the demands of any exercise/physical activity (Jones and Poole, 2005).

The $\dot{V}O_2$ kinetics is being considered as a useful, non-invasive measure of the integrated capacity of the organism to transport and utilize O_2 in order to supply the energy required by exercise (Reis et al., 2018) and can vary due to several

factors: physical aptitude; typology of muscle fibers; cardiac output; diseases; metabolic substrates; enzymatic activation; and training level (Hughson, 2009).

The $\dot{V}O_2$ response is not linear, varying across the exercise's length being dependent of the intensity of the exercise. Accordingly to the literature three phases can be discerned (Gaesser and Poole, 1996; Jones and Poole, 2005; Reis et al., 2018; Whipp and Ward, 1990; Whipp and Wasserman, 1972).

2.2.1 Phases of $\dot{V}O_2$ kinetics

Phase 1

This phase, with a duration of 15-20 seconds following the onset of exercise, also designated by Cardiodynamic phase, is characterized by an immediate increase on the $\dot{V}O_2$ typically initiated within the first breath, representing the O_2 exchange associated to the initial elevation of cardiac output and thus the pulmonary blood flow (Jones and Poole, 2005). The blood returning to the lung in these first seconds of exercise, since has not been subjected to increased O_2 extraction as result of metabolic demand by the working muscle fibers, definitely, is not representative of active muscle O_2 utilization (Reis et al., 2018). Even though this phase may not represent a high interest in the research of the sports sciences field, since it does not reflect what is happening in the muscle, it is considered for clinical studies and evaluations of certain pathologies.

Phase 2

After the initial seconds of the first phase there is a decrease in the $\dot{V}O_2$, due to the beginning of the gas exchange with the blood that is present in the muscles. The second phase of the $\dot{V}O_2$, which is designated by the fundamental part or fast component, is characterized by a rapid and exponential growth of the $\dot{V}O_2$ up to a certain higher value, which reflects the gain and the change of the oxygen consumption in the active muscle over time. This exponential response can be described by three components (Reis et al., 2018; Koga et al., 2005; Whipp and Wasserman, 1972): the Amplitude (A), which represents the increase in the

actual consumption of oxygen in the muscle; the Time Delay (TD) of the beginning of the response, which reflects the time from the beginning of the exercise to the beginning of the exponential rise of the $\dot{V}O_2$; and the Time Constant (τ), which indicates the rate at which this rise in the $\dot{V}O_2$ occurs, reflecting the time to complete 63% of the response. This time constant has been correlated with performance, since lower times seem to delay the onset of fatigue (Burnley and Jones, 2007; Ingham et al., 2007). Studies also prove that interval training of high intensity can bring important benefits, especially in reducing this constant (Berger et al., 2006; Duffield et al., 2006).

Phase 3

With continued exercise, the $\dot{V}O_2$ tends to stabilize at a metabolic equilibrium (depending on the intensity of the exercise), where the energy requirements of the body to perform the exercise are compensated by an oxygen consumption that allows a balance between the ATP that is spent to obtain energy and the ATP that is resynthesized by the process of oxidative phosphorylation (Jones and Poole, 2005).

When exercise is performed above the first ventilatory threshold, in the heavy intensity domain, the establishment of a steady state is delayed due to a complementary increase of the $\dot{V}O_2$, as well as due to some loss of efficiency of the muscle fibers and an increase in the recruitment of type II muscle fibers. This phase is designated by the slow component of $\dot{V}O_2$, and it usually occurs between 90 and 150 seconds of the exercise (Jones and Poole, 2005; Reis et al., 2012b).

If the intensity of the exercise falls within a severe intensity domain, the slow component also manifests, although with a greater amplitude, since the oxygen consumption will increase until it reaches the maximum value ($\dot{V}O_{2max}$) (Burnley and Jones, 2007; Jones and Burnley, 2009). If the intensity of the exercise is maximum or supramaximal, the individual goes into fatigue before the $\dot{V}O_2$ stabilizes (Carter et al., 2006).

The following figure resumes graphically the three phases of the $\dot{V}O_2$ kinetics above described:

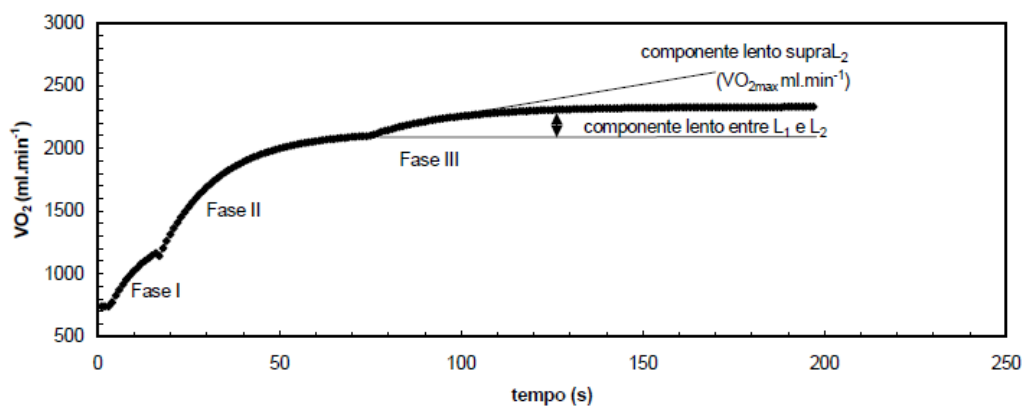


Figure 2. Three phase response of the $\dot{V}O_2$ kinetics. Phase I (cardiodynamic phase), phase II (fast component) and phase III (slow component) (Silva and Oliveira, 2004)

Since the cardiodynamic phase is rather difficult to isolate from the $\dot{V}O_2$ data and its profile can influence the accuracy of the fundamental part analysis, researchers have been using one of two methods to solve the problem: 1) some researchers (e.g., Adami et al., 2011; Barstow et al., 1996; Pringle et al., 2003) opted to fit this phase by an exponential modelling, presenting a tri-exponential or a bi-exponential modelling to fit the all $\dot{V}O_2$ response (when a slow component is observed, or not, respectively); 2) given the fact that the cardiodynamic phase does not reflect the muscles O_2 utilization leads the majority of the researchers to not consider this phase on their data handling, opting to exclude (usually) the first 20 seconds of exercise (e.g., Borrani et al., 2001; Espada et al., 2015; Reis et al., 2012a,b; Pessôa Filho et al., 2012; Sousa et al., 2014b) presenting a bi-exponential or monoexponential modelling to fit the all $\dot{V}O_2$ response, again with the presence or not of the slow component phase, respectively. In this thesis we opted for the second method accordingly to what seems to bring more consensus in the modern literature.

2.2.2 $\dot{V}O_2$ kinetics in different intensity domains

As it was previously mentioned, the response profile of the $\dot{V}O_2$ depends on the intensity domain in which the exercise is being performed. In the present work, four domains of exercise intensity are considered, namely: moderate, heavy, severe and extreme domains. The moderate, heavy and severe domains are traditionally described by authors as Gaesser and Poole (1996) and Xu and Rhodes (1999), while the extreme domain is being discriminated from the severe domain by some authors as Jones and Poole (2005), Wilkerson et al. (2004) and Whipp (1994). Accordingly do Poole and Jones (2005) the physiological boundaries that separate the several intensities are the following:

1st Ventilatory threshold – Moderate/Heavy:

This threshold represents the boundary between the moderate and the heavy intensity domain and is characterized by the onset of the lactate accumulation. Nonetheless, this accumulation is controlled up to the maximum lactate steady state. Ventilation begins to progressively increase in a controlled manner. The exercise can be maintained for 20 to 30 minutes.

2nd Ventilatory Threshold/Respiratory Compensation Point – Heavy/Severe:

This threshold marks the boundary between the heavy and severe domains and is related to the maximum lactate steady state. From this particular stage, the accumulation of lactate reaches a level that the body cannot remove it in time, therefore failing to stabilize its value. Moreover, ventilation significantly increases, and the exercise will end by entering in the exhaustion phase of the subject.

3rd Maximum Oxygen Consumption – Severe/Extreme.

This threshold marks the boundary between the severe and extreme domains and is characterized by an extremely high accumulation of lactate and the exercise will quickly end due to the exhaustion of the individual.

2.2.2.1 Moderate domain

In exercise intensities that are below the first ventilatory threshold, the $\dot{V}O_2$ response (and not considering the cardiodynamic phase) is represented by a simple exponential (Özyener et al., 2001). The time constant presents values between 20 and 35 seconds and steady-state is normally reached after 2 or 3 minutes (Whipp and Wasserman, 1972).

In this specific domain, there is no accumulation of lactate, which allows the exercise to be maintained for a long period of time. Furthermore, and disregarding the cardiodynamic phase, and due to the achievement of a steady state of oxygen consumption (without the presence of the slow component), $\dot{V}O_2$ can be represented by the following monoexponential equation (Jones and Poole, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2\text{base}} + A \cdot (1 - e^{-(t-TD)/\tau}) \quad (\text{Equation 3})$$

Where: $\dot{V}O_{2(t)}$ represents the oxygen consumption at time t ; $\dot{V}O_{2\text{base}}$, the oxygen consumption at the baseline; A , the amplitude of the exponential; t , the time in seconds; TD , the delay time of the exponential; τ , the time constant of the exponential.

2.2.2.2 Heavy domain

In this domain, the work rate occurs between the 1st ventilatory threshold and the 2nd threshold (the respiratory compensation point). The highest work rate, which occurs within this specific intensity domain, corresponds to the maximum lactate steady state (Reis et al., 2012b). The establishment of a steady state is delayed, and in about 15 to 20 minutes, mainly due to the complementary increase of $\dot{V}O_2$ (slow component). Nevertheless, the steady-state of the $\dot{V}O_2$ can be achieved, even though it requires a high effort and the consumption of glycogen.

Moreover, in a constant load and continuous exercise protocol, and at these intensities, the $\dot{V}O_2$ -time curves will have to be adjusted by a bi-exponential model (Özyener et al., 2001), especially to achieve a better settling of the curve, since there are two components with different characteristics from each other

(again, without considering the cardiodynamic phase). Hence, in a heavy intensity domain, the $\dot{V}O_2$ can be represented by the following equation (Jones and Poole, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2(b)} + A_p \cdot (1 - e^{-(t-TD_p)/\tau_p}) + A_{sc} \cdot (1 - e^{-(t-TD_{sc})/\tau_{sc}}) \quad (\text{Equation 4})$$

Where: $\dot{V}O_{2(t)}$ represents the oxygen consumption at time t ; $\dot{V}O_{2\text{base}}$, the oxygen consumption at the baseline; A , the amplitude of the exponential; t , the time in seconds; TD , the exponential delay time; τ_p , the time constant of the 1st exponential; τ_{sc} , the time constant of the 2nd exponential.

2.2.2.3 Severe domain

On the contrary, this domain is characterized by having exercise intensities above the second ventilatory threshold, but below the $\dot{V}O_{2\text{max}}$. With a response profile of the $\dot{V}O_2$ similar to what is observed in the heavy domain, however, with the continuation of the exercise the $\dot{V}O_2$ will increase (slow component) until it reaches the maximum oxygen consumption of the individual, making exhaustion a quite eminent process. Nevertheless, increased lactate and marked decline in blood pH without stabilization are some of the other factors that contribute to the fact that the exercise cannot be maintained for a long time (Burnley and Jones, 2007; Reis et al., 2018).

2.2.2.3 Extreme domain

All exercises that take place above the $\dot{V}O_{2\text{max}}$ are located in the extreme intensity domain, and the durations that correspond to the maintenance of the exercise in time are, and from the outset, compromised.

During supramaximal exercise the $\dot{V}O_2$ cannot stabilize and continues to increase until the point of fatigue, which may or may not see $\dot{V}O_2$ rise to a maximum value (Gastin, 2001). According to Reis et al. (2018), the high intensity exercise that is performed in this domain could not even allow the $\dot{V}O_{2\text{max}}$ or the maximum heart rate to be reached, considering that the rapid and uncontrolled increase in lactate

concentration, as well as the sudden decrease in blood pH, will lead to the individual's exhaustion.

At this domain and in exercises performed at the maximum intensity possible, independently of the fatigue that is imposed to the athletes in an earlier stage of the exercise, studies have reported that in maximal exercises of 30 to 60 seconds the athlete's $\dot{V}O_2$ could be raised at 90% of the individual's maximum (Gastin and Lawson, 1994; Kavanagh and Jacobs, 1988). Wilkerson et al. (2004), testing the tolerance of healthy subjects for maximal and supramaximal exercises in the cycle ergometer exercise reported times to exhaustion of 186, 131 and 96 seconds at 100%, 110% and 120% of the intensity associated to $\dot{V}O_{2max}$, respectively, while Sousa et al. (2014b) reported 194 and 123 seconds for the 100% and 105% of the velocity associated to $\dot{V}O_{2max}$, respectively.

For maximum and supramaximal intensities, several authors disregard bi-exponential analysis models, choosing, in turn, the same simple exponential model that is used in the moderate intensity domain (Bosquet et al., 2007; Caputo and Denadai, 2004; Rodríguez et al., 2003; Sousa et al., 2011 and 2013a). However, some authors claim that the bi-exponential model is the most adequate one, since it truly adapts to the effort reality.

Even though there are several proponents of the use of the exponential and of the bi-exponential models, some authors have been questioning the adequacy of these "conventional" models for intensities above $\dot{V}O_{2max}$, since a stable value of $\dot{V}O_2$ is not achievable (Hebestreit et al., 1998; Hughson et al., 2000; Margaria et al., 1965). Indeed, Carter et al. (2006) and Adami et al. (2011), together with their respective teams, innovated with their proposal, suggesting the use of a semi-logarithmic equation, which was first suggested by Hughson et al. (2000), comparing it with bi-exponential and tri-exponential analysis models (excluding or not the cardiodynamic phase). Thus, and to consider this semi-logarithmic model, as well as to estimate the values of the time constants, the authors started from three specific assumptions:

1. During a maximal exercise the $\dot{V}O_2$ projects to an unreachable, but estimable value (above the $\dot{V}O_{2max}$);
2. This unobtainable value of the $\dot{V}O_2$ ($\dot{V}O_{2pre}$) is proportional to the energy demands that are caused by the work rate that corresponds to the task;
3. The rate at which the $\dot{V}O_2$ increases is proportional to the instantaneous differences between the $\dot{V}O_{2pre}$ and the $\dot{V}O_2$ at each instant.

The equation used by Carter et al. (2006) is the following one:

$$\text{Log } \Delta\dot{V}O_2 (t) = \log_{10}[\dot{V}O_{2pre}-\dot{V}O_2(t)] \quad (\text{Equation 5})$$

Where: $\dot{V}O_{2pre}$ represents the proportional value of the $\dot{V}O_2$ to the energetic demands of the task; and the $\dot{V}O_{2(t)}$ represents the $\dot{V}O_2$ value at each instant.

As a result of Carter's study, values of time constants, of the primary component, were obtained much slower in the semi-logarithmic modeling than in the tri-exponential modeling study (62.5 against 20.3 seconds).

In addition, Adami et al. (2011) also presented some interesting results, especially when comparing the $\dot{V}O_2$ data that was obtained by a breath-by-breath gas analyzer with data that was measured by a system that measures local near-infrared spectroscopy (NIRS). As a matter of fact, these data demonstrated temporal constants measured locally in the muscle, which are much lower than those that were measured by the expired air. Such results may be due to the time delay values that were found, which were significantly lower when locally measured in the muscle. The results of Adami's and Carter's studies may question the researchers, namely as to the level of adequacy of the equations that they use for modelling the $\dot{V}O_2$ responses in the extreme domains, however the fact that this method is sustained by the premise of an impossible and *unreachable* $\dot{V}O_2$ above the $\dot{V}O_{2max}$, brings some physiological constrains that the majority of the researchers do not want to cross. Also, the fact that this method presents time constant values completely different from those obtained by the conventional exponential method does not allow a comparison with the majority of the studies.

In this thesis we opted for modeling the $\dot{V}O_2$ responses of exercises in the extreme domain through a conventional exponential fitting. However, since we tested a really short supramaximal swimming event (~30 seconds duration) where the $\dot{V}O_2$ response does not present a clear stabilization we opted to present a new approach in order to confirm the results from the exponential method. This new method comprises the characterization of the growth rate between the 20th and the 30th second of the initial exercise by averaging the time derivatives of $\dot{V}O_2$ between those two points. This period of time was chosen in order to exclude the cardiodynamic phase (first 20 seconds) and to allow a comparison between other longer exercises. This method will be better described in chapter III. The $\dot{V}O_2$ responses from rest to exercise in the four intensity domains previously described are graphically resumed in the following figure.

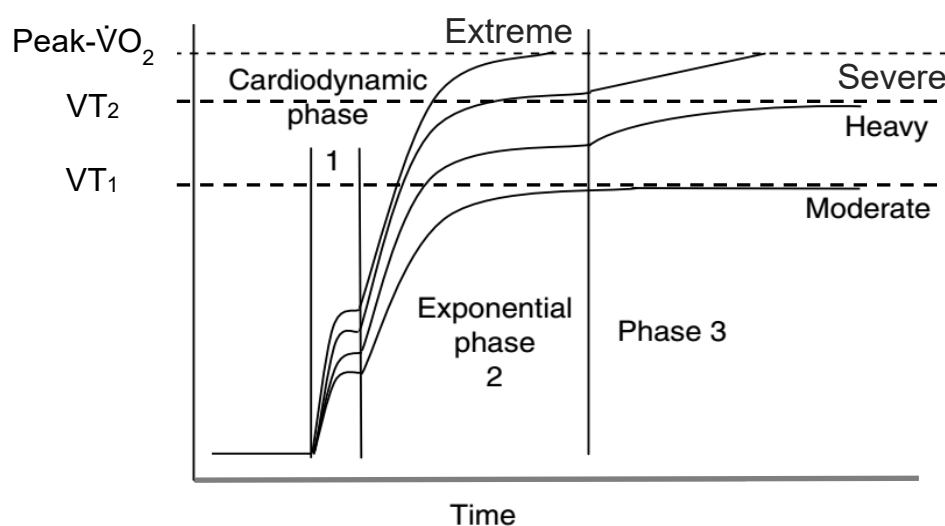


Figure 3. The three phases of the kinetic rise in the $\dot{V}O_2$ in response to a step change in exercise in four different exercise intensity domains (moderate, heavy, severe and extreme). VT_1 – first ventilatory threshold; VT_2 – second ventilatory threshold; $Peak-\dot{V}O_2$ – maximal oxygen consumption (adapted from Fawkner and Armstrong, 2003).

2.2.3 Oxygen uptake kinetics in swimming

Swimming is a sports modality that is considerably different from those that are practiced in the terrestrial environment, since in the aquatic environment a quite

distinct set of constraints arise, which can influence the “normal” response of $\dot{V}O_2$, namely due to the external conditions that generate different scenarios at both metabolic and biomechanical levels (Reis et al., 2017).

In swimming, several authors have been pointing out that some specific characteristics of the swimming exercise can influence the $\dot{V}O_2$ kinetics response compared to other modalities performed in dry land environment. Some factors, such as the horizontal position of the body, inducing a greater hydrostatic pressure and reduced blood flow and muscle perfusion, the predominance of upper limbs during exercise, which involve a higher relative percentage of “fast” fibers/type II than the lower limbs and the aquatic constraints in the cardiac output with evidence of diving bradycardia are indicated as some of the characteristics that may influence the behavior of the $\dot{V}O_2$ kinetics, making it slower (Ceretelli et al., 1979; Libicz et al., 2005; Schneider et al., 2002; Sousa et al., 2017). Nevertheless, other studies have shown that in well-trained swimmers, probably due to specific adaptations, this fact does not seem to be verified (Almeida et al., 2019a,b; Bentley et al., 2005; Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012a,b and 2018).

In addition to these biological constraints, the study of the $\dot{V}O_2$ kinetics in real swimming situation truly adds a set of difficulties to the investigator. Indeed, the fact that the tests are not performed in a laboratory, where the environment can be largely controlled, but in a swimming pool, and the existing constraints for the collection of the data of the air that is expired by the athlete, because it is in the aquatic environment, are factors that have made it quite difficult to investigate the area over time (Reis et al., 2010a). However, researchers have been able to overcome such difficulties, namely by creating innovative strategies, techniques and technologies.

Until the 1980s the majority of the studies were conducted using the Douglas Bags or a mixing chamber method (Astrand et al., 1960; Holmer et al., 1979; McArdle et al., 1971) which only allowed researchers to examine some parts of the efforts when swimmers get to the top of the pool. However, the technology

evolved and Toussaint and coworkers in 1987 developed and validated the first respiratory snorkel which allowed the gas sampling analysis during the swimming exercise. This adaptation to the swimming modality started the possibility to analyse the swimming $\dot{V}O_2$ data in real time breath-by-breath situation. Later other researchers validated adaptations of Toussaint's respiratory snorkel (Keskinen et al., 2003; Rodríguez et al., 2008). More recently a new respiratory snorkel was developed and validated for swimming exercise. The Aquatrainer snorkel (Cosmed, Rome, Italy) incorporates the same principle that its predecessors and includes a mouth piece fixed to a head set, and both inspiratory and expiratory tubes separated by a two way non re-breathing valve, allowing the breath-by-breath data collection and consequently the $\dot{V}O_2$ kinetics study (Reis et al., 2010). The low-hydrodynamic swimming snorkel used in this study, the new-Aquatrainer (Cosmed, Rome, Italy), is an improvement of its predecessor and was also previously validated for cardiorespiratory analyses for swimming tests (Baldari et al., 2012).

The use of swimming snorkels for $\dot{V}O_2$ data collection has been reported as not bringing significant changes to swimmers $\dot{V}O_2$ response (Keskinen et al., 2003, Rodríguez et al., 2008, Reis et al., 2010, Baldari et al., 2012), or in general kinematics and swimming efficiency (Barbosa et al., 2010) and does not lead to an increase in active drag during front crawl performed at a large range of velocities and, consequently, the metabolic energy necessary to overcome total drag will not be affected, even though it could influence the swimming velocity mainly because of the open turns (Ribeiro et al., 2016), that is necessary to perform because of the equipment. These facts suggest the use of the swimming snorkel as, to the date, the best way to evaluate $\dot{V}O_2$ response in swimmers, since it allows a breath-by-breath analysis in a “free” swimming situation similar to reality, even though with few referred constrains.

Besides the breath-by-breath as a “real” swimming condition way to measure the $\dot{V}O_2$ response of the swimmers (used in this thesis), several ways of research in swimming have been applied throughout the years: swimming-flume (Demarie et al., 2001; Wakayoshi et al., 1995); tethered swimming (Bonen et al., 1980; Kalva-

Filho et al., 2017; Rinehardt et al., 1991; Pessôa Filho et al., 2016); and backward extrapolation through the recovery phase of the $\dot{V}O_2$ in the end of exercise (Campos et al., 2017; Costill et al., 1985; Montpetit et al., 1981; Rinehardt et al., 1991; Rodríguez, 2000). These methods, performed without a breath-by-breath gas sampling analyses, or in specific ergometers, although with relevant importance for the development of this field, could detract the reality of swimmers effort in real life situation.

In swimming, another constraint that hinders swimmers evaluation is related to the intensity prescription of each test. Contrarily to the dry-land modalities where specific ergometers (e.g., treadmill or cycle-ergometer) could easily mark the required pacing, in swimming, and even though the swimmers are recognized as having good pacing knowledge, when small differences in the velocity are required to perform it is quite difficult for the swimmer to keep the exact prescribed intensity. In this matter, recently some pacing equipment were developed to help the swimmers to maintain the required intensities. In our studies, during all tests that required a constant and pre-defined intensity, we used an underwater visual pacer (Pacer2Swim[®], KulzerTEC, Portugal). This system, that was already successfully used in swimming studies (Almeida et al., 2019a,b; Zacca et al., 2019), is placed along the bottom of the pool and is composed by 26 lights that subsequently lit up, giving the swimmer an accurate notion of the correct velocity for each test, being useful both for research and training.

In swimming, even though some recent studies were performed in the extreme domains (Almeida et al., 2019a; Ribeiro et al., 2015; Rodríguez et al., 2003 and 2015; Sousa et al., 2011 and 2013a), the majority of the studies focus mainly on submaximal transitions (Reis et al., 2012a,b; Espada et al., 2015; Pessôa Filho et al., 2012), or at the analysis of the slow component (Demarie et al., 2001; Fernandes et al., 2003), however, swimming is a sport modality where ~86% of the indoor swimming events are performed at maximal or supramaximal intensities. Furthermore, few studies analysed female swimmers, or compared the differences between sexes (Reis et al., 2017; Rodríguez et al., 2003), which can influence the physiological responses in different swimming distances.

For the study of $\dot{V}O_2$ kinetics in general, but for swimming in particular, it is crucial to deepen the maximal and supramaximal efforts in order to better understand the swimmers real effort in competition. Just by this way we could understand how the organic systems combine in order to allow the swimmers to perform this kind of efforts. This is a fundamental parameter with practical implications for coaches and for researchers in swimmers evaluation (Davidson et al., 2009).

The study conducted by Rodríguez et al (2003) is important to the present work, since these authors were the first ones to investigate the $\dot{V}O_2$ kinetics during 100-m and 400-m maximal efforts in a real swimming condition. These authors concluded that the $\dot{V}O_{2peak}$ was significantly correlated with the swimming speed, considering the variable as a good predictor of performance. Another interesting observation of the study was that the $\dot{V}O_2$ kinetics was quite faster in the 100 meters distance, suggesting a relation between the swimming intensity and the velocity of the $\dot{V}O_2$ kinetics. This result is controversial since several studies in swimming reported that the $\dot{V}O_2$ kinetics velocity remains remarkably constant between submaximal intensities (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012b and 2017). Notwithstanding other recent swimming studies also showed an acceleration of the $\dot{V}O_2$ Kinetics in exercises at supramaximal intensities (Almeida et al., 2019a; Sousa et al, 2013; Rodríguez et al., 2003).

One possible explanation for this acceleration could be associated with the maximal and supramaximal intensities (competitive efforts) where athletes opted, usually, for a rapid pacing strategy which could trigger the oxidative system rapidly throughout its peak. A recent study performed by Jones and coworkers (2008) compared the $\dot{V}O_2$ response of athletes performing a cycle ergometer exercise in three different pacing strategies. In Jones' study the fast-start strategy showed a significant acceleration on the $\dot{V}O_2$ kinetics compared to the even-pace or to the slow-pace strategy, which could indicate that in efforts where a fast-start strategy is implemented (like in the competitive short and maximal events) this rapid and high energetic demand could accelerate the $\dot{V}O_2$ response. Also, Bishop et al. (2002) showed that well-trained kayak paddlers presented faster $\dot{V}O_{2K}$ in an all-out session compared to an even-pace strategy, relating the

performance gains in peak and average power output at the all-out session with the fast kinetics. Rønnestad et al. (2019) also presented similar conclusions with cross-country skiers. Regardless of these studies observations, this is still a matter of debate.

Reis et al. (2012b), aiming to determine which $\dot{V}O_2K$ parameters measured during square-wave transitions from rest to high-intensity swimming exercise are related to the middle-distance swimming performance, associated fast kinetics to the 400 meters' performance, enhancing also higher maximal aerobic velocities as a main performance influencer. Also, other studies performed around the maximal lactate steady state (Espada et al., 2015), or at heavy and severe intensities (Pessôa Filho et al., 2012) reached similar results, as fast kinetics seems to improve the oxidative system which will turn the exercise more efficient (Alves et al., 2009). This will contribute for delaying the processes that will lead to fatigue and by that way improve the performance in well trained swimmers, showing $\dot{V}O_2$ Kinetics parameters as an important field of study for swimming performance.

2.3 Energy systems

For any kind of exercise, a determined energetic demand will be required in order to allow the movement through the muscles contractions. The energy that the human body needs for any biological function is obtained from the breakdown (catabolism) of the food we eat in three basic chemical compounds: carbohydrates, lipids and proteins. These compounds can be stored and ultimately transformed in adenosine triphosphate (ATP) which is the only fuel that can be used directly for muscle force generation. In muscle, the energy released from the hydrolysis of ATP by the enzyme ATPase, allows the muscle contraction (Rodríguez and Mader, 2011). As ATP exists in a very low concentration in the muscle, and in order to continue the exercise, there are three distinct yet closely integrated energetic systems that operate together in order to produce the necessary energy through the re-synthesis of the ATP (Gastin, 2001).

The phosphagen system allows an immediate source of energy from the hydrolysis of the ATP stored in the muscle cells. In result the ATP transforms in

ADP (adenosine diphosphate) and inorganic phosphate (Pi). Then, the phosphocreatine (PCr), also stored in the muscle, is broken down enzymatically and donates a phosphate to ADP to re-synthesize ATP. This process, that does not use oxygen or produce lactic acid is also known as anaerobic alactic system allowing a rapid source of energy, however it is limited on its capacity lasting for a few seconds (i.e., 10 seconds or less), furthermore only two thirds of phosphagen can be depleted without the activation of glycolysis (Rodríguez and Mader, 2011). The glycolytic system provides energy from nonaerobic breakdown of carbohydrate, mainly in the form of muscle glycogen or blood-borne glucose, to pyruvic acid and then lactic acid through a process named glycolysis (Gastin, 2001). This process, that does not use oxygen but produces lactic acid is also known as anaerobic lactic system and represents a medium-term energy delivery system and needs only a few seconds in order to reach its maximum rate. Finally, the aerobic or oxidative system involves the combustion of carbohydrates, lipids and in some cases proteins in the presence of oxygen. The products of these substrates can enter in the tri-carboxylic acid (TCA or Krebs) cycle in the mitochondria and are oxidized to carbon dioxide and water. Even though this system takes more time to reach the energy demands it can provide energy for 5-7 minutes of maximal exercises and almost indefinitely for submaximal exercises (Rodríguez and Mader, 2011).

2.3.1 Energy systems interaction and relative contribution during maximal and supramaximal exercises

The energetic systems response at the exercises demands and how these different processes interact has been getting the researchers attention for the last few decades. Fox et al. (1969) performed one of the pioneer studies determining the energetic relative contributions between the high intense intermittent and continuous intense running. Measuring the total oxygen consumed during the exercise, the respiratory oxygen debt and the venous blood lactic acid accumulation and removal, the authors presented several interesting relations between the energy systems for several work-intensities.

The prior attempts to describe the relationships between the three energy systems during periods of maximal exhaustive exercise, while insightful at the time, according to Gatin (2001), have led to two misconceptions in the exercise science and coaching professions: 1) that the energy systems respond to the demands of intense exercise in a sequential manner; 2) and that the aerobic system slowly responds to the energy demands, hence playing a little role in the determination of the performance over short durations. Overall, the author claims that the three energy systems seem to be quite adequate to cope with the high, often sustained and usually diverse energy demands that are placed on the athletes during daily and sporting activities/exercises.

Indeed, Gatin (2001) clearly emphasizes that the current literature suggests that all physical activities/exercises derive some energy from each of the three energy supply processes, even though each system could be best suitable for a specific kind of exercise. The following table represents, for a given duration of maximal exercise, the relative contribution between anaerobic and aerobic systems.

Table 1. Estimates of anaerobic and aerobic energy contribution during selected periods of maximal exercise

Duration of exhaustive exercise (s)	% Anaerobic	% Aerobic ¹
0-10	94	6
0-15	88	12
0-20	82	18
0-30	73	27
0-45	63	37
0-60	55	45
0-75	49	51
0-90	44	56
0-120	37	63
0-180	27	73
0-240	21	79

¹Approximately $\pm 10\%$ at the 95% prediction level (Gatin, 2001)

In table 1 it is evident that the aerobic system plays a significant role in determining performance during high intensity exercise even in very short events, with a maximal exercise effort of 75 seconds resulting in an almost equal energy from both the aerobic and anaerobic energy systems.

Also, Spencer and Gastin (2001) testing the relative contributions of maximal runs between the 200 to 1500 meters (see figure 4) alert for the considerable and greater participation of the aerobic metabolism, than has been traditionally accepted for these short events, demonstrating that the aerobic energy system is the predominant energy system by the 30-s time period during these distances.

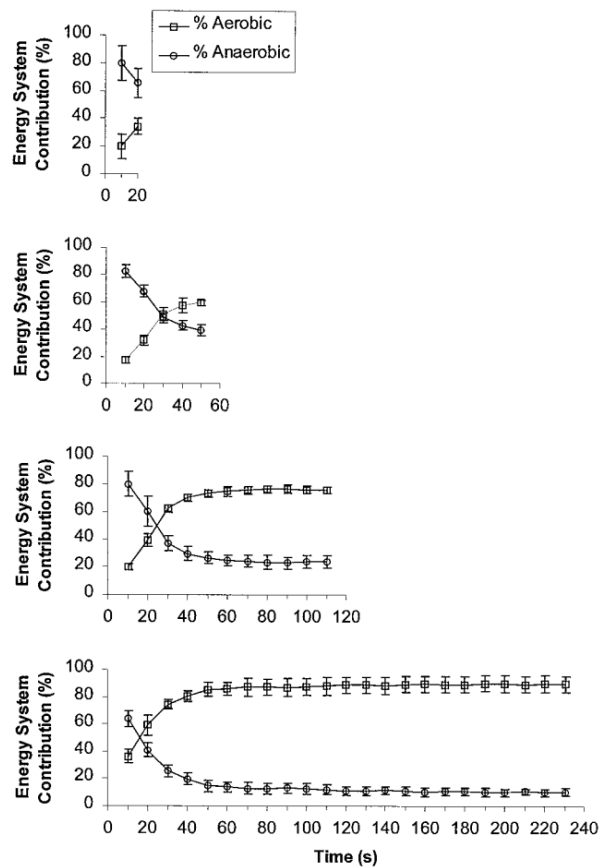


Figure 4. Energy system contribution in 10-s time intervals for the 200, 400, 800 and 1500 meters maximal running (Spencer and Gastin, 2001).

An alternative in the evaluation of the energy system contribution to a specific period of maximal exercise (table 1) is to actually consider the relative aerobic

and anaerobic contribution to sequential phases within a specific period of maximal exercise. In fact, the interaction and contribution of the energy systems will be dependent on the intensity, mode of exercise and duration, even though there are some insignificant differences for training status, as it is suggested by several authors (Spencer and Gastin, 2001). The next figure demonstrates the relative energy system contribution to the total energy supply during 90 seconds of all-out cycle exercise (Gastin, 2001).

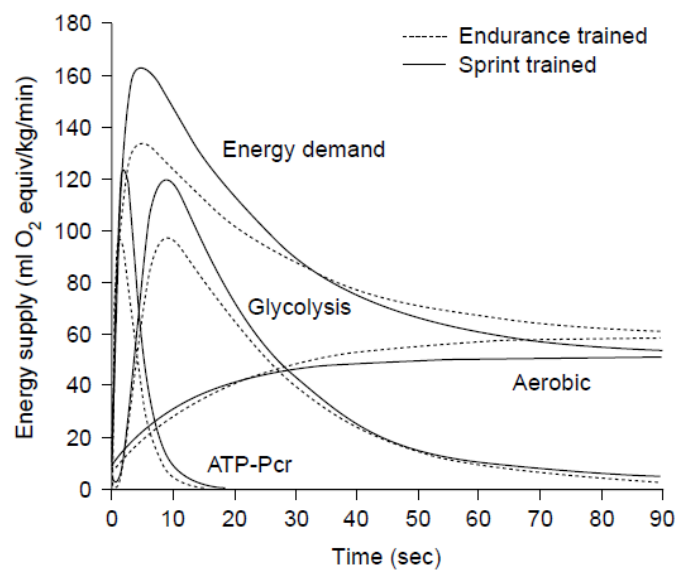


Figure 5. Relative contribution of the 3 energy systems to the total energy supply during 90 seconds of all-out cycle exercise (Gastin, 2001).

The anaerobic systems are capable to regenerate ATP at higher rates resulting in large muscle outputs, however the capacity of these systems is limited by the rapid reduction of stored PCr and the accumulation of lactic acid which reduces the blood lactate pH which will induce the processes that will lead to fatigue rapidly. Contrarily, the aerobic system is capable to produce large amounts of ATP but with lower rates (however it responds almost immediately to the energy demands at the beginning of exercise) limited by the limits of oxidative phosphorylation and the ability of the respiratory and cardiovascular systems to deliver oxygen to the muscle (Gastin, 2001).

2.3.2 Energy systems in swimming

Swimming is considerably different from dry land sports since the water environment induces in the body different metabolic and biomechanical displays. Swimming performance can be so described as the result of the transformation of swimmers' metabolic power into mechanical power with a given energetic efficiency, since most of the energy produced by the swimmer is used to overcome the water resistance or drag, being the rate of energy expenditure increased, theoretically, by the cube of the velocity (Rodríguez and Mader, 2011).

According to Zamparo et al. (2011), the energy cost of swimming (C_{sw}) is obtained by the ratio between E/v , where E is the net metabolic power and v the swimming speed, being the contribution of the aerobic and anaerobic energy sources to E , in swimming competitions, independent of the swimming style, sex or skill, depending essentially on the duration of the exercise. For the authors, all factors that influence the hydrodynamic resistance (W_d) (the higher W_d the higher C_{sw}) and the propelling efficiency (η_p) (the higher η_p the lower C_{sw}) will induce proportional changes at the final energy cost of the swimming event.

The majority of studies about metabolic contributions in exercises, focus at the analysis of submaximal intensities where the energy expenditure can be easily obtained by measuring the aerobic sources of energy (Zamparo et al., 2019), since, at these intensities, the rate of the ATP utilization is equal to the rate of ATP re-synthesis (di Prampero, 1981), and for this reason the anaerobic sources can be disregarded for the total energy determination. Therefore, the aerobic contribution can be determined as the time integral of the net $\dot{V}O_2$ during exercise by the trapezoidal method (Bertuzzi et al., 2013; Guidetti et al., 2007) and the results expressed in liters of oxygen (LO_2), as following:

$$Aer = \int_{t_0}^{t_{Lim}} \dot{V}O_2 \times dt - (\dot{V}O_{2b} \times t_{Lim}) \quad (\text{Equation 6})$$

Where $\dot{V}O_{2b}$ is baseline $\dot{V}O_2$ response, dt the time variation of the exercise and t_{Lim} is time performance.

However, in sports, and particularly in swimming, the majority of the competitive events occur at maximal and supramaximal intensities where the anaerobic sources have an important role for supplying the energy requirements. Therefore, for maximal and supramaximal intensities, as those studied in this work, the total energy expenditure should consider, besides the aerobic sources of energy, the anaerobic lactic and alactic systems.

The anaerobic lactic contribution for the total energy expenditure can be estimated from the net increase of the blood lactate concentration assessed at the end of exercise (Zamparo et al., 2019), expressed as a delta value ($\Delta[\text{La}^-]$) (Beneke et al. 2002), considering the energy equivalent of lactate of $3 \text{ mlO}_2 \cdot \text{kg}^{-1}$ as a metabolic equivalent for each $1 \text{ mmol} \cdot \text{l}^{-1}$ of $\Delta[\text{La}^-]$ (di Prampero 1981).

While the anaerobic lactic method determination is getting consensus in the literature, the alactic one has been determined by two main methods. One method estimates the alactic contribution based on the PCr breakdown at the beginning of exercise, according to the following equation (Zamparo et al., 2019):

$$E_{\text{AnAlac}} = \text{PCr} (1 - e^{-t/\tau}) \cdot t^{-1} \quad (\text{Equation 7})$$

Where PCr is the phosphocreatine concentration at rest (in the contracting muscles), t is the exercise duration and τ is the time constant of PCr splitting at work onset (about 30 seconds); the implicit assumption is thus made that the time constant of PCr breakdown at work onset is the mirror increment of the $\dot{V}\text{O}_2$ -on response at the muscle level (Zamparo et al., 2019).

The other method is based on the analysis of the fast component of the recovery curve of the $\dot{V}\text{O}_2$ after the end of the exercise (Beneke et al., 2002; di Prampero et al., 1970; Guidetti et al., 2007), since in the post-exercise period part of the oxygen debt is necessary to rebuild the high energy substrates split at the beginning of exercise (Zamparo et al., 2019). Accordingly to Scheuermann et al. (2001), the anaerobic alactic participation can be determined by the product between the time constant and amplitude of the fast component of post-exercise oxygen consumption, by the following equation:

$$\dot{V}O_{2\text{off}}(t) = EE\dot{V}O_2 - A_{1\text{off}}[1 - e^{-(t-TD_1/\tau_1)}] - A_{2\text{off}}[1 - e^{-(t-TD_2/\tau_2)}] \quad (\text{Equation 8})$$

Where $\dot{V}O_{2\text{off}}(t)$ represents the relative $\dot{V}O_2$ at a given time; $EE\dot{V}O_2$ is the oxygen uptake at the end of exercise; TD , τ , and A , represent the time delay, the time constant and the amplitude, and 1 and 2 represent the fast and slow component, respectively, for the bi-exponential response of the $\dot{V}O_2$.

Sousa et al. (2013b) tested both methods on the analysis of the 200 meters swimming maximal trial, and concluded that despite the existence of some caveats regarding both methods for estimation of the anaerobic alactic contribution, both yield similar results and both allow to estimate this contribution in supra-maximal swimming trials. Moreover, the authors reinforce the importance of the inclusion of the anaerobic alactic determination for a better understanding of the swimming energetics, since the non-inclusion of this component to total metabolic energy expenditure could lead to an underestimation of the energy cost at supra-maximal speeds.

Finally, the anaerobic energy contribution can be estimated by means of the accumulated oxygen deficit method, as first proposed by Medbø et al. (1988). This method is based in a relationship between power output and $\dot{V}O_2$ that appears to remain linear within a range of intensities (Medbø et al., 1988). Once the $\dot{V}O_2$ -power output is determined, by measuring the $\dot{V}O_2$ in several submaximal bouts, the oxygen demand can be estimated for supramaximal intensities extrapolating the regression model (Osborne and Minahan, 2000). The accumulated oxygen deficit is so determined by the difference between the accumulated oxygen demand and the total $\dot{V}O_2$ that is measured during the exercise bout. This difference represents the energy that is derived anaerobically from intramuscular phosphagens (ATP and PCr) as well as the energy derived via anaerobic glycolysis (Osborne and Minahan, 2000).

Medbø et al. (1988) suggested that the accumulated oxygen deficit reaches a maximal value during a supramaximal exhaustive exercise test, defining this value as the maximal accumulated oxygen deficit (MAOD). This concept has

been described as a valid and reliable method of quantifying an individual's anaerobic capacity and has been accepted as the gold standard to determine anaerobic capacity (Osborne and Minahan, 2000).

In this thesis, since maximal and supramaximal intensities were tested, where the anaerobic lactic and alactic supposedly should have an important contribution for exercise, we opted to use a method of analysis that could allow the compartmentation of the three energy systems in order to measure more accurately the influence of each one to the exercise performance. Having the ventilatory data, it seemed to us that the analysis of the fast component of the post-exercise $\dot{V}O_2$ curve, as presented by Beneke et al. (2002) and previously successfully tested in swimming (Sousa et al., 2013), would be the best alternative.

Understanding the energy requirements for maximal efforts is crucial to a better planning of the preparation of athletes for the respective events they perform. In swimming, energy contribution studies have been focusing, mostly, on the backward extrapolation technique for the analysis of: the MAOD in tethered swimming (Kalva-filho et al., 2016 and 2017); the anaerobic (lactic and alactic) participation on free swimming competitive distances (Campos et al., 2017); the three energetic systems in competitive events (Cappeli et al., 1998; Hellard et al., 2018) or interval training (Peyrebrune et al., 2014). Other researchers opted for using a continuous $\dot{V}O_2$ data collection for analysing MAOD (Reis et al., 2010b), or to characterize both aerobic and anaerobic participations in competitive swimming intensities (Ribeiro et al., 2015; Sousa et al., 2011, 2014b and 2015).

Overall, the findings of the literature are presented in Rodríguez and Mader's (2011) review about energetics in swimming. The following table resumes the relative contributions of the swimming competitive pool events from 50 up to 1500 meters distances.

Table 2. Suggested relative contribution of the energy systems during competitive swimming distances (Rodríguez and Mader, 2011)

Distance	Phosphagen (%)	Glycolitic (%)	Aerobic (%)
50 m	15-80	2-80	2-26
100 m	5-28	15-65	5-54
200 m	2-30	25-65	5-65
400 m	0-20	10-55	25-83
800 m	0-5	25-30	65-83
1500 m	0-10	15-20	78-90

Results are presented for male freestyle swimmers. Relative energy contribution is assumed to be similar in females for a given distance.

The majority of the studies, as those reviewed in Rodríguez and Mader’s study, have been focused on the freestyle swimming technique. Even though few data are available for comparison with the remaining swimming technics, Hellard et al. (2018) and Capelli et al. (1998) calculated the relative energy contribution for competitive swimming distances in the four techniques. In Hellard’s study the anaerobic alactic was the only system showing no differences between the four techniques, while the anaerobic lactic and aerobic participation was higher in breaststroke when compared to the freestyle technique for the 100 meters event. In Capelli’s study the authors tested swimmers for the 50, 100 and 200 yards, also in the four techniques, however they reported no significant differences on the relative energetic participation, yet the authors concluded that the freestyle technique was the most economical technique followed by backstroke, breaststroke and butterfly.

In the table 2 it is possible to observe a large disparity between the estimates, particularly in the shorter events decreasing in the longer ones, which could suggest that the anaerobic part was under or overestimated by the authors, since a greater accuracy on the aerobic contribution calculation could diminish the effect in the longer distances.

In fact, since the direct assessment of the anaerobic alactic energy sources

through invasive methods (e.g., muscle extracts) is impracticable (Zamparo et al., 2019), the non-invasive alternatives, as those above referred, are, naturally, less precise, since the anaerobic ATP production is an intracellular process with little reliance on central processes which creates difficulties to a universally acceptance of a gold standard method (Gastin, 2001).

In the Rodríguez and Mader's (2011) study, the authors also presented an interesting computing simulation that illustrates the concept of simultaneous activation of the metabolic mechanisms for the maintenance of the high energy output needed to swim at maximal intensities along the different competitive swimming distances. The following diagram shows how the three systems interact for each event.

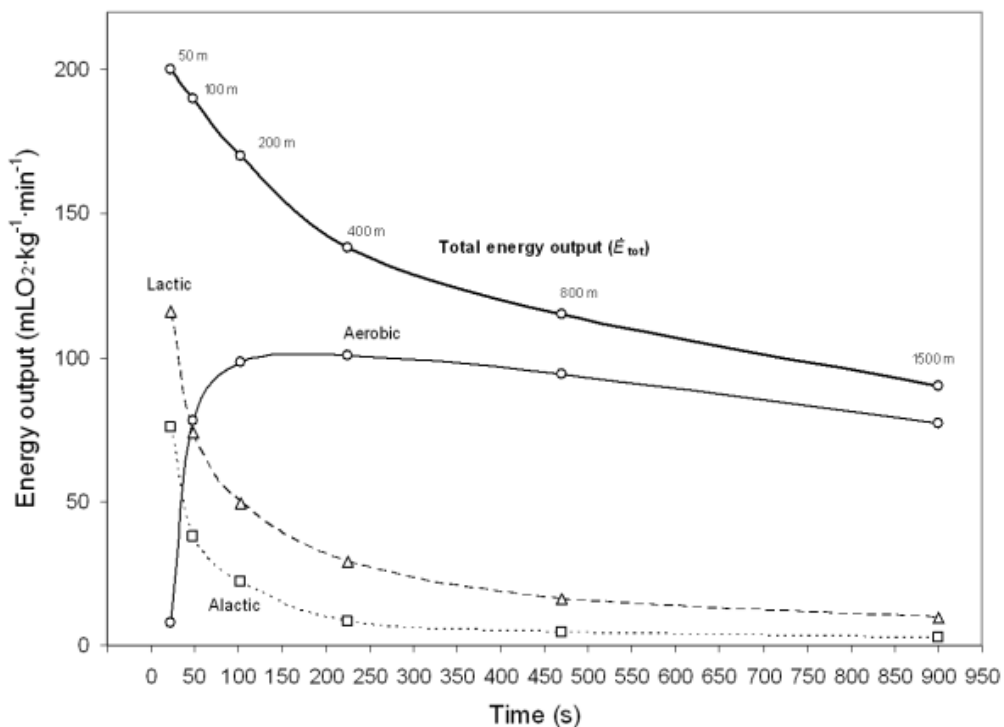


Figure 6. Interaction of the energy systems along the swimming competitive distances to 50 up to 1500 meters and the respective power output of each event. Data is presented for male top swimmers (Rodríguez and Mader, 2011)

Overall, studies reported data only from male swimmers assuming that the female swimmers should present similar results. Rodríguez et al. (2016) performed one of the few studies comparing the metabolic responses in the 100 meters

swimming reporting no differences between male and female swimmers. However, remarkably few data, comparing both sexes, are available in the literature which is an important gap on the knowledge about conditions for the female swimmers response in the metabolic contributions field of study.

2.4 Time limit at the maximal aerobic velocity

The maximal aerobic velocity (MAV) is defined by the minimal velocity at which the maximal oxygen uptake of an individual occurs during an incremental test (Billat and Koralsztein, 1996). This velocity, that combines exercise economy and $\dot{V}O_{2max}$ into a single factor, is catching the researchers' attention for the last few decades since it has been related with sports performance and could be used for monitoring athletes' training status, being considered as one of the most important variables of study in the modern sports physiology (Billat and Koralsztein, 1996; Demarie et al., 2001; Reis et al., 2012a,b; Espada et al., 2015). Furthermore, MAV, that is being associated with the 3000 meters running and the 400 meters swimming velocities, is also usually used by coaches as referential for training intensities prescription zones. (Billat and Koralsztein, 1996; Demarie et al., 2001; Demarie et al., 2000; Fernandes and Vilas-Boas, 2012; Reis et al., 2012a,b; Espada et al., 2015).

In order to provide more accurate information of how to use this velocity for training prescription, it becomes fundamental to understand the tolerance of the athletes to this velocity. The time limit (TLim) at MAV (TLim-MAV) expresses the maintenance of the velocity that elicits $\dot{V}O_{2max}$ to the point of exhaustion, being defined as the inability to maintain such velocity (Fernandes and Vilas-Boas, 2012).

Historically, the times to exhaustion in a TLim-MAV test can present a great variability among individuals, ranging between 2.5 to 10 minutes (Demarie et al., 2000), however this test is reproducible in an individual and, therefore, can be used for testing the fitness status of an athlete in different moments of a time line (Billat et al., 1994a; Renoux, 2001). One of the reasons pointed by Billat and Koralsztein (1996) for this inter-variability relies on the several ways that MAV

was determined by the researchers, which makes it difficult to compare the results. Therefore, the methodology used for achieving the MAV is of major importance in order to enable future comparisons.

Accordingly to Faina et al. (1997) the MAV has been determined by two main methods: 1) by the energy cost of the exercise at submaximal intensity, as the maximal exercise intensity that could be maintained by aerobic sources alone (di Prampero, 1986; Lacour et al., 1991); or 2) by the lowest intensity at which the maximal oxygen consumption is verified (Billat et al., 1994a,b). Testing both methods (in a total of five different methods analysed), Hill and Rowell (1996) reported values of MAV 4% lower in the first one, which lead the authors to suggest that results from different methods should be carefully compared.

Currently, the second method is getting more consensus. In this method the major traditional physiological criteria for achieving the MAV is the observation of a $\dot{V}O_2$ plateau during an incremental test, and the minimal velocity at which that occurrence is observable, despite further increase in velocity without elevating the $\dot{V}O_2$, is the MAV. This methodology has been widely used in several recent swimming studies (Espada et al., 2015; Fernandes et al., 2003 and 2008; Pessôa Filho et al., 2012; Reis et al., 2012a,b; Sousa et al., 2014b and 2018) and is the one chosen to be applied in this thesis.

The exercise performed until exhaustion at MAV is configured as an experimental condition for the analysis of the muscular tolerance to the physiological limitations imposed to the oxidative activity in this effort intensity (Billat et al., 2000). The underlying purpose of this condition is thus to characterize the pulmonary $\dot{V}O_2$ profile during exercise in response to the aerobic/anaerobic interaction for the energy supply and accumulation of the metabolites derived from this interaction (Billat et al., 2000; di Prampero, 2003).

According to the theoretical framework of the severe exercise domain, the muscle fiber will face a limit on its possibility of adjusting the oxidative metabolic rate (limitations in blood perfusion, gas diffusion and mitochondrial capacity), which will require the gradual contribution of the finite reserve of anaerobic energy, and

thus exhaustion will probably be attributed to metabolic acidosis and depletion of intramuscular substrates (Di Prampero, 2003; Murgatroyd et al., 2011; Poole et al., 2016). Therefore, exercise tolerance at MAV would be related to aerobic power (including O₂ availability and O₂ phosphorylation rate), anaerobic capacity (Faina et al., 1997; DiPrampero, 2003; Jones et al., 2010) and, particularly in swimming, to the efficiency of movement (Fernandes et al., 2006; Toussaint and Hollander, 1994).

In addition, it seems to exist a negative relationship between the TLim-MAV with the MAV in cycling, running, kayaking, swimming flume (Billat and Koralsztein, 1996) and in free swimming (Fernandes et al., 2006 and 2008; Sousa et al., 2014b), and also with the velocity at the lactate threshold (Billat and Koralsztein, 1996; Fernandes and Vilas-Boas, 2012), possibly associated with the anaerobic capacity of the swimmers (Fernandes et al., 2008; Faina et al., 1997), which could explain the differences among individuals (Billat and Koralsztein, 1996). Furthermore, a $\dot{V}O_2$ slow component during the TLim-MAV test seems to emerge, being its magnitude considered to be physiologically significant (Billat, 2000) and could be positively associated with the time to exhaustion at this intensity (Fernandes et al., 2008).

2.4.1 TLim-MAV in swimming

In swimming, the first TLim-MAV studies were not conducted in a free-swimming situation, instead those first researchers conducted their tests in specific ergometers (i.e., swimming-flume) (Billat et al., 1996; Demarie et al., 2001; Faina et al., 1997), reporting that the tolerance at this intensity was associated to the accumulated oxygen deficit and to MAV.

Even though there were some methodological constraints (no $\dot{V}O_2$ measurements were made), Renoux (2001) performed, probably, the first study in a free-swimming situation reporting ~6 minutes of tolerance to the MAV, innovating also with a proposal of a 12-week training program based at the swimmers' times to exhaustion. Renoux's results showed significant improvements at the MAV, after the training period, even though without

extended times to exhaustion, suggesting that, since the times to exhaustion seemed to be an individual and reproducible characteristic, this concept can be used for training purposes. Latter, other authors performed similar tests in a free-swimming situation and with $\dot{V}O_2$ data collection (Fernandes et al., 2008; Sousa et al., 2014b and 2015), which allowed to reach more precise values of tolerance at the MAV for swimmers.

Fernandes and Vilas-Boas (2012), reviewing the times to exhaustion at MAV in swimming, reported a low inter-variability compared with other sports modalities. The authors reported that swimmers are able to maintain the intensity during a temporal interval that ranges between 215 and 260 seconds (for elite swimmers), between 230 and 260 seconds (for high level swimmers) and between 310 and 325 seconds (for low level swimmers). As reported by Sousa et al., (2015) the times to exhaustion in swimming seem not to differ significantly compared with other modalities (i.e., rowing, running and cycling).

The $\dot{V}O_2$ slow component during the TLim-MAV test is frequently discerned at all levels of proficiency, as first reported by Demarie et al. (2001). The following figure represents a typical $\dot{V}O_2$ kinetics response to a TLim-MAV test, where it is discernible a first rapid exponential rise of $\dot{V}O_2$ followed by a secondary rise (slow component), which could be positively associated to the TLim (Fernandes et al., 2008).

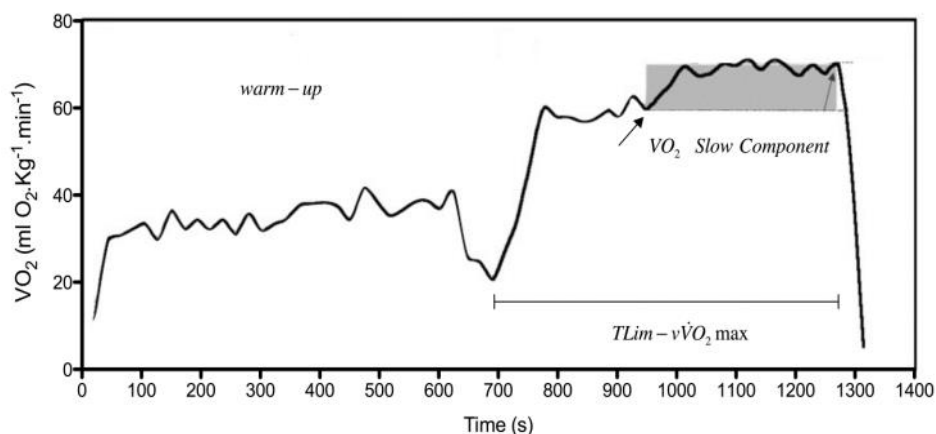


Figure 7. A typical example of the $\dot{V}O_2$ pattern during a TLim-MAV test (Fernandes and Vilas-Boas, 2012)

Also, it seems that the inverse relationship between the T_{Lim}-MAV with the MAV and the velocity of anaerobic threshold also occurs in swimming, which suggests that the swimmers' lower level of maximal aerobic metabolic rate might be associated with a quite larger capacity to sustain the exercise intensity. Contrarily, it seems that there is not an association between the T_{Lim}-MAV and the $\dot{V}O_{2max}$ in swimming (Fernandes et al, 2003), even though it has been previously reported in the running exercise (Billat and Koralsztein, 1996). Overall, it seems that there are no differences on the pattern of response between male and female athletes (Fernandes and Vilas Boas, 2012), although few studies have analysed this relationship.

For Caputo et al. (2004) the rate at which the $\dot{V}O_2$ responds at the beginning of exercise, reflects the adjustment of the systemic oxygen transport and the muscle metabolism, and so, an acceleration of the $\dot{V}O_2$ kinetics actually reduces the initial oxygen deficit and the lactate production, hence sparing the anaerobic substrates and eventually prolonging the T_{Lim}. For the authors, the training status seems to differently influence T_{Lim} during severe exercise and at the same relative intensity an acceleration in the $\dot{V}O_2$ kinetics is observed in individuals with better aerobic fitness, regardless of the exercise modality or type (e.g., cycling and running).

2.5 High-intensity interval training

Training can be defined as the systematic and regular participation in exercise in order to enhance sports performance (Billat, 2001a,b). For untrained subjects or recreational athletes, the start of almost every kind of training program, or a simple increase in submaximal training volumes to an existing program, will certainly provide improvements in their physiological parameters which will contribute positively to sports performance. However, for already trained athletes, further improvements seem to be only related with high intensity training (Laursen and Jenkins, 2002).

It is believed that an optimal stimulus to elicit both maximal cardiovascular and peripheral adaptations is one where athletes spend at least several minutes per session in their "red zone" (i.e., >90% of $\dot{V}O_{2max}$) (Buchheit and Laursen,

2013a,b), being considered by several authors as the most effective training intensity to enhance $\dot{V}O_{2max}$, especially for highly trained athletes (Midgley and Mc Naughton, 2006). Accordingly, the time that athletes can spend, during the training sessions, near their maximal oxygen uptake is being considered as one of the main factors associated to physiological improvements and consequently to sports, being also considered as a variable of training stimulus effectiveness (Bentley et al., 2005; Billat and Koralsztein, 1996; Billat, 2001a; Libicz et al., 2005; Millet et al., 2003a,b; Sousa et al., 2017a and 2018). Seeking to improve physiological parameters and performance, researchers have been studying and characterizing new methods of training protocols in order to maximize the time that athletes can spent near their maximal $\dot{V}O_2$ values.

Several authors have been comparing the effect of the interval and continuous training on the development of the aerobic parameters of subjects and it seems that both protocols can be suitable to accelerate the $\dot{V}O_2$ response at the beginning of exercise (Berger et al., 2006; Duffield et al., 2006), even though some authors relate fast improvements (e.g., after only two training sessions) to feeble initial fitness status of the subjects (McKay et al., 2009). For highly trained athletes several authors have been reporting the necessity to include a significant portion of high intensity training (Gibala and Jones, 2013; Wen et al., 2019) on the training programs, as a crucial aspect for the development of athletes (Laursen and Jenkins, 2002), associating the interval training as a useful tool in order to apply these intensities of exercise.

Since the performance of high intensities in continuous work is, at the start, compromised by the shorter duration that athletes can support these exercises (Sousa et al., 2017a), the high-intensity interval training (HIT) has been getting the researchers attention since it can provide longer periods performing high intensities, which consequently leads to longer times spent near the $\dot{V}O_2$ maximal values (Demarie et al., 2000; Helgerud et al., 2007; Wen et al., 2019) with higher improvements on the acceleration of the $\dot{V}O_2K$ (Daussin et al., 2008), which are variables well related to performance (Bentley et al., 2005; Espada et al., 2005; Libicz et al., 2005; Reis et al., 2012b; Pessôa Filho et al., 2012).

The high-intensity interval training refers to exercise that is characterized by relatively short burst of vigorous activity (i.e., from the maximal lactate steady state or the second ventilatory threshold to all-out supramaximal intensities), interspersed by periods of rest to low-intensity exercise for recovery. This is a potent stimulus to induce physiological remodeling in untrained or recreationally active individuals, and in already well-trained athletes as a supplement in already high-volume training program, this is considered as an effective way to improve both anaerobic and aerobic performance (Gibala and Jones, 2013; Laursen, 2010). Also, Buchheit and Laursen, (2013a) suggested that a polarized approach to training may be optimal, where periods of both high and low-intensity training, but high volume, are performed. Generally, it is accepted that for highly trained athletes HIT should be implemented (Laursen and Jenkins, 2002) with a component suggested of ~10-15% of training performed at very high intensities (Gibala and Jones, 2013).

2.5.1 Physiological adaptations to HIT

The HIT programming can vary accordingly to several variables such as the work intensity, bout duration, number of repetitions and training periodization which is showed to influence the time at $\dot{V}O_{2max}$ (Wen et al., 2019). The following figure represents the different kinds of HIT programming.

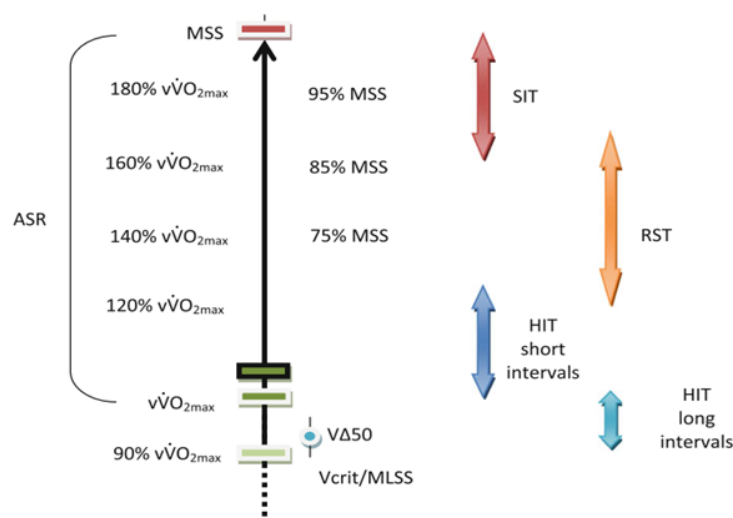


Figure 8. Intensity range used for the various run-based HIT formats. ASR anaerobic speed reserve, MLSS maximal lactate steady state, MSS maximum

sprinting speed, RST repeated-sprint training, SIT sprint interval training, $\dot{V}O_{2max}$ maximal oxygen uptake, $v\dot{V}O_{2max}$ minimal running speed required to elicit $\dot{V}O_{2max}$, $V_{\Delta 50}$ speed half way between $v\dot{V}O_{2max}$ and MLSS, V_{crit} critical velocity (Buchheit and Laursen, 2013a).

According to Buchheit and Laursen (2013a), it appears that most of the HIT formats, if properly manipulated, allows the achievement of the $\dot{V}O_{2max}$, however it seems that when the time spent near the $\dot{V}O_2$ maximal values is considered the HIT that involves long and short intervals is a better program than the repeated sprint training. Also Wen et al, (2019), stated that the different protocols of HIT, short work interval (≤ 30 seconds of work/bout at sub-maximal to all-out intensity), low-volume HIT (≤ 5 minutes of work/session) and short-term HIIT (≤ 4 weeks of intervention) are feasible and time-efficient strategies and come with high effectiveness for $\dot{V}O_{2max}$ improvements, however to ensure the improvement of the training effects on $\dot{V}O_{2max}$, the authors recommended long-interval (≥ 2 minutes of work/bout at sub-maximal intensity), high-volume (≥ 15 minutes of work/session) and moderate to long-term ($\geq 4-12$ weeks of intervention) HIT. Contrarily, other authors direct their recommendations for short work-intervals, since it may allow athletes to performed IT longer sets with greater metabolic demands (Zuniga et al. 2011) and with lower $[La^-]$ and PRE (Warr-di Piero et al., 2018) when compared with longer work-intervals.

According to Gibala and Jones (2013), the mechanisms responsible for the performance improvements through an HIT program in highly trained athletes are probably different compared to those of less trained subjects which after a short period of low volume HIT evoke a rapid increase in the muscle oxidative capacity. In highly trained athletes an improvement of skeletal muscle buffering capacity associated with training induced changes in Na^+/K^+ pump activity may help to preserve cell excitability and force production, which could delay fatigue during intense exercise. The authors also pointed that the HIT effectiveness could be associated to the higher intensities performed which activates and thus enhances the metabolic profile of the type II fibres and repeatedly induces metabolic

perturbations (rapid changes in the concentrations of ATP, ADP, Pi, PCr, etc.) in the abrupt transitions from rest to exercise which promotes cellular adaptations.

Even though several authors proposed a wide range of variables to use in the prescription of exercise intensities when programming a HIT session, one of the most used intensities is the maximal aerobic velocity, which is associated with the achievement of the maximal oxygen uptake during an incremental test. Indeed, this specific intensity is quite interesting for coaches since it is possible to achieve several improvements in the athlete's performance (Jones and Carter, 2000) during a high-intensity interval training (Denadai et al., 2006), mainly by the increased time spent near $\dot{V}O_{2max}$ of the athletes. For these reasons the interval training performed at the MAV, has been proposed as an effective way to improve aerobic power and the MAV itself, variables that are highly related with sports performance (Astrand et al., 1960; Billat, 2001b; Espada et al., 2015; Libicz et al., 2005). In this thesis we will focus our attention around the MAV intensity when testing the several IT programming.

2.5.2 HIT in swimming

In swimming, there is quite a lack of studies that measure the swimmers physiological responses during HIT sessions, mainly regarding the $\dot{V}O_2$ parameters. To the best of our knowledge, only two studies collected $\dot{V}O_2$ continuously along IT sessions (Bentley et al 2005; Libicz et al., 2005). These two studies focused on the analyses of the swimmers' gain of $\dot{V}O_2$ during simulated IT swimming sets, measuring the time spent near the individual's $\dot{V}O_2$ maximal values during sets comprising repetitions of 50, 100 and 400 meters. While Libicz et al. (2005) reported a non-significant increase at the studied variables between the 50 to 100 meters repetitions performed at the MAV, Bentley et al. (2005) has found no differences at all using 100 or 400 meters bouts at a submaximal intensity. The last study also searched for correlations between the velocity of the $\dot{V}O_{2K}$ with better physiological responses at the IT sessions getting no relationship between the variables. Also, de Jesus et al., (2015) compared the $\dot{V}O_{2K}$ response in subsequent swimming sets in an incremental test reporting an

acceleration on the kinetics from the low-moderate to the heavy and severe domains of intensity. Even though it can indicate a pattern of response associated with intensity, the fact that the task was performed with only 30 seconds of breaks between repetitions, makes it more difficult to draw conclusions, since the prior exercise effect, at least in the heavy domain, was reported to be significant (Sousa et al., 2014c) on the acceleration of the $\dot{V}O_2K$.

Dalamitros et al. (2016), even though they did not analyse the $\dot{V}O_2$ responses during the IT sets, they tested the impact of two IT swimming programs (composed by 50 vs. 100 meters bouts) performed at MAV, showing positive results for the development of the $\dot{V}O_{2max}$, rate of blood lactate recovery indices and performance for both IT's (without differences within), after an 8-week program.

Interval training, specially performed at MAV, that, in swimming, is associated with the 400 meters freestyle event (Espada et al., 2015; Reis et al., 2012a; Zacca et al., 2019), has been related with the improvement of the aerobic power since it promotes longer times spent by the athletes near their $\dot{V}O_2$ maximal values, being highly associated with sports performance (Astrand et al., 1960; Billat, 2001a; Libicz et al., 2005, Denadai et al., 2006). The time that athletes could spend near their individual's maximal $\dot{V}O_2$ values seems to be one of the most important factors that contributes for the improvement of $\dot{V}O_{2max}$ and performance, being used as a referential to measure the positive impact of training sessions (Bentley et al., 2005; Billat and Koralsztein, 1996; Billat, 2001a; Libicz et al., 2005; Millet et al., 2003a,b; Sousa et al., 2017).

The use of a fixed fraction of 50 to 60% of time to exhaustion (TLim) has been proposed as a way to individualize the training prescription, therefore providing a significant improvement in aerobic fitness (Libicz et al., 2005). The metabolic changes induced by the interval training have been, mainly, studied with exercise intensities corresponding to 80 to 120% of MAV and with exercise durations between 15 seconds and TLim for each interval. The $\frac{1}{2}$ TLim has been pointed as a probably most adequate duration in intermittent runs at MAV, in order to

improve the aerobic capacity (Millet et al., 2003b). Also, the utilization of an individualized fraction of T_{Lim} based on the individual parameters of $\dot{V}O_{2K}$ (namely with the time constant parameter), has been proposed (Millet et al. 2003a).

In swimming, it is not practical to apply work-intervals based on a fixed time, however, according to the knowledge of how swimmers respond physiologically to the exercise, coaches can estimate defined distances for the IT repetitions. For example, for Espada et al. (2015) the time constant could provide indications for training prescription, since after 4-time constants have elapsed, the $\dot{V}O_2$ response has basically reached ~98% of the total $\dot{V}O_{2max}$ and so, as swimmers evidenced a time constant around 20 seconds, coaches can prescribe training sets around 80 seconds in order to endure $\dot{V}O_{2max}$, similar to the duration of a 100 meters repetition. Accordingly, Sousa et al. (2017), testing the swimmers tolerance for continuous workout at intensities around the MAV, suggested the application of efforts that could last at least 60 seconds, since shorter exercises could not have time to tax enough the aerobic metabolism.

It is well recognized in the literature, as presented in this revision, that the capacity of an athlete responding fast and physiologically efficiently to the energetic demands required by any sport event will determine his/her success in competition or training. Understanding how swimmers respond to the competition and training efforts is crucial to prepare researchers and coaches in order to improve the planning of training or even competitive strategies. In the next chapters we will try to contribute for this purpose.

References of chapter II

- Adami A, Pogliaghi S, De Roia G, Capelli C (2011) Oxygen uptake, cardiac output and muscle deoxygenation at onset of moderate and supramaximal exercise in humans. *Eur J Appl Physiol* 111(7):1517-1527
- Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019a) Is $\dot{V}O_2$ kinetics influenced by swimming intensity in maximal and supramaximal velocities in young female swimmers? In: Proceedings of the International Seminar of Physical Education, Leisure and Health. Castelo Branco, Portugal – *Journal of Human Sport and Exercise* 14(4proc):1566-1569
- Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019b) Physiological responses at maximal aerobic swimming pacing in different distance-trials. In: Proceedings of the International Seminar of Physical Education, Leisure and Health; Castelo Branco, Portugal – *Journal of Human Sport and Exercise* 14(4proc):1686-1689
- Alves F, Reis L, Vleck V, Bruno P, Millet G (2009) Oxygen uptake kinetics in heavy intensity exercise and endurance performance in swimmers. *Med Sci Sport Exerc* 41:978
- Astrand I, Astrand P, Christensen E, Hedman, R (1960) Circulatory and respiratory adaptations to severe muscular work. *Acta Physiol Scand* 50:254-258
- Baldari C, Fernandes R, Meucci M, Ribeiro J, Vilas-Boas JP, Guidetti L (2012) Is the new aquatrainer® snorkel valid for $\dot{V}O_2$ assessment in swimming? *Int J Sports Med* 34(04):336-344
- Barbosa T, Silva AJ, Reis AM, Costa M, Garrido N, Policarpo F, Reis VM (2010) Kinematical changes in swimming front crawl and breaststroke with the aquatrainer® snorkel. *Eur J Appl Physiol* 109(6):1155-1162
- Barstow TJ, Jones AM, Nguyen PH, Casaburi R (1996) Influence of muscle fiber type and pedal frequency on oxygen uptake kinetics of heavy exercise. *J Appl Physiol* 81(4):1642-1650
- Beneke R, Pollmann C, Bleif I, Leithäuser RM, Hütler M (2002) How anaerobic is the wingate anaerobic test for humans? *Eur J Appl Physiol* 87:338-392
- Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP (2005) Physiological responses during submaximal interval swimming training: effects of interval duration. *J Sci Med Sport* 8:392-402

- Berger NJ, Tolfrey K, Williams AG, Jones AM (2006) Influence of Continuous and Interval Training on Oxygen Uptake On-Kinetics. *Med Sci Sports Exerc* 38(3):504–512
- Bertuzzi R, Nascimento EM, Urso RP, Damasceno M, Lima-Silva AE. (2013) Energy system contributions during incremental exercise test. *J Sports Sci Med* 12(3):454-460
- Billat LV (2001a) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. *Sports Med* 31(1):13-31
- Billat LV (2001b) Interval training for performance: a scientific and empirical practice special recommendations for middle- and long-distance running. Part II: anaerobic interval training. *Sports Med* 31(2):75-90
- Billat V, Faina M, Sardella F, Marini C, Fanton F, Lupo S, Faccini P, De Angelis M, Koralsztein JP, Dal Monte A. (1996) A comparison of time to exhaustion at $\dot{V}O_{2max}$ in elite cyclists, kayak paddlers, swimmers and runners. *Ergonomics* 39 (2):267-277
- Billat V, Koralsztein JP (1996) Significance of the velocity at $\dot{V}O_{2max}$ and time to exhaustion at this velocity. *Sports Med.* 22(2):90-108
- Billat V, Pinoteau J, Petit B, Renoux JC, Koralsztein JP (1994b) Time to exhaustion at 100% of velocity at $\dot{V}O_{2max}$ and modelling of the relation time-limit/velocity in elite long distance runners. *Eur J Appl Physiol Occup Physiol* 69(3):271-273
- Billat V, Renoux JC, Pinoteau J, Petit B, Koralsztein JP (1994a) Reproducibility of running time to exhaustion at $\dot{V}O_{2max}$ in subelite runners. *Med Sci Sports Exerc* 26(2):254-257
- Billat VL (2000) $\dot{V}O_2$ slow component and performance in endurance sports. *Br J Sports Med* 34(2):83-85
- Billat VL, Morton RH, Blondel N, Berthoin S, Bocquet V, Koralsztein JP, Barstow TJ (2000) Oxygen kinetics and modelling of time to exhaustion whilst running at various velocities at maximal oxygen uptake. *Eur J Appl Physiol* 82(3):178–187
- Bishop D, Bonetti D, Dawson B (2002) The influence of pacing strategy on $\dot{V}O_2$ and supramaximal kayak performance. *Med Sci Sports Exerc* 34(6):1041-1047
- Bonen A, Wilson B A, Yarkony M, Belcastro AN (1980) Maximal oxygen uptake during free, tethered, and flume swimming. *J Appl Physiol Respir Environ Exerc Physiol* 48(2):232-235

Borrani F, Candau R, Millet GY, Perrey S, Fuchslocher J, Rouillon JD (2001) Is the $\dot{V}O_2$ slow component dependent on progressive recruitment of fast-twitch fibers in trained runners? *J Appl Physiol* 90(6):2212-2220

Bosquet L, Duchene A, Dupont G, Leger L, Carter H (2007) $\dot{V}O_2$ Kinetics during Supramaximal Exercise: Relationship with Oxygen Deficit and 800-m Running Performance. *Int J Sports Med* 28:518-524

Buchheit M, Laursen PB (2013a) High-Intensity Interval Training, Solutions to the Programming Puzzle Part I: Cardiopulmonary Emphasis. *Sports Med* 43(5):313-338

Buchheit M, Laursen PB (2013b) High-Intensity Interval Training, Solutions to the Programming Puzzle Part II: Anaerobic Energy, Neuromuscular Load and Practical Applications. *Sports Med* 43(10):927-954

Burnley M, Jones A (2007) Oxygen uptake kinetics as a determinant of sports performance. *Eur J Sport Sci* 7(2):63-79

Campos EZ, Kalva-Filho C, Gobbi R, Barbieri R, Almeida NP, Papoti M (2017) Anaerobic contribution determined in swimming distances: Relation with performance. *Front Physiol* 8:1-6

Capelli C, Pendergast DR, Termin B (1998) Energetics of swimming at maximal speeds in humans. *Eur J Appl Physiol* 78(5):385-393

Caputo F, Denadai B (2004) Effects of aerobic endurance training status and specificity on oxygen uptake kinetics during maximal exercise. *Eur J Appl Physiol* 93:87-95

Carter H, Pringle JS, Barstow TJ, Doust JH (2006) Oxygen uptake kinetics during supra $\dot{V}O_{2max}$ treadmill running in humans. *Int J Sports Med* 27(2):149-157

Cerretelli P, Pendergast D, Paganelli WC, Rennie DW (1979) Effects of specific muscle training on $\dot{V}O_2$ on-response and early blood lactate. *J Appl Physiol Respir Environ Exerc Physiol* 47(4):761-769

Costill D, Kovaleski J, Porter D, Kirwan J, Fielding R, King D. (1985) Energy expenditure during front crawl swimming: predicting success in middle-distance events. *Int J Sports Med* 6 (5):266-270

Dalamitros A, Zafeiridis A, Toubekis A, Tsalis G, Pelarigo J, Manou V, Kellis S (2016) Effects of Short-Interval and Long-Interval Swimming Protocols on Performance, Aerobic Adaptations, and Technical Parameters. *J. Strength Cond Res* 30(10):2871-2879

- Daussin FN, Zoll J, Dufour SP, Ponsot E, Lonsdorfer-Wolf E, Doutreleau S, Richard R (2008) Effect of interval versus continuous training on cardiorespiratory and mitochondrial functions: relationship to aerobic performance improvements in sedentary subjects. *Am J Physiol Regul Integr Comp Physiol* 295(1):264-272
- Davison RR, Van Someren KA, Jones AM (2009) Physiological monitoring of the Olympic athlete. *J Sports Sci* 27(13):1433-1442
- De Jesus K, Sousa A, de Jesus K, Ribeiro J, Machado L, Rodríguez F, Keskinen K, Vilas-Boas JP, Fernandes RJ (2015) The effects of intensity on $\dot{V}O_2$ kinetics during incremental free swimming. *Appl Physiol Nutr Metab* 40(9):918-923
- Demarie S, Koralsztein JP, Billat V (2000) Time limit and time at $\dot{V}O_{2max}$ during a continuous and an intermittent run. *J Sports Med Phys Fitness* 40(2):96-102
- Demarie S, Sardella F, Billat V, Magini W, Faina M (2001) The $\dot{V}O_2$ slow component in swimming. *Eur J Appl Physiol* 84:95-99
- Denadai B, Ortiz M, Greco C, de Mello M (2006) Interval training at 95% and 100% of the velocity at $\dot{V}O_{2max}$: effects on aerobic physiological indexes and running performance. *Appl Physiol Nutr Metab* 31(6):737-743
- di Prampero PE (1981) Energetics of muscular exercise. *Rev Physiol Biochem Pharmacol* 89:143-222
- di Prampero PE (1986) Energy Cost of Human Locomotion on Land and in Water. *Int J Sports Med* 7(2):55-72
- di Prampero PE (2003) Factors limiting maximal performance in humans. *Eur J Appl Physiol* 90(3-4):420-429
- di Prampero PE, Davies CT, Cerretelli P, Margaria R (1970) An analysis of O₂ debt contracted in submaximal exercise. *J Appl Physiol* 29(5):547-551
- DiMenna FJ, Jones AM (2009) "Linear" Versus "Nonlinear" O₂ Responses to Exercise: Reshaping Traditional Beliefs. *J Sci Med Sport* 7(2):67-84
- Douglas CG (1911) A method for determining the total respiratory exchange in man. *J Physiol* 42:1-2
- Duffield R, Edge J, Bishop D (2006) Effects of high-intensity interval training on the response during severe exercise. *J Sci Med Sport* 9(3):249-255

- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843
- Faina M, Billat V, Squadrone R, De Angelis M, Koralsztein JP, Dal Monte A (1997) Anaerobic contribution to the time to exhaustion at the minimal exercise intensity at which maximal oxygen uptake occurs in elite cyclists, kayakists and swimmers. *Eur J Appl Physiol* 76:13-20
- Fawcner SG, Armstrong N (2003) Oxygen Uptake Kinetic Response to Exercise in Children. *Sports Med* 33(9):651–669
- Fernandes RJ, Billat VL, Cruz AC, Colaço PJ, Cardoso CS, Vilas-Boas JP (2006) Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? *J Sports Med Phys Fitness* 46(3):373-380
- Fernandes RJ, Cardoso CS, Soares SM, Ascensão A, Colaço PJ, Vilas-Boas JP (2003) Time limit and $\dot{V}O_2$ slow component at intensities corresponding to $\dot{V}O_{2max}$ in swimmers. *Int J Sports Med* 24(8):576-581
- Fernandes RJ, Keskinen KL, Colaço P, Querido AJ, Machado LJ, Morais PA, Novais D, Marinho D, Vilas-Boas JP (2008) Time limit at $\dot{V}O_{2max}$ velocity in elite crawl swimmers. *Int J Sports Med* 29(2):145-150
- Fernandes RJ, Vilas-Boas JP (2012) Time to exhaustion at the $\dot{V}O_{2max}$ velocity in swimming: A review. *J Hum Kinet* 32:121-134
- Fick A (1870) Über die Messung des Blutquantums in den Herzventrikeln. *Sitz der Physik-Med ges Wurtzberg* 2:290-291
- Fox EL, Robinson S, Wiegman DL (1969) Metabolic energy sources during continuous and interval running. *J Appl Physiol* 27(2):174–178
- Gaesser GA, Poole DC (1996) The Slow Component of Oxygen Uptake Kinetics in Humans. *Exerc Sport Sci Rev* 24:35-70
- Gastin PB (2001) Energy system interaction and relative contribution during maximal exercise. *Sports Med* 31(10):725-741
- Gastin PB, Lawson DL (1994) Variable resistance all-out test to generate accumulated oxygen deficit and predict anaerobic capacity. *Eur J Appl Physiol Occup Physiol* 69(4):331-336

Gibala MJ, Jones AM (2013) Physiological and Performance Adaptations to High-Intensity Interval Training. *Nestle Nutr Inst Workshop Ser* 76:51-60

Guidetti L, Emerenziani GP, Gallotta MC, Baldari C (2007) Effect of warm up on energy cost and energy sources of a ballet dance exercise. *Eur J Appl Physiol* 99(3):275-281

Hawkins MN, Raven PB, Snell PG, Stray-Gundersen J, Levine BD (2007) Maximal oxygen uptake as a parametric measure of cardiorespiratory capacity. *Med Sci Sports Exerc* 39(1):103-107

Hebestreit H, Kriemler S, Hughson RL, Bar-Or O (1998) Kinetics of oxygen uptake at the onset of exercise in boys and men. *J Appl Physiol* 85(5):1833-1841

Helgerud J, Hoydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, Ragnhild B, Hoff J (2007) Aerobic high-intensity intervals improve $\dot{V}O_{2max}$ more than moderate training. *Med Sci Sports Exerc* 39(4):665-671

Hellard P, Pla R, Rodríguez FA, Simbana D, Pyne DB (2018) Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *Int J Sports Physiol Perform* 13(8):1011-1120

Henry FM (1951) Aerobic Oxygen Consumption and Alactic Debt in Muscular Work. *J Appl Physiol* 3(7):427-438

Henry FM, DeMoor JC (1956) Lactic and Alactic Oxygen Consumption in Moderate Exercise of Graded Intensity. *J Appl Physiol* 8(6):608-614

Hill AV, Lupton H (1923) Muscular exercise, lactic acid, and the supply and utilization of oxygen. *Q J Med* 16:135-171

Hill DW, Rowell AL (1996) Running velocity at $\dot{V}O_{2max}$. *Med Sci Sports Exerc* 28(1):114-119

Holmér L (1979) Physiology of swimming man. *Exerc Sport Sci Rev* 7:87-123.

Howley ET, Bassett DR Jr, Welch HG (1995) Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc* 27:1292-1301

Hughson R L, O'Leary DD, Betik AC, Hebestreit H (2000) Kinetics of oxygen uptake at the onset of exercise near or above peak oxygen uptake. *J Appl Physiol* 88(5):1812-1819

Hughson RL (2009) Oxygen uptake kinetics: historical perspective and future directions. *Appl Physiol Nutr Metab* 34(5):840-850

- Ingham SA, Carter H, Whyte G, Doust JH (2007) Comparison of the oxygen uptake kinetics of club and Olympic champion rowers. *Med Sci Sports Exerc* 39(5):865-871
- Jones A, Burnley M (2009) Oxygen uptake kinetics: An underappreciated determinant of exercise performance. *Int J Sports Physiol and Perform* 4(4):524-532
- Jones A, Wilkerson D, Vanhatalo A, Burnley M (2008) Influence of pacing strategy on O₂ uptake and exercise tolerance. *Scand J Med Sci Sports* 18:615-626
- Jones AM, Carter H (2000) The Effect of Endurance Training on Parameters of Aerobic Fitness. *Sports Med* 29(6):373-386
- Jones AM, Poole DC (2005) Introduction to oxygen uptake kinetics and historical development of the discipline. In: Jones AM, Poole DC (Eds), *Oxygen uptake kinetics in sport, exercise and medicine*. Routledge, London, pp 3-37
- Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC (2010) Critical Power: Implications for Determination of $\dot{V}O_{2max}$ and Exercise Tolerance. *Med Sci Sports Exerc* 42(10):1876-1890
- Kalva-Filho C, Araújo M, Silva A, Gobatto C, Zagatto A, Gobbi R, Papoti M (2016) Determination of $\dot{V}O_2$ -Intensity Relationship and MAOD in Tethered Swimming. *Int J Sports Med* 37(9):687-693
- Kalva-Filho C, Zagatto A, da Silva A, Castanho M, Gobbi R, Gobatto C, Papoti M (2017) Relationships among the Tethered 3-min All-Out Test, MAOD and Swimming Performance. *Int J Sports Med* 38(05):353-358
- Kavanagh MF, Jacobs I (1988) Breath-by-breath oxygen consumption during performance of the Wingate Test. *Can J Sport Sci* 13(1):91-93
- Keskinen KL, Rodríguez FA, Keskinen OP (2003) Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming. *Scand J Med Sci Sports* 13(5):322-329
- Koga S, Shiojiri T, Kondo N (2005) Measuring $\dot{V}O_2$ kinetics: the practicalities. In: Jones AM, Poole DC (eds) *Oxygen uptake kinetics in sport, exercise and medicine*, Routledge, Oxon, England, pp 39-61
- Koppo K, Bouckaert J, Jones A (2004) Effects of training status and exercise intensity on phase II $\dot{V}O_2$ kinetics. *Med Sci Sports Exerc* 36(2):225-232
- Lacour JR, Padilla-Magunacelaya S, Chatard JC, Arsac L, Barthelemy JC (1991) Assessment of running velocity at maximal oxygen uptake. *Eur J Appl Physiol* 62:77-82

- Laursen PB (2010) Training for intense exercise performance: high-intensity or high-volume training? *Scand J Med Sci Sports* 20(2):1-10
- Laursen PB, Jenkins DG (2002) The scientific basis for high-intensity interval training: optimizing training programmes and maximizing performance in highly trained endurance athletes. *Sports Med* 32:53-73
- Libicz S, Roels B, Millet GP (2005) $\dot{V}O_2$ responses to intermittent swimming sets at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 30(5):543-553
- Margaria R, Manglli F, Cuttica F, Cerretelli P (1965) The kinetics of the oxygen consumption at the onset of muscular exercise in man. *Ergonomics* 8(1):49-54
- McArdle WD, Glaser RM, Magel JR (1971) Metabolic and cardiorespiratory response during free swimming and treadmill walking. *J Appl Physiol* 30(5):733-738
- McKay BR, Paterson DH, Kowalchuk JM (2009) Effect of short-term high-intensity interval training vs. continuous training on O_2 uptake kinetics, muscle deoxygenation, and exercise performance. *J Appl Physiol* 107(1):128-138
- Medbo JI, Mohn AC, Tabata I, Bahr R, Vaage O, Sejersted OM (1988) Anaerobic capacity determined by maximal accumulated O_2 deficit. *J Appl Physiol* 64(1):50-60
- Midgley AW, Carroll S, Marchant D, McNaughton LR, Siegler J (2009) Evaluation of true maximal oxygen uptake based on a novel set of standardized criteria. *Appl Physiol Nutr Metab* 34:115-123
- Midgley AW, Mc Naughton LR (2006) Time at or near $\dot{V}O_{2max}$ during continuous and intermittent running. A review with special reference to considerations for the optimisation of training protocols to elicit the longest time at or near $\dot{V}O_{2max}$. *J Sports Med Phys Fitness* 46(1):1-14
- Midgley AW, McNaughton LR, Carroll S (2006) Verification phase as a useful tool in the determination of the maximal oxygen uptake of distance runners. *Appl Physiol Nutr Metab* 31(5):541-548
- Millet GP, Candau R, Fattori P, Bignet F, Varray A (2003a) $\dot{V}O_2$ responses to different intermittent runs at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 28:410-423
- Millet GP, Libicz S, Borrani F, Fattori P, Bignet F, Candau R (2003b) Effects of increased intensity of intermittent training in runners with differing $\dot{V}O_2$ kinetics. *Eur J Appl Physiol* 90 :50-57

- Montpetit RR, Léger LA, Lavoie JM, Cazorla G (1981) $\dot{V}O_2$ peak during free swimming using the backward extrapolation of the O_2 recovery curve. *Eur J Appl Physiol Occup Physiol* 47(4):385-391
- Murgatroyd SR, Ferguson C, Ward SA, Whipp BJ, Rossiter HB (2011) Pulmonary O_2 uptake kinetics as a determinant of high-intensity exercise tolerance in humans. *J Appl Physiol* 110(6):1598-1606
- Osborne MA, Minahan CL (2000) Anaerobic Capacity. In: Tanner R, Gore C (eds) *Physiological tests for elite athletes*, 2nd edn. Human Kinetics, Australia, pp 59-76
- Özyener F, Rossiter HB, Ward SA, Whipp BJ (2001) Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. *J Physiol* 533(3):891-902
- Pessôa Filho D, Alves F, Reis J, Greco, C, Denadai, B (2012) $\dot{V}O_2$ kinetics during heavy and severe exercise in swimming. *Int J Sports Med* 33(09):744-748.
- Pessôa-Filho DM, Simionato AR, Siqueira LOC, Espada MA, Pestana D (2016) Influence of regional and whole-body composition on swimming performance and aerobic indices. *Rev Bras Med Esporte* 22(3):195-199
- Peyrebrune MC, Toubekis AG, Lakomy HK, Nevill ME (2014) Estimating the energy contribution during single and repeated sprint swimming. *Scand J Med Sci* 24 (2):369-376
- Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM (2016) Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Med Sci Sports Exerc* 48(11):2320-2334
- Poole DC, Jones AM (2017) Measurement of the maximum oxygen uptake $\dot{V}O_{2max}$: $\dot{V}O_{2peak}$ is no longer acceptable. *J Appl Physiol* 122(4):997-1002
- Poole DC, Wilkerson DP, Jones AM. (2008) Validity of criteria for establishing maximal O_2 uptake during ramp exercise tests. *Eur J Appl Physiol* 102:403-410
- Pringle JS, Doust JH, Carter H, Tolfrey K, Campbell IT, Sakkas GK, Jones AM (2003) Oxygen uptake kinetics during moderate, heavy and severe intensity submaximal exercise in humans: the influence of muscle type and capillarisation. *Eur J Appl Physiol* 89:289-300
- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012a) Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *Eur J Appl Physiol* 112(5):1689-1697

- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012b) Oxygen uptake kinetics and middle distance swimming performance. *J Sci Med Sport* 15:58-63
- Reis J, Millet GP, Bruno P, Vleck V, Alves F (2017) Sex and exercise intensity do not influence oxygen uptake kinetics in submaximal swimming. *Front Physio* 8:72
- Reis J, Millet GP, Malatesta D, Roels B, Borrani F, Vleck V, Alves F (2010a) Are oxygen uptake kinetics modified when using a respiratory snorkel? *Int J Sports Physiol Perform* 5(3):292-300.
- Reis JF, Almeida N, Alves F (2018) Oxygen uptake on-kinetics in endurance training and performance. In: Alves F, Rosado A, Leonor Moniz Pereira, Duarte Araújo (eds) *Research on Human Kinetics - Multidisciplinary Perspectives*, Edições FMH, Lisboa, pp 167-184
- Reis VM, Marinho DA, Policarpo FB, Carneiro AL, Baldari C, Silva AJ (2010b) Examining the Accumulated Oxygen Deficit Method in Front Crawl Swimming. *Int J Sports Med* 31(06):421–427
- Renoux JC (2001) Evaluating the Time Limit at Maximum Aerobic Speed in Elite Swimmers. Training Implications. *Arch Physiol Biochem* 109(5):424-429
- Ribeiro J, Figueiredo P, Guidetti L, Alves F, Toussaint H, Vilas-Boas JP, Baldari C, Fernandes RJ (2016) AquaTrainer® Snorkel does not Increase Hydrodynamic Drag but Influences Turning Time. *Int J Sports Med* 37(4):324-8
- Ribeiro J, Figueiredo P, Sousa A, Monteiro J, Pelarigo J, Vilas-Boas JP, Toussaint, HM, Fernandes R (2015) $\dot{V}O_2$ kinetics and metabolic contributions during full and upper body extreme swimming intensity. *Eur J Appl Physiol* 115(5):1117-1124
- Rinehardt K, Kraemer R, Gormely S, Colan S (1991) Comparison of Maximal Oxygen Uptakes from the Tethered, the 183- and 457-Meter Unimpeded Supramaximal Freestyle Swims. *Int J Sports Med* 12(01):6-9
- Rodríguez F, Keskinen K, Kusch M, Hoffmann U (2008) Validity of a Swimming Snorkel for Metabolic Testing. *Int J Sports Med* 29(2):120–128
- Rodríguez F, Lätt E, Jürimäe J, Maestu J, Purge P, Rämson R, Haljaste K, Keskinen K, Jürimäe T (2016) $\dot{V}O_2$ Kinetics in all-out arm stroke, leg kick and whole stroke front crawl 100-m swimming. *Int J Sports Med* 37(3):191-196

- Rodríguez FA (2000) Maximal oxygen uptake and cardiorespiratory response to maximal 400-m free swimming. Running and cycling tests in competitive swimmers. *J Sports Med Phys Fitness* 40:87-95
- Rodríguez FA, Mader A (2011) Energy systems in swimming. In: Seifert L, Chollet D, Mujika I (eds) *World Book of Swimming: From Science to Performance*. Nova Science Publishers, Hauppauge, New York, pp 225–240
- Rodríguez, FA, Keskinen, KL, Malvela, MT, Keskinen, OP (2003) Oxygen uptake kinetics during free swimming: A pilot study In: Chatard JC (ed) *Biomechanics and Medicine in Swimming IX*, Publications de l'Université de Saint-Étienne, Saint-Étienne, pp 379-384
- Rønnestad BR, Rømer T, Hansen J (2019) Increasing oxygen uptake in well-trained cross-country skiers during work intervals with a fast start. *Int J Sports Physiol Perform* 15:1-7
- Scheuermann B, Hoelting B, Noble M, Barstow T (2001) The slow component of O₂ uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. *J Physiol* 531(1):245-256
- Schneider D, Wing A, Morris N (2002) Oxygen uptake and heart rate kinetics during heavy exercise: a comparison between arm cranking and leg cycling. *Eur J Appl Physiol* 88(1-2):100-106
- Silva A, Oliveira F (2004) Consumo de oxigênio durante o exercício físico: Aspectos temporais e Ajustes de Curvas. *Rev Bras Cine Des Hum* (2):73-84
- Sousa A C, Fernandes RJ, Boas J P V, Figueiredo P (2018) High-intensity Interval Training in Different Exercise Modes: Lessons from Time to Exhaustion. *Int J Sports Med* 39(9):668-673
- Sousa A, Borrani F, Rodríguez FA (2017b) Oxygen uptake kinetics is slower in swimming than in arm cranking and cycling during heavy intensity. *Front Physio* 8:639
- Sousa A, Figueiredo P, Oliveira N, Oliveira J, Silva A, Keskinen KL, Rodríguez FA, Machado L, Vilas-Boas JP, Fernandes R (2011) $\dot{V}O_2$ Kinetics in 200-m race-pace front crawl swimming. *Int J Sports Med* 32(10):765-770
- Sousa A, Figueiredo P, Pendergast D, Kjendlie PL, Vilas-Boas JP, Fernandes RJ (2014a) Critical Evaluation of Oxygen-Uptake Assessment in Swimming. *Int J Sports Physiol Perform* 9(2):190-202

- Sousa A, Figueiredo P, Zamparo P, Pyne DB, Vilas-Boas JP, Fernandes RJ (2015) Exercise modality effect on bioenergetical performance at $\dot{V}O_{2max}$ intensity. *Med Sci Sports Exerc* 47(8):1705-1713
- Sousa A, Figueiredo P, Zamparo P, Vilas-Boas JP, Fernandes RJ (2013b) Anaerobic alactic energy assessment in middle distance swimming. *Eur J Appl Physiol* 113(8):2153-2158
- Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013a) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190
- Sousa A, Ribeiro J, Sousa M, Vilas-Boas JP, Fernandes RJ (2014c) Influence of Prior Exercise on $\dot{V}O_2$ Kinetics Subsequent Exhaustive Rowing Performance. *PLoS One* 9(1):e84208
- Sousa A, Vilas-Boas J, Fernandes R (2014a) $\dot{V}O_2$ kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at $\dot{V}O_{2max}$. *Biomed Res Int* 2014:675363
- Sousa A, Vilas-Boas JP, Fernandes RJ, Figueiredo P (2017a) $\dot{V}O_2$ at maximal and supramaximal intensities: lessons to high-intensity interval training in swimming. *Int J Sports Physiol Perform* 12(7):872-877
- Spencer MR, Gatin PB (2001) Energy system contribution during 200- to 1500-m running in highly trained athletes. *Med Sci Sports Exerc* 33(1):157-162
- Toussaint HM, Hollander AP (1994) Energetics of competitive swimming. *Sports Med* 18:384-405
- Toussaint HM, Meulemans A, de Groot G, Hollander AP, Schreurs AW, Vervoorn K (1987) Respiratory valve for oxygen uptake measurements during swimming. *Eur J Appl Physiol Occup Physiol* 56(3):363-366
- Wakayoshi K, Nakatani A, D'Acquisto LJ, Cappaert JM, Troup JP (1995) Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *Med Sci Sports Exerc* 16(1):19-23
- Warr-di Piero D, Valverde-Esteve T, Redondo-Castán JC, Pablos-Abella C, Sánchez-Alarcos Díaz-Pintado JV (2018) Effects of work-interval duration and sport specificity on blood lactate concentration, heart rate and perceptual responses during high intensity interval training. *PLoS One* 13(7):e0200690

- Weatherwax R, Richardson T, Beltz N, Nolan P, Dalleck L (2016) Verification Testing to Confirm $\dot{V}O_{2max}$ in Altitude-Residing, Endurance-Trained Runners. *Int J Sports Med* 37(07):525-530
- Wen D, Utesch T, Wu J, Robertson S, Liu J, Hu G, Chen H (2019) Effects of Different Protocols of High Intensity Interval Training for $\dot{V}O_{2max}$ Improvements in Adults: A Meta-Analysis of Randomised Controlled Trials. *J Sci Med Sport* 22(8):941-947
- Whipp BJ (1994) The slow component of O_2 uptake kinetics during heavy exercise. *Med Sci Sports Exerc* 26(11):1319-1326
- Whipp BJ, Ward SA (1990) Physiological determinants of pulmonary gas exchange kinetics during exercise. *Med Sci Sports Exerc* 22(1):62-71
- Whipp BJ, Wasserman K (1972) Oxygen uptake kinetics for various intensities of constant-load work. *J Appl Physiol* 33(3):351-356
- Wilkerson DP, Koppo K, Barstow TJ, Jones AM (2004) Effect of work rate on the functional "gain" of Phase II pulmonary O_2 uptake response to exercise. *Respir Physiol Neurobiol* 142(2-3):211-223
- Xu F, Rhodes EC (1999) Oxygen uptake kinetics during exercise. *Sports Med* 27(5):313-327
- Zacca R, Azevedo R, Silveira RP, Vilas-Boas JP, Pyne DB, de S. Castro FA, Fernandes RJ (2019) Comparison of incremental intermittent and time trial testing in age-group swimmers. *J Strength Cond Res* 33(3):801-810
- Zamparo P, Capelli C, Pendergast D (2011) Energetics of swimming: a historical perspective. *Eur J Appl Physiol* 111(3):367–378
- Zamparo P, Cortesi M, Gatta G (2019) The energy cost of swimming and its determinants. *Eur J Appl Physiol* [Epub ahead of print] doi: 10.1007/s00421-019-04270-y.
- Zuniga J, Berg K, Noble J, Harder J, Chaffin M, Hanumanthu V (2011) Physiological Responses during Interval Training with Different Intensities and Duration of Exercise. *J. Strength Cond Res* 25(5):1279-1284

Chapter III. General methodology

This present chapter will describe the general methodology applied in the studies presented in the subsequent chapters. Later, each study will display the specific characteristics of each experiment. This section is divided in the characterization of the: 1) subjects; 2) general experimental design; 3) general procedures and equipment used for the data collection; 4) data handling; and 5) statistical analysis. All the following procedures were approved by the Ethics Council of the Faculty of Human Kinetics (CEFMH: 39/2015)¹ and conducted in accordance with the 1964 Declaration of Helsinki (Harris et al., 2017).

3.1 Subjects

28 swimmers, 14 males and 14 females, composed the total sample of the athletes that participated in our studies, and for each study the sample size varied between 8 to 28 swimmers. All swimmers were submitted to the analysis of height, body weight and body fat. The swimmers descriptive and anthropometrical data are presented in table 3.

Table 3. Mean \pm SD of the descriptive characteristics and anthropometrical data of the total sample size of the swimmers

Variable	Female	Male	Combined
Sample size	14	14	28
Age (years)	15.6 \pm 2.6	16.6 \pm 1.8	16.1 \pm 2.3
Height (cm)	163.4 \pm 6.7	178.5 \pm 8.1	171.0 \pm 10.6
Total body Mass (kg)	56.0 \pm 6.7	70.5 \pm 9.9	63.3 \pm 11.2
Body fat (%)	22.5 \pm 4.1	12.2 \pm 2.8	18.3 \pm 6.2

The swimmers usually perform a training program of ~30km/week in 6 to 8 training sessions of swimming plus 3 to 5 dry-land training sessions, and were guided by 1 head coach, 2 assistant coaches and a nutritionist. The criterion for participation in the studies was the regular participation by the swimmers at state or national championships, at least in the past 3 years' prior entering in the study.

¹ See appendix V – Study approval by the Ethics Council of the Faculty of Human Kinetics.

Furthermore, it was presented to the athletes and respective coaches, a written informed consent for scientific research with human beings² containing the project of the study as well as the study procedures and the potential risks that could arise from their participation. This written consent, previously approved by the Ethics Council of the Faculty of Human Kinetics, had to be signed by the athletes and by the respective legal guardians when they were under 18 years old. A medical questionnaire³ was also presented to the swimmers to discard subjects that could present some risk factors for the high intensity exercises that would be proposed (none of the enquired swimmers presented contraindications for the practice of the proposed exercises).

The schedule of the test sessions was programed with the coaches in order to facilitate swimmers to perform the tests with a period of, at least, 24 hours preceding each test without strenuous exercise performed by the participants. Moreover, the swimmers were instructed in order to attend to the testing sessions well hydrated and to abstain from caffeine and alcohol consumption in the 24 hours preceding each testing session. Previously to the beginning of the sessions, swimmers were familiarized with the test procedures and the equipment used in the studies, which will be described below.

3.2 General experimental design

The data collection occurred in Brazil, with the swimmers of the most representative team of the Bauru city. All the sessions were performed in the beginning of the preparatory period of the second macrocycle of the swimmers competitive season, after a period of two weeks for training adaptation.

In order to apply similar conditions to all tests and avoid the effect of circadian rhythms the same environmental conditions were applied, namely time of day (\pm 2 hours), water temperature (\sim 28°C), ambient temperature (\sim 34°C) and relative humidity (\sim 50%). Differences caused by prior exercise were also avoided with all the subjects performing the same pre-test warm up protocol composed by 600

² See appendix III – Informed consent for study's participation.

³ See appendix IV – Medical questionnaire pre-workout.

meters of aerobic swimming at low to moderate intensity (Espada et al., 2015) with 50 to 100 meters at higher velocities in order to perform a proper warm-up for the tests with maximal and supramaximal velocities.

All the swimmers performed a previous evaluation at the Laboratory of Human Exercise and Sport Performance Optimization (LABOREH) of the State University of São Paulo (UNESP) in Bauru. In this first encounter the researchers were able to collect the written informed consents and the medical questionnaires, as well as to perform the evaluation of the descriptive characteristics and anthropometrical measures of the swimmers. After this first evaluation, the swimmers started to go to the swimming pool to complete the swimming tests.

At the swimming pool, firstly, all swimmers performed a discontinuous incremental test in order to access the maximal oxygen uptake ($\text{Peak-}\dot{V}\text{O}_2$), maximal aerobic velocity (MAV), which was considered as the minimal velocity at which the $\text{Peak-}\dot{V}\text{O}_2$ was achieved, the second ventilatory threshold (VT_2) and the respective velocity at the VT_2 ($v\text{VT}_2$). The test was composed by 6 sets of 250 meters plus 1 set of 200 meters, with breaks of 30 seconds for blood lactate concentration. According with the graphic representation (figure 9), the first repetition was set at 50% of the swimmers 200 meters velocity and the following sets increasing 5 to 10% in order to perform the last repetition at the maximal velocity, or until the swimmers voluntary exhaustion.

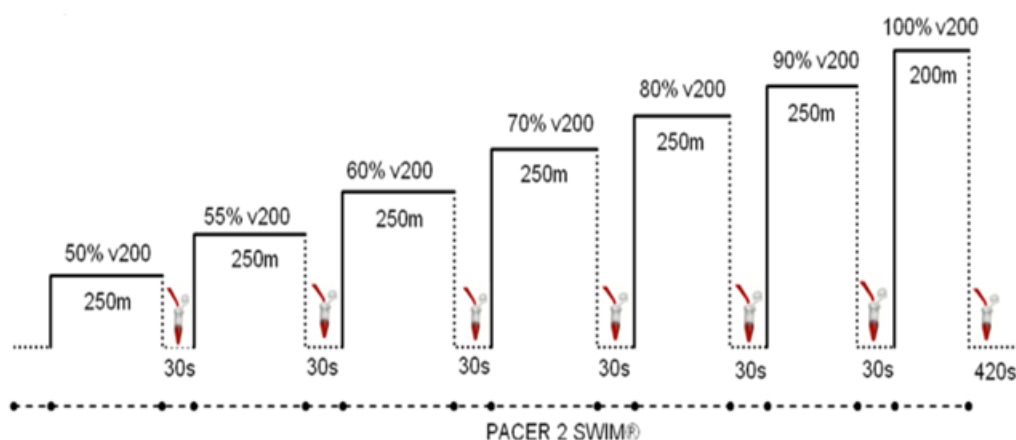


Figure 9. Graphical representation of the discontinuous incremental test performed in the studies presented in this thesis

The 200 meters velocity was obtained directly with the head coach of the team in a training session, previously to the testing sessions. This discontinuous incremental test, previously applied (Espada et al., 2015), was the only test common to all studies.

The remaining sessions were performed at maximal and supramaximal intensities, varying in the form as the intensity was placed (constant vs. maximal trials), but also in the form as the total distance was performed (continuous vs. intermittent). In total, swimmers went back to the pool between 7 to 9 times to complete the tests (figure 10), which were separated at least by 24 hours each. The following figure summarizes the general program of tests for each swimmer.

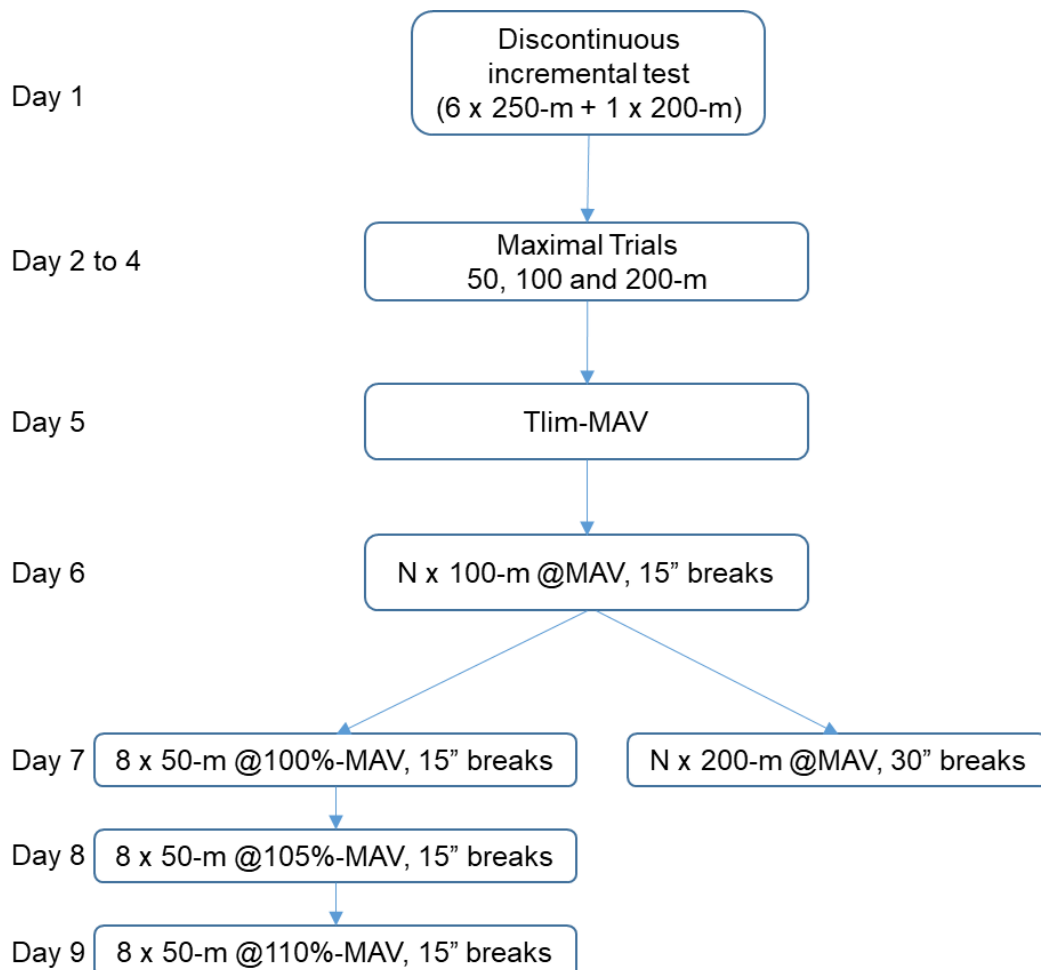


Figure 10. Graphical representation of the swimmers testing planning sessions

The picture represents an example of two different possible schedules of tests for each swimmer. As above referred, the discontinuous incremental test was, for all the participants, the first test performed. Next, the maximal trials were performed in a randomized manner, followed by the TLim-MAV and the intermittent tests performed also in randomized manner.

3.3 General procedures and equipment description

To facilitate the participation and minimize constraints to the swimmers and coaches we chose to perform the testing sessions in the 25-meters swimming pool of the team in order to provide them a well-known and friendly environment which contributed for the data collection success. This choice implied a daily transport, assembly and disassembly of all the equipment between the university laboratory to the team swimming pool, by the research team.

Several physiological parameters were collected along the tests such as $\dot{V}O_2$, heart rate (HR), blood lactate concentration $[La^-]$, as well as the rate of perceived exertion (RPE). Also, some of the tests implied the control of predetermined and constant velocities. In the next points the procedures and equipment used to collect the data and control the swimming intensities will be explained.

3.3.1 $\dot{V}O_2$ assessment

For the $\dot{V}O_2$ data collection the research team used a telemetric portable breath-by-breath gas analyser - K4b² from Cosmed, Italy – which allowed to measure the respiratory and gas exchange variables. This equipment was previously validated for the cardiorespiratory analysis and used in several studies from our research group (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012a,b). The K4b² was calibrated before each test according to the manufacturer's instructions⁴.

The calibration process is based on 4 steps (see figure 11): 1) The room air calibration (1), that performed a sampling room air updating the baselines of the

⁴ See "K4B² user manual" Cosmed Lda., 2011: pp. 44-51.

CO₂ and O₂ analysers in order to match the readings with the predicted atmospheric values (20.93% for O₂ and 0.03% for CO₂); 2) the reference gas calibration, that updates the baseline and the gain of the analysers accordingly to a sampling from a specific calibration cylinder (2) with a known composition (16% for O₂ and 5% for CO₂); 3) the delay calibration, through matching expiratory and inspiratory consecutive actions with a beeping mark from the unit (3), which measures the time necessary for the gas sample to pass through the sampling line before being analysed; 4) and the turbine calibration, which consists in measuring the volume of a 3 litres calibration syringe (4) updating the gain of the flowmeter in order to match the predicted value. The following figure represents graphically the procedures written above.

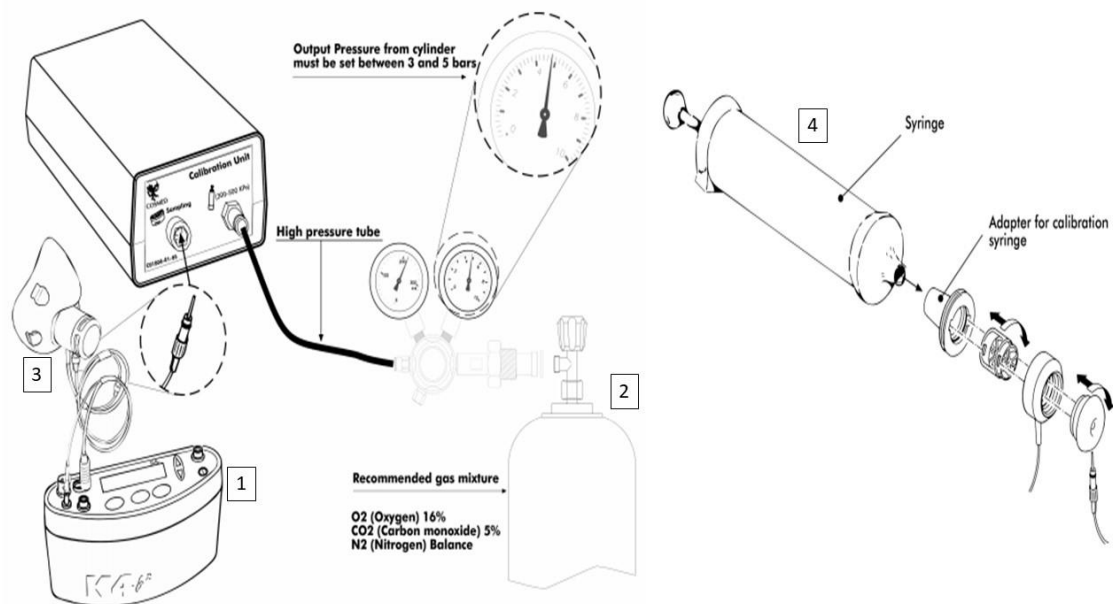


Figure 11. Calibration unit of the K4b² system. 1 - K4b² unit responsible for the room air calibration and gas analysis during exercise; 2 - reference gas calibration cylinder; 3 - mask used during the delay calibration process; and 4 - calibration syringe for turbine calibration (adapted from the “K4b² user manual, IX Edition”).

Since the $\dot{V}O_2$ data was collected breath-by-breath along all the meters performed by the swimmers that participated in our studies, which is not compatible with the usual facial masks that are used commonly in laboratory or in the terrestrial modalities, we connected the K4b² unit to a respiratory snorkel

and valve system – new Aquatrainer® from Cosmed, Italy – in order to measure the respiratory and gas exchange variables. The respiratory snorkel represented graphically and showed in figure 12, works with a mouthpiece fixed to a headset, and inspiratory and expiratory tubes separated by a two-way non-rebreathing valve. The expiratory tube is connected to the gas analyser turbine, and expiratory gas is sent to the turbine and to O₂ and CO₂ sensors via a Nafion sampling line (Reis et al., 2010). A nose clip was also used by the swimmers in order not to lose $\dot{V}O_2$ data due to possible nose expirations.

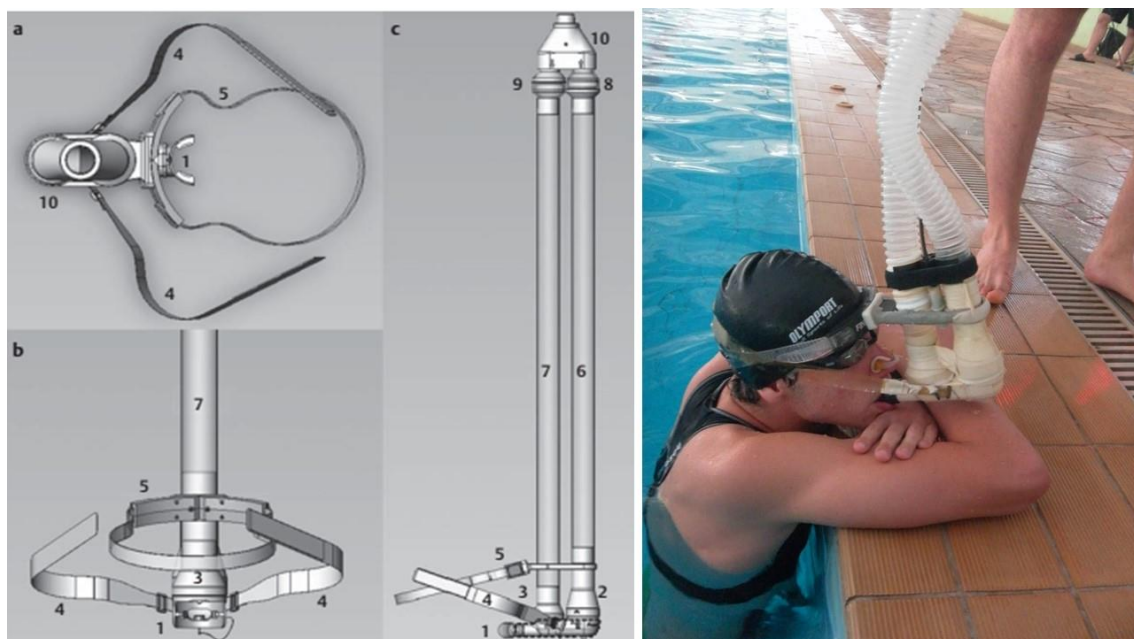


Figure 12. Graphical and real representation of the snorkel new Aquatrainer used for gas sampling collection during the tests performed in our studies.

In these figures we can observe the complete design of the new snorkel Aquatrainer (left figure, adapted from Baldari et al., 2012) in an upper (a), frontal (b) and lateral (c) visions of the equipment. All its components are numbered: 1- mouth piece, 2-lower expiration valve, 3-lower inspiration valve, 4-neck connection, 5-head connection, 6-expiration tube, 7-inspiration tube, 8-upper expiration valve, 9-upper inspiration valve, 10-connection tubes unit and, delimited in dotted line, the snorkel dead air space. In the right picture a real snorkel view during a break of a testing session.

This system, that was previously validated for cardiorespiratory analysis (Baldari et al., 2012; Reis et al., 2010), makes it impossible the starts from the starting block and conditions the usual turns from the freestyle technique, however it does not influence the stroking parameters or the swimming technique (Barbosa et al., 2010). Because of the use of the system, all tests were performed with in-water starts and open turns without underwater gliding, which could increase the turning times (Ribeiro et al., 2016).

For this reason, when programming the swimming velocities for the discontinuous incremental test, an increment of 1 ± 0.48 seconds was applied to each turn to match the time of a traditional kick-off turn, as found in a previous study performed by our research group (Espada et al., 2015), similar, also, with other previous findings (Hellard et al., 2010). In order to collect the $\dot{V}O_2$ breath-by-breath data the K4b² unit coupled to the swimming snorkel had to be carried out along the pool matching the swimmers rhythm.

The following picture represents a typical example of how the $\dot{V}O_2$ data collection occurs.

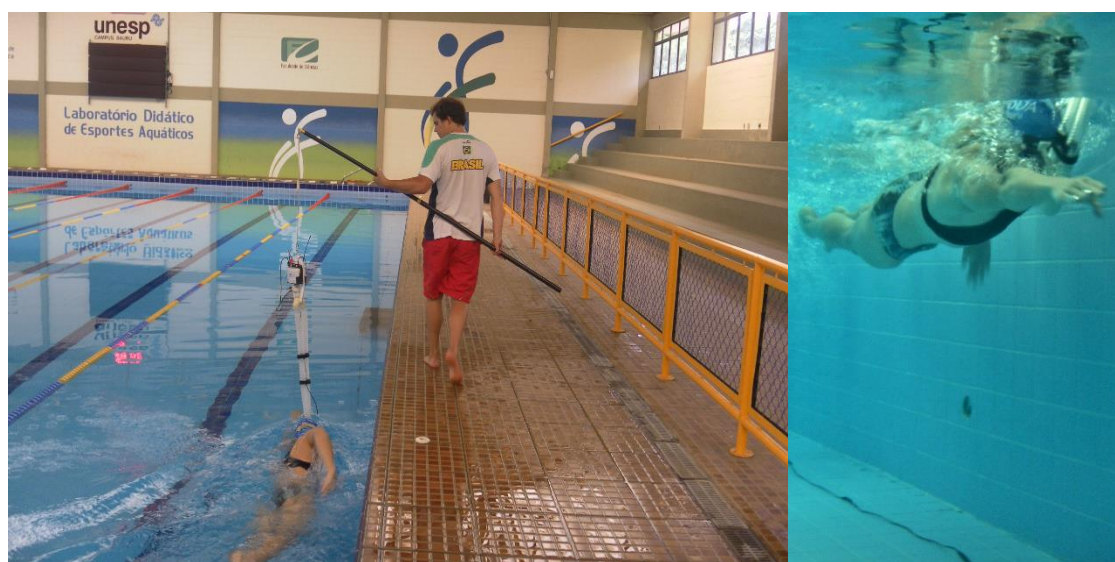


Figure 13. Typical example of the system carrying during pilot testing procedures in UNESP's swimming pool

3.3.2 Heart rate assessment

The heart rate (HR) was recorded telemetrically during all tests with a HR monitor (Polar®, Finland) coupled to the snorkel and synchronized with the K4b² system. The HR data was recorded directly in the K4b² unit software, from where it was afterward obtained.

The HR data was recorded during 3 moments: 1) Before each test during 10 minutes of passive rest for the rest HR calculation; 2) During all tests with a swimming vest used in the male swimmers in order to better fix the HR chest belt and improve the HR signal (see figure 12 right picture); 3) After all tests during an 8 minutes of passive recovery period.

3.3.3 Blood lactate concentration assessment

The blood lactate concentration ($[La^-]$) samples were collected through capillary blood samples (25 ul) collected from the earlobe of the swimmers (figure 14), carefully dried before each sampling, at rest before each test, between the steps of the discontinuous incremental test and in the end of all tests at minutes 1, 3, 5 and 7 in order to obtain the maximum concentration value.



Figure 14. Blood lactate collection from the earlobe of one of the participants

The blood samples were immediately laid in numbered Eppendorf safe-locked tubes that were frozen for latter analysis in the laboratory with a specific lactate analyzer - YSI, 2300 STAT, Yellow Springs, USA.

3.3.4 Rate of perceived exertion assessment

The rate of perceived exertion (RPE) was recorded through the Borg's CR-10 scale (Borg, 1990), previously used by our research group (Ramos et al., 2015), before and at the end of all tests and between the sets of the discontinuous incremental test and between the sets of the intermittent training sessions tests.

3.3.5 Swimming velocity control

Since several tests required specific and constant intensities an underwater visual pacer – Pacer2Swim[®], KulzerTEC, Portugal – was used in order to give the swimmers a correct notion of the velocities of each test. At figure 15 all the components of the system are presented.

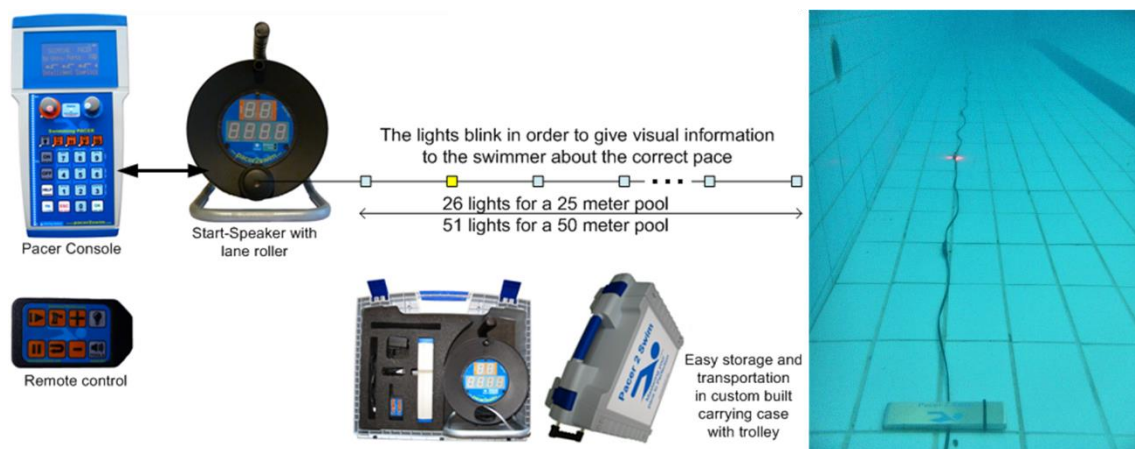


Figure 15. Underwater visual pacer used for velocity control

The figure represents the full set of the Pacer2Swim[®] unit. At the pacer control unit the required velocities are previously programmed, while the Start-Speaker indicates by visual and sound feedback the moment of the starts and breaks of the set. In the right image an example of the display of the flashing LEDs lane is presented.

The system, previously used for scientific research in swimming (Zacca et al., 2019), uses a cable equipped with 26 LEDs located on the bottom of the swimming pool. Those LEDs subsequently light up (see figure 15, right image) providing visual feedback to the swimmer about his/her correct position at all times, and therefore indicates the correct pace of the task, previously programmed by the researcher.

3.3.6 Body composition measurement

The body composition measurement was obtained through a method of dual-energy x-ray absorptiometry – DXA. The results obtained allowed to achieve the body weight as well as the total body fat of the swimmers. The following picture represents an example of the testing results.

Body Composition Results

Region	Fat Mass (g)	Lean+ BMC (g)	Total Mass (g)	% Fat	% Fat T-score	% Fat Z-score
L. Arm	504	3692	4196	12.3		
R. Arm	603	3810	4413	13.7		
Trunk	4053	26734	30787	13.2		
L. Leg	1960	11214	13174	14.9		
R. Leg	2335	10416	12750	18.3		
Subtotal	9454	55776	65230	14.5		
Head	831	3713	4544	18.3		
Total	10285	59489	69774	14.7		
Android	622	3629	4252	14.6		
Gynoid	1814	8890	10704	16.9		



Figure 16. Example of DXA results and report.

3.4 Data handling

There were mainly two kinds of data handling performed in our studies:

- 1) The $\dot{V}O_2$ data treated to determine a) the maximal oxygen uptake (Peak- $\dot{V}O_2$) and the second ventilatory threshold (VT_2) of the discontinuous incremental test, as well as the maximal rise of the $\dot{V}O_2$ ($\dot{V}O_{2peak}$) of the remaining tests, b) the time spent near the maximal oxygen uptake, c) the oxygen uptake kinetics parameters and d) the growth rate of the $\dot{V}O_2$;

- 2) The metabolic response of the exercise treated to determine the contribution of the three energetic systems a) the aerobic participation, b) the anaerobic alactic participation and c) the anaerobic lactic participation.

3.4.1 $\dot{V}O_2$ data handling

As previously mentioned, the $\dot{V}O_2$ data was obtained breath-by-breath continuously during the exercise. For the $\dot{V}O_2$ treatment the data was first visually inspected and “cleaned” by the exclusion of the outliers caused by abrupt breaths or coughing or signal interferences. The criterion of exclusion was set at three standard deviations from the local mean (Koga et al., 2005).

3.4.1.1 Peak- $\dot{V}O_2$, $\dot{V}O_{2peak}$ and VT_2

The Peak- $\dot{V}O_2$ of the discontinuous incremental test and the $\dot{V}O_{2peak}$ of the remaining tests were calculated through a moving average of the $\dot{V}O_2$ values considering the maximal value as the peak. For the discontinuous incremental test and for all the tests with 200 or more meters a 30 seconds moving average was applied, while for the tests that comprises 100 and 50 meters distances a moving average of 15 and 5 seconds, were respectively applied, in order not to influence the results, given the shorter time duration of these tests. For the intermittent tests the mean $\dot{V}O_{2peak}$ ($M\dot{V}O_{2peak}$) was also calculated, as the average value the $\dot{V}O_{2peak}$ of each one of the repetitions that compose the all set of the intermittent tests.

For the second ventilatory threshold (VT_2) determination, a graphical analysis, regarding the response pattern of the O_2 and CO_2 responses during the discontinuous incremental test, was performed by two independent observers. The VT_2 was than determined by the observation of: 1) the partial pressure of O_2 (PET_{O_2}) and CO_2 (PET_{CO_2}) when both begin to separate (PET_{O_2} rises while PET_{CO_2} decreases); 2) the ventilatory equivalents for the O_2 ($VE/\dot{V}O_2$ ratio) and CO_2 ($VE/\dot{V}CO_2$ ratio), when both start to rise at the same time; and 3) the pulmonary ventilation, when a sudden and significant increase is observable. This methodology for determining the VT_2 was already performed in several

studies from our research group (Espada et al., 2015; Pessôa Filho et al., 2012; Reais et al., 2012a,b and 2017).

3.4.1.2 Time spent near individuals $\dot{V}O_2$ maximal values

As previously mentioned, the literature has been focusing attention not only to the maximal $\dot{V}O_2$ values obtained by an athlete as a referential of physiological performance, but also to the time duration that an athlete can practice a specific exercise with $\dot{V}O_2$ values near their individual maximal $\dot{V}O_2$. Overall, the time sustained with $\dot{V}O_2$ values above 90% of the $\dot{V}O_{2max}$ has been pointed as one of the most important factors to improve the $\dot{V}O_{2max}$ itself and performance (Billat and Koralsztein, 1996; Billat, 2001).

The majority of the studies use physiological thresholds at 90% (Bentley et al., 2005; Millet et al., 2003) and 95% of the $\dot{V}O_{2max}$ (Libicz et al., 2005) in order to test the time that athletes spend near the $\dot{V}O_{2max}$. It seems that an important physiological threshold has been, wrongly, disregarded – the VT_2 (at least in the swimming sport).

In order to provide a broad investigation about the time spent near the $\dot{V}O_2$ maximal values, in this thesis we opted to test the traditional thresholds but we also introduced a new approach through the analysis of the time spent above the VT_2 . Since this physiological threshold is associated to the frontier that marks the start of the severe intensity domain it made sense to us to test also this variable.

In order to do so, the $\dot{V}O_2$ data (after the outliers being withdrawn) was interpolated into a 1-second values in order to get a continuous $\dot{V}O_2$ series (second by second). Later, a protocol built in Microsoft Excel[®] was applied to the data giving all values above each one of the three physiological thresholds considered – $\geq VT_2$, $\geq 90\%$ and $\geq 95\%$ of the individual maximal oxygen uptake determined previously in the discontinuous incremental test. Then, to understand the representativeness of the results, the percentage values for the total duration of each task were calculated.

3.4.1.3 Oxygen uptake kinetics

The oxygen uptake kinetics ($\dot{V}O_2K$) comprised the analysis of three key parameters: the time delay (TD), the time constant (τ) and the amplitude of the $\dot{V}O_2$ response. For this analysis we first disregarded the data of the first 20 seconds of exercise corresponding to the cardiodynamic phase of the $\dot{V}O_2$ response, to remove the influence of this phase on the subsequent phases, in accordance to previous studies (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012a,b; Sousa et al., 2014).

Previous findings from our research group noticed a $\dot{V}O_2K$ slower with the use of the swimming snorkel, compared with the conventional masks (Reis et al., 2010), caused by the snorkel dead space which delays the expired air from the swimmer to reach the sampling line. In Reis et al. (2010) the authors calculated and tested that delay and presented it as an individual “snorkel delay” (ISD). As in Reis’ study we also calculated the ISD for each test, that corresponds to the difference between the onset of the exercise and the time when the following breaths summed up a tidal volume superior to the outlet tube volume, and then integrated it into the time delay of the $\dot{V}O_2$ response, adapted to the specific characteristic of the snorkel device used in this study.

After the above procedures the $\dot{V}O_2$ data was then further interpolated in a 1-second value response and was submitted to a smoothing process⁵. Afterwards the $\dot{V}O_2K$ parameters were calculated by an iterative procedure, minimizing the sum of the mean squares of the differences between the modelled and the measured $\dot{V}O_2$ values. For the modelling process two possible approaches were applied accordingly to the type of the exercise.

For exercises situated in the extreme domains or characterized by shorter durations, the $\dot{V}O_2$ response was characterized by a single exponential growth, since no secondary rise on $\dot{V}O_2$ was observed, in accordance to previous studies performed with similar durations or intensities (Rodríguez et al., 2003; Sousa et

⁵ The smoothing process was performed in the SPSS software.

al., 2011 and 2013). So, the $\dot{V}O_{2K}$ parameters were calculated by monoexponential modelling, through the following equation (Poole and Jones, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2base} + A \cdot (1 - e^{-(t-TD)/\tau})$$

In this approach: the $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest, which was calculated as the average of the first 30 seconds of the last minute before the start of the exercise (after 10 minutes of passive rest); TD, τ , and A, represent the time delay, the time constant (time that is needed to complete 63% of the $\dot{V}O_2$ response) and the amplitude of the exponential response of the $\dot{V}O_2$.

However, when the exercise (e.g., at MAV) could be extended in time a secondary rise of the $\dot{V}O_2$ (slow component) was observed, being the $\dot{V}O_2$ response better modelled by a bi-exponential growth. This situation only occurred with one of the tests, when we tested the swimmers for the tolerance to the MAV. In this case the $\dot{V}O_{2K}$ parameters were calculated by bi-exponential modelling, through the following equation (Poole and Jones, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2(b)} + A_p \cdot (1 - e^{-(t-TDp)/\tau_p}) + A_{sc} \cdot (1 - e^{-(t-TDsc)/\tau_{sc}})$$

In this approach the $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest; TD, τ , and A, represent the time delay, the time constant and the amplitude of the exponential response of the $\dot{V}O_2$, respectively for the primary (p) and the slow component (sc) phases.

3.4.1.4 $\dot{V}O_2$ growth rate

A new approach on the $\dot{V}O_2$ handling for analysing how fast the $\dot{V}O_2$ rises into the individual's maximum values was applied in this study, in order to reinforce the data obtained by the traditional mono or bi-exponential modelling. Since in this work we analysed short and very short events (e.g., 30 seconds) we observed that the $\dot{V}O_2$ did not have time to clearly stabilize in these cases. For

this reason, we opted to apply a secondary treatment of the $\dot{V}O_2K$ data by averaging the time derivatives of $\dot{V}O_2$ between the 20th second of the beginning of the exercise (to exclude the cardiodynamic phase) and the 30th second (to allow a comparison between other, and longer, maximal trials) of the smoothed series referred above. This action was performed through the AcqKnowledge 3.8[®] software.

3.4.2 Metabolic characterization

For the metabolic characterization three procedures were performed in order to measure the total energy spent for each exercise: (1) the collection of the $\dot{V}O_2$ data during rest (for determine the baseline $\dot{V}O_2$) and exercise; (2) the collection of the $\dot{V}O_2$ during the recovery phase post-exercise and 3) the collection of the rest and maximal blood lactate concentration, in order to calculate the total energy expenditure of the exercise (Artioli et al., 2012). For the total energy system contribution was then considered the aerobic, anaerobic alactic and anaerobic lactic systems participation.

3.4.2.1 Aerobic energy system participation

For the aerobic energy contribution assessment, the $\dot{V}O_2$ was collected during the exercise. Then it was determined as the time integral of the net $\dot{V}O_2$ during exercise by the trapezoidal method (Bertuzzi et al., 2013; Guidetti et al., 2007), accordingly to the following equation:

$$Aer = \int_{t_0}^{t_{Lim}} \dot{V}O_2 \times dt - (\dot{V}O_{2b} \times t_{Lim})$$

Where $\dot{V}O_{2b}$ is baseline $\dot{V}O_2$ response, dt the time variation of the exercise and t_{Lim} is time performance. The results are expressed in liters of oxygen (LO_2).

3.4.2.2 Anaerobic alactic system participation

For the anaerobic alactic participation determination, the $\dot{V}O_2$ data was recorded after the end of the exercise, during the passive recovery phase of the swimmers, for a period of 8 minutes. Then a bi-exponential fitting was applied on the $\dot{V}O_2$

data of the recovery phase (Scheuermann et al., 2001; Beneke et al 2002), as follows:

$$\dot{V}O_{2\text{off}}(t) = EE\dot{V}O_2 - A_{1\text{off}}[1 - e^{-(t-TD_1/\tau_1)}] - A_{2\text{off}}[1 - e^{-(t-TD_2/\tau_2)}]$$

Where $\dot{V}O_{2\text{off}}(t)$ represents the relative $\dot{V}O_2$ at a given time; $EE\dot{V}O_2$ is the oxygen uptake at the end of exercise; TD , τ , and A , represent the time delay, the time constant and the amplitude, and 1 and 2 represent the fast and slow component, respectively, for the bi-exponential response of the $\dot{V}O_2$. The product between the time constant and amplitude of the fast component of post-exercise oxygen consumption was considered as the anaerobic lactic contribution expressed in LO_2 . A bi-exponential fitting has been considered optimal for maximal and supramaximal efforts, while for moderate intensities a monoexponential fitting seems preferable (Özyener et al., 2001).

3.4.2.3 Anaerobic lactic participation

The anaerobic lactic system was determined by the difference between maximal $[La^-]$ after exercise and resting $[La^-]$ expressed as a delta value ($\Delta[La^-]$) (Beneke et al., 2002), considering $3 \text{ ml } O_2 \cdot \text{kg}^{-1}$ as a metabolic equivalent for each $1 \text{ mmol} \cdot \text{l}^{-1}$ of $\Delta[La^-]$ (di Prampero, 1981).

3.5 Statistical analysis

The statistical analyses were performed with Statistical Package for the Social Sciences (version 25.0; SPSS, Chicago, IL, USA) and the significance value was settled at $p\text{-value} < 0.05$. Five main procedures were applied:

- Descriptive statistics – means and standard deviations (SD);
- Analysis of normality and homogeneity of data by the Shapiro-Wilk and Levene tests;
- Independent T-tests applied to all variables for testing the differences between the male group and the female group;

- T-tests for checking the differences between two tests, or ANOVA with Bonferroni correction for repeated measures;
- Establishment of significant associations between variables by the Pearson's linear correlation coefficient.

References of Chapter III

- Artioli GG, Bertuzzi RC, Roschel H, Mendes SH, Lancha Jr. AH, Franchini E (2012) Determining the Contribution of the Energy Systems During Exercise. *J Vis Exp* (61)pii:3416
- Baldari C, Fernandes R, Meucci M, Ribeiro J, Vilas-Boas JP, Guidetti L (2012) Is the new aquatrainer® snorkel valid for $\dot{V}O_2$ assessment in swimming? *Int J Sports Med* 34(04):336-344
- Barbosa T, Silva AJ, Reis AM, Costa M, Garrido N, Policarpo F, Reis VM (2010) Kinematical changes in swimming front crawl and breaststroke with the aquatrainer® snorkel. *Eur J Appl Physiol* 109(6):1155-1162
- Beneke R, Pollmann C, Bleif I, Leithäuser RM, Hütler M (2002) How anaerobic is the wingate anaerobic test for humans? *Eur J Appl Physiol* 87:338-392
- Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP (2005) Physiological responses during submaximal interval swimming training: effects of interval duration. *J Sci Med Sport* 8:392-402
- Bertuzzi R, Nascimento EM, Urso RP, Damasceno M, Lima-Silva AE. (2013) Energy system contributions during incremental exercise test. *J Sports Sci Med* 12(3):454-460
- Billat LV (2001) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. *Sports Med* 31(1):13-31
- Billat V, Koralsztein JP (1996) Significance of the velocity at $\dot{V}O_{2max}$ and time to exhaustion at this velocity. *Sports Med.* 22(2):90-108
- Borg G (1990) Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* 16(1):55-58
- di Prampero PE (1981) Energetics of muscular exercise. *Rev Physiol Biochem Pharmacol* 89:143-222
- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843
- Guidetti L, Emerenziani GP, Gallotta MC, Baldari C (2007) Effect of warm up on energy cost and energy sources of a ballet dance exercise. *Eur J Appl Physiol* 99(3):275-281

- Harriss DJ, Macsween A, Atkinson G (2017) Standards for Ethics in Sport and Exercise Science Research: 2018 Update. *Int J Sports Med* 38:1126-1131
- Hellard P, Houel N, Avalos M, Nesi X, Toussaint JF, Hauswirth C (2010) Modeling the slow component in elite long distance swimmers at the velocity associated with lactate threshold. In: Kjendlie PL, Stallman RK, Cabri J (eds) *Proceedings of the XIth International Symposium for Biomechanics and Medicine in Swimming*. Oslo, Norway, pp196-198
- Koga S, Shiojiri T, Kondo N (2005) Measuring $\dot{V}O_2$ kinetics: the practicalities. In: Jones AM, Poole DC (eds) *Oxygen uptake kinetics in sport, exercise and medicine*, Routledge, Oxon, England, pp 39-61
- Libicz S, Roels B, Millet GP (2005) $\dot{V}O_2$ responses to intermittent swimming sets at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 30(5):543-553
- Millet GP, Candau R, Fattori P, Bignet F, Varray A (2003) $\dot{V}O_2$ responses to different intermittent runs at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 28:410-423
- Pessôa Filho D, Alves F, Reis J, Greco, C, Denadai, B (2012) $\dot{V}O_2$ kinetics during heavy and severe exercise in swimming. *Int J Sports Med* 33(09):744-748.
- Ramos CA, Reis JF, Almeida T, Alves F, Wolterbeek HT, Almeida SM (2015) Estimating the inhaled dose of pollutants during indoor physical activity. *Sci Total Environ* 527-528:111-118
- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012a) Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *Eur J Appl Physiol* 112(5):1689-1697
- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012b) Oxygen uptake kinetics and middle distance swimming performance. *J Sci Med Sport* 15:58-63
- Reis J, Millet GP, Bruno P, Vleck V, Alves F (2017) Sex and exercise intensity do not influence oxygen uptake kinetics in submaximal swimming. *Front Physio* 8:72
- Reis J, Millet GP, Malatesta D, Roels B, Borrani F, Vleck V, Alves F (2010) Are oxygen uptake kinetics modified when using a respiratory snorkel? *Int J Sports Physiol Perform* 5(3):292-300.
- Ribeiro J, Figueiredo P, Guidetti L, Alves F, Toussaint H, Vilas-Boas JP, Baldari C, Fernandes RJ (2016) AquaTrainer® Snorkel does not Increase Hydrodynamic Drag but Influences Turning Time. *Int J Sports Med* 37(4):324-8

- Rodríguez, FA, Keskinen, KL, Malvela, MT, Keskinen, OP (2003) Oxygen uptake kinetics during free swimming: A pilot study In: Chatard JC (ed) Biomechanics and Medicine in Swimming IX, Publications de l'Université de Saint-Étienne, Saint-Étienne, pp 379-384
- Scheuermann B, Hoelting B, Noble M, Barstow T (2001) The slow component of O₂ uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. *J Physiol* 531(1):245-256
- Sousa A, Figueiredo P, Oliveira N, Oliveira J, Silva A, Keskinen KL, Rodríguez FA, Machado L, Vilas-Boas JP, Fernandes R (2011) $\dot{V}O_2$ Kinetics in 200-m race-pace front crawl swimming. *Int J Sports Med* 32(10):765-770
- Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190
- Sousa A, Vilas-Boas J, Fernandes R (2014) $\dot{V}O_2$ kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at $\dot{V}O_{2max}$. *Biomed Res Int* 2014:675363
- Zacca R, Azevedo R, Silveira RP, Vilas-Boas JP, Pyne DB, de S. Castro FA, Fernandes RJ (2019) Comparison of incremental intermittent and time trial testing in age-group swimmers. *J Strength Cond Res* 33(3):801-810
- Jones AM, Poole DC (2005) Introduction to oxygen uptake kinetics and historical development of the discipline. In: Jones AM, Poole DC (Eds), *Oxygen uptake kinetics in sport, exercise and medicine*. Routledge, London, pp 3-37
- Özyener F, Rossiter HB, Ward SA, Whipp BJ (2001) Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. *J Physiol* 533(3):891-902

Chapter IV. Study 1

$\dot{V}O_2$ kinetics and energy contribution in simulated maximal performance during short and middle distance-trials in swimming

Abstract

Purpose: This study aims to analyse swimmers' oxygen uptake kinetics ($\dot{V}O_2K$) and bioenergetic profiles in 50, 100 and 200 meters simulated swimming events and determine which physiological variables relates with performance.

Methods: Twenty-eight well trained swimmers completed a discontinuous incremental test for maximal oxygen uptake (Peak- $\dot{V}O_2$) and maximal aerobic velocity (MAV) assessment. In complementary days, maximal trials (MT) of 50, 100 and 200 meters were performed for $\dot{V}O_2K$ and bioenergetic profile. $\dot{V}O_2K$ parameters were calculated through monoexponential modelling and by a new growth rate method (averaging the time derivatives of $\dot{V}O_2$ between the 20th and the 30th seconds of exercise), given the shorter duration of the MT's. The recovery phase was used along with the blood lactate concentration for bioenergetics profiling. A breath-by-breath apparatus (K4b², Cosmed, Italy) connected to a swimming snorkel was used for gas sampling.

Results: Peak- $\dot{V}O_2$ did not differ from $\dot{V}O_{2peak}$ attained at the 200-MT for female and at the 100 and 200-MT for male group. From the 50 to the 200-MT the $\dot{V}O_2K$ presented a slower response and higher amplitudes, while the aerobic participation increased and the anaerobic decreased, presenting a cross-over in the 100-MT. Both energy systems, MAV, Peak- $\dot{V}O_2$, and $\dot{V}O_2$ peak of the MT's presented correlations with swimming performance.

Conclusion: The fast $\dot{V}O_2K$ response during short MT's suggested that oxidative signalization is not constrained to the amount and type of metabolic demand upon muscle activation for both sexes. Furthermore, the need to focus both anaerobic and aerobic systems training for supramaximal performances is emphasized.

Key words: Oxygen uptake kinetics; Maximal trials; Swimming; Energy system contribution; $\dot{V}O_2$ growth rate

Introduction

The evaluation of oxygen uptake kinetics ($\dot{V}O_2K$) is an important aspect of human performance, allowing a better understanding of the human bioenergetics (Jones and Burnley, 2009). According to Hughson (2009), the study of $\dot{V}O_2K$ is based on the description of the dynamic response of oxygen consumption by muscle cells, which is generated throughout the onset of exercise and involves a complex coordination between neuromuscular, cardiovascular and respiratory systems. Several studies in cycling, running, rowing and swimming exercises have associated faster $\dot{V}O_2K$ with improved fitness status and, consequently, to better sports performance (Burnley and Jones, 2007; Ingham et al., 2007; Jones and Burnley, 2009; Koppo et al., 2004; Reis et al., 2012a).

In swimming, the environment can influence the typical response of $\dot{V}O_2$, due to the external conditions that generate different scenarios at metabolic and biomechanical levels (Sousa et al., 2017). Factors such as the horizontal position of the body inducing greater hydrostatic pressure and reduced blood flow and muscle perfusion, the requirement of a lower muscle mass with predominance of upper limbs in exercise (which involve a greater relative percentage of "fast" fibers than the lower limbs) and the conditions of the aquatic environment with "diving bradycardia" evidence, may slow the $\dot{V}O_2K$ response (Bentley et al., 2005; Ceretelli et al., 1979; Schneider et al., 2002; Sousa et al., 2017). However, other studies also showed fast $\dot{V}O_2K$ in well-trained swimmers, probably due to specific adaptations (Bentley et al., 2005; Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012a, b; Sousa et al., 2013).

Several studies in swimming reported that the $\dot{V}O_2K$ remains remarkably constant as the intensity increases (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012b, 2017; Sousa et al., 2014). Conversely, other studies performed at maximal velocities (individual pacing strategies allowed) showed an acceleration of the $\dot{V}O_2K$ in exercises with higher intensities (Rodríguez et al., 2003; Sousa et al., 2013).

It is well known that the three energetic systems contribute in all exercise intensities, even though each system could be best suited to provide energy for each stimulus (Rodríguez and Mader, 2011). Therefore, all energy systems play a significant role in the determination of performance, especially in high intensity exercises. For example, it is suggested that a maximal exercise effort of 75 seconds results in an equal amount of energy produced by the aerobic and anaerobic energy systems (Gastin, 2001).

In swimming, although some recent studies have analysed the energetic contributions and $\dot{V}O_2K$ in severe and extreme domains (Campos et al., 2017; Ribeiro et al., 2015; Rodríguez et al., 2003 and 2016; Sousa et al., 2013 and 2014), the majority of studies focus mainly on submaximal transitions, although ~86% of indoor swimming events are performed at maximal or supramaximal intensities. Furthermore, few studies analysed female swimmers, or compared the differences between sexes, which can influence the physiological responses in different swimming distances (Reis et al., 2017; Rodríguez et al., 2003 and 2016).

The aim of this study was to analyse the energy system contribution and the $\dot{V}O_2K$ response at supramaximal swimming intensities, using simulated competition events of 50, 100 and 200 meters. We also wanted to determine which metabolic and cardiopulmonary variables are related with short and middle-distance swimming performance. We hypothesise that: 1) swimmers will present faster $\dot{V}O_2K$ and lower $\dot{V}O_{2peak}$ values as the distance becomes shorter and the exercise more intense; 2) swimming performance will be associated with faster $\dot{V}O_2K$, higher $\dot{V}O_{2peak}$'s and greater aerobic contributions; 3) higher anaerobic contributions will be associated with short distance performance and 4) both sexes will show similar $\dot{V}O_2K$ and bioenergetics profiles.

Methods

Participants

Twenty-eight well trained swimmers, 14 males and 14 females, gave their written informed consent to participate in the study (or their legal guardians when they were under 18 years old). Participants were instructed to avoid strenuous exercise in the 24 hours before each test session, to attend well hydrated and to abstain from caffeine and alcohol consumption 24 hours before each testing session. All participants had regularly competed in state and national championships, at least in the 3 years' period prior entering this study. Furthermore, all swimmers were fully familiarized with the equipment and with the test procedures that were used in the study prior to the beginning of the test sessions. The study was approved by the local University Ethical Committee (CEFMH: 39/2015) and conducted in accordance with the 1964 Declaration of Helsinki (Harriss et al., 2017). Anthropometrical data and swimmers personal best competition times (PB: obtained at official competitions in the last 3 months before the beginning of the test sessions) in the 50, 100 and 200 meters events (PB50, PB100 and PB200, respectively) are presented in Table 4.

Table 4. Mean \pm SD of the anthropometrical data and personal best times in competition of the swimmers N = 28 (14 F, 14 M)

Variable	Female	Male
Age (years)	15.6 \pm 2.6	16.6 \pm 1.8
Height (cm)	163.4 \pm 6.7	178.5 \pm 8.1
Total Body Mass (kg)	56.0 \pm 6.7	70.5 \pm 9.9
Body Fat (%)	22.5 \pm 4.1	12.2 \pm 2.8
PB50 (s)	29.6 \pm 1.5	25.2 \pm 1.4
PB100 (s)	65.4 \pm 3.5	55.7 \pm 3.2
PB200 (s)	138.6 \pm 7.0	121.2 \pm 6.0

PB50, PB100 and PB200: personal bests of the swimmers, respectively at the 50, 100 and 200 meters freestyle events.

Experimental design

All swimmers performed four swimming tests, separated by at least 48 hours: (1) a discontinuous incremental test; and (2), in randomized order, three maximal trials (MT) of 50, 100 and 200 meters. To minimize the effect of circadian rhythms or differences in prior exercise, the same environmental conditions were applied to all tests, namely time of day (± 2 hours), water temperature ($\sim 28^{\circ}\text{C}$) and relative humidity ($\sim 50\%$). All participants performed the same pre-test warm up protocol.

A telemetric portable breath-by-breath gas analyser (K4b², Cosmed, Italy), connected to the swimmer by a respiratory snorkel and valve system (new-AquaTrainer[®], Cosmed, Italy) was used in all tests in order to measure the respiratory and gas exchange variables for cardiorespiratory analysis (Baldari et al., 2012; Reis et al., 2010). The K4b² was calibrated before each test according to manufacturer's instructions. All tests were performed in front crawl swimming with in-water starts and open turns without underwater gliding.

The heart rate (HR) was recorded telemetrically during exercise with a HR monitor (Polar[®], Finland) coupled to the snorkel and synchronized with the K4b² system. For the blood lactate concentration ($[\text{La}^-]$) analysis (YSI, 2300 STAT, Yellow Springs, USA), capillary blood samples (25 μl) were collected from the earlobe before the start of each test, during the breaks of the discontinuous incremental test and after all tests (at minutes 1, 3, 5 and 7). The rate of perceived exertion (RPE) was also recorded through the Borg's CR-10 scale (Borg, 1990). For the swimming velocity control of the discontinuous incremental test, an underwater visual pacer (Pacer2Swim[®], KulzerTEC, Portugal) was placed along the bottom of the pool. This system, composed by 26 lights that subsequently lit up, gave the swimmers an accurate notion of the correct velocity for each step of the discontinuous incremental test.

The sessions were performed in a 25-meter swimming pool in the beginning of the preparatory period of the second macrocycle of the swimmers competitive season, after a period of two weeks for training adaptation.

Discontinuous incremental test

Firstly, all swimmers performed a discontinuous incremental test composed by 6 sets of 250 meters plus 1 set of 200 meters at maximal intensity, with 30 seconds rest in-between for blood lactate collection (Espada et al., 2015). The velocity of the first repetition was set at 50% of the swimmers 200 meters' velocity and increments of 5 to 10% were imposed in the rest of the repetitions such as the final repetition could be performed at maximal intensity or until swimmers' voluntary exhaustion.

Maximal oxygen uptake (Peak- $\dot{V}O_2$) was recorded as the highest 30 seconds average of the $\dot{V}O_2$ values and maximal aerobic velocity (MAV) was considered as the minimal velocity at which Peak- $\dot{V}O_2$ values were reached (Billat and Koralsztejn, 1996). Both were reached by all swimmers in the last 2 repetitions, with the exception of one swimmer who reached it at the 5th repetition.

Simulated swimming events

In complementary days, and in randomized order, swimmers performed three maximal trials (MT) of 50, 100 and 200 meters. $\dot{V}O_2$ peak ($\dot{V}O_{2peak50}$, $\dot{V}O_{2peak100}$, $\dot{V}O_{2peak200}$, respectively), velocity (v), percentage velocity of MAV (%MAV), oxygen deficit at the onset of exercise ($O_{2InitialDef}$), blood lactate determination ($[La^-]$) and $\dot{V}O_{2K}$ were determined for each distance. The $\dot{V}O_2$ of the recovery phase (8 minutes after the end of the exercise) was also recorded for determination of total expenditure of energy and energy systems contribution. The swimmers were encouraged to give their maximal effort and to complete the distances in the minimal possible time.

Data Analysis

Breath-by-breath $\dot{V}O_2$ data were first cleaned by exclusion of values lying more than three standard deviations from the local mean, for exclusion of outliers caused by abrupt breaths or coughing. For $\dot{V}O_2$ peak determination a 30 seconds moving average of data was used for the incremental and the 200 meters tests

considering the highest value as the peak. For the 100 and 50 meters maximal trials a moving average of 15 and 5 seconds were respectively applied, in order not to influence the results given the shorter duration of these tests.

The $\dot{V}O_2K$ parameters (time delay (TD), time constant (τ), mean response time (MRT = τ + TD) and amplitude (A)) of the maximal trials analysis, were calculated using 1-second values interpolation and monoexponential modelling. Given the nature of these supramaximal efforts, we did not observe the occurrence of a secondary rise on the $\dot{V}O_2$ response (slow component), similarly to other studies (Rodríguez et al., 2003; Sousa et al., 2014). To remove the influence of the cardiodynamic phase on the subsequent $\dot{V}O_2$ response, we chose to remove the first 20 seconds of data from analysis (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012a, b). We also calculated an individual “snorkel delay” (ISD) for each swimmers’ test. The ISD, that corresponds to the difference between the onset of exercise and the time when the following breaths summed up a tidal volume superior to the outlet tube volume, was then integrated into the time delay of the $\dot{V}O_2$ response, as described before by Reis et al. (2012a), adapted to the specific characteristics of the snorkel device used in this study.

$\dot{V}O_2K$ parameters were calculated through an iterative procedure, by minimizing the sum of the mean squares of the differences between the modelled and the measured $\dot{V}O_2$ values. Therefore, we modelled the $\dot{V}O_2$ Kinetics according to the equation (Jones and Poole, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2base} + A \cdot (1 - e^{-(t-TD)/\tau})$$

Where $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest, which was calculated as the average of the first 30 seconds of the last minute before the start of the exercise (after 10 minutes of passive rest); TD, τ , and A, represent the time delay, the time constant (time that is needed to complete 63% of the $\dot{V}O_2$ response) and the amplitude of the exponential response of the $\dot{V}O_2$.

Since we analysed a very short event, with approximately 30 seconds duration (50 meters test), where the $\dot{V}O_2$ response does not have time to clearly stabilize, we chose to apply a secondary treatment of the $\dot{V}O_2$ data, in order to confirm our results. Therefore, we analysed the growth rate of the $\dot{V}O_2$ response ($\Delta\dot{V}O_2/t$) between the 20th (to exclude the cardiodynamic phase) and the 30th second (to allow a comparison between all distances) of exercise, by averaging the time derivatives of $\dot{V}O_2$ between those two points. The procedure was applied for all the distances that were analysed in this study.

Total energy system contribution complied the aerobic (Aer), anaerobic alactic (AnaAlac) and anaerobic lactic (AnaLac) systems participation in each time trial. The aerobic contribution was determined as the time integral of the net $\dot{V}O_2$ during exercise by the trapezoidal method and the results expressed in liters of oxygen (LO₂), as follows:

$$Aer = \int_{t_0}^{t_{Lim}} \dot{V}O_2 \times dt - (\dot{V}O_2b \times t_{Lim})$$

where $\dot{V}O_2b$ is baseline $\dot{V}O_2$ response and t_{Lim} is MT time performance. For the anaerobic alactic system determination a bi-exponential fitting on the $\dot{V}O_2$ data of the 8 minutes of rest after each test was applied, accordingly to Scheuermann et al. (2001):

$$\dot{V}O_{2off}(t) = EE\dot{V}O_2 - A_{1off} [1 - e^{-(t-TD_1/\tau_1)}] - A_{2off} [1 - e^{-(t-TD_2/\tau_2)}]$$

Where $\dot{V}O_{2off}(t)$ represents the relative $\dot{V}O_2$ at a given time; $EE\dot{V}O_2$ is the oxygen uptake at the end of exercise; TD, τ , and A, represent the time delay, the time constant and the amplitude, and 1 and 2 represent the fast and slow component, respectively, of the bi-exponential response of the $\dot{V}O_2$. The product between the time constant and amplitude of the fast component of post-exercise oxygen consumption was considered as the anaerobic alactic contribution expressed in LO₂. Finally, the anaerobic lactic system was determined by the difference between maximal [La⁻] after exercise and resting [La⁻] expressed as a delta value

($\Delta[\text{La}^-]$) (Beneke et al., 2002), considering $3 \text{ mlO}_2 \cdot \text{kg}^{-1}$ as a metabolic equivalent for each $1 \text{ mmol} \cdot \text{l}^{-1}$ of $\Delta[\text{La}^-]$ (di Prampero, 1981).

Statistical Analysis

Normality of data was checked with Shapiro-Wilk test. The independent T-tests were applied to all variables to check the differences in $\dot{V}\text{O}_2\text{K}$ and energy releasing or contribution between sexes for each MT performance. The group differences in $\dot{V}\text{O}_2\text{K}$ and energy releasing or relative contribution between distances were tested for statistical significance using ANOVA for repeated measures with Bonferroni correction. The Pearson's linear correlation coefficient was used in order to establish the significant associations between physiological measures and swimmers performances in short and middle distance events.

Statistical significance was accepted at $p < 0.05$. All statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS, version 25.0, Chicago, IL, USA).

Results

Significant correlations were found between the time for 50, 100 and 200 meters performances and swimmers PB's in competition ($r = 0.86$, $r = 0.83$ and $r = 0.84$, $p < 0.01$, respectively for 50, 100 and 200 meters distances), showing consistency of the simulated swimming events.

A typical response of $\dot{V}\text{O}_2$, is showed in figure 17.

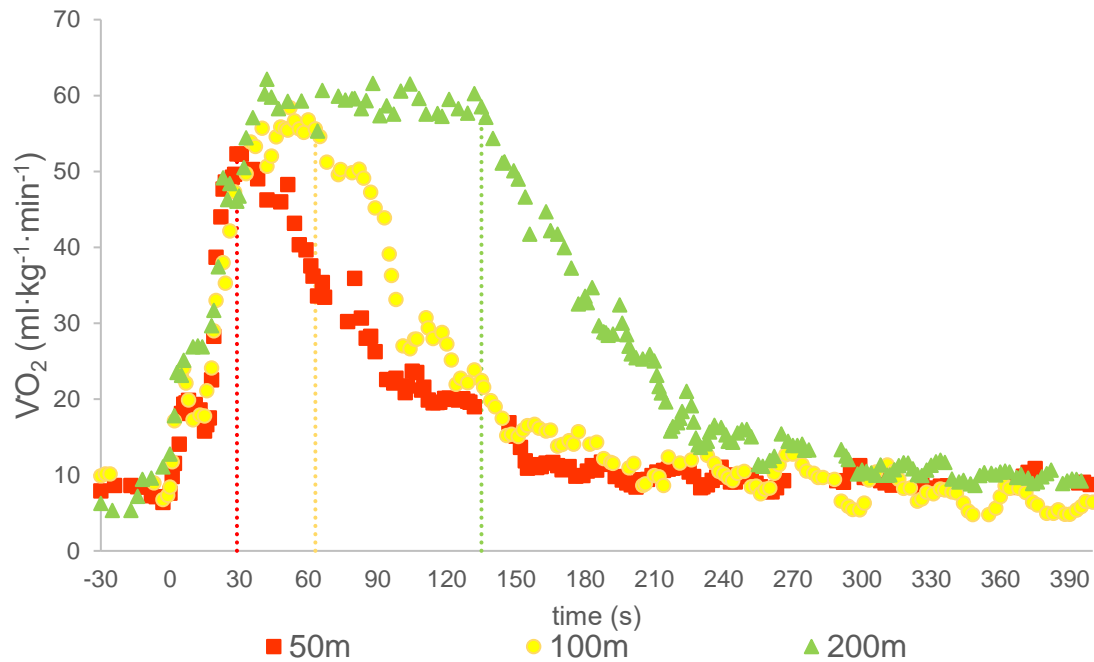


Figure 17. $\dot{V}O_2$ response profiles of the participant n^o 6 at the maximal trials. $\dot{V}O_2$ response profiles of the participant n^o 6 at the 50 (red squares), 100 (yellow circles) and 200 (green triangles) meters maximal trials. End of exercise marked with dashed lines for the 50, 100 and 200 meters tests, respectively.

In the incremental test, absolute and relative Peak- $\dot{V}O_2$, MAV, maximal HR and maximal $[La^-]$ were 4.01 ± 0.39 l·min⁻¹, 57.47 ± 5.7 ml·kg⁻¹·min⁻¹, 1.31 ± 0.07 m·s⁻¹, 180.4 ± 7.8 b·min⁻¹ and 8.63 ± 3.6 mmol·l⁻¹, respectively for male and 2.98 ± 0.25 l·min⁻¹, 53.53 ± 4.21 ml·kg⁻¹·min⁻¹, 1.20 ± 0.07 m·s⁻¹, 191.3 ± 8.4 b·min⁻¹ and 9.12 ± 2.9 mmol·l⁻¹, respectively for female swimmers.

The $\dot{V}O_{2K}$ parameters of the maximal trials are described in table 5. Male swimmers presented higher absolute and relative $\dot{V}O_{2peak}$ in all maximal tests. The Peak- $\dot{V}O_2$ was significantly different from the $\dot{V}O_{2peak50}$, but not from the $\dot{V}O_{2peak100}$ or $\dot{V}O_{2peak200}$, in the male group, and from the $\dot{V}O_{2peak50}$ and the $\dot{V}O_{2peak100}$, in the female group. MAV was significantly lower than the 50 and 100 meters tests velocity but did not show significant differences with the 200 meters test velocity, for both sexes. Although we observed statistical differences in the velocity of each test between sexes, the relative velocities to MAV were similar between groups.

The time delay and amplitude did not present any significant differences between distances with the exception of the amplitude of the 50 meters test that was lower than the remaining tests. However, the time constant was reduced as the exercise became shorter and more intense. The same profile occurred with MRT with significant differences between the 100 and the 200 meters tests. The growth rate showed an inverse profile with the time constant, declining as the distances became higher and the exercise less intense. Although with similar profiles at both sexes, male swimmers showed higher rates of $\dot{V}O_2$ response.

Oxygen deficit at the onset of exercise of the maximal trials showed significant differences between the three maximal tests, rising as the distance becomes longer. The rate of perceived exertion was significantly lower at the 50 meters test, with no differences observed between the 100 and 200 meters tests.

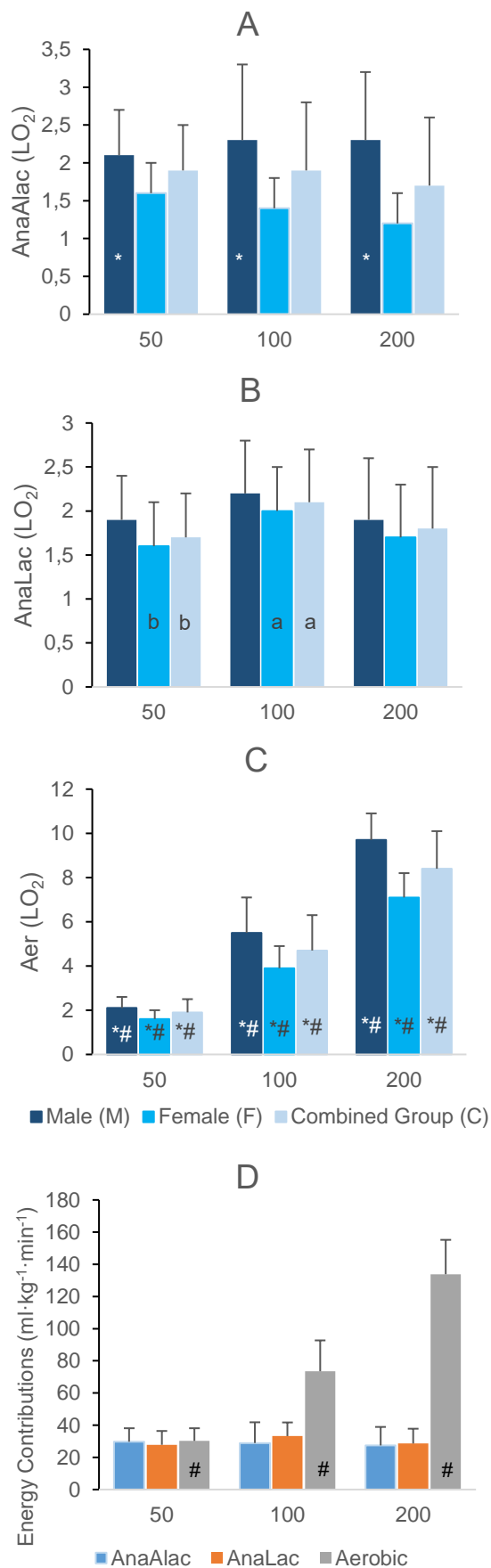
Absolute Peak- $\dot{V}O_{2peak}$ and MAV were significantly correlated with swimmers performance at PB50 ($r = -0.81$ and $r = -0.70$, $p < 0.01$), PB100 ($r = -0.82$ and $r = -0.77$, $p < 0.01$) and PB200 ($r = -0.75$ and $r = -0.75$, $p < 0.01$), respectively. Also, the $\dot{V}O_{2peak}$ of each maximal test was correlated with the swimmers PB's at the corresponding distances ($r = -0.82$, $r = -0.84$, and $r = -0.76$, $p < 0.01$, for the 50, 100 and 200 meters tests, respectively), as well as the amplitude of the primary phase at the 50 and 100 meters tests ($r = -0.39$, $p < 0.05$ and $r = -0.58$, $p < 0.01$, respectively).

The time constant of the 50 and 200 meters tests was correlated with the percentage to Peak- $\dot{V}O_2$ achieved in the corresponding tests ($r = -0.53$, $p < 0.01$ and $r = -0.41$, $p < 0.05$), being the time constant of the 200 meters test also correlated with the percentage to MAV ($r = 0.70$, $p < 0.01$) and $O_{2InitialDef}$ ($r = 0.76$, $p < 0.01$) of this test. Both the MRT and the $O_{2InitialDef}$ were correlated between the 50 and the 100 meters tests ($r = 0.44$, $p < 0.05$ and $r = 0.49$, $p < 0.01$, respectively) and between the 100 and 200m tests ($r = 0.49$ and $r = 0.59$, $p < 0.01$, respectively).

Table 5. Mean \pm SD of the $\dot{V}O_2$ on and off-kinetics and physiological parameters of the swimmers at the maximal trials.

Variable	50 meters MT			100 meters MT			200 meters MT		
	Male	Female	Combined	Male	Female	Combined	Male	Female	Combined
A (ml·kg ⁻¹ ·min ⁻¹)	45.8 \pm 6.9*	38.3 \pm 4.0c	42.1 \pm 6.8bc	48.3 \pm 6.2*	41.1 \pm 4.6	44.7 \pm 6.5a	48.5 \pm 5.8	42.4 \pm 4.8a	44.7 \pm 6.2a
TD (s)	11.3 \pm 3.8	12.0 \pm 3.6	11.7 \pm 3.7	9.3 \pm 4.5	11.8 \pm 3.4	10.5 \pm 4.2	10.4 \pm 3.2	11.1 \pm 4.5	10.7 \pm 4.0
τ (s)	8.1 \pm 2.1bc	9.1 \pm 2.4bc	8.6 \pm 2.3bc	11.2 \pm 2.2ac	11.7 \pm 2.2ac	11.5 \pm 2.4ac	17.0 \pm 6.4ab	16.4 \pm 4.5ab	16.7 \pm 5.5ab
MRT (s)	19.4 \pm 4.9c	21.3 \pm 4.9c	20.3 \pm 4.2c	20.6 \pm 4.1c	23.4 \pm 4.1c	22.0 \pm 4.2c	27.3 \pm 8.4ab	27.5 \pm 8.4ab	27.4 \pm 7.5ab
$\Delta\dot{V}O_2/t$ (ml·kg ⁻¹ ·min ⁻¹ ·s ⁻¹)	2.2 \pm 0.4*c	2.1 \pm 0.5bc	2.1 \pm 0.4bc	1.9 \pm 0.5ac	1.7 \pm 0.3ac	1.8 \pm 0.4ac	1.2 \pm 0.3ab	1.3 \pm 0.4ab	1.3 \pm 0.3ab
$\dot{V}O_{2peak}$ (l·min ⁻¹)	3.5 \pm 0.4*bc	2.3 \pm 0.3bc	2.9 \pm 0.6bc	3.9 \pm 0.4*a	2.8 \pm 0.3a	3.3 \pm 0.7ac	4.0 \pm 0.4*a	2.9 \pm 0.3a	3.5 \pm 0.6ab
$\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	49.5 \pm 4.7*bc	41.9 \pm 4.1bc	45.7 \pm 5.8bc	55.6 \pm 5.9*a	49.8 \pm 5.0a	52.7 \pm 6.2ac	57.7 \pm 6.3*a	52.5 \pm 4.2a	55.1 \pm 5.9ab
%Peak- $\dot{V}O_2$ (%)	86.6 \pm 8.4*bc	78.3 \pm 6.0bc	82.5 \pm 8.4bc	96.8 \pm 4.0*bc	93.1 \pm 5.1bc	94.9 \pm 5.0ac	100.4 \pm 3.8bc	98.2 \pm 3.5bc	99.3 \pm 3.8ab
v (m·s ⁻¹)	1.7 \pm 0.1*bc	1.5 \pm 0.1bc	1.6 \pm 0.1bc	1.5 \pm 0.1*ac	1.3 \pm 0.1ac	1.4 \pm 0.1ac	1.3 \pm 0.1*ab	1.2 \pm 0.1ab	1.3 \pm 0.1ab
%MAV (%)	128.0 \pm 10.2bc	121.8 \pm 6.5bc	124.8 \pm 9.1bc	114.6 \pm 6.9ac	111.6 \pm 5.2ac	113.1 \pm 6.3ac	102.9 \pm 2.6ab	102.2 \pm 2.4ab	102.6 \pm 2.5ab
Peak HR (b·min ⁻¹)	167.3 \pm 5.8bc	168.0 \pm 9.5bc	167.9 \pm 9.1bc	173.6 \pm 8.1a	174.1 \pm 7.1a	173.8 \pm 7.9a	172.5 \pm 7.3a	177.5 \pm 5.8a	175.1 \pm 7.1a
Peak [La ⁻¹] (mmol·l ⁻¹)	9.8 \pm 2.6	9.8 \pm 3.1	9.8 \pm 2.9	12.0 \pm 3.1	12.2 \pm 2.9	12.1 \pm 3.0	10.1 \pm 3.1	11.0 \pm 3.7	10.5 \pm 3.5
RPE (0 - 10 units)	6.4 \pm 2.2bc	7.1 \pm 1.7bc	6.8 \pm 2.0bc	8.4 \pm 1.4a	8.4 \pm 1.3a	8.4 \pm 1.4a	8.4 \pm 1.8a	9.2 \pm 0.9a	8.8 \pm 1.5a
O _{2InitialDef} (l)	0.9 \pm 0.2c	0.8 \pm 0.2c	0.9 \pm 0.2bc	1.0 \pm 0.3	1.0 \pm 0.2c	1.0 \pm 0.2ac	1.3 \pm 0.4*a	1.18 \pm 0.4ab	1.2 \pm 0.4ab
A ₁ off-K (l·min ⁻¹)	2.2 \pm 0.7*	1.7 \pm 0.4	1.9 \pm 0.6	2.6 \pm 0.8*	1.6 \pm 0.6	2.1 \pm 0.9	2.3 \pm 0.7*	1.5 \pm 0.7	1.8 \pm 0.8
A ₁ off-K (m·kg ⁻¹ ·min ⁻¹)	31.2 \pm 9.8	30.2 \pm 10.4	30.7 \pm 10.1	37.1 \pm 13.3	28.1 \pm 11.1	33.0 \pm 13.2	31.8 \pm 8.3	28.4 \pm 15.7	30.0 \pm 12.9
τ_1 off-K (s)	57.4 \pm 10.4	61.1 \pm 11.8	59.2 \pm 11.3	55.4 \pm 19.2	55.0 \pm 13.9	55.2 \pm 17.0	54.1 \pm 16.9	53.3 \pm 19.9	53.6 \pm 18.6

*: differences between sexes for the same test ($p < 0.05$); a, b and c: statistical differences with the 50, 100 and 200 meters tests, respectively, for the same sex ($p < 0.05$); A, TD and τ : amplitude, time delay and time constant of the $\dot{V}O_2K$; MRT: mean response time; $\Delta\dot{V}O_2/t$: growth rate of the $\dot{V}O_2$ response between the 20th and the 30th seconds of exercise; $\dot{V}O_{2peak}$: absolute and corrected to body mass $\dot{V}O_2$ maximal values of the MT; %Peak- $\dot{V}O_2$: percentage of $\dot{V}O_2$ to Peak- $\dot{V}O_2$; v: velocity; %MAV: percentage of velocity to MAV; Peak HR and Peak [La⁻¹]: maximal HR and blood lactate concentration of the MT; O_{initialDef}: oxygen deficit at the onset of the exercise; A₁ off-K and τ_1 off-K: amplitude and time constant of the fast component of the recovery phase.



The energy system contributions for the maximal tests are shown in figure 18. Both sexes showed a similar profile between the 3 distances. Even though male swimmers showed higher absolute values of the anaerobic alactic and aerobic systems, these differences did not exist when relative values for body weight were considered (panel D). The anaerobic alactic system contribution was not different between distances. This system contribution was significantly correlated with the swimmers PB's in the 50 and 200 meters distances ($r = -0.52$ and $r = -0.61$, $p < 0.01$, respectively). The anaerobic lactic system contribution was higher in the 100 meters test, showing significant differences only with the 50 meters test. The aerobic contribution significantly increased as the distance became longer (~19.7 and 36.3% between the 50 meters test to the 100 and to the 200 meters tests, respectively). Swimmers PB's at the 50, 100 and 200 meters distances were correlated with the aerobic contribution ($r = -0.44$, $p < 0.05$, $r = -0.52$, $p < 0.01$, and $r = -0.66$, $p < 0.01$, respectively).

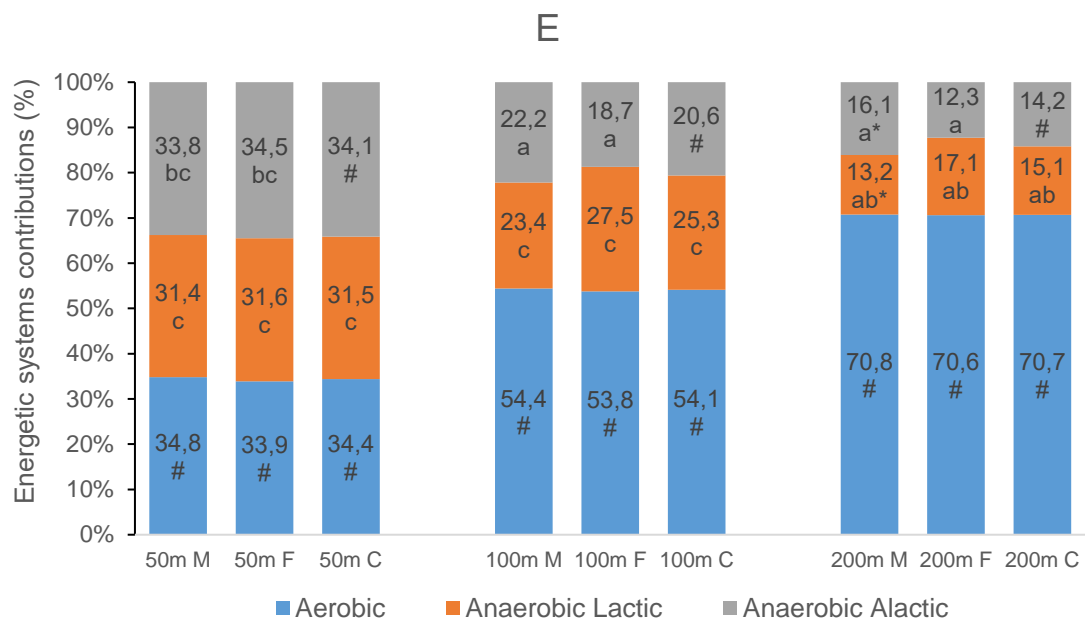


Figure 18. Energy systems contributions of the 50, 100 and 200 meters tests. Anaerobic Alactic (panel A), Anaerobic Lactic (Panel B) and Aerobic (panel C); values corrected for body weight of the combined group (panel D); Relative contributions for the total expenditure energy (panel E). *: Differences between sexes; #: Statistical differences among the 3 distances; a, b and c: statistical differences to the 50, 100 and 200 meters tests, respectively.

The total anaerobic contribution showed negative correlations with all PB's ($r = -0.55, p < 0.01$, $r = -0.43, p < 0.05$, and $r = -0.51, p < 0.01$, for the 50, 100 and 200 meters, respectively), similarly to the total energy expenditure ($r = -0.53, p < 0.01$, $r = -0.49, p < 0.05$, and $r = -0.66, p < 0.01$ for the 50, 100 and 200 meters, respectively).

Discussion

The aim of our study was to analyse the energy system contribution and the oxygen uptake response at supramaximal swimming intensities, seeking to understand if physiological variables are related with short and middle-distance swimming performance. Even though the literature has already studied the $\dot{V}O_2K$ and bioenergetics in swimming in different exercise domains, most of the studies

focus on intensities that do not correspond to those found in competitive swimming, or were performed at constant load velocities, not reflecting the specific pacing strategies used in competition. In order to provide a better understanding of the changes of bioenergetics and $\dot{V}O_2$ response on the spectrum of the competitive swimming distances, the present study analysed maximal trials performances in 50, 100 and 200 meters swimming events. To the best of our knowledge, this is the first study approaching energy requirements from $\dot{V}O_2$ “on” and “off” response comparing three competitive swimming distances performed by different sexes.

The main findings of our study are: (1) both $\dot{V}O_{2K}$ and $\dot{V}O_{2peak}$ were significantly different among the three distances in study, showing a slower $\dot{V}O_2$ response with a higher uptake as the distance becomes longer and the exercise less intense; (2) swimming performance was not related with faster $\dot{V}O_{2K}$, but it was correlated with higher $\dot{V}O_{2peak}$'s, and aerobic contribution in all distances; (3) the anaerobic contribution showed the highest correlation with the shorter distance in our study, despite being significantly correlated with all distances, highlighting the importance for short and middle distance performance; (4) finally, even though male swimmers had higher $\dot{V}O_{2peak}$'s and absolute values for the metabolic contributions, we observed that the differences at the response profile between distances were similar between sexes, with the exception of the 100-MT where the male group trend to reach the Peak- $\dot{V}O_2$. Also, no differences were registered between sexes for the TD's or time constants and for relative values or energy contributions during all MT's.

The strong correlations found between the maximal tests and swimmers PB's, demonstrate the representativeness of the analysis. The correlations found between swimmers performances with the absolute Peak- $\dot{V}O_2$, MAV, $\dot{V}O_{2peak}$'s and amplitudes of the primary phase of the maximal tests, seem to suggest these variables as the best predictors of performance in 50, 100 and 200 meters freestyle swimming events, as it was found in other studies for the 400 and 800m performances (Espada et al., 2015; Reis et al., 2012b).

Regarding the $\dot{V}O_2K$ parameters, TD and amplitude showed similar values between tests, with the exception of the amplitude at the 50 meters test that was significantly lower. On the other hand, the time constant was significantly different between all distances, decreasing as the exercise becomes shorter and more intense. It could suggest that both the rate of O_2 deliver to muscle and mitochondrial phosphorylation had different adjustments over time in order to match target aerobic energy requirements along the different MT's (Whipp and Rossiter, 2005).

These differences found at $\dot{V}O_2K$ contradicts several comparative studies where the time constant remained unchanged between intensities: around the maximal lactate steady state (Espada et al., 2015); between heavy and severe domains (Pessôa Filho et al., 2012; Reis et al., 2012b); or at intensities around the MAV (Sousa et al., 2014). Conversely, our results are in accordance with other studies which analysed maximal velocities without imposed pacing strategies, in swimming (Rodríguez et al., 2003, Sousa et al., 2013), cycling (Hettinga et al., 2009), or running (Carter et al., 2006).

In fact, in the first $\dot{V}O_2K$ study focused on simulated swimming events, Rodríguez et al. (2003) reported significant differences on the time constant between the 100 and 400 meters distances (22.7 vs. 27.9s for men and 23.1 vs. 30.6s for women, respectively). Also, Sousa et al. (2013) reported that the $\dot{V}O_2K$ was slower in moderate than in maximal velocity, in a 200 meters test, suggesting that, since the time constant describes the adaptation of the cardiovascular and muscular systems, the sudden and exponential need of $\dot{V}O_2$ in the maximal test could be able to explain the lower values of this parameter. Our results are in line with these studies contributing for the thesis that the $\dot{V}O_2K$, at supramaximal intensities or when tests are performed in a time trial mode, are faster than in lower exercise intensities.

Jones et al. (2008) demonstrated that in a fast-start strategy the $\dot{V}O_2$ truly increased more rapidly towards its peak, which justifies the highest $\dot{V}O_2$ in the first 120 seconds of the exercise and extended times to exhaustion, when

compared with the even-pace strategy or with the slow-start strategy. Overall, it is possible to conclude that a fast-start pacing strategy might actually enhance the exercise tolerance, since it increases the oxidative contribution to the energy turnover and therefore spares some of the anaerobic capacity across the transition to higher intensity exercises.

Hence, the fast $\dot{V}O_2$ response reported in the present study, with time constant values between ~8 and 17 seconds, are in line with other studies performed in terrestrial environments (Carter et al., 2006; Hettinga et al., 2009) contradicting those who predict lower kinetics in swimming due to the constraints of the aquatical environment and the nature of the exercise (Sousa et al., 2017). As a matter of fact, our results are in line with recent studies that showed fast kinetics in well trained swimmers (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012a, b and 2017; Ribeiro et al., 2015; Rodríguez et al., 2016; Sousa et al., 2011 and 2013). These fast kinetics and the statistical differences observed in the three studied swimming distances, could be explained by a fast start strategy that induces a rapid increase in the oxidative contribution to exercise (Jones et al., 2008), also observed in cycling (Hettinga et al., 2009) in all-out sets.

Also, the correlations found at the MRT and the $O_{2\text{initialDef}}$ between the 50 and the 100 meters tests, demonstrate that the swimmers with fast kinetics and with lower O_2 initial deficits in one distance, also showed better results in the other distance. The fact that this relation repeats between the 100 and 200 meters tests, but not between the 50 and the 200 meters tests supports the idea that a closely physiological relation could be found in the 50/100 and 100/200 distances, existing a separation in the efforts' physiological logic. That could explain why the majority of swimmers specialized in the 50 meters distance usually also swim the 100 but not the 200 meters distance and, on the other hand, swimmers that are specialized in the 200 could also swim the 100 meters, but not (usually) the 50 meters distance.

Regarding the energy system contribution, we observed an increase of the relative aerobic contribution while the anaerobic follows an opposite direction

from the 50 to the 200 meters tests. Even though male swimmers present higher absolute values at the aerobic and anaerobic alactic systems, probably caused by the higher $\dot{V}O_2$'s achieved during the MT's, a similar profile between groups was observed when relative values for the total energy expenditure was considered.

In line with the energy metabolism interplay suggested for Gastein (2001), and reported also for swimming by Holmér (1979), Toussaint and Hollander (1994) and Rodríguez and Mader (2011), the anaerobic alactic releasing reaches its maximal contribution during the first ~30 seconds in trials performed maximally, as observed in the present study for all MT's. Correlations with swimmers' performances in the 50 and 200 meters tests showed the anaerobic alactic system relevance both in the shorter and the longer distance. On the other hand, the anaerobic lactic system reached its maximal value in the 100 meters test, only with significant differences to the 50 meters test. Considering the total anaerobic contribution, both sexes presented a remarkable similar response, with no significant differences between distances.

The present study highlights the higher supply, in terms of the absolute values, of the alactic and aerobic energy for men than for women for all trials, despite lactic energy supply did not differ between sexes and distances. However, when values were corrected for body mass values, no differences between sexes are observed.

Although we observed the highest correlation of the anaerobic system with the 50 meters test and of the aerobic system with the 200 meters test, both systems were related with swimmers' performances in all distances, showing that both contribute significantly to their swimming performance and should be carefully included in the training routines, especially, when training for the 100 meters freestyle event, where both systems have similar relative contributions.

Campos et al. (2017) using backward extrapolation, concluded that the contribution of the anaerobic system influences swimming performances up to

the 400 meters' distance, corroborating the findings of our study. However, they found a significant increase in the anaerobic alactic contribution between the 50 to the 100 and to the 200 meters distances, contradicting our findings, where this value stayed constant. Maybe, the methodological differences regarding alactic assessment account to the lack of similarities between alactic contributions in both studies, despite the present results being better aligned with theoretical assumptions for alactic energy supply during trials performed maximally.

The observed aerobic energy contributions are also aligned with other studies in swimming. For the maximal performance in 100 (Hellard et al., 2018, Ribeiro et al., 2015) and 200 meters distances (Sousa et al., 2011), a significant increase of aerobic energy releasing has been reported as the distance increases and velocity decreases. Such profile for aerobic energy contribution was replicated for other swimming circumstances around the MAV (Sousa et al., 2014) and running (Spencer and Gastin, 2001). In this last study the authors highlight the significant and greater participation that is traditionally accepted of the aerobic contribution in the 30 seconds time period especially for the 400-1500 meters running events, corroborating our results.

The change in predominance between energetic systems interplay was evident at 75 seconds of maximal exercise performance, as suggested by Gastin (2001). Such change was also observed in the present study, which is evidenced for 100 meters performance lasting about ~71s and showing anaerobic (~46%) and aerobic (~54%) with contributions close to 50%. Furthermore, our findings seem to corroborate the Rodríguez and Mader's (2011) schematization of the relative energy systems contributions for swimming, even though our results showed small higher aerobic contributions in the 50 meters and 200 meters tests, probably due to the longer exercise times observed in our study (when compared with swimming without the snorkel). In this study, the authors only presented values for male swimmers assuming that there should be no differences with female swimmers. Based in our results, we can suggest that their assumption is correct since we did not find differences between sexes at the relative contribution of the total anaerobic or aerobic systems.

The main limitation of this study relates to the 50 meters test $\dot{V}O_2K$'s analysis, since, due to its short duration, a typical $\dot{V}O_2$ monoexponential modeling is challenging. However, the use of the growth rate, seems to corroborate the data. Also, the inexistence of $\dot{V}O_2K$ studies for this distance cannot provide a direct comparison, despite that, similar values of the time constant and amplitude were found in running (Draper and Wood, 2005), or even faster in cycling (Hettinga et al., 2009).

This work also provides important information to coaches, since the understanding of the bioenergetics and $\dot{V}O_2$ response could help them to plan training sessions as well as to establish new strategies in order to increase swimmers' performance. Therefore, according to our findings we recommend that:

- The aerobic power should have an important role on the training programs in order to increase the individual's Peak- $\dot{V}O_2$, that is highly related with short and middle-distance swimming performance;
- Even when training exclusively for a 50 meters event, the aerobic system seems to have an important role since it represents ~34% of the effort, and on the other hand, the anaerobic system should not be neglected even when training for the 200 meters distance (~29% of participation effort);
- Tasks that elicit a rapid increase of the oxidative system should be implemented (e.g., high-intensity interval training), since fast kinetics allows to achieve higher $\dot{V}O_2$'s with lower $O_{2InitialDef}$.

In conclusion, the results suggest that the $\dot{V}O_2$ kinetics are slower in longer distances where the intensities are naturally lower which can be partially explained by a rapid increased of the oxidative contribution to the energy turnover promoted by the faster initial pacing strategies usually used in the shorter distances. The fast kinetics found, even though the Peak- $\dot{V}O_2$ in the female group was reached only in the 200 meters test, allowed that near maximal values of the $\dot{V}O_2$ (~95% for the combined group) can actually be reached within ~1 minute of strenuous exercise, as it was seen in the 100 meters test. A closely physiological

logic between the efforts of the 50/100 meters distances and between the 100/200 meters distances seemed to be found, which could explain why swimmers, usually, choose these distinct sets of competition events separately. Both energetic systems have an important role when training for the distances considered in our study, since they were significantly related with the performances in competition. Finally, the few differences found between sexes, when relative values are considered, in accordance to a previous study from our research group (Reis et al. 2017), suggest that the adaptations in training protocols can be applied both in male and female swimmers.

References of chapter IV

- Baldari C, Fernandes R, Meucci M, Ribeiro J, Vilas-Boas JP, Guidetti L (2012) Is the new aquatrainer® snorkel valid for $\dot{V}O_2$ assessment in swimming? *Int J Sports Med* 34(04):336-344
- Beneke R, Pollmann C, Bleif I, Leithäuser RM, Hütler M (2002) How anaerobic is the wingate anaerobic test for humans? *Eur J Appl Physiol* 87:338-392
- Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP (2005) Physiological responses during submaximal interval swimming training: effects of interval duration. *J Sci Med Sport* 8:392-402
- Billat V, Koralsztein JP (1996) Significance of the velocity at $\dot{V}O_{2max}$ and time to exhaustion at this velocity. *Sports Med.* 22(2):90-108
- Borg G (1990) Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* 16(1):55-58
- Burnley M, Jones A (2007) Oxygen uptake kinetics as a determinant of sports performance. *Eur J Sport Sci* 7(2):63-79
- Campos EZ, Kalva-Filho C, Gobbi R, Barbieri R, Almeida NP, Papoti M (2017) Anaerobic contribution determined in swimming distances: Relation with performance. *Front Physiol* 8:1-6
- Carter H, Pringle JS, Barstow TJ, Doust JH (2006) Oxygen uptake kinetics during supra $\dot{V}O_{2max}$ treadmill running in humans. *Int J Sports Med* 27(2):149-157
- Cerretelli P, Pendergast D, Paganelli W, Rennie, D (1979) Effects of specific muscle training on $\dot{V}O_2$ on-response and early blood lactate. *J Appl Physiol Respir Environ Exerc Physiol* 47(4):761-769
- di Prampero PE (1981) Energetics of muscular exercise. *Rev Physiol Biochem Pharmacol* 89:143-222
- Draper SB, Wood DM (2005) The $\dot{V}O_2$ response for an exhaustive treadmill run at 800-m pace: a breath-by-breath analysis. *Eur J Appl Physiol* 93(4):381-389
- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843

Gastin PB (2001) Energy system interaction and relative contribution during maximal exercise. *Sports Med* 31(10):725-741

Harriss DJ, Macsween A, Atkinson G (2017) Standards for Ethics in Sport and Exercise Science Research: 2018 Update. *Int J Sports Med* 38:1126-1131

Hellard P, Pla R, Rodríguez FA, Simbana D, Pyne DB (2018) Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *Int J Sports Physiol Perform* 13(8):1011-1120

Hettinga FJ, De Koning JJ, Foster C (2009) $\dot{V}O_2$ response in supramaximal cycling time trial exercise of 750 to 4000m. *Med Sci Sports Exerc* 41(1):230-236

Holmér L (1979) Physiology of swimming man. *Exerc Sport Sci Rev* 7:87-123.

Hughson RL (2009) Oxygen uptake kinetics: historical perspective and future directions. *Appl Physiol Nutr Metab* 34(5):840-850

Ingham SA, Carter H, Whyte G, Doust JH (2007) Comparison of the oxygen uptake kinetics of club and Olympic champion rowers. *Med Sci Sports Exerc* 39(5):865-871

Jones A, Burnley M (2009) Oxygen uptake kinetics: An underappreciated determinant of exercise performance. *Int J Sports Physiol and Perform* 4(4):524-532

Jones A, Wilkerson D, Vanhatalo A, Burnley M (2008) Influence of pacing strategy on O_2 uptake and exercise tolerance. *Scand J Med Sci Sports* 18:615-626

Jones AM, Poole DC (2005) Introduction to oxygen uptake kinetics and historical development of the discipline. In: Jones AM, Poole DC (Eds), *Oxygen uptake kinetics in sport, exercise and medicine*. Routledge, London, pp 3-37

Koppo K, Bouckaert J, Jones A (2004) Effects of training status and exercise intensity on phase II $\dot{V}O_2$ kinetics. *Med Sci Sports Exerc* 36(2):225-232

Pessôa Filho D, Alves F, Reis J, Greco C, Denadai B (2012) $\dot{V}O_2$ kinetics during heavy and severe exercise in swimming. *Int J Sports Med* 33(09):744-748

Reis J, Alves F, Bruno P, Vleck V, Millet G (2012a) Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *Eur J Appl Physiol* 112(5):1689-1697

Reis J, Alves F, Bruno P, Vleck V, Millet G (2012b) Oxygen uptake kinetics and middle distance swimming performance. *J Sci Med Sport* 15:58-63

Reis J, Millet GP, Bruno P, Vleck V, Alves F (2017) Sex and exercise intensity do not influence oxygen uptake kinetics in submaximal swimming. *Front Physio* 8:72

- Reis J, Millet GP, Malatesta D, Roels B, Borrani F, Vleck V, Alves F (2010) Are oxygen uptake kinetics modified when using a respiratory snorkel? *Int J Sports Physiol Perform* 5(3):292-300
- Ribeiro J, Figueiredo P, Sousa A, Monteiro J, Pelarigo J, Vilas-Boas JP, Toussaint HM, Fernandes R (2015) $\dot{V}O_2$ kinetics and metabolic contributions during full and upper body extreme swimming intensity. *Eur J Appl Physiol* 115(5):1117-1124
- Rodríguez F, Lätt E, Jürimäe J, Maestu J, Purge P, Rämson R, Haljaste K, Keskinen K, Jürimäe T (2016) $\dot{V}O_2$ Kinetics in all-out arm stroke, leg kick and whole stroke front crawl 100-m swimming. *Int J Sports Med* 37(3):191-196
- Rodríguez FA, Mader A (2011) Energy systems in swimming. In: Seifert L, Chollet D, Mujika I (eds) *World Book of Swimming: From Science to Performance*. Nova Science Publishers, Hauppauge, New York, pp 225–240
- Rodríguez, FA, Keskinen, KL, Malvela, MT, Keskinen, OP (2003) Oxygen uptake kinetics during free swimming: A pilot study In: Chatard JC (ed) *Biomechanics and Medicine in Swimming IX*, Publications de l'Université de Saint-Étienne, Saint-Étienne, pp 379-384
- Scheuermann B, Hoelting B, Noble M, Barstow T (2001) The slow component of O_2 uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. *J Physiol* 531(1):245-256
- Schneider D, Wing A, Morris N (2002) Oxygen uptake and heart rate kinetics during heavy exercise: a comparison between arm cranking and leg cycling. *Eur J Appl Physiol* 88(1-2):100-106
- Sousa A, Borrani F, Rodríguez FA (2017) Oxygen uptake kinetics is slower in swimming than in arm cranking and cycling during heavy intensity. *Front Physio* 8:639
- Sousa A, Figueiredo P, Oliveira N, Oliveira J, Silva A, Keskinen KL, Rodríguez FA, Machado L, Vilas-Boas JP, Fernandes R (2011) $\dot{V}O_2$ Kinetics in 200-m race-pace front crawl swimming. *Int J Sports Med* 32(10):765-770
- Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190
- Sousa A, Vilas-Boas J, Fernandes R (2014) $\dot{V}O_2$ kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at $\dot{V}O_{2max}$. *Biomed Res Int* 2014:675363

Spencer MR, Gustin PB (2001) Energy system contribution during 200- to 1500-m running in highly trained athletes. *Med Sci Sports Exerc* 33(1):157-162

Toussaint HM, Hollander AP (1994) Energetics of competitive swimming. *Sports Med* 18(6):384-405

Whipp BJ, Rossiter HB (2005) The kinetics of oxygen uptake: physiological inferences from the parameters. In: Jones AM, Poole DC (eds) *Oxygen uptake kinetics in sport, exercise and medicine*, Routledge, Oxon, England, pp 64-94

Chapter V. Study 2

**Time limit at maximal aerobic velocity in swimming –
Continuous Vs. Intermittent sets**

Abstract

Objective: The maximal aerobic velocity (MAV) is usually used by coaches for training intensity prescriptions since it combines exercise economy and maximal oxygen uptake (Peak- $\dot{V}O_2$) into a single factor. In swimming there is a lack of studies which analyses the time sustained at this intensity and compare it with real training specific situations. This study aimed to characterize and compare swimmers' physiological responses when performing two different time limit tests at the MAV – continuous vs. intermittent sets and observe which one could be better to boost aerobic capacity's development.

Design: Twenty-two well trained swimmers (13 males and 9 females) completed a discontinuous incremental test for Peak- $\dot{V}O_2$, second ventilatory threshold (VT_2) and MAV assessment. In complementary days and in randomized order two time-limit sessions, continuous (CT) vs. intermittent (IT100), were evaluated for maximal oxygen uptake ($\dot{V}O_{2peak}$), oxygen initial deficit ($O_{2InitialDef}$) determination, $\dot{V}O_2$ kinetics ($\dot{V}O_2K$) analysis and the time spent above the VT_2 , 90% and 95% of Peak- $\dot{V}O_2$ were registered. All tests were conducted using a breath-by-breath apparatus (K4b², Cosmed, Italy) connected to a swimming snorkel (new-AquaTrainer[®], Cosmed, Italy) for pulmonary gas sampling.

Results: Peak- $\dot{V}O_2$ of the incremental test was only reached in the CT, still, higher values of $\dot{V}O_2$ were reached at the IT100. The IT100 test presented significantly higher values for time-limit, total distance and time spent above VT_2 and 90% of Peak- $\dot{V}O_2$. Both the time constants and the $O_{2InitialDef}$ were correlated between tests ($r=0,76$, $p<0.01$ and $r=0,64$, $p<0.01$, respectively) and the time constants were highly correlated with the corresponding $O_{2InitialDef}$ ($r=0,87$, $p<0.01$ and $r=0,89$, $p<0.01$) for CT and IT100, respectively. Time limit at the CT test presented (1) direct relations: with swimmers' personal bests (PB) at the 800 meters' freestyle event ($r=0,52$, $p<0.05$) and with the percentage times spent near the $\dot{V}O_2$ maximal values for the total duration of the test ($\geq VT_2$ $r=0,56$, $p<0.01$; $\geq 90\%$ $r=0,55$, $p<0.01$ and $\geq 95\%$ $r=0,49$, $p<0.05$); and (2) inverse relations: with MAV ($r=-0,69$, $p<0.01$) and vVT_2 ($r=-0,53$, $p<0.05$). The CT presented ~82%, 10%

and 8%, respectively for the aerobic, anaerobic alactic and lactic energy systems. MAV, vVT_2 and absolute Peak- $\dot{V}O_2$ were the most related variables associated with performance. The aerobic contribution was inversely related with swimmers PB's ($r=-0,49$, $p<0.05$; $r=-0,58$, $p<0.01$ and $r=-0,46$, $p<0.05$ for the 200, 400 and 800 meters events, respectively) and with Peak [La^{-1}] of the same test ($r=-0,48$, $p<0.05$). The amplitude of the recovery phase of the CT was related with MAV, vVT_2 , Peak- $\dot{V}O_2$, $\dot{V}O_{2peak}$ of the CT and swimming performances at the 200, 400 and 800 meters events.

Discussion: Times to exhaustion between the time-limit tests were not associated between tests or with swimming performance. Just the CT reached the Peak- $\dot{V}O_2$, however, both time-limit tests promote high levels of $\dot{V}O_2$ with higher times spent near individual's maximal $\dot{V}O_2$ values. The IT100 is the best methodology to aerobic capacity training since it presented a significantly higher time-limit, time spent above VT_2 and above 90% of the Peak- $\dot{V}O_2$. No differences were found at time-limit or $\dot{V}O_2$ responses between sexes.

Key words: Maximal aerobic velocity; Interval training; Swimming; $\dot{V}O_2$ response; Time limit

Introduction

The maximal aerobic velocity (MAV) that corresponds to the minimal velocity at which the maximal oxygen consumption of an athlete occurs, is one of the most important variables of study in sports physiology since it combines exercise economy and $\dot{V}O_{2max}$ into a single factor, being well related with performance (Billat and Koralsztein, 1996; Demarie et al., 2000; Reis et al., 2012a,b; Espada et al., 2015). This velocity, associated with the 3000 meters running or the 400 meters swimming velocities, is usually used by coaches for training intensity prescriptions (Demarie et al., 2000; Fernandes and Vilas-Boas, 2012; Espada et al., 2015). Therefore, the study of the time to exhaustion (TLim) at this velocity is extremely important, especially in order to provide insightful information regarding to the athletes' capacity at this intensity, aiming for a better planning of the training sets.

It is generally accepted that exercise intensities in the range between 70 and 100% of $\dot{V}O_{2max}$ will improve the aerobic capacity parameters (Demarie et al., 2000). In fact, during a training set, the time sustained near $\dot{V}O_2$ maximal values, namely above 90% of $\dot{V}O_{2max}$ (Billat and Koralsztein, 1996) is one of the most important factors that are presented for promoting long term adaptations in order to improve $\dot{V}O_{2max}$ and performance (Bentley et al., 2005; Libicz et al., 2005).

The primary phase of the oxygen uptake kinetics ($\dot{V}O_2K$) has been associated with better fitness status and performance (Jones and Burnley, 2009; Reis et al., 2012a,b; Espada et al., 2015) and in running IT sessions could be related with the time spent near $\dot{V}O_2$ maximal values (Millet et al., 2003) since faster kinetics could accelerate the oxidative rate. However, in swimming, just one study analysed this relationship in IT sessions (Bentley et al., 2005), and it is important to understand how the improvement of this variable could affect the $\dot{V}O_2$ response during a training session.

Even though the study of the time to exhaustion at the MAV (TLim-MAV) is being developed throughout the last years, in swimming, most of the studies were not performed in a free-swimming situation (e.g., Swimming flume) and do not

compare the results with real training situations. Also, no study compares the differences between sexes in order to understand if changes are needed to be applied in training protocols when training male or female swimmers.

The main goal of the present study is to characterize and compare swimmers physiological responses when performing two different time-limit tests – continuous (CT) vs. intermittent (IT100) swimming sets – and observe which one could be better for the aerobic capacity development.

We hypothesize that: 1) both time-limit tests will promote a high $\dot{V}O_2$ response, near individual's maximal values; 2) the intermittent test will present a higher TLim and a longer time spent near $\dot{V}O_2$ maximal values; 3) faster $\dot{V}O_{2K}$, associated with lower slow component amplitudes and with higher aerobic contributions will be related with longer times to exhaustion and swimming performance; 4) performances at the time-limit tests will be directly related between tests and the time to exhaustion will be inversely associated with swimming middle and long distances performances; and (5) both sexes will present a similar response profile.

Methods

Participants

Twenty-two well trained swimmers (9 females and 13 males), regular participants in state or national championships (at least in the past 3 years prior entering the study) were informed about the procedures and experimental risks and gave their written informed consent (or the respective legal guardians, when they were under 18 years old) in order to participate in this study. All swimmers were fully familiarised with the equipment and the test procedures before the beginning of the test sessions, being also frequent participants in similar experimental studies that were undertaken by our research group. This study was approved by the local University Ethical Committee (CEFMH: 39/2015) and conducted in accordance with the 1964 Declaration of Helsinki (Harriss et al. 2017). Anthropometrical data and swimmers personal best competition times (obtained

at official competitions in the last 3 months before the beginning of the test sessions) in the 400 and 800 meters freestyle events (PB400 and PB800, respectively) are presented in Table 6.

Table 6. Mean \pm SD of the descriptive characteristics of the swimmers and personal best times in competition of the swimmers, N = 22 (9 F, 13 M)

Variable	Female	Male	Combined
Age (yr)	15.3 \pm 1.2	16.5 \pm 1.9	16.1 \pm 1.7
Height (m)	1.7 \pm 6.5	1.8 \pm 8.4	1.7 \pm 10.6
Total Body Mass (kg)	58.4 \pm 6.0	70.4 \pm 10.3	65.5 \pm 10.6
Body Fat (%)	21.2 \pm 3.9	11.9 \pm 2.8	16.8 \pm 5.8
PB400	316.1 \pm 21.0	265.6 \pm 10.7	286.3 \pm 29.4
PB800	704.7 \pm 32.2	599.2 \pm 33.5	642.4 \pm 61.5

PB400 and PB800: personal bests of the swimmers, respectively at the 400 and 800 meters freestyle events.

Methodology

All swimmers performed three testing sessions, separated by at least 48 hours: firstly, (1) a discontinuous incremental test; and secondly (2) two time-limit sessions at the MAV intensity – continuous test (CT) vs. intermittent test (IT100). All subjects performed the same pre-test warm up protocol and were instructed to avoid strenuous exercise in the preceding 24 hours before each session, to attend well hydrated and fed, and to be abstained from caffeine and alcohol in the preceding 24 hours before each session. To minimize the effect of circadian rhythms or differences in prior exercise, the same environmental conditions were applied to all tests, namely time of day (\pm 2 hours), water temperature (\sim 28°C) and relative humidity (\sim 50%).

A telemetric portable breath-by-breath gas analyser (K4b², Cosmed, Italy), connected to the swimmer by a respiratory snorkel and valve system (new-AquaTrainer[®], Cosmed, Italy) was used in all tests in order to measure the respiratory and gas exchange variables for cardiorespiratory analysis (Reis et al.,

2010; Baldari et al., 2012). The K4b² was calibrated before each test according to manufacturer's instructions. All tests were performed in front crawl swimming with in-water starts and open turns without underwater gliding.

The heart rate (HR) was recorded telemetrically during exercise with a HR monitor (Polar®, Finland) coupled to the snorkel and synchronized with the K4b² system. For the blood lactate concentration [La⁻] analysis (YSI, 2300 STAT, Yellow Springs, USA), capillary blood samples (25 ul) were collected from the earlobe before the start of each test, during the breaks of the discontinuous incremental test and at 1, 3, 5 and 7 minutes after all tests. Rate of perceived exertion (RPE) was also recorded through the Borg's CR-10 scale (Borg, 1990).

For the swimming velocity control an underwater visual pacer (Pacer2Swim®, KulzerTEC, Portugal) was disposed along the bottom of the pool. This system, which is composed by 26 lights that subsequently light up, gives the swimmer an accurate notion of the correct velocity for each test. For time-limit tests, a tolerance of 2% of the overall time was given to the swimmers and tests were finished when the swimmers exceeded the tolerance or when the individual's voluntary exhaustion was observed.

The sessions were performed in a 25-meters swimming pool in the beginning of the preparatory period of the second macrocycle of the swimmers competitive season, after a period of two weeks for training adaptation.

Discontinuous incremental test

This test was composed by 6 sets of 250 meters, plus 1 set of 200 meters at maximal intensity, with 30 seconds rest for blood lactate collection (Espada et al., 2015), in order to allow the determination of maximal oxygen uptake (Peak- $\dot{V}O_2$), second ventilatory threshold (VT₂) and MAV. The velocity of the first repetition was set at 50% of swimmers 200 meters velocity and increments of 5 to 10% were imposed in the rest of the repetitions, until the swimmers voluntary exhaustion. Peak- $\dot{V}O_{2peak}$ was recorded as the highest 30 seconds average of

the $\dot{V}O_2$ and MAV was considered as the minimal velocity at which the Peak- $\dot{V}O_2$ values were reached (both reached in the last 2 repetitions).

Time-limit sessions

In complementary days, and in a randomized order, swimmers performed two time-limit sessions at MAV, until exhaustion: (a) a constant load set (CT); (b) and an interval set composed by 100 meters repetitions (IT100), with 15 seconds breaks for passive rest. In both sessions, the TLim and the total distance were recorded. The maximal $\dot{V}O_2$ response ($\dot{V}O_{2peak}$), oxygen deficit at the onset of exercise ($O_{2InitialDef}$), maximal $[La^-]$ and the $\dot{V}O_{2K}$ parameters were determined (we use the first bout at the IT100 session to compare to the CT). Also, the time spent above the VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$, as well as the corresponding percentage values for the total duration of the tasks, were registered. For the IT100 the mean $\dot{V}O_{2peak}$ ($M\dot{V}O_{2peak}$) as the average value of the $\dot{V}O_{2peak}$'s of each repetition was calculated.

The $\dot{V}O_2$ of the recovery phase (8 minutes after the end of the exercise) was also recorded for the total expenditure of energy and energy systems contribution determination at the CT.

Swimmers were encouraged to give their maximal effort at the incremental test and to perform the maximal distance at the time-limit tests.

Data Analysis

Breath-by-breath $\dot{V}O_2$ data were first cleaned by exclusion of values lying more than three standard deviations from the local mean, for exclusion of outliers caused by abrupt breaths or coughing. For maximal oxygen uptake determination, a 30 seconds moving average of data was used for the incremental and time-limit tests considering the highest value as the peak. For the time spent above the VT_2 , 90%, 95% of Peak- $\dot{V}O_2$ and respective percentage values for the total duration of the sessions, $\dot{V}O_2$ data was further interpolated

into 1-second values, and all values above the referred physiological thresholds were registered.

$\dot{V}O_2K$ parameters (time delay (TD), time constant (τ) and amplitude (A)) of the time-limit tests were determined by using: 1) a bi-exponential modelling for the CT, since after a primary rise of the $\dot{V}O_2$ values, a secondary one (slow component) was observed (except for two swimmers); or 2) by a monoexponential modelling for the IT100 test, since due to the short duration of the sets we did not observed the secondary rise of the $\dot{V}O_2$ values, in accordance to previous studies (Rodríguez et al., 2003; Sousa et al., 2013). To remove the influence of the cardiodynamic phase on the subsequent $\dot{V}O_2$ response, we chose to remove the first 20 seconds of data from analysis (Reis et al., 2012a, b; Pessôa Filho et al., 2012, Espada et al., 2015). We also calculated an individual “snorkel delay” (ISD) for each test. The ISD, that corresponds to the difference between the onset of exercise and the time when the following breaths summed up a tidal volume superior to the outlet tube volume, was then integrated into the time delay of the $\dot{V}O_2$ response, as described before by Reis et al (2012a), adapted to the specific characteristic of the snorkel device used in this study.

$\dot{V}O_2K$ parameters were calculated through an iterative procedure, by minimizing the sum of the mean squares of the differences between the modelled and the measured $\dot{V}O_2$ values. Therefore, we modelled the $\dot{V}O_2K$ according to the equation (Jones and Poole, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2(b)} + A_p \cdot (1 - e^{-(t-TD_p)/\tau_p}) + A_{sc} \cdot (1 - e^{-(t-TD_{sc})/\tau_{sc}})$$

Where $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest, which was calculated as the average of the first 30 seconds of the last minute before the start of the exercise (after 10 minutes of passive rest); TD, τ , and A, represent the time delay, the time constant (time that is needed to complete 63% of the $\dot{V}O_2$ response) and the amplitude of the exponential response of the $\dot{V}O_2$, respectively for the primary (p) and the slow component (sc)

phases. , we considered the aerobic (Aer), anaerobic alactic (AnaAlac) and anaerobic lactic (AnaLac) systems.

For the analysis of the total energy expenditure of the CT, three energetic systems were considered: the aerobic system participation, calculated by the trapezoidal method through the time integral of the net $\dot{V}O_2$ during exercise (Bertuzzi et al., 2013; Guidetti et al., 2007); the anaerobic lactic participation determined by the net $[La^-]$ at the end of the test (the difference between maximal after exercise and resting $[La^-]$) expressed as a delta value ($\Delta[La^-]$) (Beneke et al., 2002), considering $3 \text{ ml}O_2 \cdot \text{kg}^{-1}$ as a metabolic equivalent for each $1 \text{ mmol} \cdot \text{l}^{-1}$ of $\Delta[La^-]$ (di Prampero, 1981); and the anaerobic alactic system participation, determined by the product between the time constant and amplitude of the fast component of post-exercise (during a 8 minutes period) oxygen consumption (Beneke et al., 2002; Guidetti et al., 2007), the following equation (Scheuermann et al., 2001):

$$\dot{V}O_{2\text{off}}(t) = EE\dot{V}O_2 - A_{1\text{off}}[1 - e^{-(t-TD_1/\tau_1)}] - A_{2\text{off}}[1 - e^{-(t-TD_2/\tau_2)}]$$

Where $\dot{V}O_{2\text{off}}(t)$ represents the relative $\dot{V}O_2$ at a given time; $EE\dot{V}O_2$ is the oxygen uptake at the end of exercise; TD , τ , and A , represent the time delay, the time constant and the amplitude, and 1 and 2 represent for the fast and slow component, respectively, for the bi-exponential response of the $\dot{V}O_2$.

Statistical Analysis

All statistical analyses were performed with the Statistical Package for the Social Sciences (version 25.0; SPSS, Chicago, IL, USA). Firstly, normality and homogeneity of data were confirmed with Shapiro-Wilk and Levene tests, secondly, independent T-tests were applied to all variables to check the differences between sexes. The differences between the discontinuous incremental test and the time-limit tests were tested for statistical significance using ANOVA for repeated measures with Bonferroni correction, while T-tests were used for test differences between the time-limit tests. At last, the Pearson's

linear correlation coefficient was used in order to establish the significant associations between physiological measures and swimmers performance. Statistical significance was accepted at $p < 0.05$.

Results

The physiological responses of the swimmers at the incremental test are presented in table 7.

Table 7. Mean \pm SD of the physiological parameters of the swimmers at the incremental test, N = 22 (9 F, 13 M)

Variable	Female	Male	Combined
Peak- $\dot{V}O_2$ (ml·kg ⁻¹ ·min ⁻¹)	52.5 \pm 4.2	57.0 \pm 5.7	55.2 \pm 5.6
VT ₂ (ml·kg ⁻¹ ·min ⁻¹)	46.4 \pm 4.3	49.9 \pm 4.8	48.4 \pm 5.0
VT ₂ (%Peak- $\dot{V}O_2$)	88.3 \pm 2.5	87.6 \pm 3.5	87.9 \pm 3.2
MAV (m·s ⁻¹)	1.2 \pm 0.1	1.3 \pm 0.1	1.3 \pm 0.1
Peak [La ⁻] (mmol·l ⁻¹)	7.9 \pm 2.5	8.8 \pm 3.6	8.4 \pm 3.3
Peak HR (b·min ⁻¹)	188.7 \pm 9.2	180.3 \pm 7.8	184.1 \pm 9.4

Peak- $\dot{V}O_2$: corrected to body mass values of the maximal oxygen uptake; VT₂: $\dot{V}O_2$ at the second ventilatory threshold and corresponding percentage value for the Peak- $\dot{V}O_2$; MAV: maximal aerobic velocity; Peak HR and Peak [La⁻]: maximal HR and blood lactate concentration at the test.

The physiological responses at the time-limit sessions are presented in table 8 and a typical response of $\dot{V}O_2$ is demonstrated in figure 19.

Table 8. Mean \pm SD of the physiological parameters of the time-limit tests N = 22 (9 F, 13 M)

Variable	Continuous Test			Intermittent Test		
	Male	Female	Combined	Male	Female	Combined
$\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	57.0 \pm 4.8	53.2 \pm 4.7	55.4 \pm 5.1	54.8 \pm 5.1	49.9 \pm 4.3	52.9 \pm 5.36*
% $\dot{V}O_{2peak}$ (%Peak- $\dot{V}O_2$)	100.2 \pm 3.0	101.3 \pm 3.1	100.7 \pm 3.1	96.3 \pm 4.6	96.5 \pm 3.7	96.4 \pm 4.3*
M $\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	-	-	-	52.0 \pm 4.5	47.8 \pm 4.5	50.4 \pm 4.9
%M $\dot{V}O_{2peak}$ (%Peak- $\dot{V}O_2$)	-	-	-	91.4 \pm 4.3	92.3 \pm 4.2	91.8 \pm 4.3
Peak HR (b·min ⁻¹)	182.1 \pm 6.2	188.6 \pm 5.9	184.4 \pm 6.9	178.1 \pm 7.5	188.1 \pm 11.3	182.2 \pm 10.4
Peak [La ⁻] (mmol·l ⁻¹)	7.5 \pm 2.9	8.4 \pm 1.9	7.8 \pm 2.7	6.5 \pm 1.3	9.7 \pm 3.4	7.8 \pm 2.9
PRE (0 - 10 units)	8.8 \pm 1.0	9.0 \pm 0.8	8.6 \pm 0.9	9.5 \pm 0.8	9.3 \pm 0.8	9.4 \pm 0.8
Distance (m)	309.6 \pm 64.7	325.0 \pm 60.1	315.9 \pm 63.3	1215.4 \pm 612.5*	1366.7 \pm 663.3*	1277.3 \pm 638.13*
TLim (s)	243.6 \pm 59.3	274.5 \pm 57.0	256.2 \pm 60.3	940.0 \pm 471.0*	1120.0 \pm 513.1*	1013.6 \pm 496.6*
$\geq VT_2$ (s)	137 \pm 80.2	151.9 \pm 75.4	143.4 \pm 78.5	419.7 \pm 196.5*	500.8 \pm 216.1*	455.0 \pm 206.1*
$\geq VT_2$ (%)	53.3 \pm 19.0	53.6 \pm 21.5	53.4 \pm 20.1	44.5 \pm 14.7	52.7 \pm 18.9	48.1 \pm 17.2
$\geq 90\%$ of Peak- $\dot{V}O_{2peak}$ (s)	115 \pm 79.1	144.7 \pm 70.6	127.5 \pm 77.1	290.7 \pm 214.7*	380.1 \pm 203.7*	329.6 \pm 214.6*
$\geq 90\%$ of Peak- $\dot{V}O_{2peak}$ (%)	44.4 \pm 18.9	51.5 \pm 19.8	47.3 \pm 19.6	32.7 \pm 20.4	40.9 \pm 22.9	36.3 \pm 21.9
$\geq 95\%$ of Peak- $\dot{V}O_{2peak}$ (s)	73.9 \pm 83.5	95.1 \pm 65.4	82.6 \pm 77.3	117 \pm 129.6	197.3 \pm 162.5	152.1 \pm 150.1
$\geq 95\%$ of Peak- $\dot{V}O_{2peak}$ (%)	26.4 \pm 22.1	34.1 \pm 21.1	29.5 \pm 22.0	12.1 \pm 12.6	22.4 \pm 19.0	16.6 \pm 16.5
A _p (ml·kg ⁻¹ ·min ⁻¹)	44.0 \pm 4.8	40.8 \pm 5.4	42.7 \pm 5.3	44.6 \pm 3.9	41.1 \pm 6.1	43.1 \pm 5.2
TD _p (s)	12.2 \pm 2.6	13.1 \pm 0.9	12.6 \pm 2.2	12.1 \pm 3.0	11.4 \pm 0.5	11.8 \pm 2.3
τ_p (s)	26.8 \pm 7.0	26.0 \pm 8.3	26.5 \pm 7.5	26.4 \pm 10.2	25.3 \pm 8.5	25.9 \pm 9.4
O _{2InitialDef} (mlO ₂)	1713.0 \pm 381.1	1579.7 \pm 343.9	1658.5 \pm 372.2	1736.0 \pm 646.1	1530.6 \pm 505.4	1652.0 \pm 601.2
A _{sc} (ml·min ⁻¹)	311.5 \pm 193.5	203.8 \pm 131.8	266.2 \pm 178.4	-	-	-
A _{sc} (ml·kg ⁻¹ ·min ⁻¹)	4.5 \pm 2.9	3.4 \pm 1.9	4.0 \pm 2.6	-	-	-
TD _{sc} (s)	137.5 \pm 20.3	125.8 \pm 18.9	132.5 \pm 20.5	-	-	-
τ_{sc} (s)	39.7 \pm 25.1	39.3 \pm 28.1	39.6 \pm 26.4	-	-	-

$\dot{V}O_{2peak}$ and % $\dot{V}O_{2peak}$: maximal $\dot{V}O_2$ in the test and corresponding percentage to Peak- $\dot{V}O_2$; M $\dot{V}O_2$ and %M $\dot{V}O_{2peak}$: average value of the $\dot{V}O_{2peak}$'s achieved in each repetition of the set and corresponding percentage to Peak- $\dot{V}O_2$; Peak [La⁻] and Peak HR: maximal blood lactate concentration and heart rate, respectively; RPE: rate of perceived exertion; Distance and TLim: maximal distance and time performed by the swimmers; $\geq VT_2$, $\geq 90\%$ and $\geq 95\%$ of Peak- $\dot{V}O_2$: time spent by the swimmers with $\dot{V}O_2$ values above the VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$, and corresponding percentage values for the total duration of each test, respectively; A, TD and τ : amplitude, time delay and time constant parameters of the $\dot{V}O_2K$, for the primary (p) and slow component phases (sc); *: statistical differences for the continuous test ($p < 0.05$).

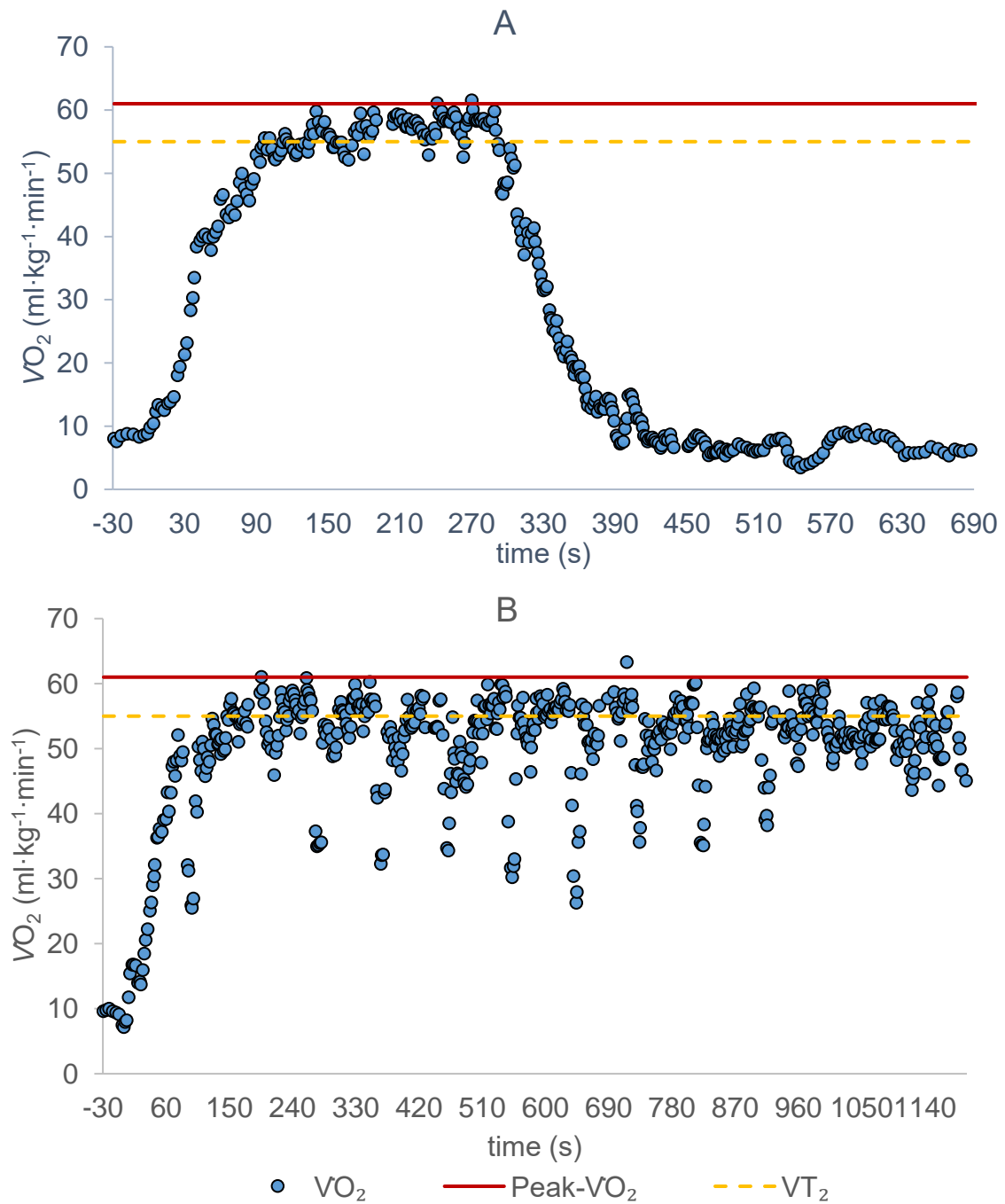


Figure 19. Example of the $\dot{V}O_2$ response profiles of the participant n° 12 at the CT (panel A) and at the IT100 (panel B). The participant's Peak- $\dot{V}O_2$ and VT₂ are marked by the red line and orange dash line, respectively.

The $\dot{V}O_2$ on-kinetics were similar between sexes, with no significant differences observed. Peak- $\dot{V}O_2$ of the incremental test was only reached in the CT, still,

higher values of $\dot{V}O_2$ were reached at the IT100 (~92% and ~96%, for $M\dot{V}O_{2peak}$ and $\dot{V}O_{2peak}$, respectively). Moreover, Peak- $\dot{V}O_2$ was highly correlated with $\dot{V}O_{2peak}$'s ($r = 0.95$ and $r = 0.92$, $p < 0.01$) for CT and IT tests, respectively, $\dot{V}O_{2peak}$'s were also correlated between the time-limit tests ($r = 0.81$, $p < 0.01$).

At the CT, $\dot{V}O_{2peak}$ and $\% \dot{V}O_{2peak}$ for the Peak- $\dot{V}O_2$ were significantly higher than the IT100 test. However, the IT100 test presented significantly higher values for TLim, total distance and time spent above the VT_2 and 90% of Peak- $\dot{V}O_2$. Regarding the time spent above the studied thresholds, when the percentage values for the total duration of the sessions were considered, no differences were observed. Also, none of these variables seem to be related between tests.

No differences were found at the $\dot{V}O_{2K}$ parameters and at the $O_{2InicialDef}$ between the CT and the first bout of the IT100 test, nor at the maximal $[La^-]$ and PRE. However, both the time constants and the $O_{2InicialDef}$ were correlated between tests ($r = 0.76$ and $r = 0.64$, $p < 0.01$, respectively) and the time constants seem to be highly correlated with the corresponding $O_{2InicialDef}$ ($r = 0.87$ and $r = 0.89$, $p < 0.01$) for CT and IT100, respectively.

At the IT100 no significant relations were found between these test variables, however TLim, total distance and the percentage time spent above the 90% of Peak- $\dot{V}O_2$ were related with the amplitude of the slow component of the CT ($r = 0.53$, $r = 0.56$ and $r = -0.50$, $p < 0.05$, respectively).

TLim at the CT presented (1) direct relations: with swimmers PB's at the 800 meters freestyle event ($r = 0.52$, $p < 0.05$) and with the percentage times spent near the $\dot{V}O_2$ maximal values for the total duration of the test ($\geq VT_2$ $r = 0.56$, $p < 0.01$; $\geq 90\%$ $r = 0.55$, $p < 0.01$ and $\geq 95\%$ $r = 0.49$, $p < 0.05$); and (2) inverse relations: with MAV ($r = -0.69$, $p < 0.01$) and vVT_2 ($r = -0.53$, $p < 0.05$).

MAV and vVT_2 were highly correlated ($r = -0.87$, $p < 0.01$).

The metabolic contributions and the off-kinetics fast component parameters at the CT are presented in table 9 and figure 20.

Table 9. Mean \pm SD of the metabolic contributions and off-kinetics fast component parameters of swimmer in the CT, N = 22 (9 F, 13 M)

Variable	Continuous Test		
	Male	Female	Combined Group
Anaerobic Alactic (IO ₂)	2.1 \pm 0.7*	1.2 \pm 0.5	1.7 \pm 0.8
Anaerobic Alactic (mlO ₂ ·kg ⁻¹)	30.3 \pm 8.4*	20.6 \pm 8.4	25.9 \pm 9.7
Anaerobic Lactic (IO ₂)	1.4 \pm 0.5	1.3 \pm 0.4	1.3 \pm 0.4
Anaerobic Lactic (mlO ₂ ·kg ⁻¹)	19.9 \pm 8.3	22.5 \pm 5.4	21.1 \pm 7.3
Total Anaerobic (IO ₂)	3.5 \pm 0.9*	2.5 \pm 0.8	3.0 \pm 1.0
Total Anaerobic (mlO ₂ ·kg ⁻¹)	50.1 \pm 13.0*	43.2 \pm 11.7	47.0 \pm 12.9
Aerobic (IO ₂)	17.1 \pm 3.2*	11.6 \pm 2.9	14.6 \pm 4.1
Aerobic (mlO ₂ ·kg ⁻¹)	244.4 \pm 39.6*	198.6 \pm 43.1	223.6 \pm 47.1
Total (IO ₂)	20.6 \pm 3.4*	14.1 \pm 3.3	17.6 \pm 4.6
Total (mlO ₂ ·kg ⁻¹)	294.5 \pm 42.4*	241.7 \pm 46.2	270.5 \pm 51.4
Amplitude (IO ₂)	2.4 \pm 0.3*	1.4 \pm 0.4	1.9 \pm 0.6
Amplitude (mlO ₂ ·kg ⁻¹)	35.8 \pm 8.2*	23.4 \pm 7.0	29.9 \pm 9.8
Time constant (s)	51.1 \pm 14.9	50.4 \pm 13.9	50.8 \pm 14.4

*: Differences between sexes p<0.05

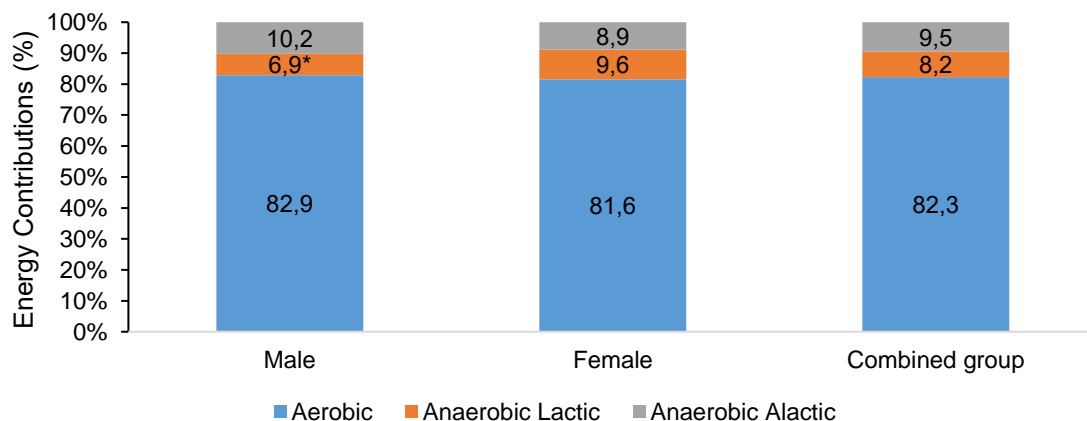


Figure 20. Relative contributions of the energy systems of the CT.

*: Differences between sexes p<0.05

No differences were found at the relative contributions for the total energy expenditure of the test between sexes, however male swimmers presented higher absolute values at the aerobic and anaerobic alactic systems. The aerobic contribution was inversely related with Peak [La] of the same test ($r = -0.48, p < 0.05$).

The CT showed a relative contribution of ~82%, 10% and 8%, respectively for the aerobic, anaerobic alactic and lactic energy systems. The relative contributions of the CT showed a direct correlation in the aerobic system ($r = 0.53, p < 0.05$) with the time spent above 90% of Peak- $\dot{V}O_2$ of the IT100, while the anaerobic system presented an inverse one ($r = -0.54, p < 0.05$).

Finally, the amplitude of the recovery phase was directly related with MAV, vVT_2 , Peak- $\dot{V}O_2$ and CT's $\dot{V}O_{2peak}$ ($r = 0.50, p < 0.05$; $r = 0.66, p < 0.01$; $r = 0.51, p < 0.05$ and $r = 0.52, p < 0.05$, respectively). Significant correlations between physiological variables with swimmers performances are showed at table 10:

Table 10. Significant correlations coefficients between swimmers performances and physiological variables

Variable	Swimmers PB's		
	200m	400m	800m
Peak- $\dot{V}O_2$	-0.75*	-0.81*	-0.86*
MAV	-0.75*	-0.74*	-0.78*
vVT_2	-0.81*	-0.82*	-0.88*
Aer (CT)	-0.49*	-0.58*	-0.46**
A off-kinetics (CT)	-0.49*	-0.69*	-0.65*

Peak- $\dot{V}O_2$: maximal oxygen uptake at the incremental test; MAV: maximal aerobic velocity; vVT_2 : velocity at the second ventilatory threshold; Aer (CT): aerobic system contribution of the CT; A off-kinetics (CT): amplitude of the primary phase of the recovery phase of the CT; significant correlations marked with * ($p < 0.01$) and ** ($p < 0.05$).

Discussion

The main goal of the present study was to analyse and compare the TLim and the $\dot{V}O_2$ response at MAV, assuming two different kinds of training sets – continuous vs. intermittent swimming until exhaustion. The relevance of the study is essentially justified by the general use of this intensity for training prescription, however there is still a lack of studies that compare the TLim-MAV to real training situations, which could help the understanding of how to implement this concept in practice. As a matter of fact, this specific parameter is quite crucial for both the aerobic power and the lactate tolerance bioenergetical training intensity zones (Fernandes et al., 2003). Hence, and to the best of our knowledge, this is the first study within the literature to compare the time to exhaustion at the MAV between both continuous and intermittent sets in swimming.

The main conclusions of the present study are: 1) both time-limit tests promote high levels of $\dot{V}O_2$ with higher times spent near individual's maximal $\dot{V}O_2$ values, (i.e., ~53% and 48% of time above VT_2 , for CT and IT100, respectively), demonstrating the training sets efficiency for the aerobic training, and confirming our first hypothesis; 2) our second hypothesis was also confirmed since, even though the $\dot{V}O_{2peak}$ values in the IT100 are lower compared to the CT, in the IT100 we observed that the TLim was significantly higher (~757 seconds higher), leading to a significantly higher amount of time spent above the VT_2 and 90% of the Peak- $\dot{V}O_2$ (~312 and ~202 seconds higher, respectively); 3) our third hypothesis was not confirmed since fast kinetics were not associated with higher TLim's and performances or with higher aerobic contributions in the CT. However, both time constants were highly associated with the O_2 initial deficits, suggesting that swimmers with faster kinetics could spare the anaerobic contribution in the beginning of the exercise; 4) performances between the time-limit tests were not associated, and the time to exhaustion just presented a direct correlation with the time of the 800 meters freestyle event, rejecting our fourth hypothesis; (5) finally the absence of significant differences at the TLim and physiological responses during the exercises between sexes confirmed our fifth hypothesis.

According to Billat and Koralsztein (1996), MAV can be determined through several ways, which makes it difficult to compare maintenance times. As a matter of fact, the TLim-MAV, and despite being reproducible in an individual, presents a great variability among individuals, ranging between 2.5 to 10 minutes (Billat et al., 1996; Demarie et al., 2001), which could be explained by the lactate threshold, where the role of the anaerobic contribution is quite significant. In swimming, it seems to exist a lower inter-individual variability, ranging from 215 to 260 seconds, 230 to 260 seconds and from 310 to 325 seconds, respectively for elite, high and lower-level swimmers (Fernandes and Vilas-Boas, 2012), as reported by other studies (Fernandes et al., 2008; Sousa et al., 2014) and confirmed by our results. Also, no differences were found between sexes, as they were not in our study. When compared with other sport modalities it seems that this variable did not present significant differences, namely between swimming, rowing, running and cycling, even with lower $\dot{V}O_{2max}$ values reported for the swimming modality (Sousa et al., 2015).

In previous studies (Billat et al., 1996; Faina et al., 1997; Billat and Koralsztein, 1996; Fernandes and Vilas-Boas, 2012; Fernandes et al., 2008), the TLim at the CT presented inverse correlations with the MAV and vVT_2 . This fact seems to confirm that swimmers with higher aerobic power velocities could not perform an exercise at this relative intensity so much longer than less proficient swimmers. This inverse relationship with MAV is similar for several exercise modes such as swimming, cycling, running and kayaking (Billat and Koralsztein, 1996). This could be important when training sets are prepared since high proficient swimmers should perform shorter duration sets at this relative intensity, in order not to get into fatigue in an earlier stage of the task. In fact, coaches should take into account the time sustained of ~256s obtained in this study, when performing training sets at the MAV, knowing that individual adjustments should be applied to each athlete. Also, adaptations could be applied to this velocity in order to prepare sets with lower or higher durations, since, in swimming, a variability of just 5% around the MAV intensity seems to promote significant changes at the

TLim, ~344,194 and 123 seconds, respectively for 95, 100 and 105% of the MAV intensity (Sousa et al., 2014).

One possible explanation for this relationship could be that higher velocities imply a more strenuous effort, which could lead to fatigue in an earlier stage by the higher anaerobic energy consumption required, as reported by Fernandes et al. (2008). In addition, this last study also found an inverse correlation between TLim-MAV and the velocity corresponding to the anaerobic threshold, which is highly correlated to MAV, as it is in our study. This could be explained by distinct phenotypes, which probably did influence the motor unit's recruitment patterns during the tests that were conducted, suggesting that swimmers with higher values of anaerobic threshold and MAV should use less extensive training sets for aerobic power improvement purposes. Also, these authors reported that the TLim-MAV is influenced by stroking parameters, having a direct relationship with stroke index and stroke length and an inverse correlation with stroke rate. Even though in this study the kinematic parameters were not analysed, it is logic to believe that the same should occur since these variables will influence the swimming economy and thereby contribute for the delay of fatigue in an earlier stage of the test.

The $\dot{V}O_2$ slow component is another bioenergetical factor that is pointed as being able to influence the TLim-MAV. The impact of the amplitude of this parameter on the capacity of sustaining an exercise at the MAV, is still an open issue since literature has been giving contradicting results regarding to the relation with the time to exhaustion. Demarie et al. (2001) were the first group proving that, as well as in running or cycling, in swimming athletes also present a $\dot{V}O_2$ "drift", as reported in more recent studies (Reis et al., 2012a,b; Pessôa-Filho et al., 2012; Espada et al., 2015) probably because of the effect of fatigue induced by the exercise on the increase in muscle temperature, on muscular contraction characteristics, higher recruitment of motor units (particularly "fast-twitch" fibres), lower mechanical efficiency (associated with the changes on stroking technique) and the energy cost of breathing (which has a higher relevance in swimming) (Fernandes et al., 2003; Espada et al., 2015). In the Demarie's study (2001) the

relationship with the TLim was not found in running, as not in other modalities (Billat and Koralsztein, 1996; Billat et al., 1998), or in our study. However, recent studies reported a direct relationship, suggesting that longer times to exhaustion lead to higher $\dot{V}O_2$ slow components (Fernandes et al., 2003 and 2008; Fernandes and Vilas-boas, 2012). Moreover, some studies also reported the $\dot{V}O_2$ slow component brought the " $\dot{V}O_{2max}$ " values quite above than those that were measured in an incremental test for the majority of the athletes (Demarie et al., 2000; Fernandes et al. 2003). Such results, as well as the inverse relationship between the TLim and the MAV, emphasized that the swimmers' lower level of maximal aerobic metabolic rate might be related to a larger capacity to sustain the exercise intensity. Furthermore, this particular hypothesis suggests that the inverse relationship discussed above might be explained by the anaerobic capacity, as it is also pointed out by Billat and Koralsztein (1996) and by Faina et al. (1997).

In our study, although we did not find direct relationship with the CT's TLim, the amplitude of the $\dot{V}O_2$ slow component demonstrated direct correlations with the TLim and total distance and an inverse correlation with the percentage time spent above the VT_2 in the IT100 test. This could suggest that a higher capacity to endure with a higher $\dot{V}O_2$ slow component is related with a better performance in an IT session, but on the other hand, swimmers with a less proficient physiological response cannot perform an IT session with such higher relative $\dot{V}O_2$ values.

The direct correlation with the swimmers PB's at the 800 meters freestyle event seems to confirm that the TLim, per se, is not a related performance variable, since swimmers with lower values of TLim presented best performances at this distance. This goes in line with the inverse correlations found in our study between the MAV and swimming middle and long-distances performances, suggesting MAV, as well as the vVT_2 and the Peak- $\dot{V}O_2$ of the incremental test (that presented similar relations), as good predictor variables of performance.

The relation between the Peak- $\dot{V}O_2$ ($\dot{V}O_{2max}$) and the TLim is also inconsistent in the literature, since reports exist supporting a direct relationship (Billat and Koralsztein, 1996) and no relationship at all (Demarie et al., 2000; Fernandes and Vilas-Boas 2012). The absence of a significant correlation in our results makes sense to us, since Peak- $\dot{V}O_2$ is usually directly related with MAV (as in our study), which in turn is, as it is widely referred in the literature, inversely related with the TLim, as observed in our study.

The metabolic contributions of the CT showed that the exercise was essentially aerobic (~82%), however the anaerobic contribution represented an important part of the exercise (~10% and ~8%, for de anaerobic alactic and lactic systems, respectively). Our values are in line of those found for similar tests (Sousa et al., 2015) and were associated with those reported for the 400 and 800 meters freestyle swimming (Rodríguez and Mader, 2011). Even though we did not find relations with the TLim, the aerobic contribution presented moderate inverse correlations with swimmers performances at middle and long-distance swimming. Moreover, higher aerobic contributions were related with a lower $[La^-]$, thus evidencing responsibility for a lower anaerobic participation in the exercise.

If the $\dot{V}O_2$ responses during square-wave TLim-MAV transitions seem not to present differences between different kinds of exercises, the $\dot{V}O_2$ responses during the recovery period seem to be exercise mode dependent, since swimmers and rowers presented higher times to recovery in comparison to cyclists and runners, as reported by Sousa et al. (2018). Besides, the authors claimed that, for all exercise modes, the subjects who presented higher $\dot{V}O_{2max}$ values were those who recovered faster. In our study we also observed that swimmers with higher Peak- $\dot{V}O_2$ and CT's $\dot{V}O_{2peak}$ also presented higher amplitudes of the primary phase at the recovery phase. Furthermore, these athletes were also those who present better performances in official events and higher MAV's and vVT_2 's.

In a study similar to ours, but performed with running at 92.2% of MAV, Demarie et al. (2000), comparing the $\dot{V}O_2$ of intermittent and continuous exercise, found

out, contrarily to our results, that there is a significantly higher $\dot{V}O_{2peak}$ in absolute values for the intermittent test. This could be explained by the short duration of ours IT100 repetitions compared to those of the Demarie's study (~82s vs. 240 to 390s). Nonetheless, such value was no longer statistically higher when calculated in terms of $\dot{V}O_{2max}$ percentage. Even though these authors claimed that both training protocols (continuous and intermittent) have efficacy in terms of endurance performance, they demonstrated that subjects were truly able to run for a significant longer time at the required velocity during the intermittent test (more ~555s), suggesting this one as the best one to stimulate the aerobic metabolism at its maximum value. Our results are in line with this study, since we found significantly higher values both in the TLim and at the time spent near individual's maximal values at the IT100. Accordingly, our results, also suggest the intermittent test as the best one for promoting long term adaptations in order to improve $\dot{V}O_{2max}$ and performance (Bentley et al., 2005; Libicz et al., 2005).

The differences found between the CT and IT100 could be explained by: 1) the recovery phase between the intervals of the IT session, which, even though shorter (15 seconds), must have been enough for a significant restoration of the natural declining of the phosphocreatine after an intense exercise, throughout the re-synthesis of the muscular ATP (Simoneau et al., 1987); and 2) the fast $\dot{V}O_{2K}$ along the task that contributed for the promotion of a high percentage of time spent near $\dot{V}O_{2max}$ values rising the oxidative contribution, making the exercise more efficient/aerobic. Although without direct relations with the TLim or performance, the time constant of the primary phase of the $\dot{V}O_{2K}$ presented strong correlations with the $O_{2InitialDef}$, being by this way responsible for an initial saving of the anaerobic energetic contribution.

Another perspective proposes an increase on the $\dot{V}O_{2}$ values in the last bouts of a highly intense intermittent exercise, which could be responsible for an extra ATP resynthesized through the oxidised of carbohydrates, instead of being metabolized into lactate (Demarie et al., 2000). However, we did not observe this supposed rise on the $\dot{V}O_{2}$ values in the last bouts, instead, the values stayed constant almost practically from the second to the last bout, or even presented a

small decreased (see panel B of figure 1). Accordingly, and in the absence of significant differences observed at the $[La^-]$ between tests (even though the much higher duration of the IT100), we can suppose that the lactate itself could be responsible for supplying the energetic demands of the exercise, being oxidised and used as energy substrate instead of being continuously accumulated (Demarie et al., 2000).

The Peak- $\dot{V}O_2$ obtained at the incremental test was only reached at the CT, even though the swimmers showed high values of time and percentage time spent near $\dot{V}O_2$ maximal values in both tests, which suggests that both training sets could be effective for the aerobic training. Still, Peak- $\dot{V}O_2$ was highly directly correlated with both $\dot{V}O_{2peak}$'s of the time-limit tests (which are also related together), demonstrating that, independently of the type of exercise, the higher oxidative rates were presented by the same swimmers. Instead, the TLim, the time and respective percentages spent near $\dot{V}O_2$ maximal values did not present any correlations between tests.

Although the $\dot{V}O_{2peak}$ is higher in the CT, the results demonstrated that in the IT100 the time-limit was significantly higher, hence leading to a greater amount of time spent above the VT_2 and 90% of the Peak- $\dot{V}O_2$. Still, no differences were found on the $\dot{V}O_{2K}$ parameters, nor at the PRE or peak $[La^-]$ between tests. In turn, and between the time-limits tests, direct correlations were found at the $\dot{V}O_{2K}$ parameters and at the $O_{2InitialDef}$, considering that the time constants are significantly correlated to each corresponding $O_{2InitialDef}$. The results also showed that the swimmers who presented higher percentages of aerobic contribution in the CT test, performed the IT100 with longer times spent near individual's Peak- $\dot{V}O_2$, translating to a more efficient exercise. On the contrary, an opposite profile was found for those who presented higher anaerobic contributions.

The present study emphasizes the necessity of characterizing the TLim-MAV, since this specific parameter is crucial for both the lactate tolerance and the aerobic power of the swimmers. This parameter, that can be easily accessed through the velocity of the swimmers 400 meters performance, or more precisely

throughout the velocity of the 300 central meters of the 400 meters event (Espada et al., 2015), can truly help coaches when planning exercises and training sessions, considering the swimmers physiological characteristics, as well as the TLim-MAV, given the fact that it helps to understand the relationship between both aspects and the expected outcomes of the swimmers performances (Fernandes et al., 2008).

In conclusion, our results suggest: 1) the intermittent training set of 100 meters repetitions, with 15 seconds breaks, as a better training set in order to promote longer times spent near swimmers $\dot{V}O_2$ maximal values and by this way promoting gains on the swimmers $\dot{V}O_{2max}$; 2) test swimmers TLim-MAV in order to achieve the individual's times to exhaustion, so that the training sets planning could be more individualized, having into account the value of ~256 seconds obtained in the present work; 3) time to exhaustion is not directly related with swimming performance, however MAV, the velocity at the anaerobic threshold and higher $\dot{V}O_2$ responses are variables well related to performance, deserving a prominent place in training protocols; and 4) that the adaptations to training protocols can be applied equally in male and female swimmers.

References of chapter V

- Baldari C, Fernandes RJ, Meucci M, Ribeiro J, Vilas-Boas J P, Guidetti L (2013) Is the new AquaTrainer(R) snorkel valid for $\dot{V}O_2$ assessment in swimming? *Int J Sports Med* 34:336-344
- Beneke R, Pollmann C, Bleif I, Leithäuser RM, Hütler M (2002) How anaerobic is the wingate anaerobic test for humans? *Eur J Appl Physiol* 87:338-392
- Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP (2005) Physiological responses during submaximal interval swimming training: effects of interval duration. *J Sci Med Sport* 8:392-402
- Bertuzzi R, Nascimento EM, Urso RP, Damasceno M, Lima-Silva AE. (2013) Energy system contributions during incremental exercise test. *J Sports Sci Med* 12(3):454-460
- Billat V, Faina M, Sardella F, Marini C, Fanton F, Lupo S, Dalmonte A (1996) A comparison of time to exhaustion at $\dot{V}O_{2max}$ in elite cyclists, kayak paddlers, swimmers and runners. *Ergonomics* 39(2):267-277
- Billat V, Koralsztein JP (1996) Significance of the velocity at $\dot{V}O_{2max}$ and time to exhaustion at this velocity. *Sports Med.* 22(2):90-108
- Billat V, Richard R, Binsse VM, Koralsztein JP, Haouzi P (1998) The $\dot{V}O_2$ slow component for severe exercise depends on type of exercise and is not correlated with time to fatigue. *J Appl Physiol* 85:2118-2124
- Borg G (1990) Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* 16(1):55-58
- Demarie S, Koralsztein JP, Billat V (2000) Time limit and time at $\dot{V}O_{2max}$ during a continuous and an intermittent run. *J Sports Med Phys Fitness* 40(2):96-102
- Demarie S, Sardella F, Billat V, Magini W, Faina M (2001) The $\dot{V}O_2$ slow component in swimming. *Eur J Appl Physiol* 84:95-99
- Di Prampero PE (1981) Energetics of muscular exercise. *Rev Physiol Biochem Pharmacol* 89:144–222
- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843

- Faina M, Billat V, Squadrone R, De Angelis M, Koralsztein JP, Dal Monte A (1997) Anaerobic contribution to the time to exhaustion at the minimal exercise intensity at which maximal oxygen uptake occurs in elite cyclists, kayakists and swimmers. *Eur J Appl Physiol* 76:13-20
- Fernandes RJ, Cardoso CS, Soares SM, Ascensão A, Colaço PJ, Vilas-Boas JP (2003) Time limit and $\dot{V}O_2$ slow component at intensities corresponding to $\dot{V}O_{2max}$ in swimmers. *Int J Sports Med* 24(8):576-581
- Fernandes RJ, Keskinen KL, Colaço P, Querido AJ, Machado LJ, Morais PA, Novais D, Marinho D, Vilas-Boas JP (2008) Time limit at $\dot{V}O_{2max}$ velocity in elite crawl swimmers. *Int J Sports Med* 29(2):145-150
- Fernandes RJ, Vilas-Boas JP (2012) Time to exhaustion at the $\dot{V}O_{2max}$ velocity in swimming: A review. *J Hum Kinet* 32:121-134
- Guidetti L, Emerenziani GP, Gallotta MC, Baldari C (2007) Effect of warm up on energy cost and energy sources of a ballet dance exercise. *Eur J Appl Physiol* 99(3):275-281
- Harriss DJ, Macsween A, Atkinson G (2017) Standards for Ethics in Sport and Exercise Science Research: 2018 Update. *Int J Sports Med* 38:1126-1131
- Jones A, Burnley M (2009) Oxygen uptake kinetics: An underappreciated determinant of exercise performance. *Int J Sports Physiol and Perform* 4(4):524-532
- Jones AM, Poole DC (2005) Introduction to oxygen uptake kinetics and historical development of the discipline. In: Jones AM, Poole DC (Eds), *Oxygen uptake kinetics in sport, exercise and medicine*. Routledge, London, pp 3-37
- Libicz S, Roels B, Millet GP (2005) $\dot{V}O_2$ responses to intermittent swimming sets at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 30(5):543-553
- Millet GP, Libicz S, Borrani F, Fattori P, Bignet F, Candau R (2003) Effects of increased intensity of intermittent training in runners with differing $\dot{V}O_2$ kinetics. *Eur J Appl Physiol* 90:50-57
- Pessôa Filho D, Alves F, Reis J, Greco, C, Denadai, B (2012) $\dot{V}O_2$ kinetics during heavy and severe exercise in swimming. *Int J Sports Med* 33(09):744-748.
- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012a) Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *Eur J Appl Physiol* 112(5):1689-1697

- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012b) Oxygen uptake kinetics and middle distance swimming performance. *J Sci Med Sport* 15:58-63
- Reis J, Millet GP, Malatesta D, Roels B, Borrani F, Vleck V, Alves F (2010) Are oxygen uptake kinetics modified when using a respiratory snorkel? *Int J Sports Physiol Perform* 5(3):292-300.
- Rodríguez FA, Mader A (2011) Energy systems in swimming. In: Seifert L, Chollet D, Mujika I (eds) *World Book of Swimming: From Science to Performance*. Nova Science Publishers, Hauppauge, New York, pp 225–240
- Rodríguez, FA, Keskinen, KL, Malvela, MT, Keskinen, OP (2003) Oxygen uptake kinetics during free swimming: A pilot study In: Chatard JC (ed) *Biomechanics and Medicine in Swimming IX*, Publications de l'Université de Saint-Étienne, Saint-Étienne, pp 379-384
- Scheuermann B, Hoelting B, Noble M, Barstow T (2001) The slow component of O₂ uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. *J Physiol* 531(1):245-256
- Simoneau JA, Lortic G, Boulay MR, Marcotte M, Thibault MC, Bouchard C (1987) Effects of two high-intensity intermittent training programs interspaced by detraining on human skeletal muscle and performance. *Eur J Appl Physiol* 56:516-521
- Sousa A C, Fernandes RJ, Boas J P V, Figueiredo P (2018) High-intensity Interval Training in Different Exercise Modes: Lessons from Time to Exhaustion. *Int J Sports Med* 39(9):668-673
- Sousa A, Figueiredo P, Zamparo P, Pyne DB, Vilas-Boas JP, Fernandes RJ (2015) Exercise modality effect on bioenergetical performance at $\dot{V}O_{2max}$ intensity. *Med Sci Sports Exerc* 47(8):1705-1713
- Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190
- Sousa A, Vilas-Boas J, Fernandes R (2014) $\dot{V}O_2$ kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at $\dot{V}O_{2max}$. *Biomed Res Int* 2014:675363

Chapter VI. Study 3

Comparing $\dot{V}O_2$ response during two interval swimming sets at the maximal aerobic velocity

Abstract

Objective: This study aims to analyse the physiological impact of two interval training (IT) swimming sets performed with different work-intervals at maximal aerobic velocity (MAV) and to determinate if physiological variables are related with middle-distance performance.

Design: Twelve swimmers completed a discontinuous incremental test for second ventilatory threshold (VT_2), maximal oxygen uptake (Peak- $\dot{V}O_2$) and MAV assessment. Secondly, two IT sets at MAV until exhaustion, with 100 (IT100) and 200 meters (IT200) bouts, respectively, were performed for $\dot{V}O_2$ maximal value ($\dot{V}O_{2peak}$) and time spent above VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$, determination. To allow a direct comparison between IT's the first 800 meters were considered (IT100_{8x100} vs. IT200_{4x200}). A breath-by-breath apparatus (K4b², Cosmed, Italy) connected to a swimming snorkel was used for gas sampling and an underwater visual pacer used for velocity control. The rate of perceived exertion (RPE) was recorded.

Results: $\dot{V}O_{2peak}$ of the IT's were not different from Peak- $\dot{V}O_2$ and both IT's presented similar physiological responses. $\dot{V}O_{2peak}$ and $M\dot{V}O_{2peak}$ were correlated between IT's and inversely correlated with performance of the 400 meters event. The RPE was significantly lower at the IT100_{8x100} compared to the IT200_{4x200}.

Discussion: Both IT's seemed to be useful for aerobic training purposes with higher oxidative responses being correlated with swimming middle-distance performance. However, independently of the work-intervals the physiological responses were similar, which cannot give a clear indication of which is better to improve aerobic performance. Notwithstanding, considering the first 800-m, the IT100_{8x100} could be a preferable set, as swimmers could perform it easily with the same benefits of the IT200_{4x200}.

Key Words: Interval training; oxygen uptake kinetics; work-interval; performance; swimming

Introduction

Interval Training (IT), namely when performed at the maximal aerobic velocity (MAV), the minimal velocity that elicits the maximal oxygen uptake ($\dot{V}O_{2max}$) (Billat and Koralsztein, 1996) and, in swimming, associated with the velocity of the 400 meters freestyle event (Espada et al., 2015; Zacca et al., 2019), has been proposed as an effective way to improve aerobic power and the MAV itself, variables that are highly related with sports performance (Astrand et al., 1960; Billat, 2001; Denadai et al., 2006; Espada et al., 2015; Libicz et al., 2005, Reis et al., 2012a,b). Additionally, the time sustained during exercise near the $\dot{V}O_2$ maximal values, especially at intensities corresponding to 90% - 100% of $\dot{V}O_{2max}$, seems to be one of the most important factors to promote long term adaptations in order to improve $\dot{V}O_{2max}$ and performance, being used to measure the effectiveness of the training stimulus (Bentley et al., 2005; Billat and Koralsztein, 1996; Billat, 2001; Libicz et al., 2005; Millet et al., 2003a,b; Sousa et al., 2017).

Interval training programming is complex and involves the coordination of several parameters, namely work interval intensity and duration, relief interval intensity and duration, exercise modality, number of repetitions, number of series, between-series recovery duration and intensity (Buchheit and Laursen, 2013a,b) and even though the research on this field dates back to the 60's (Astrand et al., 1960), there are still doubts on how to best define the parameters in order to provide the best results for athletes performance (Millet et al., 2003a).

Generally, it has been reported that longer work-intervals are more efficient for increasing aerobic capacity than short work-intervals (Astrand et al., 1960; Billat, 2001; Wen et al., 2019). However, performing short-duration intervals could allow the athlete to complete longer IT sessions with greater metabolic demands ($\dot{V}O_2$) and lower blood lactate accumulation ($[La^-]$) (Zuniga et al., 2011).

The oxidative rate measured through the $\dot{V}O_2$ kinetics ($\dot{V}O_2K$) has been associated with performance (Jones and Burnley, 2009; Reis et al., 2012a,b; Espada et al., 2015) and could be associated with the time spent near the athletes' $\dot{V}O_2$ maximal values (Millet et al., 2003a,b; Sousa et al., 2018). These

parameters, taken together with other biomarkers of fatigue as $[La^-]$, heart rate (HR) and rate of perceived exertion (RPE) (Libicz et al., 2005) can provide insightful information about the athletes' physiological profiles in an IT session.

Considering that different combinations of the IT parameters truly induce different acute physiological responses, namely the time spent near athletes $\dot{V}O_2$ maximal values, it is crucial to investigate different types of IT, aiming to prescribe more precisely which type of training will actually maximize the desired adaptations in distinct athletes (Bentley et al., 2005; Libicz et al., 2005).

While in the terrestrial modalities the study of IT as already some history, in swimming, probably due the natural constrains that make the swimmers evaluation difficult, there is a lack of studies that evaluate the athletes' physiological responses in real life training settings, mainly regarding to the $\dot{V}O_2$ response (Libicz et al., 2005).

Therefore, the main goal of the present study was to compare the $\dot{V}O_2$ responses in two different swimming intermittent sets, composed by 100 (IT100) or 200 (IT200) meters bouts, at MAV, until exhaustion and to determine which one induces more time near the individual's $\dot{V}O_2$ maximal values. The first 800 meters of each IT session were also considered for analysis, in order to allow a direct comparison between training sets (IT100_{8x100} vs. IT200_{4x200}). We chose this relation of distances/intensities/recovery periods to try to represent two intermittent sets that are usually used by coaches in their daily practice, and on the other hand, that could be of interest according to the literature's previous findings. Furthermore, we aimed to establish if the physiological responses in these IT sessions are related to middle distance swimming performance.

We hypothesize that: 1) both IT sessions will elicit the achievement of the Peak- $\dot{V}O_2$; 2) the IT100 will lead to longer times to exhaustion and consequently to longer times spent near swimmers $\dot{V}O_2$ maximal values; 3) when the IT's are normalized for equal distance-trial, the IT200_{4x200} will present higher values of $\dot{V}O_2$ response, HR, $[La^-]$ and RPE; 4) faster $\dot{V}O_2K$ will promote longer times spent

near swimmers $\dot{V}O_2$ maximal values and lower oxygen initial deficits ($O_{2initialDef}$); and 5) higher $\dot{V}O_2$'s and lower $[La^-]$'s will be related with longer times to exhaustion at the IT sessions and with middle-distance swimming performance.

Methods

Participants

Twelve well-trained swimmers, 5 females and 7 males, participated in this study and were instructed to report to the swimming pool well hydrated, fed and to abstain from caffeine, alcohol and strenuous exercise in the 24 hours preceding the testing sessions. All swimmers gave their written informed consent (or legal guardians when under 18 years old) and were fully familiarised with the equipment and test procedures before the beginning of the test sessions. All the swimmers were regular participants in state or national swimming championships at least in the 3 years prior entering the study.

This study was approved by the local University Ethical Committee (CEFMH: 39/2015) and was conducted in accordance with the 1964 Declaration of Helsinki (Harriss et al., 2017). The descriptive characteristics of the swimmers and their personal best times (PB) at the 400 meters freestyle event (obtained at official competitions in the last 3 months before the study) are presented in table 11.

Table 11. Mean \pm SD of swimmers anthropometrical data and personal best times in competition of the swimmers, N = 12 (5 F, 7 M)

Variable	Female	Male	Combined
Age (yr)	14.2 \pm 1.0	16.1 \pm 1.1	15.3 \pm 1.4
Height (m)	1.58 \pm 0.1	1.76 \pm 0.1	1.69 \pm 0.1
Total Body Mass (kg)	50.6 \pm 5.1	64.8 \pm 7.8	58.9 \pm 9.8
Body Fat (%)	25.3 \pm 2.9	12.5 \pm 2.2	19.6 \pm 6.9
PB400	337.7 \pm 11.3	264.9 \pm 14.4	295.3 \pm 38.2

PB400: personal bests of the swimmers at the 400 meters freestyle event.

Experimental Design

All swimmers performed three testing sessions in a 25-meters swimming pool, separated by at least 48 hours: (1) a discontinuous incremental test; and (2), in randomized order, two different IT sets one composed by 100 and another composed by 200 meters bouts at the MAV, until voluntary exhaustion. The same environmental conditions (time of day \pm 2 hours, water temperature \sim 28°C and relative humidity \sim 50%) and the same pre-test warm up protocol were applied to all tests in order to minimize the effects of circadian rhythms and differences in prior exercise. The sessions were performed in the beginning of the preparatory period of the second macrocycle of the swimmers competitive season, after a period of two weeks for training adaptation.

For the gas sampling analysis, a telemetric portable gas analyser (K4b², Cosmed, Italy) was connected to the swimmers by a respiratory snorkel and valve system (new-AquaTrainer[®], Cosmed, Italy) allowing a breath-by-breath data collection (Reis et al., 2010; Baldari et al., 2012). The K4b² was calibrated before each test according to manufacturer's instructions. All tests were performed in front crawl swimming with in-water starts and open turns without underwater gliding.

A HR monitor (Polar[®], Finland) was coupled to the snorkel and synchronized with the K4b² system to HR data collection. Before the start of the protocol, in the breaks of the incremental test and after all tests (at minutes 1, 3, 5 and 7), capillary blood samples (25 ul) were collected from the swimmers earlobe for [La⁻] analysis (YSI, 2300 STAT, Yellow Springs, USA). RPE was also recorded through the Borg's CR-10 scale (0-10) (Borg, 1990).

For the swimming velocity control, an underwater visual pacer, composed by 26 lights that subsequently light up (Pacer2Swim[®], KulzerTEC, Portugal), was used in order to give to the swimmers an accurate notion of the correct velocity for each test.

Discontinuous incremental test

Firstly, swimmers performed an incremental test, composed by 6 sets of 250 meters, plus 1 set of 200 meters at maximal intensity, with 30 seconds breaks for blood lactate collection (Espada et al., 2015), in order to access the maximal oxygen uptake (Peak- $\dot{V}O_2$), the second ventilatory threshold (VT_2) and the MAV. Peak- $\dot{V}O_{2peak}$ was recorded as the highest 30 seconds average $\dot{V}O_2$ and MAV was considered as the minimal velocity at which the Peak- $\dot{V}O_2$ values were reached (Billat and Koralsztein, 1996). The velocity of the first repetition was set at 50% of swimmers 200 meters velocity and increments of 5 to 10% were imposed in the rest of the repetitions, until the final maximal set or until swimmers voluntary exhaustion.

Interval training sets

Secondly, in complementary days and in a randomized order, swimmers performed two different intermittent swimming tests at the MAV, until voluntary exhaustion: (1) a set composed by 100 meters repetitions (IT100) with 15 seconds breaks, and (2) a set composed by 200 meters repetitions (IT200) with 30 seconds breaks. To allow a direct comparison between IT sessions, the first 800 meters of each IT were considered separately, in order to evaluate the same overall time swum (IT100_{8x100} and IT200_{4x200}, respectively for the IT's performed with 100 and 200 meters bouts).

For each session, the maximal oxygen uptake value ($\dot{V}O_{2peak}$) was registered and the $\dot{V}O_{2peak}$ of each repetition was averaged to calculate the mean $\dot{V}O_{2peak}$ ($M\dot{V}O_{2peak}$) of the whole set. Also, the time spent by the swimmers above the VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$ during the set and the corresponding percentage for the total duration of the set, as well as the oxygen deficit at the onset of exercise ($O_{2InitialDef}$), maximal $[La^-]$ and the $\dot{V}O_2K$ parameters of the respective first bouts, were determined.

Data analysis

Firstly, for exclusion of outliers caused by abrupt breaths or coughing, $\dot{V}O_2$ data were cleaned by the exclusion of values lying over three standard deviations (SD) from the local mean. For $\dot{V}O_2$ peak determination a 30 seconds moving average was used for the incremental and intermittent tests. $\dot{V}O_2$ data was further interpolated into 1-second values and all values above the $VT_{2, 90\%, 95\%}$ of Peak- $\dot{V}O_2$ were registered in order to achieve the total duration that swimmers spent above the referred physiological thresholds. Then, the respective percentage values for the total duration of each IT session were calculated.

The first bout of each IT session was used in order to determinate the $\dot{V}O_{2K}$ parameters (time delay (TD), time constant (τ), mean response time ($MRT = \tau + TD$) and amplitude (A). To remove the influence of the cardiodynamic phase on the subsequent $\dot{V}O_2$ response, the first 20 seconds of data were removed from analysis (Reis et al., 2012a, b; Pessôa Filho et al., 2012; Espada et al., 2015). As described before by Reis et al (2012a) an individual “snorkel delay” (ISD), that corresponds to the difference between the onset of exercise and the time when the following breaths summed up a tidal volume superior to the outlet tube volume, was calculated for each test. The ISD was adapted to the specific characteristic of the snorkel device used in this study and then integrated into the time delay of the $\dot{V}O_2$ response.

The $\dot{V}O_{2K}$ parameters were calculated through an iterative procedure, by minimizing the sum of the mean squares of the differences between the modelled and the measured $\dot{V}O_2$ values. Similarly to previous studies (Rodríguez et al., 2003; Sousa et al., 2013), at these maximal intensities we did not observe a secondary rise on the $\dot{V}O_2$ response (slow component), therefore we opted for a monoexponential modelling, according to the following equation (Jones and Poole, 2005):

$$\dot{V}O_{2(t)} = \dot{V}O_{2base} + A \cdot (1 - e^{-(t-TD)/\tau})$$

Where $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest, which was calculated as the average of the first 30 seconds of the last minute before the start of the exercise (after 10 minutes of passive rest); TD, τ , and A, represent the time delay, the time constant (time that is needed to complete 63% of the $\dot{V}O_2$ response) and the amplitude of the exponential response of the $\dot{V}O_2$.

Statistical Analysis

Normality and homogeneity of data were confirmed with Shapiro-Wilk and Levene tests, then, independent T-tests were applied to all variables to check the differences between sexes and the differences between tests were tested for statistical significance using ANOVA for repeated measures with Bonferroni correction. At last, the Pearson's linear correlation coefficient was used in order to establish the significant associations between physiological measures and swimmers' performance. All statistical analyses were performed with the Statistical Package for the Social Sciences (version 25.0; SPSS, Chicago, IL, USA) and statistical significance was accepted at $p < 0.05$.

Results

Swimmers physiological responses at the discontinuous incremental test were $59.2 \pm 4.2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, $52.0 \pm 3.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, $87.9 \pm 3.1\%$, $1.27 \pm 0.1 \text{ m}\cdot\text{s}^{-1}$, $187.2 \pm 8.5 \text{ b}\cdot\text{min}^{-1}$, $9.7 \pm 3.1 \text{ mmol}\cdot\text{l}^{-1}$, respectively for Peak- $\dot{V}O_2$, VT_2 , percentage value of VT_2 to Peak- $\dot{V}O_2$, MAV, maximal HR and maximal $[La^-]$.

The physiological responses at the IT sessions and the $\dot{V}O_2K$ parameters of the corresponding first bouts are presented in table 12.

Table 12. Mean \pm SD of the physiological responses at the intermittent sets and $\dot{V}O_2$ parameters of the corresponding first bouts (N = 12, 5 F, 7 M)

Variable	IT100 _{8x100}	IT200 _{4x200}	IT100	IT200
$\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	57.3 \pm 4.9	57.2 \pm 4.6	57.5 \pm 5.0	57.3 \pm 4.4
% $\dot{V}O_{2peak}$ (% to Peak- $\dot{V}O_2$)	96.8 \pm 5.8	96.7 \pm 4.4	97.1 \pm 5.9	96.8 \pm 3.8
M $\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	54.5 \pm 4.2	55.2 \pm 4.0	54.3 \pm 4.1	55.1 \pm 4.1
%M $\dot{V}O_{2peak}$ (% to Peak- $\dot{V}O_2$)	92.1 \pm 4.6	93.3 \pm 4.5	91.8 \pm 4.6	93.3 \pm 4.8
HR (b·min ⁻¹)	183.8 \pm 8.0	191.6 \pm 7.0	184.4 \pm 8.9	191.6 \pm 7.0
Peak [La ⁻] (mmol·l ⁻¹)	-	-	7.9 \pm 3.4	8.7 \pm 1.5
RPE (0 - 10 units)	7.62 \pm 2.0*	9.5 \pm 0.7*	9.4 \pm 0.9	9.7 \pm 0.9
Distance (m)	800	800	1308.3 \pm 611.7	1016.7 \pm 403.8
TLim (s)	-	-	1034.8 \pm 462.8	826.1 \pm 302.7
\geq LV2 (s)	274.7 \pm 89.9	290.1 \pm 104.9	412.8 \pm 202.6	325.2 \pm 109.5
\geq LV2 (%)	42.9 \pm 13.7	43.4 \pm 14.9	42.4 \pm 15.8	42.6 \pm 14.7
\geq 90% of Peak- $\dot{V}O_2$ (s)	208.0 \pm 118.2	234.4 \pm 114.8	306.9 \pm 216.4	218.4 \pm 122.1
\geq 90% of Peak- $\dot{V}O_2$ (%)	32.4 \pm 17.4	35.0 \pm 16.3	31.9 \pm 19.3	29.1 \pm 17.8
\geq 95% of Peak- $\dot{V}O_2$ (s)	97.3 \pm 95.8**	103.8 \pm 115.4**	147.5 \pm 143.1	86.2 \pm 109.1
\geq 95% of Peak- $\dot{V}O_2$ (%)	12.9 \pm 14.6**	15.3 \pm 17.0**	15.0 \pm 15.1	11.8 \pm 16.5
$\dot{V}O_{2peak}$ 1 st bout (ml·kg ⁻¹ ·min ⁻¹)	-	-	50.4 \pm 4.3	53.3 \pm 3.7*
τ (s)	-	-	24.9 \pm 8.4	25.1 \pm 6.3
O ₂ InitialDef (mlO ₂)	-	-	1705.4 \pm 678.9	1555.4 \pm 377.4

$\dot{V}O_{2peak}$ and % $\dot{V}O_{2peak}$: maximal $\dot{V}O_2$ achieved in the test and corresponding percentage to Peak- $\dot{V}O_2$; M $\dot{V}O_2$ and %M $\dot{V}O_{2peak}$: average value of the $\dot{V}O_{2peak}$ achieved in the repetitions of the set and corresponding percentage to Peak- $\dot{V}O_2$; Peak [La⁻]: maximal blood lactate concentration at the end of the set; \geq VT₂, \geq 90% of Peak- $\dot{V}O_2$ and \geq 95% of peak- $\dot{V}O_2$: time with $\dot{V}O_2$ values at or above the VT₂, 90% and 95% of the Peak- $\dot{V}O_2$, and corresponding percentage values for the total duration of each test; * statistical difference between IT sessions for p<0.05; ** statistical differences to the \geq VT₂ and \geq 90% of Peak- $\dot{V}O_2$ for p<0.05.

A typical response of the $\dot{V}O_2$ at the IT sessions for the first 800 meters is demonstrated in figure 21.

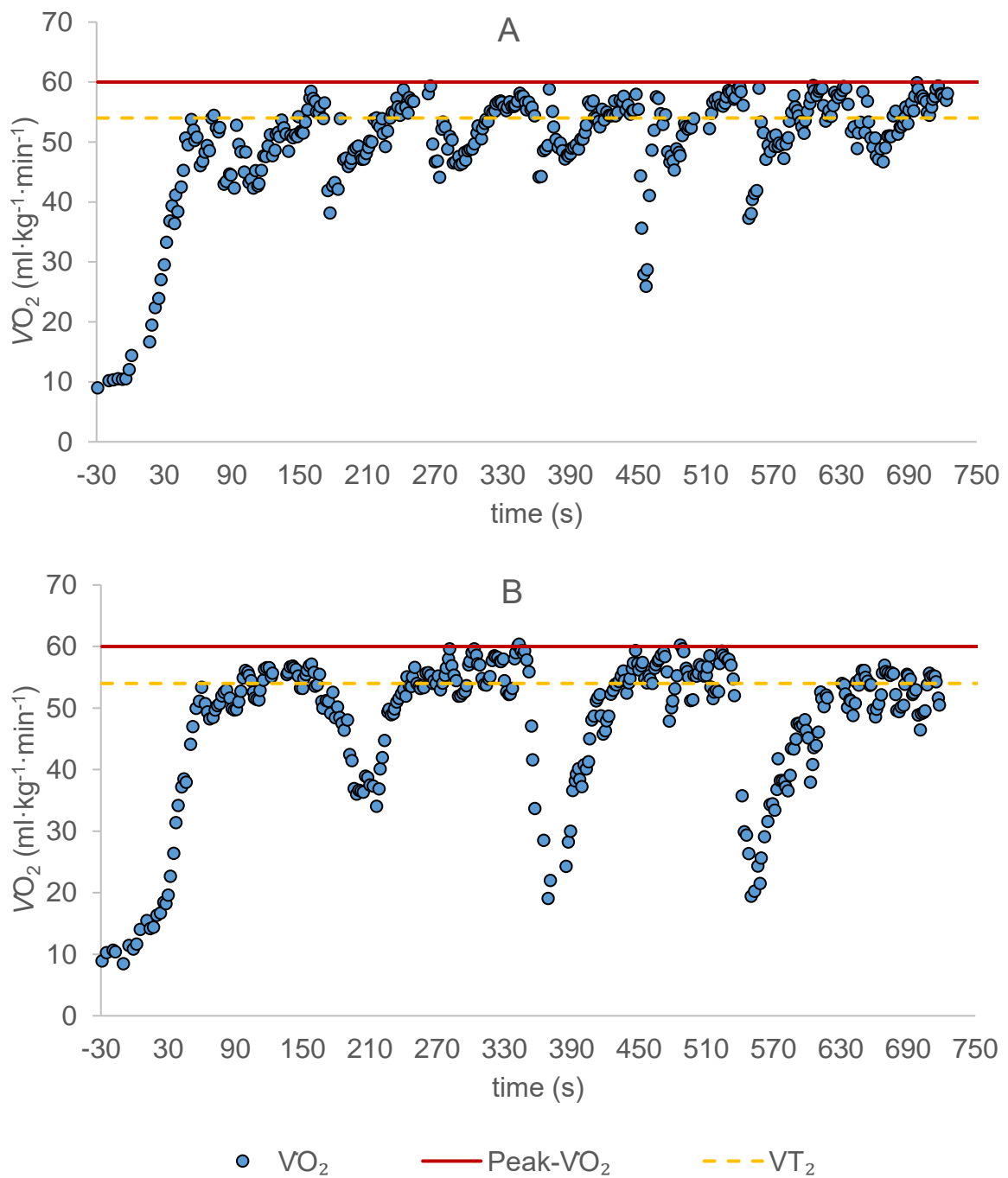


Figure 21. Example of the $\dot{V}O_2$ response profiles of the first 800 meters of the participant n° 8 at the IT100 (panel A) and at the IT200 (panel B). The participant's Peak- $\dot{V}O_2$ and VT_2 are marked by the red line and orange dash line, respectively.

Both sexes presented similar profiles at the IT sessions, without statistically significant differences observed in the studied variables. The $\dot{V}O_2$ response was quite similar between the two IT sessions, either analysing the whole set or just the first 800 meters, since the $\dot{V}O_{2K}$ parameters, $\dot{V}O_{2peak}$, $M\dot{V}O_{2peak}$ and the time sustained above $VT_{2, 90\%}$ and 95% of the Peak- $\dot{V}O_2$, or the corresponding percentage values for the total duration of the IT tests did not evidence statistically significant differences. Also, the other physiological variables did not show significant differences between the IT sessions, with the exception to the RPE that was significantly higher at the IT200_{4x200} compared to the IT100_{8x100}.

Even though the TLim at the IT100 was ~209 seconds longer than the IT200, the difference was not statistically significant. Nevertheless, this variable was strongly correlated between the IT sessions ($r = 0.93$, $p < 0.01$) and inversely correlated with the peak $[La^-]$ ($r = -0.69$, $p < 0.01$) at the IT200 test.

The $\dot{V}O_{2peak}$'s of the IT sessions were not statistically different from the Peak- $\dot{V}O_2$ achieved in the incremental test, being also correlated with this variable ($r = 0.91$ and $r = 0.77$, $p < 0.05$, respectively for IT100 and IT200). Both $\dot{V}O_{2peak}$'s and $M\dot{V}O_{2peak}$'s were positively correlated between both IT sessions ($r = 0.72$ and $r = 0.70$, $p < 0.01$, respectively), and inversely associated with the swimmers 400 meters performance ($r = -0.58$ and $r = -0.68$, $p < 0.05$, respectively for IT100; and $r = -0.61$ and $r = -0.58$, $p < 0.05$, respectively for IT200).

Maximal HR at the IT200 and peak $[La^-]$ at the IT100 were correlated with better performances at the 400 meters swimming ($r = 0.52$ and $r = 0.78$, $p < 0.01$, respectively). Peak $[La^-]$ at the IT100 was also inversely correlated with the MAV ($r = -0.56$, $p < 0.01$).

The time constant of the first bouts was also correlated between both IT sessions ($r = 0.73$, $p < 0.01$), showing that the swimmers with faster kinetics in one IT session were those who presented faster kinetics in the other IT session. Furthermore, both time constants were correlated with the respective $O_{2initialDef}$ ($r = 0.89$ and $r = 0.90$, $p < 0.01$, for IT100 and IT200, respectively).

Discussion

The main goal of the present study was to analyse the $\dot{V}O_2$ response in two different swimming intermittent sets at MAV composed by 100 vs. 200 meters bouts until exhaustion, determining the time sustained near $\dot{V}O_2$ maximal values, as well as if physiological variables are related to middle-distance swimming performance. We also analysed the first 800 meters of each IT in order to allow a direct comparison between both sessions (8x100 vs. 4x200 meters).

The main finding of the present study is that two interval training sessions at the MAV, broken either in 100 or 200 meters bouts, with 15 and 30 seconds rest respectively, induced a similar physiological response to the swimmers. Nevertheless, when the same overall distance is considered (the first 800 meters) there was a significantly higher RPE in the IT200_{4x200}, which seems to indicate that the swimmers could perform IT100_{8x100} more easily with the same physiological benefits that is obtained with the IT200_{4x200}.

The results of the present study indicate that: 1) there was no significant differences between the $\dot{V}O_{2peak}$'s attained in the two interval sets and the Peak- $\dot{V}O_2$ achieved at the incremental test. Also, the time sustained above VT_2 , 90% and 95% of Peak- $\dot{V}O_2$ suggests that both IT protocols could be suitable for aerobic performance improvement, which corroborates our first hypothesis; 2) the absence of statistical differences at the times to exhaustion and times spent above VT_2 , 90% and 95% of Peak- $\dot{V}O_2$ between the IT sessions performed with 100 or 200 meters bouts, showed a similar profile of swimmers responses between IT's, rejecting our second hypothesis; 3) our third hypothesis was also rejected since, when the first 800 meters of each IT session was considered, we found a quite similar $\dot{V}O_2$ response between both IT sessions, considering that the $\dot{V}O_{2peak}$, the $M\dot{V}O_{2peak}$ and the time sustained above the studied thresholds (or percentage values for the total duration of each set) as well as maximal HR and $[La^-]$ were not significantly different. However, the IT200_{4x200} presented a significantly higher RPE compared to IT100_{8x100}; 4) our fourth hypothesis was also not confirmed since faster $\dot{V}O_2K$ was not associated with longer times spent

above the studied physiological thresholds. Furthermore, the time constants were not significantly correlated with longer times to exhaustion, higher $\dot{V}O_{2peak}$'s or lower $[La^-]$. However, faster $\dot{V}O_{2K}$, leading to lower $O_{2InitialDef}$, could be responsible for an initial spare of the anaerobic contribution of each repetition of the IT sessions, as it could accelerate the rise of the oxidative contribution making the exercise more efficient for the swimmers with faster $\dot{V}O_{2K}$; 5) finally, our fifth hypothesis was confirmed since higher oxidative rates and lower values of HR and $[La^-]$ at the IT sessions seem to be associated to longer times to exhaustion and to better swimming performances at the 400 meters freestyle event. Also, swimmers with higher MAV's seems to be capable to perform the IT100 more efficiently, with lower values of $[La^-]$.

Several studies have pointed out an optimal improvement in aerobic fitness at intensities corresponding to about 90-100% of $\dot{V}O_{2max}$, with the time sustained at these intensities being one of the most important factors to induce long term adaptations (Billat et al., 1996; Billat, 2001; Millet et al., 2003a,b; Libicz et al., 2005; Bentley et al., 2005; Sousa et al., 2017). Is it also, recognized that compared to continuous exercise, the high intensity interval training is more effective for the improvement of the aerobic parameters (Demarie et al., 2000; Helgerud et al., 2007).

To the best of our knowledge, only two studies analysed the athletes $\dot{V}O_2$ response in swimming during IT sessions (Libicz et al., 2005; Bentley et al 2005). Libicz et al. (2005), reported that, in well-trained triathletes, even though the time spent above 95% of $\dot{V}O_{2max}$ was twice as long using 8x100 than with 16x50 meters repetitions, the results were not statistically different, probably because of the large variability observed in the $\dot{V}O_2$ data of the athletes. Our IT100_{8x100} results are in line with those presented in the Libicz' study for the same IT set.

Bentley et al. (2005), also measured the time sustained near the $\dot{V}O_{2max}$ (>90% of $\dot{V}O_{2max}$) in two IT swimming sessions comprising 4x400 and 16x100 meters bouts, this time with well-trained swimmers but at a submaximal intensity corresponding to 25% of the difference between the gas exchange threshold and

the $\dot{V}O_{2max}$. The authors concluded that, for the same exercise intensity, increasing the duration of the work interval did not influence the duration that was sustained above 90% of $\dot{V}O_{2max}$ and maximal HR, nor the highest $\dot{V}O_2$ that was reached during each IT session. Similarly to our study, these authors reported no correlation between faster $\dot{V}O_2K$ and longer times spent near $\dot{V}O_{2max}$ values.

Also, Millet et al. (2003b) reported no significant relationship between the time constant of the $\dot{V}O_2K$ and the time spent by runners above 90% of $\dot{V}O_{2max}$ in IT sets performed at 100% or 105% of MAV. However, the authors reported an interesting fact that the runners with slower kinetics incur in a greater increase on the time spent above 90% of $\dot{V}O_{2max}$ when comparing the two intensities, assuming that the increase in O_2 availability caused by prior heavy exercise could be greater in subjects with slower kinetics, suggesting that these athletes could benefit more from an increase in work intensity or a reduction of the recovery interval on an IT set, in order to improve $\dot{V}O_{2max}$.

The absence of relationship between fast $\dot{V}O_2K$ and the capacity of performing an IT set with longer times near the individual's $\dot{V}O_2$ maximal values observed in our study, but also reported by the Bentley's and Millet's studies is somewhat unexpected since, theoretically, if an athlete could rise faster their $\dot{V}O_2$ it should be reasonable to expect that he/she will spend more time near $\dot{V}O_{2max}$. However, it seems that it does not occur. Maybe other factors that are responsible for maintaining the $\dot{V}O_2$ higher during the set, as other biomarkers of fatigue, as [La⁻] or kinematical parameters, could help to explain this lack of relationship. Nevertheless, further investigations are needed in this regard in order to unveil our doubts.

In our study, the $\dot{V}O_{2peak}$'s and $M\dot{V}O_{2peak}$'s were correlated between both IT sessions and with the Peak- $\dot{V}O_2$ obtained at the incremental test, showing that independently of the type of the IT session, higher $\dot{V}O_2$ responses were presented by the same swimmers. Furthermore, in both IT sessions, these variables were associated with better performances at the 400 meters freestyle events. Dalamitros et al. (2016), testing the efficacy of an IT swimming 8-week

program using 6-8x100 meters bouts (similar to our IT100_{8x100}), observed significant improvements in $\dot{V}O_{2max}$, MAV and swimming performance in the 100 and 400 meters freestyle events. In their study the $\dot{V}O_2$ response was not analysed during the IT sessions, however, accordingly to our findings we can speculate that higher $\dot{V}O_2$ responses during the program could be responsible for those improvements.

Regarding the time constant, the results demonstrated that there is a correlation between both IT sessions, proving that swimmers with faster kinetics in one IT presented faster kinetics in the other session, which seems to suggest that the swimmers who were aerobically more developed (faster $\dot{V}O_2K$ with higher values of $\dot{V}O_2$) in the IT100 were also those who presented better $\dot{V}O_2$ responses in the IT200. Similarly, the swimmers that performed the IT sessions with higher $\dot{V}O_2$ responses were those that also presented better performances at the 400 meters, freestyle event, in accordance with previous studies that related, also, higher Peak- $\dot{V}O_2$'s to the performance of the same event (Espada et al., 2015, Reis et al., 2012b), probably because of the high aerobic demand reported for this swimming distance (Rodríguez and Mader, 2011).

At the MAV swimmers spent a considerable time near the Peak- $\dot{V}O_2$ at both IT sessions (i.e. ~43% above VT_2). In order to improve the time spent near the $\dot{V}O_2$ maximal values, we suggest that higher intensities could actually be imposed at these specific IT sessions. However, the increments of intensities in IT sessions should be applied with caution since when the intensities rise much above the MAV intensity, the benefits on the physiological adaptations seem to stop as reported by Raleigh et al. (2017) when testing an IT program performed in cycle ergometer. These authors concluded that, in an IT 3-week program using intensities of 80, 115 and 150% of MAV, the 115% intensity showed the better response in the athletes' physiological adaptations, with a lower percentage of non-responders, suggesting that training at intensities around the $\dot{V}O_{2max}$ may represent a threshold intensity above which further increases in intensity do not provide additional adaptive benefits for the aerobic capacity development. Also, running IT sessions at 115% of MAV did not show differences at the time spent

above 95% of $\dot{V}O_{2max}$ when compared with the same IT session performed only at 105% of MAV (Wakefield and Glaister, 2009), and a 4-week IT running program at 100% of MAV showed improvements at the MAV, running economy and at the 1500 meters running performance, improvements that were not observed when compared with the same program performed at 95% of MAV (Denadai et al., 2006). Finally, Billat et al. (1999) testing intensities that allow runners to achieve the longest time near the $\dot{V}O_{2max}$ suggested the 100%-MAV condition as the one preferable instead of the 90, 120 and 140%-MAV conditions. Nonetheless, if we speculate that in the IT100_{8x100} an increment of intensity, in order to improve the time spent near the $\dot{V}O_2$ maximal values, can be practiced by swimmers (RPE ~8/10), in the IT200_{4x200} we could speculate that the increment of the intensity will lead to swimmers fatigue even before the 4th bout, as we observed in several swimmers great difficulty to finish the fourth bout at the MAV (RPE ~10/10).

Libicz et al. (2005) argues that an IT set that shows longer times spent near $\dot{V}O_{2max}$ values per se, could not necessarily be the best one to improve endurance and performance, if, at the same time, it was the one which induces an excessive muscular fatigue or acidosis, being therefore also important to understand other biomarkers of fatigue. Accordingly, Zuniga et al. (2011) reported that short work-intervals (30 seconds) compared with longer ones (3 minutes) may allow the athletes to complete longer IT sessions with greater metabolic demands and lower [La⁻] accumulations. Also, Warr-di Piero et al. (2018) showed that short work-intervals (below 60 seconds) allow to complete a IT session with lower [La⁻] and PRE compared to longer ones, reporting a significant direct correlation between these variables. In our study, we did not measure the lactate concentration at the end of each 800 meters (only in the end of each session), however we can speculate that at the end of the 800 meters, besides a similar $\dot{V}O_2$ response, athletes could have presented a lower muscular fatigue and acidosis at the IT100_{8x100}, since they reported significantly lower RPE's. Furthermore, the correlations observed at the maximal HR and peak [La⁻] variables, suggests that the swimmers that could perform the IT sessions in a

more efficient way (with lower HR and $[La^-]$) could also hold the intensity prescribed at the IT200 longer and were those who presented better results at the 400 meters freestyle event.

An important observation, that must be made after the analysis of our data, is related to the referential used for the time spent near swimmers $\dot{V}O_2$ maximal values, since in the literature different studies have been using different referentials (i.e. >90% or >95% of $\dot{V}O_{2max}$). Our study was the first to compare, in IT swimming, different physiological thresholds (VT_2 , 90% and 95% of Peak- $\dot{V}O_2$) and the results showed that significantly lower values were found between the $\geq 95\%$ of Peak- $\dot{V}O_2$ to the remaining physiological thresholds (no significant differences were found between the $\geq VT_2$ and $\geq 90\%$ of Peak- $\dot{V}O_2$). This fact should alert researchers that the observations performed for one percentage of Peak- $\dot{V}O_2$ could significantly differ when another percentage is used.

The findings of the present study might be quite useful from a practical point of view, namely for the training prescription by coaches, with the aim to improve the athletes aerobic performance. Swimmers were efficient at the physiological point of view, when working with 100 or 200 meters bouts, since they presented $\dot{V}O_2$ responses that elicit $\dot{V}O_2$ values similar to the Peak- $\dot{V}O_2$ obtained at the incremental test, which lead them to spend a considerable amount of time near their $\dot{V}O_2$ maximal values. Despite those similarities, considering the first 800 meters, the results suggested a swimmers' preference for the IT performed with 100 meters bouts, since they could easily perform this IT session (with a lower RPE) getting similar physiological responses as those obtained with 200 meters bouts.

Our main conclusion is that when working with IT sets at MAV, with 100 or 200 meters bouts, no significant differences occur at the physiological point of view that can give us a clear suggestion of which one should be better for the aerobic capacity development. However, both IT sets are suitable for eliciting the Peak- $\dot{V}O_2$ and promote longer times spent near the swimmers' maximal $\dot{V}O_2$ values. Notwithstanding, coaches should consider to implement the IT100 with 15

seconds rest, instead of the IT200 with 30 seconds rest at MAV, given the fact that swimmers will easily perform with similar physiological benefits. Finally, since higher $\dot{V}O_2$'s at both IT sessions seems to be related with swimming middle-distance performance, it suggests that these training sets could be used by coaches in order to enhance swimmers aerobic parameters and performance.

References of chapter VI

- Astrand I, Astrand P, Christensen E, Hedman, R (1960) Circulatory and respiratory adaptations to severe muscular work. *Acta Physiol Scand* 50:254-258
- Baldari C, Fernandes R, Meucci M, Ribeiro J, Vilas-Boas JP, Guidetti L (2012) Is the new aquatrainer® snorkel valid for $\dot{V}O_2$ assessment in swimming? *Int J Sports Med* 34(04):336-344
- Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP (2005) Physiological responses during submaximal interval swimming training: effects of interval duration. *J Sci Med Sport* 8:392-402
- Billat LV (2001) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. *Sports Med* 31(1):13-31
- Billat V, Koralsztein JP (1996) Significance of the velocity at $\dot{V}O_{2max}$ and time to exhaustion at this velocity. *Sports Med.* 22(2):90-108
- Billat VL, Blondel N, Berthoin S (1999) Determination of the velocity associated with the longest time to exhaustion at maximal oxygen uptake. *Eur J Appl Physiol Occup Physiol* 80(2):159–161
- Borg G (1990) Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* 16(1):55-58
- Buchheit M, Laursen PB (2013a) High-Intensity Interval Training, Solutions to the Programming Puzzle Part I: Cardiopulmonary Emphasis. *Sports Med* 43(5):313-338
- Buchheit M, Laursen PB (2013b) High-Intensity Interval Training, Solutions to the Programming Puzzle Part II: Anaerobic Energy, Neuromuscular Load and Practical Applications. *Sports Med* 43(10):927-954
- Dalamitros A, Zafeiridis A, Toubekis A, Tsalis G, Pelarigo J, Manou V, Kellis S (2016) Effects of Short-Interval and Long-Interval Swimming Protocols on Performance, Aerobic Adaptations, and Technical Parameters. *J. Strength Cond Res* 30(10):2871-2879
- Demarie S, Koralsztein JP, Billat V (2000) Time limit and time at $\dot{V}O_{2max}$ during a continuous and an intermittent run. *J Sports Med Phys Fitness* 40(2):96-102

- Denadai B, Ortiz M, Greco C, de Mello M (2006) Interval training at 95% and 100% of the velocity at $\dot{V}O_{2max}$: effects on aerobic physiological indexes and running performance. *Appl Physiol Nutr Metab* 31(6):737-743
- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843
- Harriss DJ, Macsween A, Atkinson G (2017) Standards for Ethics in Sport and Exercise Science Research: 2018 Update. *Int J Sports Med* 38:1126-1131
- Helgerud J, Hoydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, Ragnhild B, Hoff J (2007) Aerobic high-intensity intervals improve $\dot{V}O_{2max}$ more than moderate training. *Med Sci Sports Exerc* 39(4):665-671
- Jones A, Burnley M (2009) Oxygen uptake kinetics: An underappreciated determinant of exercise performance. *Int J Sports Physiol and Perform* 4(4):524-532
- Jones AM, Poole DC (2005) Introduction to oxygen uptake kinetics and historical development of the discipline. In: Jones AM, Poole DC (Eds), *Oxygen uptake kinetics in sport, exercise and medicine*. Routledge, London, pp 3-37
- Libicz S, Roels B, Millet GP (2005) $\dot{V}O_2$ responses to intermittent swimming sets at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 30(5):543-553
- Millet GP, Candau R, Fattori P, Bignet F, Varray A (2003a) $\dot{V}O_2$ responses to different intermittent runs at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 28:410-423
- Millet GP, Libicz S, Borrani F, Fattori P, Bignet F, Candau R (2003b) Effects of increased intensity of intermittent training in runners with differing $\dot{V}O_2$ kinetics. *Eur J Appl Physiol* 90:50-57
- Pessôa Filho D, Alves F, Reis J, Greco, C, Denadai, B (2012) $\dot{V}O_2$ kinetics during heavy and severe exercise in swimming. *Int J Sports Med* 33(09):744-748
- Raleigh J, Giles M, Scribbans T, Edgett B, Sawula L, Bonafiglia J, Graham R, Gurd B (2016) The impact of work-matched interval training on $\dot{V}O_{2peak}$ and $\dot{V}O_2$ kinetics: diminishing returns with increasing intensity. *Appl Physiol Nutr Metab* 41(7):706-713
- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012a) Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *Eur J Appl Physiol* 112(5):1689-1697

- Reis J, Alves F, Bruno P, Vleck V, Millet G (2012b) Oxygen uptake kinetics and middle distance swimming performance. *J Sci Med Sport* 15:58-63
- Reis J, Millet GP, Malatesta D, Roels B, Borrani F, Vleck V, Alves F (2010) Are oxygen uptake kinetics modified when using a respiratory snorkel? *Int J Sports Physiol Perform* 5(3):292-300
- Rodríguez FA, Mader A (2011) Energy systems in swimming. In: Seifert L, Chollet D, Mujika I (eds) *World Book of Swimming: From Science to Performance*. Nova Science Publishers, Hauppauge, New York, pp 225–240
- Rodríguez, FA, Keskinen, KL, Malvela, MT, Keskinen, OP (2003) Oxygen uptake kinetics during free swimming: A pilot study In: Chatard JC (ed) *Biomechanics and Medicine in Swimming IX*, Publications de l'Université de Saint-Étienne, Saint-Étienne, pp 379-384
- Sousa A C, Fernandes RJ, Boas JPV, Figueiredo P (2018) High-intensity Interval Training in Different Exercise Modes: Lessons from Time to Exhaustion. *Int J Sports Med* 39(9):668-673
- Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190
- Sousa A, Vilas-Boas JP, Fernandes RJ, Figueiredo P (2017) $\dot{V}O_2$ at maximal and supramaximal intensities: lessons to high-intensity interval training in swimming. *Int J Sports Physiol Perform* 12(7):872-877
- Wakefield B, Glaister M (2009) Influence of work-interval intensity and duration on time spent at a high percentage of $\dot{V}O_{2max}$ during intermittent supramaximal exercise. *J Strength Cond Res* 23(9):2548-2554
- Warr-di Piero D, Valverde-Esteve T, Redondo-Castán JC, Pablos-Abella C, Sánchez-Alarcos Díaz-Pintado JV (2018) Effects of work-interval duration and sport specificity on blood lactate concentration, heart rate and perceptual responses during high intensity interval training. *PLoS One* 13(7):e0200690
- Wen D, Utesch T, Wu J, Robertson S, Liu J, Hu G, Chen H (2019) Effects of Different Protocols of High Intensity Interval Training for $\dot{V}O_{2max}$ Improvements in Adults: A Meta-Analysis of Randomised Controlled Trials. *J Sci Med Sport* 22(8):941-947
- Zacca R, Azevedo R, Silveira RP, Vilas-Boas JP, Pyne DB, de S. Castro FA, Fernandes RJ (2019) Comparison of incremental intermittent and time trial testing in age-group swimmers. *J Strength Cond Res* 33(3):801-810

Zuniga J, Berg K, Noble J, Harder J, Chaffin M, Hanumanthu V (2011) Physiological Responses during Interval Training with Different Intensities and Duration of Exercise. *J. Strength Cond Res* 25(5):1279-1284

Chapter VII. Study 4

Physiological responses at similar high-intensity interval training sets performed with different intensities in swimming

Abstract

Objective: The interval training (IT) has been proposed as an effective way to improve aerobic performance. However, in swimming, the studies are scarce and focus on different distances with the same intensity (Libicz et al., 2005; Bentley et al., 2005), and do not analyse the effect that different intensities could impose on swimmer's physiological responses. The aim of this study is to analyse the oxygen uptake response ($\dot{V}O_2$) during a high-intensity interval training (HIT) set performed at different intensities and compare HIT sets performed with 50 and 100 meters' bouts, in swimming.

Methods: Fourteen well trained swimmers, 7 females and 7 males, completed a discontinuous incremental test for the assessment of second ventilatory threshold (VT_2), maximal oxygen uptake (Peak- $\dot{V}O_2$) and maximal aerobic velocity (MAV), which corresponds to the minimal velocity at which the Peak- $\dot{V}O_2$ is achieved. In 4 different days and in randomized order, swimmers performed 4 broken 400m intermittent swimming tests (IT): (a) 3 sets of 8x50m (IT50) at 100%, 105% and 110% of MAV with 15 seconds rest, and (b) 4x100m (IT100) at 100% of MAV, with 15s rest. For each IT session, mean ($M\dot{V}O_{2peak}$) and maximal oxygen uptake ($\dot{V}O_{2peak}$) and time spent above VT_2 , 90% and 95% of Peak- $\dot{V}O_2$ were recorded. All tests were conducted using a breath-by-breath apparatus (K4b², Cosmed, Italy) connected to a swimming snorkel (new-AquaTrainer[®], Cosmed, Italy) for pulmonary gas sampling and an underwater visual pacer for velocity control (Pacer2Swim[®], KulzerTEC, Portugal).

Results: $M\dot{V}O_{2peak}$ and $\dot{V}O_{2peak}$ in the HIT50' at 100%, 105% and 110%-MAV were higher as the intensity increases, ($42.94 \pm 4.65/45.83 \pm 4.62$ vs. $46.19 \pm 5.37/49.07 \pm 5.14$ vs. $49.69 \pm 5.34/52.92 \pm 5.21$ ml·kg⁻¹·min⁻¹, respectively). Time spent above VT_2 showed the same profile (34.8 ± 43.4 vs. 113.1 ± 68.9 vs. 199 ± 68.5 s for 100%, 105% and 110%-MAV, respectively). At the HIT100, the $M\dot{V}O_{2peak}$ (47.34 ± 4.65 ml.kg.min⁻¹) and time above VT_2 (144 ± 68.8 seconds) were different from the HIT50 at 100%-MAV but not from HIT50' at 105% and 110%-MAV. Peak- $\dot{V}O_2$ from the incremental test (52.07 ± 4.5 ml·kg⁻¹·min⁻¹) was

significantly different from HIT50' $\dot{V}O_{2peak}$ at 100%-MAV and 105%-MAV, but not from 110%-MAV or HIT100' $\dot{V}O_{2peak}$ ($49.07 \pm 4.79 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). MAV ($1.24 \pm 0.09 \text{ m}\cdot\text{s}^{-1}$) was correlated with the time spent above VT_2 ($r = 0.60$, $p < 0.05$), mean and $\dot{V}O_{2peak}$ ($r = 0.56$, $p < 0.05$ and $r = 0.62$, $p < 0.05$, respectively) at the 110%-MAV HIT50's test.

Discussion: The results suggested that higher swimming velocities than 100%-MAV are better to keep oxidative rate at maximal level (6 to 13% higher) and improve tolerance (~20 to 46%) to swimming in severe domain (ie, above VT_2), whilst training with short distance bouts (50-m). These results are in line with Millet et al (2003a) for running at 100 and 105% of MAV. In HIT50 sessions higher MAVs seem to be related with better performance at the highest intensity (110%-MAV), the only test where Peak- $\dot{V}O_2$ was achieved. Seeking for training schedule effectiveness to improve endurance and aerobic power, the results recommend IT50 tests at least at 105%-MAV, which attained oxidative rates similar to HIT100 at 100%-MAV.

Key words: High-intensity interval training; short and medium work-intervals; $\dot{V}O_2$ response, Intensities' effect on HIT sets; swimming

Introduction

Contrarily to sedentary or recreational athletes where an additional increase in submaximal exercise training (e.g., volume) can promote significant improvements at the physiological variables, which will contribute directly to sports performance, in already highly trained athletes further improvements seem to be only achieved through high-intensity training, mainly through high-intensity interval training (HIT) (Laursen and Jenkins, 2002). HIT has been reported as an effective way for athletes perform high exercise intensities longer than in a continuous training (Demarie et al, 2000), since the performance of continuous work, at these intensities, cannot be sustained for a long time, therefore limiting the total training time in a single training session (Sousa et al., 2017). HIT is defined as repeated short to moderate duration bouts (i.e., 10 seconds to 5 minutes) of high-intensity exercise (from maximal lactate steady state or second ventilatory threshold to “all-out” supramaximal exercise), interspersed with incomplete recovery periods of low-intensity exercise or complete rest (Laursen and Jenkins, 2002; Laursen, 2010), and has been proposed as an effective way to improve both the aerobic and the anaerobic performance, being the time sustained during exercise near maximal oxygen uptake values ($\dot{V}O_{2max}$) (i.e., >90% and 95% of $\dot{V}O_{2max}$) one of the most important factors to promote long term adaptations, namely in order to improve $\dot{V}O_{2max}$ and performance (Bentley et al., 2005; Buchheit and Laursen, 2013; Libicz et al., 2005; Sousa et al., 2017 and 2018).

Interval training (IT) involving short duration efforts (~30s) at the maximal aerobic velocity (MAV), the minimal velocity that elicits $\dot{V}O_{2max}$ in an incremental test (Billat, 2001), is frequently used in endurance sports and has been shown to be more effective to improve $\dot{V}O_{2max}$ than submaximal continuous running, however it may not be taxing enough to the aerobic system and that supramaximal IT (i.e., >100% of MAV) could lead to more enhancement of maximal aerobic capacity, $\dot{V}O_{2max}$, time to exhaustion at MAV, oxidative or glycolytic enzyme activity and sports performance (Millet et al., 2003a). In another perspective, the use of longer duration bouts could also be a more appropriate stimulus for

increasing the physiological responses to higher levels contributing for the development of the aerobic capacity (Astrand et al., 1960; Billat, 2001; Wen et al., 2019), since for the same pace, the higher duration time could allow higher $\dot{V}O_2$'s (e.g., 100 instead of 50 meters bouts in swimming) (Sousa et al., 2017).

The effectiveness of the HIT's characteristics continues to be a matter of debate, and the researchers are still searching for the best programming in order to the improvement of the athlete's capacities. Even though the physiological adaptations in terrestrial modalities is being well studied, in swimming the studies regarding the metabolic responses to interval training are quite scarce, focusing in different distances with the same intensities (Bentley et al., 2005; Libicz et al., 2005) and none examined the swimmers' physiological responses at supramaximal IT or analysed the effect that different intensities could impose on athletes' physiological responses to an IT session. Therefore, it is essential to deepen this theme for a better understanding of the benefits of HIT for swimmers and for coaches, especially when prescribing the training sessions. In fact, in swimming, the constrains imposed by the aquatic environment could lead to significant changes on $\dot{V}O_2$ and bioenergetics responses and the results obtained in the terrestrials' modalities should not be assumed to this modality (Libicz et al., 2005).

The aim of the present study is to compare the $\dot{V}O_2$ response during similar HIT sets performed, with 50 meters bouts, at different maximal and supramaximal intensities. A secondary goal of our work is to compare the differences between two HIT sessions with the same broken distance composed by short (50 meters distances) and medium distances (100 meters distance) bouts at the MAV, in order to quantify if increments in the intensity are necessary to achieve similar physiological responses when using 50 compared to 100 meters bouts. We also seek to understand if the $\dot{V}O_2$ and the time spent near $\dot{V}O_2$ maximal values achieved in the IT sessions can be related to performance. We hypothesized that: 1) increments in the intensity at similar interval training sets will induce significant changes on the $\dot{V}O_2$ response, and therefore in the time spent by the swimmers near their $\dot{V}O_2$ maximal values; 2) significant differences at the physiological

variables studied will occur when using 50 or 100 meters bouts for the same broken distance at the MAV; 3) higher $\dot{V}O_2$'s and times spent near $\dot{V}O_2$ maximal values will be related with swimming performance; and 4) no significant differences will be found between sexes that could suggest that these HIT sessions could not be applied similarly to male and female swimmers.

Methods

Participants

Fourteen well trained swimmers (7 females and 7 males) gave their written informed consent in order to participate in the study (or their legal guardians, if they were under 18 years old), and were instructed to avoid strenuous exercise in the preceding 24 hours before each test session, to attend well hydrated and fed, and to abstain from caffeine and alcohol in the preceding 24 hours before each test session. The descriptive characteristics of the swimmers and their personal best times (PB) at the 50 to 800 meters freestyle events (obtained at official competitions in the last 3 months before the study) are presented in table 13.

Table 13. Mean \pm SD of the descriptive characteristics of the swimmers (N = 14, 7 F, 7 M)

Variable	Female	Male	Combined
Age (yr)	15.71 \pm 1.03	17.00 \pm 2.20	16.36 \pm 1.84
Height (m)	1.66 \pm 0.07	1.80 \pm 6.83	1.73 \pm 0.10
Total Body Mass (kg)	60.43 \pm 5.29	76.21 \pm 8.49	68.32 \pm 10.60
Body Fat (%)	20.60 \pm 4.04	11.98 \pm 3.12	17.01 \pm 5.63
PB50	29.14 \pm 1.25	24.70 \pm 1.05	26.92 \pm 2.50
PB100	65.57 \pm 2.97	54.84 \pm 2.61	60.21 \pm 6.05
PB200	140.43 \pm 6.69	120.23 \pm 5.47	130.33 \pm 11.81
PB400	319.16 \pm 18.46	263.53 \pm 7.28	291.34 \pm 31.15
PB800	706.36 \pm 32.94	593.80 \pm 30.45	650.08 \pm 64.60

PB: personal bests of the swimmers at the 50 to 800 meters freestyle events.

All the participants had regularly participated at State and National Championships, at least in the past 3 years and before entering this study. Furthermore, all swimmers were frequent participants in similar experimental studies that were undertaken by our research group, being fully familiarised with the equipment and with the test procedures that were used in the study before the beginning of the test sessions.

The study was approved by the local University Ethical Committee (CEFMH: 39/2015) and conducted in accordance with the 1964 Declaration of Helsinki (Harriss et al. 2017).

Experimental design

All swimmers performed 5 testing sessions, which were at least 48 hours apart from each other: (1) a discontinuous incremental test; and (2) in randomized order, four broken 400 meters HIT sets, three of them composed by 50 meters repetitions (HIT50) and one composed by 100 meters repetitions (HIT100). To minimize the effect of circadian rhythms or differences in prior exercise, the same environmental conditions (time of day \pm 2 hours, water temperature \sim 28°C and relative humidity \sim 50%) and the same pre-test warm up protocol were applied. All sessions were performed in the same 25 meters swimming pool in the beginning of the preparatory period of the second macrocycle of the swimmer's competitive season, after a period of two weeks for training adaptation.

To measure the respiratory and the gas exchange variables for cardiorespiratory analysis, a telemetric portable breath-by-breath gas analyser (K4b², Cosmed, Italy), connected to the swimmer by a respiratory snorkel and valve system (new-AquaTrainer[®], Cosmed, Italy) was used in all tests. This low hydrodynamic swimming snorkel, previously validated (Reis et al., 2010; Baldari et al., 2012), allowed the swimmer to perform the tests in a free-swimming situation, similar to the real swimming environment. All tests were performed in front crawl swimming and involved in-water starts and open turns without underwater gliding.

The K4b² was calibrated before each test and according to manufacturer's instructions. The heart rate (HR) was telemetrically recorded during exercise, with a HR monitor (Polar[®], Finland) coupled to the snorkel and synchronized with the K4b² system. For blood lactate concentration ([La⁻]) analysis (YSI, 2300 STAT, Yellow Springs, USA), capillary blood samples (25 ul) were collected from the earlobe, before the start of each test, during the breaks and after the discontinuous incremental test and after the end of the HIT50' tests (minutes 1, 3, 5 and 7). The Borg's CR-10 scale (Borg, 1990), was used along all tests for recording the rate of perceived exertion (RPE).

For the swimming velocity control of the steps of the incremental test and the intensities of the HIT sessions, an underwater visual pacer (Pacer2Swim[®], KulzerTEC, Portugal) was disposed along the bottom of the pool. This system provided to the swimmers an accurate notion of the correct velocity for each test., through the 26 lights that subsequently light up along the bottom of the pool.

Discontinuous incremental test

Firstly, all swimmers performed an incremental test that was composed by 6 sets of 250 meters, plus 1 set of 200 meters at maximal intensity (Espada et al., 2015), with 30 seconds rest between steps for [La⁻] determination. The velocity of the first repetition was set at 50% of the subjects' 200 meters velocity and increments of 5 to 10% were imposed in the rest of the repetitions, so that the final repetition could be performed at maximal intensity or until swimmers voluntary exhaustion. Maximal oxygen uptake (Peak- $\dot{V}O_2$), second ventilatory threshold (VT₂) and maximal aerobic velocity (MAV) were registered. Peak- $\dot{V}O_2$ was recorded as the highest 30 seconds average of the $\dot{V}O_2$ values and the MAV was considered as the minimal velocity at which the Peak- $\dot{V}O_2$ values were reached (Billat, 2001). Overall, both were reached by all swimmers in the last 2 repetitions.

High intensity interval training sets

In complementary days and in a randomized order, swimmers performed 4 simulated HIT sets of 400 meters: (1) Three sets of 8 x 50 meters at 100%, 105% and 110% at the MAV (HIT50-100%, HIT50-105% and HIT50-110%, respectively); and (2) a set of 4 x 100 meters at 100% at the MAV (HIT100-MAV). All HIT sessions were performed with 15 seconds breaks for passive rest between repetitions and the velocity of each test remained constant between the first to the last repetition. If the velocity of the test was not complied the test was interrupted and repeated in another day. For each HIT session, the mean $\dot{V}O_{2peak}$ of each repetition ($M\dot{V}O_{2peak}$) and the corresponding maximal $\dot{V}O_2$ value of each session ($\dot{V}O_{2peak}$) were calculated and the time spent above VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$ were registered. The gain on the time spent above the VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$ between the HIT50-100% and the HIT50-110% was also calculated expressed as a delta value, ΔVT_2 , $\Delta 90\%$ and $\Delta 95\%$ 100/110%-MAV.

Furthermore, the rate of perceived exertion (RPE) was also recorded through the Borg's CR-10 scale (0-10 units). For the HIT50's the total energy expenditure was also calculated, in order to analyse the impact of the exercise intensity increment on the different energetic systems relative participations.

Data Analysis

Breath-by-breath $\dot{V}O_2$ response data was first selected, through the exclusion of the values that presented more than three standard deviations from the local mean, in order to exclude outliers caused by abrupt breaths, coughing or signal interferences. For the Peak- $\dot{V}O_2$ determination, a 30s moving average was used for the incremental test, with the highest value being considered as the peak. Moving averages of 15 and 5 seconds were used for $\dot{V}O_{2peak}$ determination, for the HIT100 and the HIT50's, respectively, in order not to influence the results given the duration of each test. $\dot{V}O_2$ data was further interpolated into 1-second values to register all values above the VT_2 , 90% and 95% of Peak- $\dot{V}O_2$, for the

time spent above the referred physiological thresholds calculation. The respective percentage values for the total duration of the sessions were then determined through the total time of each HIT session.

The total energy expenditure of the HIT50' was calculated considering the aerobic, anaerobic lactic and alactic systems. The aerobic system participation was calculated by the trapezoidal method through the time integral of the net $\dot{V}O_2$ during exercise (Bertuzzi et al., 2013; Guidetti et al., 2007). The anaerobic lactic participation was determined by the difference between maximal after exercise and resting $[La^-]$ expressed as a delta value ($\Delta[La^-]$) (Beneke et al., 2002), considering $3 \text{ ml}O_2 \cdot \text{kg}^{-1}$ as a metabolic equivalent for each $1 \text{ mmol} \cdot \text{l}^{-1}$ of $\Delta[La^-]$ (di Prampero, 1981). Finally, the anaerobic alactic system participation was determined by the product between the time constant and amplitude of the fast component of post-exercise (during an 8 minutes period) $\dot{V}O_2$ recovery curve (Beneke et al., 2002; Guidetti et al., 2007), the following equation (Scheuermann et al., 2001):

$$\dot{V}O_{2\text{off}}(t) = EE\dot{V}O_2 - A_{1\text{off}}[1 - e^{-(t-TD_1/\tau_1)}] - A_{2\text{off}}[1 - e^{-(t-TD_2/\tau_2)}]$$

Where $\dot{V}O_{2\text{off}}(t)$ represents the relative $\dot{V}O_2$ at a given time; $EE\dot{V}O_2$ is the oxygen uptake at the end of exercise; TD , τ , and A , represent the time delay, the time constant and the amplitude, and 1 and 2 represent for the fast and slow component, respectively, for the bi-exponential response of the $\dot{V}O_2$.

Statistical Analysis

Firstly, normality and homogeneity of data were confirmed with Shapiro-Wilk and Levene tests. Secondly, independent T-tests were applied to all variables in order to check the differences between sexes, and the differences between the HIT sessions were tested for statistical significance using ANOVA for repeated measures with Bonferroni correction. At last, the Pearson's linear correlation coefficient was used in order to establish the significant associations between physiological measures and swimmers' performance. Statistical significance was

accepted at $p < 0.05$. All statistical analyses were performed with the Statistical Package for the Social Sciences (version 25.0; SPSS, Chicago, IL, USA).

Results

The swimmers physiological responses at the incremental test are presented in table 14.

Table 14. Mean \pm SD of swimmers physiological responses at the discontinuous incremental test, N = 14 (7 F, 7 M)

Variable	Female	Male	Combined
Peak- $\dot{V}O_2$ (ml·kg ⁻¹ ·min ⁻¹)	50.53 \pm 2.38	53.60 \pm 5.49	52.07 \pm 4.50
VT ₂ (ml·kg ⁻¹ ·min ⁻¹)	44.20 \pm 1.84	47.17 \pm 4.81	45.69 \pm 3.93
VT ₂ (% $\dot{V}O_{2peak}$)	87.54 \pm 2.31	88.08 \pm 3.57	87.81 \pm 3.02
MAV (m·s ⁻¹)	1.19 \pm 0.07	1.29 \pm 0.08	1.24 \pm 0.09
Peak HR (b·min ⁻¹)	190.1 \pm 9.9	179.5 \pm 8.9	185.2 \pm 10.9
Peak [La ⁻] (mmol·l ⁻¹)	7.5 \pm 2.5	8.0 \pm 3.5	7.7 \pm 3.0
PRE (0 – 10 units)	8.9 \pm 0.9	9.7 \pm 0.70	9.3 \pm 1.0

Peak- $\dot{V}O_2$: corrected to body mass values of the maximal oxygen uptake; VT₂: $\dot{V}O_2$ at the second ventilatory threshold and corresponding percentage value for the Peak- $\dot{V}O_2$; MAV: maximal aerobic velocity; Peak HR and Peak [La⁻]: maximal HR and blood lactate concentration at the test; PRE: rate of perceived exertion.

The physiological responses at the HIT sessions are presented in table 15.

Peak- $\dot{V}O_2$ from the incremental test was significantly different from the $\dot{V}O_{2peak}$ of the HIT50-100%, HIT50-105% and HIT100 but not from HIT50-110%.

At the HIT50' sessions, the increments of intensity of 5 and 10% promoted significant changes on the $\dot{V}O_2$ response, which was higher as the intensity increased. The same profile occurred with the time spent above the studied physiological thresholds, with the exception for the $\geq 95\%$ of Peak- $\dot{V}O_2$, where just the HIT50-110% showed significantly higher values.

Table 15. Mean \pm SD of swimmers physiological responses at the HIT sessions, N = 14 (7 F, 7 M)

Variable	8 x 50 at 100%	8 x 50 at 105%	8 x 50 at 110%	4 x 100 at 110%
$\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	45.8 \pm 4.6 ^{bcd}	49.1 \pm 5.1 ^{ac}	52.9 \pm 5.2 ^{abd}	49.1 \pm 4.8 ^{ac}
% $\dot{V}O_{2peak}$ (%Peak- $\dot{V}O_2$)	87.9 \pm 3.3 ^{bcd}	94.2 \pm 5.0 ^{ac}	101.7 \pm 5.7 ^{abd}	94.3 \pm 6.2 ^{ac}
M $\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	42.9 \pm 4.7 ^{bcd}	46.2 \pm 5.4 ^{ac}	49.7 \pm 5.3 ^{ab}	47.3 \pm 4.7 ^a
%M $\dot{V}O_{2peak}$ (%Peak- $\dot{V}O_2$)	82.4 \pm 3.7 ^{bcd}	88.6 \pm 5.3 ^{ac}	95.4 \pm 5.2 ^{ab}	91.0 \pm 5.9 ^a
$\geq VT_2$ (s)	34.8 \pm 43.4 ^{bcd}	113.1 \pm 69.0 ^{ac}	219.9 \pm 64.6 ^{ab}	144.2 \pm 68. ^{ac}
$\geq 90\%$ of Peak- $\dot{V}O_2$ (s)	20.4 \pm 20.6 ^{bcd}	91.1 \pm 62.1 ^{ac}	199.0 \pm 68.5 ^{ab}	114.9 \pm 74.8 ^a
$\geq 95\%$ of Peak- $\dot{V}O_2$ (s)	1.8 \pm 3.2 ^c	30.4 \pm 28.3 ^c	119.2 \pm 75.3 ^{ab}	56.2 \pm 65.4
Peak HR (b·min ⁻¹)	160.9 \pm 8.4 ^{bcd}	174.8 \pm 6.6 ^a	180.6 \pm 4.7 ^a	176.1 \pm 9.2 ^a
Peak [La ⁻] (mmol·l ⁻¹)	3.4 \pm 1.7 ^{bc}	6.4 \pm 2.4 ^{ac}	10.6 \pm 3.9 ^{ab}	-
RPE (0 - 10 units)	3.3 \pm 1.5 ^{bc}	5.9 \pm 2.0 ^{ac}	9.1 \pm 1.0 ^{abd}	5.9 \pm 1.4 ^{ac}

$\dot{V}O_{2peak}$ and % $\dot{V}O_{2peak}$: maximal $\dot{V}O_2$ achieved in the test and corresponding percentage to Peak- $\dot{V}O_2$; M $\dot{V}O_2$ and %M $\dot{V}O_{2peak}$: average value of the $\dot{V}O_{2peak}$'s achieved in each repetition of the set and corresponding percentage to Peak- $\dot{V}O_2$; $\geq VT_2$, $\geq 90\%$ and $\geq 95\%$ of Peak- $\dot{V}O_2$: time spent by the swimmers with $\dot{V}O_2$ values above the VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$, and corresponding percentage values for the total duration of each test, respectively; Peak [La⁻] and Peak HR: maximal blood lactate concentration and heart rate at the end of the set, respectively; RPE: rate of perceived exertion; a, b, c and d: statistical differences for the HIT50 100%-MAV, HIT50 105%-MAV, HIT50 110%-MAV and HIT100, respectively.

At the HIT100 test the physiological responses of the swimmers showed higher similarities with the HIT50-105%, presenting no differences at the $\dot{V}O_{2peak}$, M $\dot{V}O_{2peak}$, times above 90% and 95% of Peak- $\dot{V}O_2$, HR and PRE. Also no differences were found with the HIT50-110% at the M $\dot{V}O_{2peak}$ and the times above the studied thresholds. The $\dot{V}O_2$ responses of the swimmers along each HIT session are represented, as mean percentage values to Peak- $\dot{V}O_2$, in figure 22. The time sustained by the swimmers with $\dot{V}O_2$ values above the VT_2 , 90% and 95% of Peak- $\dot{V}O_2$ are graphically presented in figure 23 as percentage values for the total duration of each HIT session.

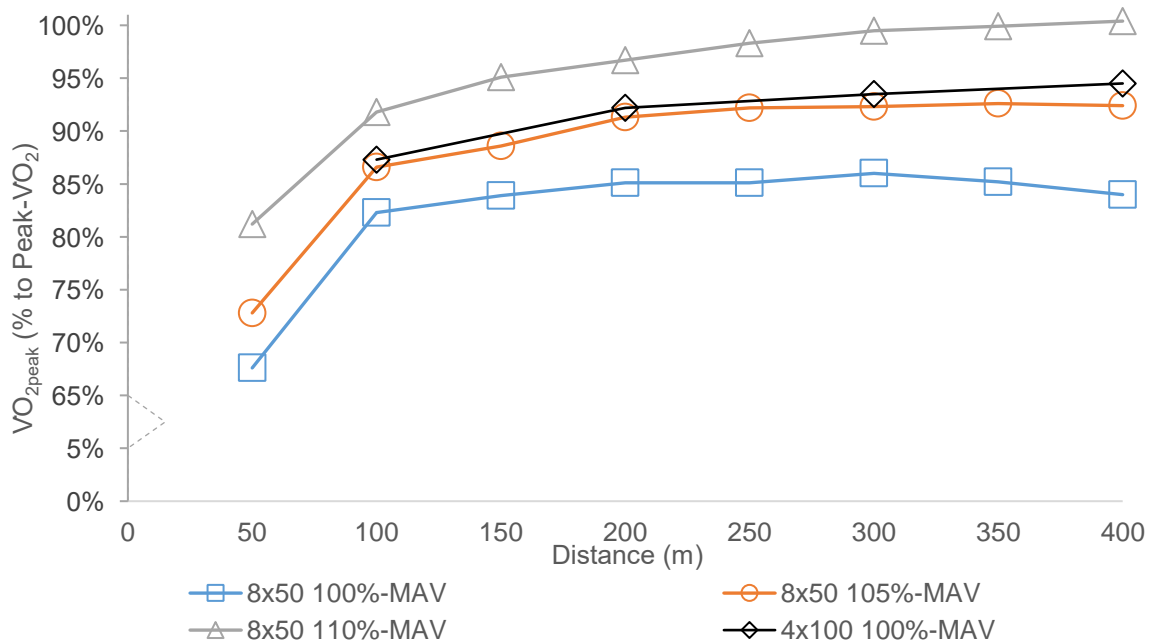


Figure 22. Swimmers $\dot{V}O_2$ responses along the HIT sessions. Values are presented as percentages to Peak- $\dot{V}O_2$. HIT sessions represented by blue squares (HIT50-100%), orange circles (HIT50-105%), grey triangles (HIT50-110%) and black lozenges (HIT100).

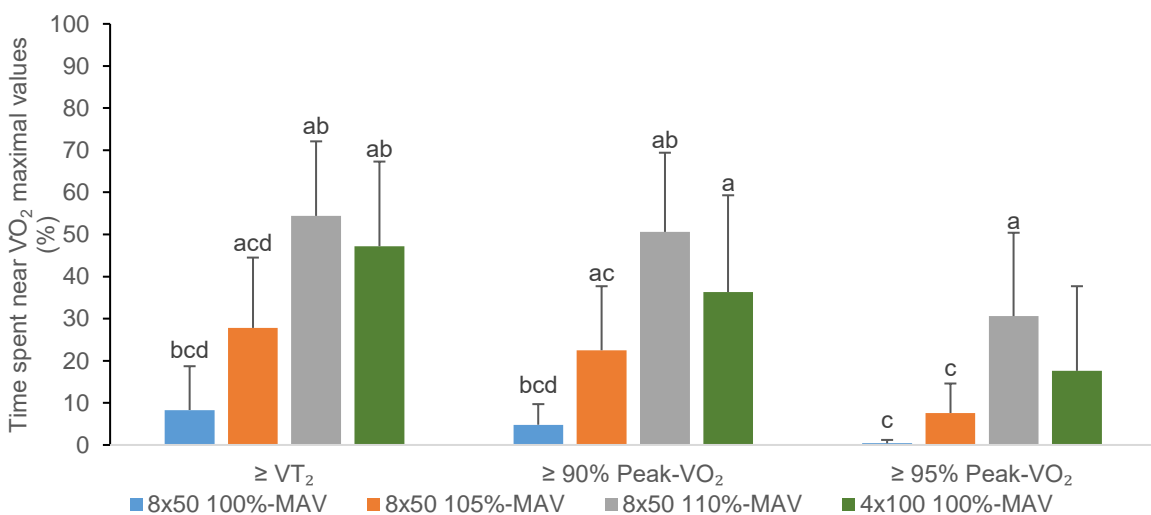


Figure 23. Time spent by swimmers with $\dot{V}O_2$ values above the second ventilatory threshold, 90% and 95% of Peak- $\dot{V}O_2$ during the HIT sessions. Values are presented as percentage for the total duration of each session: a, b, c and d: statistical differences for the HIT50-100%, HIT50-105%, HIT50-110% and HIT100, respectively.

With the exception of the HIT50-100% that was performed always under the VT_2 , the remaining HIT sessions were performed in the severe intensity domain of exercise. However, only at the HIT50 at 110%-MAV a continuous rise of the $\dot{V}O_2$ values was observable, that led to the achievement of the Peak- $\dot{V}O_2$ obtained at the incremental test.

Regarding the time spent by the swimmers near their individual's $\dot{V}O_2$ maximal values a significant increase in the HIT50's as the intensity increases was observable, showing the HIT50-110% the highest result. The HIT100 presented significantly longer times above the VT_2 than the HIT50-100% and HIT50-105% tests, but was not different from the HIT50-110% test. The observable differences were more marked above the VT_2 and 90% of Peak- $\dot{V}O_2$ than from above the 95% of Peak- $\dot{V}O_2$.

For a better understanding of the intensity effect on the HIT50' sessions the energy system contributions are presented at figure 24.

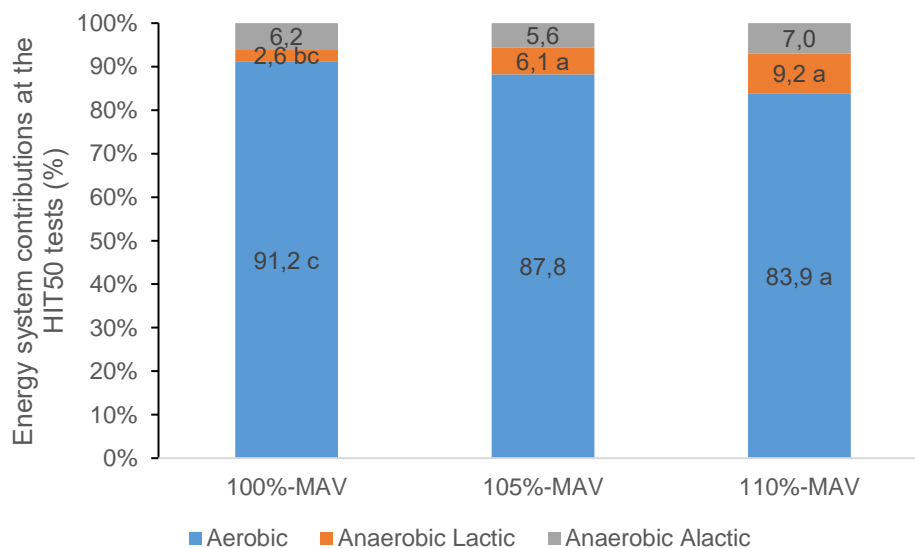


Figure 22. Energy system contributions of the HIT50's tests. Values are presented as percentage for the total energy expenditure: a, b and c: statistical differences for the HIT50-100%, HIT50-105% and HIT50-110%, respectively.

The energy system contributions of the HIT50' tests showed a significantly lower participation of the aerobic system between the HIT50-100% to the HIT50-110% tests. An opposite profile occurs with the anaerobic lactic participation. Regarding this system, the swimmers who presented lower values were those with better personal best performance at the 400 meters freestyle event ($r=0.59$ and $r=0.59$, $p<0.05$, respectively for the HIT50-100% and HIT50-110% tests). The anaerobic alactic participation presented the same relative participation along the different intensities.

Correlations between physiological variables with swimmers' performances are showed in table 16.

Table 16. Correlations coefficients between swimmers performances and physiological variables of the HIT sessions

Variable	Swimmers PB's				
	50m	100m	200m	400m	800m
MAV	-0.74**	-0.75**	-0.74**	-0.73**	-0.83*
$M\dot{V}O_{2peak}$ HIT50 100%-MAV			-0.56*		
$M\dot{V}O_{2peak}$ HIT50 105%-MAV	-0.56*		-0.58*		
$M\dot{V}O_{2peak}$ HIT50 110%-MAV	-0.61*	-0.58*	-0.70**	-0.64*	0.67**
Time $\geq VT_2$ HIT50 110%-MAV (%)			-0.60*	-0.61*	-0.55*
Time $\geq 90\%$ of Peak- $\dot{V}O_2$ HIT50 110%-MAV (%)	-0.55*	-0.54*	-0.63*	-0.71**	-0.64*
Time $\geq 95\%$ of Peak- $\dot{V}O_2$ HIT50 110%-MAV (%)	-0.55*	-0.56*	-0.60*	-0.72**	-0.64*
ΔVT_2 100/110%-MAV				-0.60*	
$\Delta 90\%$ 100/110%-MAV			-0.54*	-0.63*	-0.55*
$\Delta 95\%$ 100/110%-MAV			-0.56*	-0.69*	-0.60*

*: statistical significance for $p < 0.05$; **: statistical significance for $p < 0.01$ $M\dot{V}O_2$: average value of the $\dot{V}O_{2peak}$ achieved in each repetition of set of the corresponding test; $\geq VT_2$, $\geq 90\%$ and $\geq 95\%$ of Peak- $\dot{V}O_2$: time spent by the swimmers with $\dot{V}O_2$ values above the VT_2 , 90% and 95% of the Peak- $\dot{V}O_2$ for the corresponding test; ΔVT_2 , $\Delta 90\%$ and $\Delta 95\%$ 100/110%-MAV: differences of the time spent above VT_2 , 90% and 95% between the 100% and 110%-MAV intensities.

MAV was the variable that was more related to performance and also showed significant correlations with the HIT50-110% test at the $\dot{V}O_{2peak}$ and the times spent above the VT_2 , 90% and 95% of Peak- $\dot{V}O_2$ ($r = 0.62$, $r = 0.65$, $r = 0.65$, and $r = 0.56$, $p < 0.05$, respectively).

The HIT50' sessions performed at 100% and 105% MAV were only related with swimming performance at the corresponding $M\dot{V}O_{2peak}$'s, while the HIT50-110% presented several correlations between its variables and swimmers performances at several distances.

At the HIT50's tests, the differences on the time spent above the studied thresholds, between the 100% and 110%-MAV intensities, showed that the swimmers who improved more with the increase of the intensity were those with better performances in middle and long-distance swimming. Furthermore, this variable was also correlated with MAV ($r = 0.58$ and $r = 0.55$, $p < 0.05$, respectively for $\geq 90\%$ and $\geq 95\%$ of Peak- $\dot{V}O_2$) and vVT_2 ($r = 0.63$, $p < 0.05$, $r = 0.66$, $p < 0.01$, and $r = 0.59$, $p < 0.05$, respectively for $\geq VT_2$, $\geq 90\%$ and $\geq 95\%$ of Peak- $\dot{V}O_2$).

No significant differences were found at the HIT's variables between male and female group.

Discussion

The main goal of this study was to compare the $\dot{V}O_2$ response during similar HIT sets composed by 50 meters bouts (8x50m) in swimming, and observe the effects that different intensities (100%, 105% and 110% of MAV) will induce on swimmers' physiological responses. Our secondary goal was to understand if, at the MAV and for the same broken distance, physiological differences exist when using 50 meters bouts compared with 100 meters bouts. Overall, we seek to understand if the physiological variables were related with swimming performance, namely regarding to the $\dot{V}O_{2peak}$'s achieved at the HIT sessions and the time spent by the swimmers near their $\dot{V}O_2$ maximal values. The reason why we chose these HIT sessions was to try to represent usual sets daily used by

coaches, as regarding the distances chosen but also the intensities performed. To the best of our knowledge, this is the first study focused on the effects that different intensities could impose to athletes' physiological responses when performing swimming interval training.

Our main conclusions are that: 1) increments of just 5 and 10% to the MAV, at an 8 x 50 meters front crawl swimming HIT session, significantly increased the swimmers $\dot{V}O_2$ response and consequently the time spent near their $\dot{V}O_2$ maximal values, which corroborates our first hypothesis. So, the obtained results suggest the use of higher velocities than the MAV, in order to keep the oxidative rate at the maximal level (i.e., ~6 to 13% higher), also contributing to the improvement of tolerance to exercise in the severe domain (i.e., more ~20 to 46% of time above the VT_2) whilst training with short swimming distance bouts (50 meters distance); 2) our second hypothesis was also confirmed since significant differences occurred when using 50 meters compared to 100 meters bouts, as the task composed by 100 meters swimming bouts presented $\dot{V}O_2$ values ~6 and ~9% higher (for $\dot{V}O_{2peak}$ and $M\dot{V}O_{2peak}$, respectively) and longer times spent above the studied variables (i.e., more ~39% of time above VT_2). In order to achieve similar results (statistically non different), an increase of, at least, 5% is necessary to impose to the 50 meters bouts HIT sessions performed at the MAV, to observe similar physiological responses than when using 100 meters bouts; 3) our third hypothesis was also corroborated since significant correlations were found between both the $M\dot{V}O_{2peak}$'s and times spent above the studied physiological thresholds with swimmers performances; 4) finally, the absence of significant differences between sexes support the conclusion that these HIT sessions, and the process of its programming, could be applied equally to male and female swimmers.

At the HIT swimming sessions composed by 50 meters bouts, the rise on the $\dot{V}O_2$ response and time spent above the studied thresholds as the intensity increased, are in line with a similar running study conducted by Millet et al. (2003a) that compared two HIT sessions (30 seconds of exercise with 30 seconds recovery at 50%-MAV, until athletes' TLim) at 100% and 105%-MAV. The authors

concluded that, even though the work interval intensity at the HIT performed at the 105%-MAV was only 5% higher, it actually allowed the athletes to spend twofold more time above 90% of the $\dot{V}O_{2max}$ or HR_{max} . As a matter of fact, at this intensity, the athletes of Millet's study were able to reach 100% of the $\dot{V}O_{2max}$ compared to the 93% of the $\dot{V}O_{2max}$ that was achieved when the HIT session was performed at 100%-MAV. In our study, we also observed a significant increase between the same intensities, however, the $\sim 100\%$ of Peak- $\dot{V}O_2$ was only achieved with the 110%-MAV and $\sim 93\%$ of Peak- $\dot{V}O_2$ with the 105%-MAV, suggesting that, in swimming, an increase of about 5% may be imposed in order to achieve similar oxidative rates when compared to the running exercise.

Other studies also suggested that intensities around or above the MAV are better to the aerobic training efficacy, as reported in running between 95% and 100%-MAV (Denadai et al., 2006), or in cycling between 80% and 115%-MAV (Raleigh et al., 2017), where the higher intensities provided higher enhancements at swimmers physiological responses. The last study, however, alerts for the possibility that no additional adaptative effects occur when the IT is performed much above the MAV, since, when compared with the 150%-MAV no further gains were reported when compared with the 115%-MAV intensity, in a 3-weeks IT program. Moreover, the results of the 150%-MAV intensity did not present statistical differences to the 80%-MAV intensity results. Also, Wakefield et al. (2009), measuring the time spent above 95% of $\dot{V}O_{2max}$ concluded that no differences exist between the same running IT session performed at 105% or 115%-MAV. Furthermore, in this study the authors compared different work-intervals of 20, 25 and 30s, reporting the longer one as the best to stimulate the oxidative rate. In swimming, accordingly to our results, it seems that, at least, until the 110%-MAV swimmers could have significant physiological benefits.

It was previously stated by Millet et al. (2003a) that short-interval supra-maximal IT could be an effective method for eliciting and developing $\dot{V}O_{2max}$, considering that after a few repeated sprints, the aerobic metabolism provides an important part of the energy for 30 seconds intervals, i.e., 34% and 49%, respectively for the first and second of two 30-s cycling sprints interspersed by 4 minutes of

recovery, while $\dot{V}O_2$ reached 85% of the $\dot{V}O_{2max}$ in the second sprint. Also, Peyrebrune et al. (2014) estimating the energy contribution during a maximal sprint (30 seconds) and repeated sprints (4x30 seconds with 30s-rest) at 95% of the maximal single sprint intensity on tethered swimming, observed an increase on the aerobic contribution from ~33% to 52% in the last bout, while the $\dot{V}O_2$ reached 84% of the $\dot{V}O_{2max}$, suggesting that this kind of HIT session simulates the intensity and the energy demands of the 100 meters freestyle swimming race, which is why they can be used as a specific type of training for this particular competitive distance.

The effect of the prior exercise seems to be significant in the cumulative effect of the repeated bouts, whether this is due to the increase in intracellular oxidative phosphorylation in the contracting muscles (Behnke et al., 2002), or just because of the greater increase in the $\dot{V}O_2$ amplitude in the remaining bouts after the initial one, being this effect intensity dependent (Burnley et al., 2000; Burnley and Jones, 2007; Millet et al., 2003a, Sousa et al., 2014a). In fact, our swimmers, during the breaks, did not decrease much their $\dot{V}O_2$ values, which allowed to rapidly return to the values near the $\dot{V}O_{2peak}$ achieved in each repetition.

When analysing the differences at the time spent above the studied thresholds between the 50 meters bouts HIT' sessions, a higher difference was observed between the HIT50-105% to the HIT50-110% than between the HIT50-100% to the HIT50-105% tests, however without statistical significance. Furthermore, the total increase between the HIT50-100% to the HIT50-110% tests showed to be related to MAV, suggesting that the increase at the HIT50' intensities benefit more the faster swimmers. Also, it seems that the fastest swimmers, where those who could reach higher $\dot{V}O_{2peak}$'s and times spent above the studied thresholds, as the correlations between the MAV and the HIT50-110%' variables seem to suggest. Furthermore, those swimmers who performed the HIT50-110% test with higher $\dot{V}O_2$ s seem to be those with better swimming performances.

Our comparison between the 50 and the 100 meters bouts strongly evidenced that, for this same relative intensity (MAV), the HIT session composed by 100

meters bouts is the best one in order to stimulate the oxidative rate of the swimmers, having a more taxing effect on the aerobic training. With the 100 meters bouts, swimmers reached significantly higher $\dot{V}O_2$'s and spent approximately 4 times longer (i.e., above VT_2) near their $\dot{V}O_2$ maximal values. These results are in line with a previous study conducted by Libicz et al. (2005) with triathletes, which compared the time spent above 95% of the $\dot{V}O_{2max}$ and HR_{max} when swimming 16x50m and 8x100m, also at the MAV. These authors reported that, even though without statistical significance probably due the great variability observed among the athletes' results, the time spent near $\dot{V}O_{2max}$ double with the set composed by 100 meters bouts, suggesting that training at or near $\dot{V}O_{2max}$ would be the optimal intensity to elicit maximum improvements in performance. However, they alerted for the importance of controlling other biomarkers of fatigue to have a better understanding of the effect of the HIT session on the athletes' response, and that the results found truly differ from other modalities as cycling and running, suggesting that the methods of individualizing IT should not be applied to swimming before conducting more longitudinal training studies, which should aim to clarify, as well as to confirm, the long-term effects of swimming IT sets.

Also, Millet et al. (2003b) found a significant increase both at the $\dot{V}O_{2peak}$ and at the time spent above 90% of $\dot{V}O_{2max}$ in intermittent runs with 60 seconds time duration compared with the 30 seconds work-interval, suggesting that the longer interval allowed the runners to have a more taxing effect on that aerobic training. In addition, the authors concluded that the athletes with longer TLim in a continuous set at MAV, beneficiate more from the use of the longer IT sets, proposing the use of longer work-interval sets for those runners.

Dalamitros et al. (2016), tested the efficacy of two HIT sessions composed with 50 and 100 meters bouts (12-16x50m vs. 6-8x100) at MAV during an 8-week program, concluding that both HIT sessions improved swimming performance in 100 and 400 meters tests, stroke length, MAV and $\dot{V}O_{2max}$, suggesting that both protocols could be applied alternately to avoid monotony in training since promote similar improvements. In the Dalamitros' study, the physiological responses

during the HIT sessions were not analysed, however, accordingly to our results and with Libicz's study, those different sessions should induce significant differences on swimmers $\dot{V}O_2$ responses, being expected that the group who performed the 100 meters bouts training would have higher improvements than the group with the 50m's bouts. One possible explanation for the absence of significant differences could be the fact that the study was performed by former swimmers, with no swimming activity for at least 6 months and with lower levels of aerobic fitness. Perhaps, with well-trained swimmers those improvements could differ (also pointed by the authors), and probably would be more pronounced at the 100 meters HIT group where the aerobic system is much more solicited. In fact, in a pilot study for the present one (unpublished data), we tested two female swimmers for 50 meters bouts at MAV until exhaustion, having to stop those swimmers after forty bouts, since their $\dot{V}O_2$ and RPE values indicated that they would continue the task for a much longer duration.

Sousa et al. (2017), testing the swimming tolerance for a continuous workout at 95, 100 and 105% of MAV, reported that for the 50 meters effort (first 30 seconds of exercise), or for the 100 meters effort (first 60 seconds) the $\dot{V}O_2$ was not taxed enough in a single bout to elicit $\dot{V}O_{2max}$. However, at the MAV, in the 60 seconds time period swimmers reached ~88% of $\dot{V}O_{2max}$ compared with the ~74% of $\dot{V}O_{2max}$ for the 30 seconds time period, suggesting the longer time period as a more adequate stimulus for the aerobic training purposes. Our results, are similar for the first bout of each HIT session, however, by testing the whole HIT session, we observed that the $\dot{V}O_2$ response ranged from ~68% to 84% of Peak- $\dot{V}O_2$ and from ~87% to ~95% of Peak- $\dot{V}O_2$ between the first to the final bout (see figure 2), respectively for the HIT session performed with 50 and 100 meters bouts. Still, it is also our suggestion that when working with this intensity (MAV) the use of 100 meters bouts is highly recommended instead of the 50 meters bouts for aerobic training purposes.

When working with short bouts, and in order to achieve similar results as those obtained with the 100 meters bouts at 100%-MAV, it is required that the HIT50 sessions increase their velocity at least 5% for achieving similar oxidative rates

of those observed for the 100 meters HIT session. Nevertheless, when comparing all four HITs in study it is clear that the one which elicits more the swimmers' physiological responses is the HIT50 performed at 110% of MAV, the only one which presented higher values than the HIT100, being this our best suggestion from those we tested.

The literature regarding the IT in swimming is quite scarce, which makes it more difficult to analyse swimmers' physiological responses for this kind of training. However, it seems that when comparing IT sessions performed with longer bouts (with the same overall time and intensity), the differences reported and also pointed by the Libicz's study for shorter distances, are diluted as reported by Bentley et al. (2005) when comparing 100 and 400 meters bouts in swimming (16x100 vs. 4x400). In Bentley's study, the authors concluded that despite a similar exercise intensity, the increase of the duration of a work interval during aerobic swimming IT did not influence the duration that was sustained above 90% of $\dot{V}O_{2max}$ and HR_{max} , nor did it influence the highest $\dot{V}O_2$ that was reached during each IT session, that was also quite similar between both IT sessions. Also, in another study performed by our research group (unpublished data), we did not find significant differences between two IT sessions composed by 100 or 200 meters bouts (8x100m vs. 4x200m swimming) at $\dot{V}O_{2peak}$, nor at the time spent near swimmers' $\dot{V}O_2$ maximal values.

In conclusion, seeking for training schedule effectiveness to improve endurance and aerobic power, the obtained results truly recommend HIT50' tests, at least, at 105%-MAV, which attained oxidative rates similar to those obtained in the HIT100 at 100%-MAV. However, coaches should consider the possibility to increase the HIT50' until the 110%-MAV, where swimmers presented the best physiological results, being the HIT50 at 110%-MAV the only session in study that elicited the Peak- $\dot{V}O_2$ obtained at the incremental test was actually achieved.

References of chapter VII

- Astrand I, Astrand P, Christensen E, Hedman R (1960) Circulatory and respiratory adaptations to severe muscular work. *Acta Physiol Scand* 50:254-258
- Baldari C, Fernandes R, Meucci M, Ribeiro J, Vilas-Boas JP, Guidetti L (2012) Is the new aquatrainer® snorkel valid for $\dot{V}O_2$ assessment in swimming? *Int J Sports Med* 34(4):336-344
- Behnke BJ, Kindig CA, Musch TI, Sexton WL, Poole DC (2002) Effects of prior contraction on muscle microvascular oxygen pressure at onset of subsequent contractions. *J Physiol* 539(3):927-934
- Beneke R, Pollmann C, Bleif I, Leithäuser RM, Hütler M (2002) How anaerobic is the wingate anaerobic test for humans? *Eur J Appl Physiol* 87:338-392
- Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP (2005) Physiological responses during submaximal interval swimming training: effects of interval duration. *J Sci Med Sport* 8:392-402
- Bertuzzi R, Nascimento EM, Urso RP, Damasceno M, Lima-Silva AE. (2013) Energy system contributions during incremental exercise test. *J Sports Sci Med* 12(3):454-460
- Billat LV (2001) Interval training for performance: a scientific and empirical practice. Special recommendations for middle- and long-distance running. Part I: aerobic interval training. *Sports Med* 31(1):13-31
- Borg G (1990) Psychophysical scaling with applications in physical work and the perception of exertion. *Scand J Work Environ Health* 16(1):55-58
- Buchheit M, Laursen PB (2013) High-Intensity Interval Training, Solutions to the Programming Puzzle Part I: Cardiopulmonary Emphasis. *Sports Med* 43(5):313-338
- Burnley M, Jones A (2007) Oxygen uptake kinetics as a determinant of sports performance. *Eur J Sport Sci* 7(2):63-79
- Burnley M, Jones AM, Carter H, Doust JH (2000) Effects of prior heavy exercise on phase II pulmonary oxygen uptake kinetics during heavy exercise. *J Appl Physiol* 89:1387-1396
- Dalamitros A, Zafeiridis A, Toubekis A, Tsalis G, Pelarigo J, Manou V, Kellis S (2016) Effects of Short-Interval and Long-Interval Swimming Protocols on Performance,

Aerobic Adaptations, and Technical Parameters. *J. Strength Cond Res* 30(10):2871-2879

Demarie S, Koralsztein JP, Billat V (2000) Time limit and time at $\dot{V}O_{2max}$ during a continuous and an intermittent run. *J Sports Med Phys Fitness* 40(2):96-102

Denadai B, Ortiz M, Greco C, de Mello M (2006) Interval training at 95% and 100% of the velocity at $\dot{V}O_{2max}$: effects on aerobic physiological indexes and running performance. *Appl Physiol Nutr Metab* 31(6):737-743

di Prampero PE (1981) Energetics of muscular exercise. *Rev Physiol Biochem Pharmacol* 89:143-222

Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843

Guidetti L, Emerenziani GP, Gallotta MC, Baldari C (2007) Effect of warm up on energy cost and energy sources of a ballet dance exercise. *Eur J Appl Physiol* 99(3):275-281

Harriss D., Macsween, A., Atkinson, G. (2017). Standards for Ethics in Sport and Exercise Science Research: 2018 Update. *Int J Sports Med*. 38: 1126-1131

Laursen PB (2010) Training for intense exercise performance: high-intensity or high-volume training? *Scand J Med Sci Sports* 20(2):1-10

Laursen PB, Jenkins DG (2002) The scientific basis for high-intensity interval training: optimizing training programmes and maximizing performance in highly trained endurance athletes. *Sports Med* 32:53-73

Libicz S, Roels B, Millet GP (2005) $\dot{V}O_2$ responses to intermittent swimming sets at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 30(5):543-553

Millet GP, Candau R, Fattori P, Bignet F, Varray A (2003b) $\dot{V}O_2$ responses to different intermittent runs at velocity associated with $\dot{V}O_{2max}$. *Can J Appl Physiol* 28:410-423

Millet GP, Libicz S, Borrani F, Fattori P, Bignet F, Candau R (2003a) Effects of increased intensity of intermittent training in runners with differing $\dot{V}O_2$ kinetics. *Eur J Appl Physiol* 90 :50-57

Peyrebrune MC, Toubekis AG, Lakomy HK, Nevill ME (2014) Estimating the energy contribution during single and repeated sprint swimming. *Scand J Med Sci* 24 (2):369-376

- Raleigh J, Giles M, Scribbans T, Edgett B, Sawula L, Bonafiglia J, Graham R, Gurd B (2016) The impact of work-matched interval training on $\dot{V}O_{2peak}$ and $\dot{V}O_2$ kinetics: diminishing returns with increasing intensity. *Appl Physiol Nutr Metab* 41(7):706–713
- Reis J, Millet GP, Malatesta D, Roels B, Borrani F, Vleck V, Alves F (2010) Are oxygen uptake kinetics modified when using a respiratory snorkel? *Int J Sports Physiol Perform* 5(3):292-300.
- Scheuermann B, Hoelting B, Noble M, Barstow T (2001) The slow component of O_2 uptake is not accompanied by changes in muscle EMG during repeated bouts of heavy exercise in humans. *J Physiol* 531(1):245-256
- Sousa A C, Fernandes RJ, Boas J P V, Figueiredo P (2018) High-intensity Interval Training in Different Exercise Modes: Lessons from Time to Exhaustion. *Int J Sports Med* 39(9):668-673
- Sousa A, Ribeiro J, Sousa M, Vilas-Boas JP, Fernandes RJ (2014) Influence of Prior Exercise on $\dot{V}O_2$ Kinetics Subsequent Exhaustive Rowing Performance. *PLoS One* 9(1):e84208
- Sousa A, Vilas-Boas JP, Fernandes RJ, Figueiredo P (2017) $\dot{V}O_2$ at maximal and supramaximal intensities: lessons to high-intensity interval training in swimming. *Int J Sports Physiol Perform* 12(7):872-877
- Wakefield B, Glaister M (2009) Influence of work-interval intensity and duration on time spent at a high percentage of $\dot{V}O_{2max}$ during intermittent supramaximal exercise. *J Strength Cond Res* 23(9):2548-2554
- Wen D, Utesch T, Wu J, Robertson S, Liu J, Hu G, Chen H (2019) Effects of Different Protocols of High Intensity Interval Training for $\dot{V}O_{2max}$ Improvements in Adults: A Meta-Analysis of Randomised Controlled Trials. *J Sci Med Sport* 22(8):941-947

Chapter VIII. General Discussion

Throughout this thesis we have developed a broad investigation about the physiological responses of the swimmers when performing maximal and supramaximal exercises trying to match these efforts to those they perform whether in competition or in training. Surely that any kind of simulated swimming practice is not the real swimming conditions that swimmers come across in competition or in the daily training practice. However, our methodology has tried to shorten the gap between what happens in reality to what is possible to do in a “laboratory” simulated scientific research, in this field. Currently, this seems to be the best way to evaluate the physiological parameters, here in study, with the less possible constraints to the swimmers and with the most possible similarity to the reality of swimming.

Even though the literature has been giving some good information about swimmers physiological responses at several levels of efforts, the level of effort that is most commonly performed by athletes in competition has been less deepened. For this reason, in this thesis we focused our attention on the maximal and supramaximal intensities that correspond to the intensities of the majority of the events practice in indoor swimming, but also corresponds to the intensities of an important part of the training practice.

Along the different studies presented in this thesis, we have focused our analysis on the swimmers $\dot{V}O_2$ response, bioenergetics profiles and swimming tolerance at the maximal aerobic velocity, both in the continuous workout but also in the intermittent exercise. In this final discussion, the final observations that we deem important will be retrieved from each of these studies and hereby presented.

In the first study it was clear that the $\dot{V}O_2$ kinetics presented an acceleration with the increase of the exercise intensity. This fact seems to link the velocity of the $\dot{V}O_2$ response with the immediate need of energetic demand which was higher in the shorter and more demanding distances. This fact contradicts what seems to happen in the submaximal (and constant) intensities where differences were not previously found on the $\dot{V}O_2K$ velocity (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012b) between moderate, heavy and severe intensities. Even

though, De Jesus et al. (2015) has found an acceleration on the $\dot{V}O_2K$ between low-moderate to the heavy and severe domains of exercise, due to the fact that the authors performed their analysis based on an incremental test (with just 30 seconds between bouts), makes the results inconclusive to us, since the effect of prior exercise could have affected the $\dot{V}O_2$ response, as reported in swimming (Sousa et al., 2014a). Also, our study 3 showed a tendency of maintenance of the $\dot{V}O_2K$ velocity when the same intensity is applied to two different distances, as well as occurs when three different tests (100 and 200 meters tests at MAV, and TLim-MAV test) are performed at the same intensity⁶ (Almeida et al., 2019b).

The acceleration on the $\dot{V}O_2K$ showed in the study 1 is in line with other swimming studies where a clear acceleration was observed when the intensity of swimming is maximal for different distances (100 and 400 meters events) (Rodríguez et al., 2003), or when comparing maximal trials of 100 (Almeida et al., 2019a⁷) and 200 meters (Sousa et al., 2013) with less demanding, and constant, intensities for the corresponding distances. Besides, Ribeiro et al. (2015) and Rodríguez et al. (2016) comparing in the 100 meters freestyle swimming the full body use versus the use of only the upper body for performed the maximal trial, reported that the full body situation swimmers presented a significant faster $\dot{V}O_2K$, associating this with a higher energetic demand compared with the use of only the upper body. Also, Alves et al. (1996) reported that the front crawl swimming has a higher low muscle participation than it is often recognized, which could contribute to increase the total metabolic cost of the exercise and elevate the energetic demand of the exercise. This relationship between high exercise intensity and the $\dot{V}O_2K$ velocity was also observed in other sports modalities like cycling (Hettinga et al., 2009) and running (Carter et al., 2006)

⁶ See appendix II (Study 6 - Physiological responses at maximal aerobic swimming pacing in different distance-trials)

⁷ See appendix I. (Study 5 - Is $\dot{V}O_2$ kinetics influenced by swimming intensity in maximal and supramaximal velocities in young female swimmers?)

Sousa et al. (2013) has suggested that the higher energetic demand at the start of a more demanding exercise stimulates a rapid rise of the $\dot{V}O_2$ in order to supply that need. In the same line, Zignoli et al. (2019) in their recent systematic revision suggest that at higher intensities the time to reach $\dot{V}O_{2max}$ is shorter and related to the increase of the intensity. Also, Burnley and Jones (2007) suggested that the pacing strategy could accelerate the $\dot{V}O_{2K}$, while Jones et al. (2008) concluded that a fast-start strategy will promote a faster growth of the $\dot{V}O_2$ when compared with an even pace or low-start strategy. Bishop et al. (2002) also reported similar conclusions comparing an all-out with an even-pace testing sessions.

In our study 2 we also observed this tendency for a slow $\dot{V}O_{2K}$ in a less demanding exercise at the starting point. In this study the time constant of the TLim-MAV test presented a higher value than the MT's which is in accordance with the logic presented in the MT's. Even though the average velocity of the TLim-MAV test did not vary much from the 200-MT velocity, the fact is that in the 200-MT the swimmers started with a higher velocity in the first meters of exercise which should be accountable for the differences on the time constant (~17 vs. ~27 seconds, for the 200-MT and TLim-MAV tests, respectively).

Based on our results the $\dot{V}O_{2K}$ seemed not to influence the tolerance to MAV neither the time that swimmers spent above VT_2 , 90% and 95% of Peak- $\dot{V}O_2$ both in the continuous and intermittent workout exercise modes. This result was unexpected since a fast $\dot{V}O_{2K}$ response should, theoretically, contribute for the exercise efficiency. However, the correlation found in the time constants between the continuous and intermittent exercises, reinforces the idea that the time constant *per se* does not influence a higher tolerance at this intensity, since neither in the continuous nor in the intermittent exercise no relations were found with the TLim.

Even though fast $\dot{V}O_{2K}$ was previously reported as correlated with tolerance to running exercise (Demarie et al., 2001), in swimming, several studies presented any correlation between these two variables for a standard TLim-MAV test

(Fernandes et al., 2003 and 2008; Sousa et al., 2014b). Also in an interval training study, Bailey et al. (2009), testing the effect of an all-out sprint interval training program concluded that both the tolerance to exercise as the $\dot{V}O_2K$ presented improvements after the program, however those two variables were not correlated within. In swimming, Bentley et al. (2005) also tested the relation between the time spent near the $\dot{V}O_{2max}$ values during an intermittent exercise to the $\dot{V}O_2K$ velocity, also no relations were found, in accordance with our findings.

Reis et al. (2012b), associated fast $\dot{V}O_2K$ with the 400 meters' performance, enhancing also higher MAVs as a main performance influencer. Other studies performed around the maximal lactate steady state (Espada et al., 2015), or at heavy and severe intensities (Pessôa Filho et al., 2012) reached similar results, showing a positive relation between fast $\dot{V}O_2K$ with improved swimming performances.

In our studies this direct relationship between the $\dot{V}O_2K$ velocity with the swimming performance was not found, as it was not in other studies performed with maximal swimming tests (Rodríguez et al., 2003, Sousa et al., 2011 and 2013). Despite the lack of direct correlations between the time constant and performance, probably because of the nature of the maximal and supramaximal tests performed in our studies, where fast kinetics and similar results between subjects could constrain the occurrence of statistical correlations, the $\dot{V}O_2K$ was related with some physiological and performance variables as the $\dot{V}O_{2peak}$ ⁸, % to Peak- $\dot{V}O_2$ and % to MAV reached in the MT's that were related in turn with the swimming performance. These observations could lead to similar conclusions from those presented previously by other swimming studies (Espada et al., 2015; Pessôa Filho et al., 2012; Reis et al., 2012b), as fast kinetics seem to improve the oxidative response, with swimmers presenting higher $\dot{V}O_2$ values during exercise with lower values of $O_{2initialDef}$'s, swimming at higher relative velocities to MAV, which will turn the exercise more efficient (Alves et al., 2009). This could contribute for delaying the processes that will lead to fatigue and by that way

⁸ See appendix I. (Study 5 - Is $\dot{V}O_2$ kinetics influenced by swimming intensity in maximal and supramaximal velocities in young female swimmers?)

improve the performance in well trained swimmers, showing $\dot{V}O_2K$ parameters as an important field of study for swimming performance.

Even though in the present studies no comparison was made with other sports modalities, in line with the previous observations for swimming (Espada et al. 2015; Pessôa Filho et al. 2012; Reis et al. 2012a, b, 2017; Ribeiro et al. 2015; Rodríguez et al. 2016; Sousa et al. 2011, 2013), it seems to us that the $\dot{V}O_2K$ in swimming is not necessarily slower than in other terrestrial sports modalities, since the values found for the time constant of the continuous tests (between ~7 to ~27 seconds) are similar to several studies performed with dry-land sports (Carter et al. 2006; Draper and Wood, 2005; Hettinga et al. 2009).

The constraints that the aquatic environment could imply to the physiological responses of the swimmers pointed by several authors (Bentley et al. 2005; Ceretelli et al. 1979; Schneider et al. 2002; Sousa et al. 2017) seem not to influence the $\dot{V}O_2$ response in well trained swimmers, as those who participated in this study. Probably, the fact that swimmers spend so many hours training in this environment, and the use of a significative lower body muscle participation (Alves et al., 1996; Ribeiro et al., 2015; Rodríguez et al., 2016) could induce specific adaptations to the athletes which could override the theoretical constraints caused by the aquatic mode of exercise (Reis et al., 2018).

Traditionally, the studies which involve the $\dot{V}O_2$ data treatment by the exponential models (mono, bi and tri-exponential modelling) focus at longer exercise durations (e.g. > than 2 minutes). However, if we want to test the swimmers responses in efforts close to the competition efforts, due to the nature of these supramaximal efforts, it is not possible to get this traditional times of effort, since the swimmers will get into fatigue faster. Few were the studies that presented $\dot{V}O_2K$ data for shorter distances (e.g. < than 2 minutes), focusing on the analysis of the 100 meters swimming performance (Ribeiro et al. 2015; Rodríguez et al., 2003 and 2016) and none, until now, presented data for very short events (e.g. ~30 seconds).

Having the goal to present a broad analysis of the faster events in swimming (50, 100 and 200 meters swimming, which represent ~86% of the indoor swimming events) we couldn't leave apart from analysis the only event that has never been studied – the 50 meters swimming. The limitations to the mathematical modelling of such a short effort are well known and have already been highlighted throughout this work, however it seemed incomplete for us if we left this distance aside. In this sense the need arose to present a new strand of data analysis that could, somehow, give strength and confirm the logic obtained on the $\dot{V}O_2K$ data analysis by the traditional exponential model.

The growth rate thus supported the data initially obtained by the exponential model, proving to be a useful and simpler tool to apply in order to test the $\dot{V}O_2K$ velocity in response to the abrupt start of a maximal exercise. The temporal interval chosen between the 20th and 30th seconds of the initial exercise, although in the specific case of the study served perfectly to the characteristics of the tests, as far as it disregards the cardiodynamic phase and fixes on the upper time of the shorter test (i.e., the 50 meters test), could be also advised for future studies with different distances. This suggestion is based on the fact that after the 30 seconds of exercise the $\dot{V}O_2$ response tends to present a clear stabilization, and the increment of more seconds in the temporal interval of analysis would diminish the growth rate average value and by this way detract the interpretative value of the variable, as well as it would make it impossible the comparison between different distances.

The use of the growth rate, as it is here presented, should be, naturally, replicated in future studies in order to attest its applicability and reliability, however, as a tool of support for checking data obtained through an already validated methodology seems to be a good and useful instrument ready to use.

In the MT's the fast $\dot{V}O_2$ kinetics induces similar results between the tests at the variables amplitude and time delay. Only the amplitude of the 50 meters test (probably due to the short duration of the test) was significantly lower compared to the remaining tests. Also, comparing the 100, 200 and TLim-MAV tests we did

not observe significant differences on the amplitude as not at the $\dot{V}O_{2peak}$ of the same tests.

The time constant, being one of the variables that accounts for the calculation of the $O_{2initialDef}$, showed, as expected, several correlations with this variable. Therefore, the fast $\dot{V}O_2$ kinetics were responsible for lower O_2 initial deficits which influenced positively the start of the exercises that consequently became more efficient and less anaerobic. Also, the MRT, another variable related to the time constant, showed interesting characteristics of how the $\dot{V}O_2$ rises until its maximal values.

An interesting observation found in the MT's is based in these two variables. Both in the MRT as in the $O_{2InitialDef}$, intra-variables interesting correlations were found between the 50 and 100 meters tests and between the 100 and 200 meters tests. These correlations found in the 50/100 and in the 100/200 but not replicated between the 50 and 200 meters tests led us to suggest, in study 1, a physiological proximity between these two sets of events. As a matter of fact, it is usual to see swimmers perform the 50 and the 100 meters events and on the other hand the 100 and 200 meters events with good performance markers, while it is not so usual to see a specialized swimmer of the 50 meters being also specialized in the 200 meters event and vice versa. Based on our results, we can suppose that it may exist a physiological adaptation in the sprinters whose barrier of adaptability ends in the 100 meters distance while in the 200 meters event they need other physiological adaptations. In fact, according to the results, the bioenergetic profiles of the 50 and 200 meters distances were quite distinct. Another fact is that, in swimming, in clubs with larger structures the planning of the daily training practice is already well distinct for the sprinters compared to the remaining swimmers, sometimes with the practice being oriented by different coaches. Based on our results it seems to us that this separation in training practice would be useful providing a better individualization and specialization that should occur throughout the swimmers' career.

Comparing the continuous with the interval training, it seems to us, in the same line with Demarie et al. (2000) suggestions for running, that interval training is more beneficial for the development of aerobic capacity. Even though the maximal $\dot{V}O_2$ values were higher for the continuous work (study 2) and the percentage value of the time swam near the $\dot{V}O_2$ maximal values were similar between the two exercise modes in study, the swimmers were able to perform the requested intensity for a significantly longer time in the interval training, which, consequently, led to significantly higher times spent near their $\dot{V}O_2$ maximal values. This fact led us to indicate the interval training as the best one for stimulating the oxidative system and inducing better chronic adaptations on swimmers physiology parameters (Demarie et al., 2000; Helgerud et al., 2007).

In study 3 we have seen that no differences exist on the physiological parameters between IT sets performed with 100 or 200 meters bouts, with both tasks eliciting the Peak- $\dot{V}O_2$ obtained in the corresponding incremental tests and similar times spent near the individuals $\dot{V}O_2$ maximal values. However, the IT performed with 100 meters bouts was suggested as the preferable one since, it appears to be the one that swimmers performed more easily (i.e., significantly lower PRE in the first 800 meters) for the same physiological benefits. If between IT sets composed by 100 and 200 meters bouts, we did not see different physiological responses, the case was different when we compared the use of 50 instead of 100 meters bouts. In study 4 a quite significant difference was observable at the $\dot{V}O_{2peak}$ and the times spent near the $\dot{V}O_2$ maximal values of the swimmers, with the task performed with 100 meters bouts, getting much higher results, indicating it as the better one in order to get better physiological adaptations. This led us to a clear conclusion that the MAV IT sets performed with 100 or 200 meters bouts can be useful for the aerobic training purpose, while IT sets performed with 50 meters bouts, for the same intensity, are not.

In study four we also tested higher intensities for HIT sets performed with 50 meters bouts, concluding that significant differences occur at a physiological level with increments of 5 and 10%. In fact, only the HIT50 at 110%-MAV was able to elicit the Peak- $\dot{V}O_2$, and only at 105%-MAV the results at the $\dot{V}O_{2peak}$ were not

statistically different for the same distance performed with 100 meters bouts. For these reasons, our recommendation is that, when working with 50 meters bouts an intensity of at least 105% of MAV should be applied.

At the level of the metabolic contributions, it becomes clear that the three energetic systems had a significant effect on the performance of the exercises tested, mainly at the MT's tests.

The aerobic contribution increases as the exercise becomes longer and less intense. An increase on the aerobic relative participation in the continuous tests was also observable, which starts in the ~34% in the shorter test (the 50 meters test) until ~82% in the longer one (the TLim-MAV test). With an opposite profile a decrease on the total anaerobic participation was observable from ~66% to ~18% for the same tests. Notwithstanding the percentage values are higher or lower, several correlations between the results of both systems with swimming performances in the MT's tests showed both systems relevance on the participation of these efforts.

The 100 meters test showed to be the one where the aerobic and anaerobic participation have the most similar relevance for performance showing results close to 50%, as reported previously by other studies (Hellard et al., 2018; Ribeiro et al., 2015; Zamparo et al., 2000). This fact could support the idea that when training for a 100 meters distance the planning should include at the same level of importance the development of both aerobic and anaerobic capacities. This can be assumed for the freestyle technique and, even though we have tested only this technique, Hellard et al. (2018) reported values of anaerobic and aerobic participation close to 50% for the four swimming techniques at the 100 meters distance, which could support the idea that this recommendation could be extended for the training of the remaining swimming techniques. Although the 100 meters is the most balanced distance in terms of the aerobic and anaerobic systems participation, when training for the 50 and 200 meters distances both the aerobic or the anaerobic capacities should not be disregarded in the training planning, since both are accountable for the swimming performance at least by

~34% (the aerobic participation in the shorter distance) and 29% (the anaerobic participation in the longer distance). Additionally, both anaerobic and aerobic participations were correlated with the swimmers' personal best at official competitions for the three distances in study.

Regarding the MT's, we noticed that the response of the anaerobic component presented remarkable similarities, mainly if we consider the total anaerobic response, where no significant differences were observable in the absolute values between the three distances. Only the anaerobic lactic response showed differences being higher in the 100 compared with the 50 meters distances, differences that were diluted when the results were corrected for the swimmers body weight. When the percentage values for the total energy systems participation were considered, the anaerobic participation presented significant differences caused by the growing aerobic participation as the tests became longer. Regarding the aerobic system participation, contrarily to the anaerobic, it presented significant differences both in the absolute and the relative values, growing as the distance became longer and the exercise less intense.

Hence, we can conclude that when performing supramaximal efforts (MT's) the swimmers present a quite similar anaerobic response and what is significantly different on the participation of the three energetic systems is the aerobic system, which plays the most significant difference on the exercise metabolic relative contributions.

The TLim-MAV test, being a test with a longer duration performed with a lower intensity, followed the logic that was observed firstly in the MT's, presenting, in terms of relative values, the highest aerobic and the lowest anaerobic participation in exercise from all continuous workouts studied.

The metabolic contributions obtained in the continuous tests were in accordance with the results of a previous study for 30 seconds of maximal swimming, similar to the duration of our 50 meters test (Peyrebrune et al., 2014) and for maximal trials of 100 (Ribeiro et al., 2015; Hellard et al., 2018, Zamparo et al., 2000) and

200 meters swimming (Sousa et al., 2011). Regarding the TLim-MAV test, the results showed similarities with comparable studies which tested swimmers tolerance for the same intensity (Sousa et al., 2014b) and to values reported for the 400 and 800 meters distances (Rodríguez and Mader, 2011).

Contrarily to the MTs, where both the anaerobic and aerobic participations were correlated with swimming performance in the corresponding distances, in the TLim-MAV test only the aerobic participation was correlated with middle- and long-distance swimming and also associated with a lower $[La^-]$, highlighting its contribution towards a higher effort efficiency. This could indicate that a higher relevance for the aerobic participation, compared to the anaerobic one, could be found in longer distances than 200 meters. Nevertheless, Campos et al. (2017) suggested the total anaerobic contribution as significantly associated to swimming distances up to 400 meters.

Regarding the analysis of the off-kinetics of the $\dot{V}O_2$ fast recovery phases of exercise, a fundamental tool for the analysis of the anaerobic alactic contribution, a quite similar profile was observable between the continuous tests. The time constant varied from ~51 to ~59 seconds, while the amplitude ranges between the ~30 to ~33 $ml \cdot kg^{-1} \cdot min^{-1}$, with both variables not showing statistical differences.

Our values obtained at the recovery phases for the time constant were slightly higher from those reported by Campos et al. (2017) for the 50 and 100 meters distances, however they were similar to those reported for the 200 meters distance. Regarding the amplitude, our values were similar for the 50 meters distance, but, apparently lower for the 100 and 200 meters distances. For both variables, contrarily to what was reported by Campos' study, we did not find any statistical difference between distances. The statistical differences found in Campos' study could justify why they reported a growing anaerobic alactic participation from the 50 to the 100 and to the 200 meters distances. Our results contradict the findings of Campos' study, since it seems that the anaerobic alactic participation is already "maximal" in the shorter test and maintains its participation

in the longer tests, accordingly to Gastin (2001) who suggests that for maximal exercises the anaerobic alactic participation is maximal in the first 30 seconds of exercise.

In our continuous tests we observed that the recovery phase presented a longer time to reach the base line values of $\dot{V}O_2$ when compared to the on-kinetics. This slower recovery phase seems to be in line with Zignoli et al. (2019) that suggests that in the severe and extreme domains the recovery phase will be longer than the exercise phase, contrarily to what occurs in the moderate domain when both phases are equivalent. In fact, at the moderate domain there is no lactate accumulation and the recovery phase will be the mirror of the $O_{2\text{initialDef}}$ caused by the time that comprises from the start of the exercise until the energetic equilibrium is restored when the $\dot{V}O_2$ values match the energetic demand. Thus, it makes sense why at the moderate domain both phases should present similar times, unlike what happens at the severe or extreme domains where, to the oxygen initial deficit, the remaining part of the anaerobic contribution caused by the lactate accumulation should be added, rising the total O_2 debt and consequently increasing the time of recovery compared to the time of the on-kinetics.

The findings regarding the swimmers' physiological responses to maximal and supramaximal simulated swimming events and IT sets, here reported, contribute for an improved knowledge about the characterization of these specific exercise modes, as well as highlights, that higher capacities of oxidative responses, associated with higher MAVs, and higher capacities of metabolic responses seem to be related with best swimming performances both in training as in competition. Overall, our studies seem to confirm that the analysis of the $\dot{V}O_{2K}$ parameters as well as profiling swimmers bioenergetics, especially in the intensities associated with training and competitive events, are important aspects for a true understanding of human sports performance.

References of chapter VIII

- Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019a) Is $\dot{V}O_2$ kinetics influenced by swimming intensity in maximal and supramaximal velocities in young female swimmers? In: Proceedings of the International Seminar of Physical Education, Leisure and Health; Castelo Branco, Portugal. *Journal of Human Sport and Exercise* 14(4proc):1566-1569
- Almeida T, Pessôa Filho D, Espada M, Reis J, Simionato A, Siqueira L, Sancassani A, Oliveira J, Alves F (2019b) Physiological responses at maximal aerobic swimming pacing in different distance-trials. In: Proceedings of the International Seminar of Physical Education, Leisure and Health; Castelo Branco, Portugal. *Journal of Human Sport and Exercise* 14(4proc):1686-1689
- Alves F, Gomes-Pereira J, Pereira F (1996) Determinants of energy cost of front-crawl and backstroke swimming and competitive performance. In cost of front crawl and backstroke swimming and competitive performance. In: Troup JP, Hollander AP, Strasse D, Trappe SW, Cappaert JM, Trappe TA (eds) *Biomechanics and Medicine in Swimming VII*, E & FN Spon, London, pp 185-191
- Alves F, Reis L, Vleck V, Bruno P, Millet G (2009) Oxygen uptake kinetics in heavy intensity exercise and endurance performance in swimmers. *Med Sci Sport Exerc* 41:978
- Bailey SJ, Wilkerson DP, DiMenna FJ, Jones AM (2009) Influence of repeated sprint training on pulmonary O_2 uptake and muscle deoxygenation kinetics in humans. *J Appl Physiol* 106(6):1875-1887
- Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP (2005) Physiological responses during submaximal interval swimming training: effects of interval duration. *J Sci Med Sport* 8:392-402
- Bishop D, Bonetti D, Dawson B (2002) The influence of pacing strategy on $\dot{V}O_2$ and supramaximal kayak performance. *Med Sci Sports Exerc* 34(6):1041-1047
- Burnley M, Jones A (2007) Oxygen uptake kinetics as a determinant of sports performance. *Eur J Sport Sci* 7(2):63-79
- Campos EZ, Kalva-Filho C, Gobbi R, Barbieri R, Almeida NP, Papoti M (2017) Anaerobic contribution determined in swimming distances: Relation with performance. *Front Physiol* 8:1-6

- Carter H, Pringle JS, Barstow TJ, Doust JH (2006) Oxygen uptake kinetics during supra $\dot{V}O_{2max}$ treadmill running in humans. *Int J Sports Med* 27(2):149-157
- Cerretelli P, Pendergast D, Paganelli W, Rennie, D (1979) Effects of specific muscle training on $\dot{V}O_2$ on-response and early blood lactate. *J Appl Physiol Respir Environ Exerc Physiol* 47(4):761-769
- De Jesus K, Sousa A, de Jesus K, Ribeiro J, Machado L, Rodríguez F, Keskinen K, Vilas-Boas JP, Fernandes RJ (2015) The effects of intensity on $\dot{V}O_2$ kinetics during incremental free swimming. *Appl Physiol Nutr Metab* 40(9):918-923
- Demarie S, Koralsztejn JP, Billat V (2000) Time limit and time at $\dot{V}O_{2max}$ during a continuous and an intermittent run. *J Sports Med Phys Fitness* 40(2):96-102
- Demarie S, Quaresima V, Ferrari M, Sardella F, Billat V, Faina M (2001) $\dot{V}O_2$ slow component correlates with vastus lateralis de-oxygenation and blood lactate accumulation during running. *J Sports Med Phys Fitness* 41(4):448-55
- Draper SB, Wood DM (2005) The $\dot{V}O_2$ response for an exhaustive treadmill run at 800-m pace: a breath-by-breath analysis. *Eur J Appl Physiol* 93(4):381-389
- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843
- Fernandes RJ, Cardoso CS, Soares SM, Ascensão A, Colaço PJ, Vilas-Boas JP (2003) Time limit and $\dot{V}O_2$ slow component at intensities corresponding to $\dot{V}O_{2max}$ in swimmers. *Int J Sports Med* 24(8):576-581
- Fernandes RJ, Keskinen KL, Colaço P, Querido AJ, Machado LJ, Morais PA, Novais D, Marinho D, Vilas-Boas JP (2008) Time limit at $\dot{V}O_{2max}$ velocity in elite crawl swimmers. *Int J Sports Med* 29(2):145-150
- Gastin PB (2001) Energy system interaction and relative contribution during maximal exercise. *Sports Med* 31(10):725-741
- Helgerud J, Hoydal K, Wang E, Karlsen T, Berg P, Bjerkaas M, Simonsen T, Helgesen C, Hjorth N, Ragnhild B, Hoff J (2007) Aerobic high-intensity intervals improve $\dot{V}O_{2max}$ more than moderate training. *Med Sci Sports Exerc* 39(4):665-671
- Hellard P, Pla R, Rodríguez FA, Simbana D, Pyne DB (2018) Dynamics of the metabolic response during a competitive 100-m freestyle in elite male swimmers. *Int J Sports*

Physiol Perform 13(8):1011-1120

Hettinga FJ, De Koning JJ, Foster C (2009) $\dot{V}O_2$ response in supramaximal cycling time trial exercise of 750 to 4000m. *Med Sci Sports Exerc* 41(1):230-236

Jones A, Wilkerson D, Vanhatalo A, Burnley M (2008) Influence of pacing strategy on O_2 uptake and exercise tolerance. *Scand J Med Sci Sports* 18:615-626

Pessôa Filho D, Alves F, Reis J, Greco, C, Denadai, B (2012) $\dot{V}O_2$ kinetics during heavy and severe exercise in swimming. *Int J Sports Med* 33(09):744-748

Peyrebrune MC, Toubekis AG, Lakomy HK, Nevill ME (2014) Estimating the energy contribution during single and repeated sprint swimming. *Scand J Med Sci* 24 (2):369-376

Reis J, Alves F, Bruno P, Vleck V, Millet G (2012a) Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. *Eur J Appl Physiol* 112(5):1689-1697

Reis J, Alves F, Bruno P, Vleck V, Millet G (2012b) Oxygen uptake kinetics and middle distance swimming performance. *J Sci Med Sport* 15:58-63

Reis JF, Almeida N, Alves F (2018) Oxygen uptake on-kinetics in endurance training and performance. In: Alves F, Rosado A, Leonor Moniz Pereira, Duarte Araújo (eds) *Research on Human Kinetics - Multidisciplinary Perspectives*, Edições FMH, Lisboa, pp 167-184

Ribeiro J, Figueiredo P, Sousa A, Monteiro J, Pelarigo J, Vilas-Boas JP, Toussaint, HM, Fernandes R (2015) $\dot{V}O_2$ kinetics and metabolic contributions during full and upper body extreme swimming intensity. *Eur J Appl Physiol* 115(5):1117-1124

Rodríguez F, Lätt E, Jürimäe J, Maestu J, Purge P, Rämson R, Haljaste K, Keskinen K, Jürimäe T (2016) $\dot{V}O_2$ Kinetics in all-out arm stroke, leg kick and whole stroke front crawl 100-m swimming. *Int J Sports Med* 37(3):191-196

Rodríguez FA, Mader A (2011) Energy systems in swimming. In: Seifert L, Chollet D, Mujika I (eds) *World Book of Swimming: From Science to Performance*. Nova Science Publishers, Hauppauge, New York, pp 225–240

Rodríguez, FA, Keskinen, KL, Malvela, MT, Keskinen, OP (2003) Oxygen uptake kinetics during free swimming: A pilot study In: Chatard JC (ed) *Biomechanics and Medicine in Swimming IX*, Publications de l'Université de Saint-Étienne, Saint-Étienne, pp 379-384

Schneider D, Wing A, Morris N (2002) Oxygen uptake and heart rate kinetics during heavy exercise: a comparison between arm cranking and leg cycling. *Eur J Appl Physiol* 88(1-2):100-106

Sousa A, Borrani F, Rodríguez FA (2017) Oxygen uptake kinetics is slower in swimming than in arm cranking and cycling during heavy intensity. *Front Physio* 8:639

Sousa A, Figueiredo P, Oliveira N, Oliveira J, Silva A, Keskinen KL, Rodríguez FA, Machado L, Vilas-Boas JP, Fernandes R (2011) $\dot{V}O_2$ Kinetics in 200-m race-pace front crawl swimming. *Int J Sports Med* 32(10):765-770

Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190

Sousa A, Ribeiro J, Sousa M, Vilas-Boas JP, Fernandes RJ (2014a) Influence of Prior Exercise on $\dot{V}O_2$ Kinetics Subsequent Exhaustive Rowing Performance. *PLoS One* 9(1):e84208

Sousa A, Vilas-Boas J, Fernandes R (2014b) $\dot{V}O_2$ kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at $\dot{V}O_{2max}$. *Biomed Res Int* 2014:675363

Zamparo P, Capelli C, Cautero M, Di Nino A (2000) Energy cost of front-crawl swimming at supra-maximal speeds and underwater torque in young swimmers. *Eur J Appl Physiol* 83(6):487-491

Zignoli A, Fornasiero A, Bertolazzi E, Pellegrini B, Schena F, Biral F, Laursen PB (2019) State-of-the art concepts and future directions in modelling oxygen consumption and lactate concentration in cycling exercise. *Sport Sci Health* 15:295-310

Chapter IX. Final Conclusions

One of the main goals of this investigation was to present new inputs and findings that could contribute for the development of the state of the art regarding the swimmers physiological responses to maximal and supramaximal exercises. To our knowledge, this was the first study in swimming that: provides a broad and comparative analysis of the $\dot{V}O_2$ kinetics and metabolic profiles of three competitive distances; tested swimmers tolerance to the MAV between continuous and intermittent exercise; compared two sets of IT composed by 100 and 200 meters bouts; and analysed the impact of different intensities applied on similar HIT sessions on swimmers physiological responses. In this final chapter the main conclusions of the investigation will be presented.

- At maximal and supramaximal intensities, fast $\dot{V}O_2$ kinetics seemed to be associated with the increment of the exercise intensity, as suggested by the faster time constants and MRT's found in the shorter events and confirmed by higher growth rates at these events;
- In well trained swimmers the $\dot{V}O_2$ kinetics seem not to be slower when compared with previous reports from the literature for dry-land sports;
- The fast kinetics found (with time constants varying between ~9 to ~27 seconds) allowed the achievement of high $\dot{V}O_2$ values, even in the shorter events, showing swimmers good adaptability on the oxidative capacity in this kind of efforts;
- At the continuous tests, both sexes achieved the Peak- $\dot{V}O_2$ in the TLim-MAV and 200 meters tests while in the 100 meters test only the male group attained it. The 50 meters was the only test where no group achieved the Peak- $\dot{V}O_2$, however ~83% of Peak- $\dot{V}O_2$ were reached only within ~32 seconds of exercise;
- The correlations found at the MRT and at the $O_{2initialDef}$ suggests a closely physiological logic between the 50 and 100 meters tests and between the 100 and 200 meters tests, which could explain the swimmers usual preferences for this two separate sets of events in competition and reinforce the need of individualization and specialization of the training programs;

- Even though the time constant of the continuous tests did not present correlations with the swimmers PB's, the variable showed correlations with performance and physiological parameters as seen with the % to MAV and % to Peak- $\dot{V}O_2$, showing its relevance for the swimming exercise;
- Peak- $\dot{V}O_2$, $\dot{V}O_{2peak}$'s, amplitude of the primary phase of the $\dot{V}O_2K$, MAV and the metabolic contributions (aerobic and total anaerobic) were the best variables predictors of performance with several correlations found with the swimmers PB's;
- The aerobic and total anaerobic contribution showed to be directly correlated with performance in the MTs, however in longer tests only the aerobic participation seems to have a significant impact on performance;
- The metabolic profiles showed an inverse response as the distance becomes longer and the exercise less intense, with the relative aerobic participation rising (from ~34 to ~82%) and the anaerobic decreasing (from ~66 to ~18%, respectively from the 50 MT to the TLim-MAV tests), presenting a cross over at the 100 meters test;
- The TLim-MAV performance (TLim) seemed to be inversely associated with the MAV and vVT_2 , suggesting that swimmers with higher aerobic power velocities could not perform an exercise at this relative intensity for as long as less proficient swimmers. Notwithstanding, coaches could take into account the time sustained of ~256 seconds obtained in this study, when planning training sets at the MAV, knowing that individual adjustments should be applied to each athlete;
- The tolerance to MAV was not associated with faster $\dot{V}O_2K$ or swimming performance, nor was it correlated between the continuous and the intermittent exercise mode;
- The intermittent exercise at MAV seemed to be a preferable mode when compared to the continuous workout, since it promotes longer times of exercise and consequently longer times spent by the swimmers near their $\dot{V}O_2$ maximal values;
- At the IT tests a significant improvement at the physiological parameters (specially at the time spent by the swimmers near their individual's $\dot{V}O_2$

maximal values) was observable when the distance of the repetitions increases from 50 to 100 meters, however no further improvements were registered when the distance rises to 200 meters;

- When comparing the IT sessions performed with 100 or 200 meters bouts, no differences were found at the physiological variables. However, when the first 800 meters of exercise were considered, the IT100_{8x100} could be a preferable set to apply instead of the IT200_{4x200}, since the swimmers could easily perform the task with lower values of RPE, while getting similar physiological benefits;
- At the IT100 and IT200 the times to exhaustion, $\dot{V}O_{2peak}$'s and the time constants of the primary phase were correlated between tests, showing that the swimmers more efficient at the physiological point (faster $\dot{V}O_{2K}$, with higher $\dot{V}O_2$'s and longer tolerance to the exercise) in one set were those who presented better results in the other;
- At the HIT50', increments of 5 and 10% induced significant improvements on swimmers physiological responses compared with the starting intensity of 100%-MAV, with the 110%-MAV intensity being the only capable to achieve the Peak- $\dot{V}O_2$;
- An increase of, at least, 5% of intensity is necessary to apply on a HIT50 session in order to get similar physiological results to an IT session performed with 100 meters bouts;
- The IT sessions performed at MAV with 100 and 200 meters bouts seem to be useful for the aerobics capacity and performance development, while an increase of 5% to 10% of intensity is advisable when working with repetitions of 50 meters;
- Finally, the few significant differences found between sexes suggests that the adaptations to training protocols can be applied equally in male and female swimmers.

Based on our investigation some practical implications for coaches arise:

- Coaches should implement training programs focused on the development of the aerobic power, promoting tasks that could tax the aerobic metabolism to maximal values (e.g., at or above the MAV) in order to increase the Peak- $\dot{V}O_2$ of swimmers, since higher $\dot{V}O_2$ responses are highly related with swimming performance;
- When training for the 50, 100 and 200 meters swimming events the development of both aerobic and anaerobic capacities should be considered, since both correlate with performance. Even in the shorter event ~34% derives from the aerobic contribution and in the longest ~29% from the anaerobic participation, which highlights the importance of all energetic systems for short and middle-distance swimming performance. However, when training for distances longer than 200 meters the focus should be on the aerobic parameters development;
- The application of IT sets at MAV could be a useful manner to improve the swimmers' time spent near their $\dot{V}O_2$ maximal values, compared to the continuous workout, which could contribute for inducing long term positive effects on swimmers' aerobic parameters;
- Coaches should implement IT sets at MAV with 100 and 200 meters bouts (with 15 and 30 seconds breaks, respectively), which will elicit swimmers' Peak- $\dot{V}O_2$, and where higher $\dot{V}O_2$'s responses were associated with swimming performance. Working for a total volume of 800 meters coaches should consider ITs with 100 meters bouts that swimmers can easily perform. Notwithstanding, coaches should consider testing swimmers' tolerance to MAV to better plan the training sessions;
- When working with short bouts ITs (i.e., 50 meters bouts), coaches should consider increasing the exercise intensity until the 110%-MAV to maximize the swimmers' physiological responses;
- The use of HIT swimming sets should be also considered in order to promote repeated elicitation of the oxidative system which could contribute to accelerate the $\dot{V}O_{2K}$ and maximize the effort's efficiency.

Chapter X. Appendix

APPENDIX I. Study 5

Is $\dot{V}O_2$ kinetics influenced by swimming intensity in maximal and supramaximal velocities in young female swimmers?

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Abstract

Objective: The aim of the present study was to determine if $\dot{V}O_2$ Kinetics ($\dot{V}O_{2K}$) and specifically, the time constant (τ) from rest to maximal and supramaximal velocities is influenced by the swimming intensity.

Design: Thirteen well trained female swimmers performed a discontinuous incremental test for maximal oxygen uptake (Peak- $\dot{V}O_2$) and maximal aerobic velocity (MAV) assessment and, two 100-m transitions for MAV (100_{MAV}) and all-out sprint (100_{MT}). In the 100-m tests, maximal rise of $\dot{V}O_2$ ($\dot{V}O_{2peak}$), oxygen deficit at the onset of exercise ($O_{2InitialDef}$) and $\dot{V}O_{2K}$ were determined. All tests were conducted using a breath-by-breath apparatus (K4b², Cosmed, Italy) connected to a swimming snorkel (new-AquaTrainer[®], Cosmed, Italy) for pulmonary gas sampling and an underwater visual pacer for velocity control.

Results: Peak- $\dot{V}O_2$ at the incremental test was significantly higher than the $\dot{V}O_{2peak}$ of both 100-m tests. Swimmers presented a significantly faster $\dot{V}O_{2K}$ response (lower τ) at the 100_{MT} (~12s vs. ~26s) which led to a significantly lower $O_{2InitialDef}$ compared to the 100_{MAV}. $\dot{V}O_{2peak}$ and τ were correlated between tests ($r=0.71$, $p<0.01$ and $r=0.59$, $p<0.05$, respectively).

Discussion: Based on our results it seems that the $\dot{V}O_{2K}$ is influenced by the exercise intensity at maximal and supramaximal intensities, getting faster as the exercise becomes more demanding. Furthermore, the capacity of attaining higher oxidative rates could be related to the physiological characteristics of the swimmers, since those who were more efficient in a physiological point of view (faster kinetics with higher $\dot{V}O_2$) in one test were those who presented better results in the other.

Key words: Swimming, $\dot{V}O_2$ kinetics, Supramaximal Intensity, Female swimmers, Youth athletes.

Introduction

The evaluation of oxygen uptake kinetics ($\dot{V}O_2K$) is an important aspect of human performance, allowing a better understanding of human bioenergetics (Jones and Burnley, 2009). In swimming, studies have associated faster $\dot{V}O_2K$ to better performance (Espada et al., 2015), however the characteristics that may influence the $\dot{V}O_2K$ response are controversial since several studies reported that the $\dot{V}O_2K$ remains remarkably constant as the intensity increases (Pessoa Filho et al., 2012; Espada et al., 2015; Reis et al., 2017), while others, showed an acceleration of the $\dot{V}O_2K$ in maximal trials (Rodríguez et al., 2003; Sousa et al., 2013).

The aim of this study was to analyze the $\dot{V}O_2K$ response between maximal (but constant) and supramaximal (without pacing strategies imposed) intensities in order to test if the increment of the intensity will change the $\dot{V}O_2K$ parameters.

Methods

Subjects

Thirteen well trained female swimmers (age 15.0 ± 1.2 yr.; mass 56.0 ± 6.9 kg; height 163.1 ± 6.9 cm) that regularly competed at state or national championships, volunteered to participate in this study and were fully familiarized with the equipment and with the test procedures that were used in the study prior to the beginning of the test sessions. The study was approved by the local University Ethical Committee and conducted in accordance with the 1964 Declaration of Helsinki.

Experimental design

All swimmers completed three testing sessions in a 25-meters swimming pool, separated by at least 48 hours: Firstly, swimmers performed a discontinuous incremental test, composed by 6 sets of 250-m, plus 1 set of 200-m at maximal intensity (Espada et al., 2015), in order to access the maximal oxygen uptake

(Peak- $\dot{V}O_2$) and the maximal aerobic velocity (MAV), the minimal velocity at which the $\dot{V}O_{2peak}$ was reached; Secondly, in randomized order, swimmers performed two 100-m tests, one at the MAV (100_{MAV}) and another in a maximal trial mode (100_{MT}), to access the maximal rise of $\dot{V}O_2$ ($\dot{V}O_{2peak}$), $\dot{V}O_2K$ parameters (time delay, time constant and amplitude) and the oxygen deficit at the onset of exercise ($O_{2InitialDef}$).

Data analysis

For $\dot{V}O_2$ data collection a telemetric portable breath-by-breath gas analyser (K4b², Cosmed, Italy), connected to the swimmers by a swimming snorkel (new-AquaTrainer[®], Cosmed, Italy), was used (Reis et al., 2017). An underwater visual pacer (Pacer2Swim[®], KulzerTEC, Portugal) set the velocity for the incremental and 100_{MAV} tests. For maximal oxygen uptake determination, a 30 seconds moving average of data was used for the incremental test, while at the 100m tests, given the shorter duration of the exercise, a 15 seconds moving average were applied for $\dot{V}O_{2peak}$ determination.

The $\dot{V}O_2K$ parameters were calculated, according to the following equation:

$$\dot{V}O_{2(t)} = \dot{V}O_{2base} + A \cdot (1 - e^{-(t-TD)/\tau})$$

Where $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest, which was calculated as the average of the first 30 seconds of the last minute before the start of the exercise (after 10 minutes of passive rest); TD, τ , and A, represent the time delay, the time constant (time that is needed to complete 63% of the $\dot{V}O_2$ response) and the amplitude of the exponential response of the $\dot{V}O_2$.

Statistical analysis

Normality of data was evaluated by the Shapiro-Wilk test. Paired t-test was used to check the differences between the 100-m tests and Pearson's linear correlation

coefficient was used in order to establish the significant associations between physiological measures. Statistical significance was accepted at $p < 0.05$.

Results

The Peak- $\dot{V}O_2$ ($53.3 \pm 4.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) of the incremental test was significantly higher than the $\dot{V}O_{2\text{peak}}$ of both 100-m tests. MAV ($1.20 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$) was significantly lower than the 100_{MT} velocity.

The swimmers physiological responses at the 100 meters tests (table 1) showed a significantly higher $\dot{V}O_{2\text{peak}}$, with faster $\dot{V}O_{2K}$ for the 100_{MT}, which lead to a significantly lower $O_{2\text{InitialDef}}$ compared to the 100_{MAV}. $\dot{V}O_{2\text{peak}}$ and τ were significantly correlated between tests ($r = 0.71$, $p < 0.01$ and $r = 0.59$, $p < 0.05$, respectively).

Table 17. Mean \pm SD of swimmers physiological responses at the 100-m tests.

Variable	100 _{MAV}	100 _{MT}
time (s)	82.9 ± 4.0	$75.1 \pm 5.2^*$
v ($\text{m}\cdot\text{s}^{-1}$)	1.21 ± 0.06	$1.34 \pm 0.09^*$
% to MAV (%)	100.7 ± 1.3	$111.8 \pm 5.4^*$
$\dot{V}O_{2\text{peak}}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	46.0 ± 4.8	$49.6 \pm 5.1^*$
% to Peak- $\dot{V}O_2$ (%)	86.3 ± 5.6	$93.1 \pm 5.1^*$
A ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	40.4 ± 5.6	40.9 ± 4.7
TD (s)	11.2 ± 3.3	11.7 ± 3.5
τ (s)	26.3 ± 7.9	$11.6 \pm 2.3^*$
$O_{2\text{InitialDef}}$ ($\text{ml}O_2$)	1406.3 ± 666.8	$953.0 \pm 234.9^*$

*Statistical differences to the 100_{MAV} test. v: velocity; %MAV: percentage of velocity to MAV; $\dot{V}O_{2\text{peak}}$: corrected to body mass $\dot{V}O_2$ maximal values of the 100 meters tests; % to Peak- $\dot{V}O_2$: percentage of $\dot{V}O_2$ to Peak- $\dot{V}O_2$; A, TD and τ :

amplitude, time delay and time constant of the $\dot{V}O_2K$; $O_{2InitialDef}$: oxygen deficit at the onset of the exercise.

Discussion

When comparing a swimming set at the MAV with a maximal trial it seems that there exists a clear acceleration on the $\dot{V}O_2K$ in the latter, expressed by the time constant (~26s vs. ~12s, respectively).

Our results contradict other studies that reported similar time constants at different intensities around the maximal lactate steady state (Espada et al., 2015) or between the moderate, heavy and severe domains (Pessôa Filho et al., 2012; Reis et al., 2017), however, they are in line with studies performed at maximal intensities or when swimmers are able to choose their own pacing strategies (Rodríguez et al., 2003; Sousa et al., 2013).

Jones et al. (2008) demonstrated that in a fast-start strategy, compared with the even-pace or with the slow-start strategy, the $\dot{V}O_2$ increased more rapidly towards its peak in the first seconds of exercise, rising the oxidative contribution to the energy turnover which led to a spare of the anaerobic capacity across the transition to higher intensity exercises, as observed with our values of $O_{2InitialDef}$.

Contrarily to what seems to occur with submaximal intensities, the $\dot{V}O_2K$ seemed to be influenced by the exercise intensity at maximal and supramaximal velocities, getting faster as the exercise becomes more demanding. Also, higher oxidative rates could be associated with specific physiological characteristics of the swimmers, since fast kinetics and higher oxygen uptakes seem to be related between both 100 meters tests.

References

- Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843
- Jones A, Burnley M (2009) Oxygen uptake kinetics: An underappreciated determinant of exercise performance. *Int J Sports Physiol and Perform* 4(4):524-532
- Jones A, Wilkerson D, Vanhatalo A, Burnley M (2008) Influence of pacing strategy on O₂ uptake and exercise tolerance. *Scand J Med Sci Sports* 18:615-626
- Pessôa-Filho DM, Simionato AR, Siqueira LOC, Espada MA, Pestana D (2016) Influence of regional and whole-body composition on swimming performance and aerobic indices. *Rev Bras Med Esporte* 22(3):195-199
- Reis J, Millet GP, Bruno P, Vleck V, Alves F (2017) Sex and exercise intensity do not influence oxygen uptake kinetics in submaximal swimming. *Front Physio* 8:72
- Rodríguez, FA, Keskinen, KL, Malvela, MT, Keskinen, OP (2003) Oxygen uptake kinetics during free swimming: A pilot study In: Chatard JC (ed) *Biomechanics and Medicine in Swimming IX*, Publications de l'Université de Saint-Étienne, Saint-Étienne, pp 379-384
- Sousa A, Jesus K, Vilas-Boas JP, Fernandes R (2013) Oxygen uptake kinetics at moderate and extreme swimming intensities. *Rev Bras Med Esporte* 19(3):186-190

APPENDIX II. Study 6

Physiological responses at maximal aerobic swimming pacing in different distance-trials

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Abstract

Objective: The aim of this study was to analyse the physiological responses of swimmers while performing different swimming distances at the maximal aerobic velocity (MAV) in order to understand the swimmers physiological impact along different levels of effort.

Design: Eight well trained swimmers performed a discontinuous incremental test for maximal oxygen uptake (Peak- $\dot{V}O_2$) and MAV assessment. Also, three different sets at the MAV, a time-limit session until exhaustion (TLim-MAV) and two distance trials of 100 (100_{mav}) and 200 meters (200_{MAV}) long, were performed. At the MAV tests, maximal rise of $\dot{V}O_2$ ($\dot{V}O_{2\text{peak}}$), oxygen initial deficit ($O_{2\text{InitialDef}}$) and $\dot{V}O_2$ kinetics ($\dot{V}O_{2K}$) were determined. All tests were conducted using a breath-by-breath apparatus (K4b², Cosmed, Italy) connected to a swimming snorkel (new-AquaTrainer[®], Cosmed, Italy) for pulmonary gas sampling and an underwater visual pacer for velocity control.

Results: Peak- $\dot{V}O_2$ at the incremental test was significantly higher than the $\dot{V}O_{2\text{peak}}$ of 100_{MAV} and 200_{MAV} but not from the TLim-MAV, which presented the highest $\dot{V}O_{2\text{peak}}$ among the MAV tests. At the TLim-MAV swimmers were able to hold the intensity for $235.7 \pm 34.1\text{s}$ performing $306.3 \pm 46.4\text{m}$.

Discussion: The main finding of our work is that independently of the continuous rise of the $\dot{V}O_2$ along different swimming distances at the MAV, it does not affect the $\dot{V}O_{2K}$ response, which remained remarkably similar. The reference values of $\dot{V}O_{2\text{peak}}$ for each swimming distance obtained in this study, as well as the ~236 seconds of swimmers capacity to hold the MAV, could be taken into account by coaches for their daily training routines planning.

Key words: Maximal aerobic velocity, $\dot{V}O_2$ kinetics, $\dot{V}O_2$ slow component, Swimming, Youth athletes.

Introduction

The maximal aerobic velocity (MAV), that corresponds to the minimal velocity at which the maximal oxygen consumption (Peak- $\dot{V}O_2$) of an athlete occurs in an incremental test, is one of the most important variables of study in sports physiology since it combines exercise economy and Peak- $\dot{V}O_2$ into a single factor (Billat and Koralsztein, 1996). MAV, that can be easily accessed through the velocity of the swimmers 400 meters performance, or more precisely throughout the velocity of the 300 central meters of the 400 meters event, is being well related with performance and is usually used by coaches for training prescription (Espada et al., 2015).

The aim of this study was to analyse the physiological responses of swimmers while performing different swimming distances at the MAV in order to understand the swimmers physiological impact along different levels of effort.

Methods

Subjects

Eight well trained swimmers, 6 males and 2 females (age 15.5 ± 1.3 yr.; mass 60.6 ± 8.5 kg; height 172.9 ± 10.8 cm), volunteered to participate in this study and were fully familiarised with the equipment and test procedures before the beginning of the test sessions. The criterion for swimmers participation was the regular participation at state or national championships. The study was approved by the local University Ethical Committee and conducted in accordance with the 1964 Declaration of Helsinki.

Experimental design

All swimmers performed four testing sessions separated by at least 48 hours: Firstly, a discontinuous incremental test composed by 6 sets of 250-m, plus 1 set of 200-m at maximal intensity (Espada et al., 2015) was used to determine the Peak- $\dot{V}O_2$ and MAV; Secondly, in randomized order, swimmers performed three

different sets at the MAV intensity, one time-limit session until exhaustion (TLim-MAV), and the other two with a previous defined distance of 100 (100_{mav}) and 200 meters (200_{MAV}) long. At the MAV tests the maximal heart rate (HR), rate of perceived exertion (RPE), maximal rise of the $\dot{V}O_2$ ($\dot{V}O_{2peak}$), $\dot{V}O_2K$ parameters (time delay (TD), time constant (τ) and amplitude (A) and the oxygen deficit at the onset of exercise ($O_{2InitialDef}$), were determined.

Data analysis

All tests were conducted using a breath-by-breath apparatus (K4b², Cosmed, Italy) connected to a swimming snorkel (new-AquaTrainer[®], Cosmed, Italy) for pulmonary gas sampling (Espada et al., 2015) and an underwater visual pacer (Pacer2Swim[®], KulzerTEC, Portugal) was used for setting the correct velocity of each test. For the maximal $\dot{V}O_2$ assessment, a 30 seconds moving average of the $\dot{V}O_2$ data was used for the incremental and 200_{mav} tests, while a sampling interval of 15s was applied to the 100_{mav} test given its shorter duration.

The $\dot{V}O_2K$ parameters were calculated, according to the following equation:

$$\dot{V}O_{2(t)} = \dot{V}O_{2(b)} + A_p \cdot (1 - e^{-(t-TD_p)/\tau_p}) + A_{sc} \cdot (1 - e^{-(t-TD_{sc})/\tau_{sc}})$$

Where $\dot{V}O_{2(t)}$ represents the relative $\dot{V}O_2$ at a given time; $\dot{V}O_{2base}$ represents the $\dot{V}O_2$ at rest; TD, τ , and A, represent the time delay, the time constant (time that is needed to complete 63% of the $\dot{V}O_2$ response) and the amplitude of the exponential response of the $\dot{V}O_2$; p and sc represent the primary and secondary (slow component) exponential $\dot{V}O_2$ responses.

Data analysis

Normality of data was evaluated by the Shapiro-Wilk test. The differences between each session were tested for statistical significance using ANOVA for repeated measures with Bonferroni correction. Statistical significance was accepted at $p < 0.05$.

Results

At the incremental test the Peak- $\dot{V}O_2$ and MAV were $60.5 \pm 2.1 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and $1.31 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$, respectively. Peak- $\dot{V}O_2$ was significantly higher than the $\dot{V}O_{2\text{peak}}$ of 100_{MAV} and 200_{MAV} tests but not from the TLim-MAV test. At the TLim-MAV test swimmers were able to perform the intensity for 235.7 ± 34.1 seconds performing 306.3 ± 46.4 meters. At the MAV tests (table 1), the TLim-MAV presented the higher $\dot{V}O_{2\text{rise}}$.

The $\dot{V}O_2K$ parameters did not show significant differences at the primary component, while the slow component was just observed in the TLim-MAV test.

Table 18. Mean \pm SD of the swimmers physiological responses at the MAV tests.

Variable	100 _{MAV}	200 _{MAV}	TLim-MAV
$\dot{V}O_{2\text{peak}}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	52.0 ± 2.9^c	53.8 ± 2.5^c	$60.1 \pm 1.8^{a,b}$
% to Peak- $\dot{V}O_2$ (%)	86.1 ± 5.2^c	89.0 ± 4.4^c	$99.4 \pm 2.4^{a,b}$
A_p ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	44.0 ± 1.9	44.2 ± 3.9	46.8 ± 3.1
TD_p (s)	12.1 ± 2.5	12.0 ± 1.8	11.7 ± 3.1
τ_p (s)	22.8 ± 9.3	24.5 ± 7.2	23.7 ± 7.0
A_{sc} ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	-	-	3.9 ± 2.0
TD_{sc} (s)	-	-	156.7 ± 29.3
τ_{sc} (s)	-	-	22.2 ± 18.4
$O_{2\text{InitialDef}}$ ($\text{ml}O_2$)	1583.7 ± 508.0	1620.8 ± 414.7	1667.7 ± 402.8
HR ($\text{b}\cdot\text{min}^{-1}$)	159.2 ± 11.3^c	171.4 ± 9.2	185.8 ± 8.7^a
RPE (0-10 units)	$2.6 \pm 0.9^{b,c}$	5.8 ± 2.0^a	8.5 ± 0.8^a

*Statistical differences are identified by a, b and c for the 100_{MAV}, 200_{MAV} and TLim-MAV tests, respectively. $\dot{V}O_{2\text{peak}}$: corrected to body mass $\dot{V}O_2$ maximal values of the MAV tests; % to Peak- $\dot{V}O_2$: percentage of $\dot{V}O_2$ to Peak- $\dot{V}O_2$ at the MAV tests; A, TD and τ : amplitude, time delay and time constant of the $\dot{V}O_2K$; p and sc: identifies the primary and slow component of the $\dot{V}O_2K$ response; $O_{2\text{InitialDef}}$: oxygen deficit at the onset of the exercise; HR: maximal HR of each test; RPE: Rate of perceived exertion.

Discussion

It is generally accepted that training with exercise intensities around the MAV could improve the athletes' aerobic parameters. The study of the physiological responses along different swimming distances could provide insightful information for a better planning of the training sets, especially for the high-intensity interval training (Sousa et al., 2018).

Our results suggest that the main difference on the $\dot{V}O_2$ response occurs between the 100_{MAV} and 200_{MAV} in relation to the TLim-MAV test. Since the $\dot{V}O_2K$ parameters of the primary component remained remarkably similar, which lead to similar values of $O_{2InitialDef}$, the appearance of the $\dot{V}O_2$ slow component at the ~158s of the TLim-MAV test, which is usually associated to the effect of fatigue induced by the exercise, could justify the significantly higher $\dot{V}O_2$ found (Fernandes et al., 2003; Espada et al., 2015), while the 100_{MAV} and 200_{MAV} tests showed similar profiles between each other.

Notwithstanding, swimmers reported significantly higher values of PRE at the 200_{MAV} compared to the 100_{MAV} test which indicates that some level of fatigue was already in the swimmers at that point.

The main finding of our work is that independently of the continuous rise of the $\dot{V}O_2$ along different swimming distances at the MAV, it does not affect the primary phase of $\dot{V}O_2K$ response. The reference values of $\dot{V}O_{2peak}$ for each distance obtained in this study, as well as the ~236 seconds of swimmers capacity to hold the MAV, could be taken into account by coaches for their daily training routines planning.

References

Billat V, Koralsztein JP (1996) Significance of the velocity at $\dot{V}O_{2max}$ and time to exhaustion at this velocity. *Sports Med.* 22(2):90-108

Espada M, Reis J, Almeida T, Bruno P, Vleck V, Alves F (2015) Ventilatory and Physiological Responses in swimmer below and above their maximal lactate steady state. *J Strength Cond Res* 29(10):2836-2843

Fernandes RJ, Cardoso CS, Soares SM, Ascensão A, Colaço PJ, Vilas-Boas JP (2003) Time limit and $\dot{V}O_2$ slow component at intensities corresponding to $\dot{V}O_{2max}$ in swimmers. *Int J Sports Med* 24(8):576-581

Sousa A C, Fernandes RJ, Boas J P V, Figueiredo P (2018) High-intensity Interval Training in Different Exercise Modes: Lessons from Time to Exhaustion. *Int J Sports Med* 39(9):668-673

APPENDIX III

Informed consent for study's participation

CONSELHO DE ÉTICA DA FACULDADE DE MOTRICIDADE HUMANA

CONSENTIMENTO INFORMADO LIVRE E ESCLARECIDO PARA INVESTIGAÇÃO CIENTÍFICA COM SERES HUMANOS

Título do projeto ou estudo: Caracterização da Cinética do Consumo de Oxigênio em Nadadores, em intensidades Máximas e Supramáximas. Caracterização de um tipo de Treino Intervalado com diferentes tempos de recuperação à velocidade aeróbia máxima

Pessoa responsável pelo projeto: Tiago André Freire de Almeida

Instituição de acolhimento: Faculdade de Motricidade Humana e Universidade Estadual Paulista Júlio De Mesquita Filho – Campus de Bauru

Este documento, designado **Consentimento, Informado, Livre e Esclarecido**, contém informação importante em relação ao estudo para o qual foi abordado/a, bem como o que esperar se decidir participar no mesmo. Leia atentamente toda a informação aqui contida. Deve sentir-se inteiramente livre para colocar qualquer questão, assim como para discutir com terceiros (amigos, familiares) a decisão da sua participação neste estudo.

Informação geral
Este projeto pretende contribuir para colmatar as lacunas existentes na investigação na área, através de uma caracterização cuidada da cinética do $\dot{V}O_2$ em nadadores, em resposta a exercícios de intensidades máximas e supramáximas, em natação, bem como analisar típicos tipos de treino intervalado, com diferentes tempos de recuperação à velocidade aeróbia máxima (VAM). Iremos estudar a forma como um nadador responde às demandas energéticas, de esforços intensos (característico de provas de 50, 100 e 200 metros), impostas subitamente pelo sinal de partida,

<p>bem como a resposta fisiológica de um nadador perante tarefas intervaladas típicas de treino.</p>
<p style="text-align: center;">Qual a duração esperada da minha participação?</p>
<p>O período de participação previsto será de 3 a 4 semanas.</p> <p>A duração prevista de cada sessão experimental é de 30 a 60 minutos.</p>
<p style="text-align: center;">Quais os procedimentos do estudo em que vou participar?</p>
<ol style="list-style-type: none"> 1. Para a realização das sessões experimentais é necessário equipamento desportivo (fato de banho touca e óculos (opcional)). 2. Os participantes devem abster-se da prática desportiva vigorosa nas 24 horas precedentes a cada sessão de teste. 3. A análise cardiorrespiratória do ar expirado, em situação de nado, será realizada em todas as sessões através da utilização de um analisador de gases “breath-by-breath” (K4b², Cosmed, Italia). O analisador será acoplado ao atleta através de um tubo respiratório, “snorkel” (Aquatrainner, Cosmed, Itália). Este aparelho surge como uma adaptação necessária para o desenvolvimento de estudos relacionados com a cinética do $\dot{V}O_2$ no meio aquático. O atleta utilizará também um cardiofrequencímetro Polar® série S810 e software específico “Polar Precision Performance™ Software”, para o registo constante da frequência cardíaca, enquanto para o doseamento do lactato sanguíneo recorrer-se-á sua recolha (25µl) em tubos de ensaio (Eppendorf) para armazenamento e posterior análise enzimática pelo Lactímetro 2500 STAT (Yellow Spring). 4. Cada participante irá participar em 7 a 9 sessões experimentais. 5. Cada sessão deverá ter um intervalo mínimo de 24 horas.
<p style="text-align: center;">A minha participação é voluntária?</p>
<p>A sua participação é voluntária. Caso decida participar neste estudo é importante ter conhecimento que pode desistir a qualquer momento, sem qualquer tipo de consequência para si.</p>
<p style="text-align: center;">Quais os possíveis benefícios da minha participação?</p>

Participação num estudo de investigação inovador na área do treino desportivo. Acesso teórico e prático a metodologias de elevada qualidade e pertinência no contexto científico.
Quais os possíveis riscos da minha participação?
Visto os participantes serem atletas bem treinados os riscos são mínimos. No entanto em alguns testes, devido ao seu carácter de intensidade máxima, poderá causar algum desconforto natural da prática de exercício vigoroso.
Quem assume a responsabilidade, no caso de um evento negativo?
A assinatura deste consentimento funciona como termo de responsabilidade.
Quem deve ser contactado em caso de urgência?
Serviços de Emergência.
Como é assegurada a confidencialidade dos dados?
Será assinada uma declaração de confidencialidade dos dados por parte dos investigadores, a ser entregue aos participantes.
O que acontecerá aos dados quando a investigação terminar?
Os dados serão utilizados para a publicação de artigos em revistas nacionais e/ou internacionais e na tese de doutoramento. Poderão ser úteis para a estruturação de investigações futuras.
Como irão os resultados do estudo ser divulgados e com que finalidades?
Os resultados serão publicados através de artigos em revistas nacionais e/ou internacionais e na elaboração da tese de doutoramento, sem que os sujeitos sejam alguma vez identificados.
Em caso de dúvidas quem devo contactar?
Para qualquer questão relacionada com a sua participação neste estudo, por favor, contactar: Mestre Tiago Almeida; Professor Doutor Dalton Muller Pessoa Filho

Assinatura do Consentimento Informado, Livre e Esclarecido

Li (ou alguém leu para mim) o presente documento e estou consciente do que esperar quanto à minha participação no estudo Caracterização da Cinética do Consumo de Oxigénio em Nadadores, em intensidades Máximas e Supramáximas. Caracterização de um tipo de Treino Intervalado com diferentes tempos de recuperação à velocidade aeróbia máxima. Tive a oportunidade de colocar todas as questões e as respostas esclareceram todas as minhas dúvidas. Assim, aceito voluntariamente participar neste estudo. Foi-me dada uma cópia deste documento.

Nome do participante

Assinatura do participante

Nome do representante legal do participante
(se aplicável)

Data

Grau de relação com o participante

Investigador/Equipa de Investigação

Os aspetos mais importantes deste estudo foram explicados ao participante ou ao seu representante, antes de solicitar a sua assinatura. Uma cópia deste documento ser-lhe-á fornecida.

Nome da Pessoa que obtém o consentimento

Assinatura da Pessoa que obtém o consentimento

Data

APPENDIX IV

Medical questioner pre-exercise

Questionário Médico Pré-exercício

Toda informação fornecida é confidencial. Este questionário será útil para conhecermos melhor os seus hábitos de exercício físico e a sua saúde. Para garantir que não se insere em nenhum dos critérios de exclusão deverá responder a todas as questões com toda a sinceridade.

Sujeito ID: _____ Data: _____

Data de Nascimento: ____/____/____

Masculino/Feminino: _____ Idade: _____

Questionário Médico

- | | Sim | Não |
|---|-----|-----|
| 1. Costuma ter dores no peito enquanto repousa e/ou realiza esforço? | ___ | ___ |
| a. Se respondeu "Sim", o seu médico já diagnosticou estas dores? | ___ | ___ |
| 2. Já sofreu um enfarte do miocárdio ou foi informado de quaisquer problemas cardíacos? | ___ | ___ |
| a. Caso a sua resposta seja "Sim", o enfarte ocorreu durante o último ano? | ___ | ___ |
| 3. Já fez algum electrocardiograma? Se sim, quando? (_____) | ___ | ___ |
| 4. Costuma ter hipertensão? (> 140/90 mmHg) | ___ | ___ |
| a. Se respondeu "Sim", está a controlar de alguma forma a sua pressão arterial elevada, por exemplo tomando medicamentos? | ___ | ___ |
| 5. Costuma ter perda de equilíbrio devido a tonturas ou perdas de consciência? | ___ | ___ |
| 6. O seu médico disse-lhe especificamente para não fazer exercício "severo" ou "pesado"? | ___ | ___ |
| 7. Tem ou já teve alguma doença associada ao sistema vascular (ex. insuficiência venosa)? | ___ | ___ |

Anamnese Clínica

Tem ou já teve: (marque X em caso afirmativo)

- | | |
|---|--------------------------------------|
| ___ Sopro cardíaco | ___ Acidente vascular cerebral (AVC) |
| ___ Extrasístolia/Pausas compensatórias | ___ Arritmias |
| ___ Dor ou pressão no peito | ___ Asma |
| ___ Hipertensão | ___ Cirurgias (Qual? _____) |
| ___ Enfarte agudo do miocárdio | ___ Cancro |

_____ Diabetes

_____ Enfisema pulmonar

(continuação)

_____ Convulsões

_____ Dor nas costas

_____ Trombose Venosa Profunda/Tromboflebite

_____ Falta de ar

_____ Tonturas/ desmaio

_____ Epilepsia

Explicações/comentários/Descrições: _____

Outras doenças/lesões/problemas médicos: _____

Medicamentos/medicamentos que está a tomar (Lista a dosagem por favor): _____

Sintomatologia

Sente alguns dos seguintes sintomas durante a prática de exercício? (marque x em caso afirmativo)

_____ Dor no peito

_____ Falta de ar

_____ Palpitações

_____ Tosse durante o esforço

(Data)

(Assinatura do Participante)

(Assinatura do Encarregado de Educação quando o participante for menor de idade)

APPENDIX V

Study approval by the Ethics Council of the Faculty of Human Kinetics



ETHICS COUNCIL

MEMBERS

Pedro Teixeira (President)
Paulo Armada (Vice-president)
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Hermínio Barreto (Supl.)

To:

Dr. Tiago Almeida
Faculdade de Motricidade Humana

Date: November 2, 2015

Research Project: *Caracterização da Cinética do Consumo de Oxigénio em Nadadores, em intensidades Máximas e Supramáximas. Caracterização de um tipo de Treino Intervalado com diferentes tempos de recuperação à velocidade aeróbia máxima.*

CEFMH Status: Approved
CEFMH Approval Number: 39/2015

This Council has reviewed the project indicated above. We declare that this project is in accordance with Portuguese and international guidelines for scientific research involving human beings, including the 2013 Declaration of Helsinki on Ethical Principles for Medical Research Involving Human Subjects, and the 1997 Convention on Human Rights and Biomedicine (the "Oviedo Convention").

The President of the Ethics Council

A handwritten signature in black ink, appearing to read 'Pedro J. Teixeira'.

Pedro J. Teixeira, Ph.D.

APPENDIX VI

Letter of acceptance for doctoral internship at UNESP

Letter of acceptance as doctoral fellow on a full-time associated to the Research Group of Applied Morphology, Physiology and Psychology to Human Exercise Performance and Health at the School of Sciences at the São Paulo State University.



Bauru, May 18, 2015

TO WHON IT MAY CONCERN

The purpose of this letter is to accept the visit of Tiago André Freire de Almeida, (Passport: N144776), PhD student with the project "Caracterização da Cinética do Consumo de Oxigênio em Intensidades Máximas e Supramáximas e em Treino Intervalado" from the Faculty of Human Kinetics (University of Lisbon, Portugal), to the School of Sciences of São Paulo State University (UNESP) from July 1, 2015 until September 30, 2015.

We are pleased to offer an appointment as doctoral fellow on a full-time associated to the Research Group of Applied Morphology, Physiology and Psychology to Human Exercise Performance and Health, under my supervision for 3 months. There is no commitment of the part of School of Sciences of the UNESP to supplement any fellowship support given to the student.

He is required to maintain a medical insurance coverage throughout your appointment.

We look forward to meeting you.

A handwritten signature in blue ink, appearing to be "Dalton Muller Pessoa Filho". The signature is written over a horizontal line.

Dr. Dalton Muller Pessoa Filho
Professor Assistant
São Paulo State University (UNESP)