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The effect of warm-up on swimming performance
The impact of volume, intensity and post warm-up recovery in elite swimmers

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"The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge."

Stephen Hawking

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List of Publications

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Beyond these papers, some preliminary studies were conducted as a preliminary approach to warm-up issue:

- **Neiva, H.P**, Morouço, P., Silva, A.J., Marques, M.C., & Marinho, D.A. (2011). The effect of warm up on tethered front crawl swimming forces. *Journal of Human Kinetics, (Special Issue)*, 113-119.

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Abstract

Warming-up before training or competition has become one of the most interesting topics in sport sciences in the last years. The technical and scientific community has been aware of the key role of warm up in swimming performance and the deepening of the knowledge on this subject is presented as an asset to optimize training and competition performance. Thus, the purpose of this work was to analyze the effects of warm-up on 100 m freestyle swimming performance in high-level swimmers. In addition, we intended to verify the effects of different volumes, intensities and post warm-up recovery times, by measuring the performance, and the biomechanical, physiological and psychophysiological responses of the swimmers. For the accomplishment of these purposes the following sequence was used: (i) reviewing the available literature; (ii) comparing the warm-up and no warm-up condition on 100 m freestyle; (iii) assessing three different volumes of warm-up, with the same intensity, and their effects on 100 m freestyle; (iv) analyzing two different intensities (race-pace vs. aerobic stimulation) on the 100 m race; (v) comparing two different post warm-up periods on the 100 m freestyle. The main conclusions drawn were (i) there is a limited research on warm-up and its structure in swimming; (ii) the warm-up improved swimming performance on 100 m freestyle race; (iii) the volume of warm-up should be up to 1200 m, with the risk of impaired performances with longer warm-ups; (iv) the stimulation of aerobic metabolism during warm-up is a reliable alternative to traditional race-pace; (v) the positive effects of warm-up, as increased core temperature, oxygen uptake, and heart rate are reduced over time and warm-up should be performed close to the race; (vi) different biomechanical patterns were used in response to the different warm-ups and these protocols could be used according to race strategy. In addition, it can be stated that high-level swimmers presented an individual adaptation to each warm-up design. Our results give clear remarks about the effects of volume, intensity and recovery periods and main physiological and biomechanical changes. These findings can be used by coaches and researches as a source for development of individual approaches or/and for further investigations.

Key words

Warm-up, swimming, performance, freestyle, physiology, biomechanics.

Resumo

O aquecimento antes do treino e da competição tem-se tornado um dos tópicos mais interessantes de investigação em Ciências do Desporto nos últimos anos. A comunidade técnica e científica está consciente do papel fundamental do aquecimento no rendimento em natação e o aprofundar do seu conhecimento é apresentado enquanto um trunfo para otimizar a performance de nado. Assim, o objetivo deste trabalho foi analisar os efeitos do aquecimento na prova de 100 m livres em nadadores de elevado nível. Pretendemos analisar os efeitos da utilização de diferentes volumes, intensidades e períodos de recuperação pós aquecimento, através da avaliação da performance e de variáveis biomecânicas, fisiológicas e psicofisiológicas. Para tal, foram adotados os seguintes passos: (i) revisão da literatura; (ii) comparação entre a realização ou não de aquecimento antes dos 100 m livres; (iii) avaliação de três diferentes volumes de aquecimento, com a mesma intensidade, e os seus efeitos nos 100 m livres; (iv) análise da influência de duas intensidades de aquecimento (ritmo de prova vs. estimulação aeróbia) nos 100 m livres; (v) comparação de dois diferentes intervalos de recuperação após o aquecimento. As principais conclusões que advêm do trabalho são as seguintes: (i) existe pouca literatura e conhecimento limitado acerca dos efeitos do aquecimento e da sua estrutura em natação; (ii) o aquecimento é benéfico para os 100 m livres; (iii) um volume de aquecimento até aos 1200 m parece ser o mais apropriado para a otimização dos 100 m livres, sendo que maiores volumes podem comprometer a performance; (iv) a estimulação aeróbia durante o aquecimento é uma alternativa viável ao ritmo de prova tradicional; (v) os efeitos positivos do aquecimento, como a temperatura, a frequência cardíaca e o consumo de oxigénio, diminuem ao longo do tempo e o aquecimento deve ser realizado o mais próximo possível da prova; (vi) existem diferentes respostas biomecânicas às diferences condições testadas, informação que poderá ser útil para preparar a estratégia de prova. É ainda de referir que os nadadores de elevado nível apresentam adaptações individuais em função de cada aquecimento. Os efeitos do volume, intensidade e intervalos entre o aquecimento e a prova, assim como as principais adaptações fisiológicas e biomecânicas, podem ser utilizados por treinadores e investigadores para desenvolvimento de abordagens individualizadas e investigações futuras.

Palavras-chave

Aquecimento, natação, performance, estilo livre, fisiologia, biomecânica.

Resumen

El calentamiento antes del entrenamiento y de la competición se ha convertido en uno de los temas más interesantes de la investigación en Ciencias del Deporte en los últimos años. La comunidad técnica y científica es consciente del papel fundamental de calentamiento en la natación y la mejora de su conocimiento se presenta como una ventaja para optimizar el rendimiento durante la competición. Nuestro objetivo fue analizar los efectos del calentamiento en los 100 m libres en nadadores de alto nivel. Así, se examinaran los efectos del diferentes volúmenes, intensidades y períodos de recuperación post-calentamiento, mediante la evaluación del desempeño y variables biomecánicas, fisiológicas y psicofisiológicas. Para ello, se utilizaron los siguientes pasos: (i) la revisión de la literatura; (ii) la comparación de la realización o no de calentamiento antes de los 100 m libres; (iii) la evaluación de tres volúmenes de calentamiento, con la misma intensidad, y sus efectos sobre los 100 m estilo libre; (iv) el análisis de la utilización de dos intensidades (ritmo vs. estimulación aeróbica) antes de los 100 m libres; (v) comparar dos intervalos diferentes entre calentamiento y la prueba. Las principales conclusiones que del trabajo son: (i) una escasez y conocimiento del calentamiento y su estructura en la natación en la literatura; (ii) el calentamiento beneficia a 100 m libre; (iii) un volumen de calentamiento hasta 1.200 m parece ser el más adecuado para la optimización de los 100 m libres, y volúmenes más grandes pueden comprometer el rendimiento; (iv) la estimulación aeróbica durante el calentamiento es una alternativa viable a lo ritmo tradicional; (v) los efectos positivos del calentamiento, como la temperatura, la frecuencia cardiaca y el consumo de oxígeno, disminuye con el tiempo de reposo y el calentamiento debe realizarse lo más cercano posible de la prueba; (vi) la existencia de diferentes respuestas biomecánicas después de las condiciones ensayadas, se puede utilizar para preparar la estrategia de prueba. Cabe señalar que los nadadores de alto nivel tienen ajustes individuales a cada calentamiento. Las indicaciones sobre el volumen, intensidad y los intervalos entre calentamiento y la prueba, así como las adaptaciones biomecánicas y fisiológicas también pueden ser utilizados por los formadores y los investigadores como un punto de partida para el desarrollo individualizado y para futuras investigaciones.

Palabras-clave

Calentamiento, natación, rendimiento, nado libre, fisiología, biomecánica.

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List of Abbreviations

BT	Body temperature
Chol	Cholesterol
CWU	Control warm-up
EMG	Electromyography signal
EWU	Experimental warm-up
F_{max}	Maximal force
F_{mean}	Mean force
HCO_3	Bicarbonate
HCT	Hematocrit
HR	Heart rate
HR_{max}	Maximal heart rate
IM	Individual medley
l	Arm length
$[La^-]$	Blood lactate concentrations
$[La^-]_{peak}$	Highest value of blood lactate concentration post-trial
LWU	Long warm-up
NWU	Without warm-up
η_ρ	Propelling efficiency
pCO_2	Carbon dioxide pressure
PHF	Peak horizontal force
pO_2	Oxygen pressure
PP	Plasma protein
PVF	Peak vertical force
RBC	Red blood cell
RP	Race-pace
RPE	Ratings of perceived exertion
SF	Stroke frequency
SI	Stroke index
SL	Stroke length
SWU	Short Warm-up
Tcore	Core Temperature
$Tcore_{net}$	Net values of core temperature
TG	Triglyceride
TS	Tethered swim
v	Swimming velocity
VO_2	Oxygen uptake

VO_2max	Maximal oxygen uptake
VO_{2peak}	Peak oxygen uptake
WBC	White blood cell
WU	Usual or standard warm-up

Chapter 1. General Introduction

Warm up is a common practice that precedes most of athletic events and it is a widely accepted routine to enhance performance and to prevent injuries (Ekstrand *et al.*, 1983; Woods *et al.*, 2007). As the name suggests, an increase in muscle and body temperature is the major contributing factor to positively influence performance. This rise in athletes' temperature results in multiple changes, such as the decreased time to achieve peak tension and relaxation (Segal *et al.*, 1986), the reduced viscous resistance of the muscles and joints (Wright, 1973), the vasodilatation and increased muscle blood flow (Pearson *et al.*, 2011), most likely resulting in optimized aerobic function (Gray & Nimmo, 2001; Pearson *et al.*, 2011), improved efficiency of muscle glycolysis and high-energy phosphate degradation during exercise (Febbraio *et al.*, 2006) and increased nerve conduction rate (Karvonen, 1992).

The increase in muscle and core body temperature could be achieved with (active) or without physical activity (passive). Any activity that raises the body's temperature without exertion such as hot showers, heated clothes, hot environments, could be considered as passive procedures (Bishop, 2003a). However, active warm-up, involving physical exertion, is the preferred and most applied method in almost all athletic events, with some studies reporting additional effects beyond the increased temperature. Priming exercitation might stimulate the buffering capacity, maintaining the acid-base balance of the body (Beedle & Mann, 2007; Mandengue *et al.*, 2005) and perhaps an increased baseline of oxygen uptake (VO_2) at the start of subsequent practice, that potentiate the aerobic system (Burnley *et al.*, 2011). Additionally, literature found a post activation potentiation after heavy loading activities that could increase motor neuron excitability and influencing post performances (Saez Saez de Villarreal *et al.*, 2007). The movement during the priming physical activities also reduces muscle stiffness (Proske *et al.*, 1993), allowing an easier and efficient action.

Although these abovementioned changes theoretically improve the performance, the existing research is far from being consensual. Several studies have reported improvements in performance after warm-up in cycling (Burnley *et al.*, 2005), running (Stewart & Sleivert, 1998) or even specific activities as the vertical jump (Burkett et al., 2005). However, in other similar activities the performances are impaired (Di Cagno *et al.*, 2010; Bradley *et al*, 2007; Stewart, & Sleivert, 1998; Tomaras, & MacIntosh, 2011), which is interesting and shows how warm-up can be crucial to sports performance. Moreover, the combination of different variables, the complexity of their relationship and the lack of a standardized warm-up, prevent the characterization of a warm-up ideal design (Fradkin *et al.*, 2010). This difficulty may be the reason why athletes and their coaches commonly use this practice based on personal experiences, developing their own different warm-up procedures.

In swimming this context is not different and scientific research showed ambiguous effects of warm-up (Bobo, 1999; Mitchell & Huston, 1993; Robergs *et al.*, 1990). In fact, these investigations were not performed during many years, resulting in a lack of research and restrictions. The first studies about warm-up in competitive swimming dated from the 50s, showed that warming up could lead to 1% faster performances on distances up to 91 m (De Vries *et al.*, 1959; Thompson, 1958). The positive influence of warm-up was later confirmed for longer distances, with a higher stroke length (SL) in 385.5 m of submaximal swimming (Houmard *et al.*, 1991) and lower lactate concentrations ([La^-]) after 200 m of intense swimming (Robergs *et al.*, 1990). Yet, the positive effect of warm-up was then challenged by the findings of Mitchell and Huston (1993), and Bobo (1999). The first authors found higher peaks in [La^-] after 2 min of high intensity swimming after warm-up while the others found no differences in a 91.4 m performance between in-water warm-up, dry-land warm-up and no warm-up. The results were not clear and even when the studies found increased race performances, those differences were lower than 1%. Therefore, it seems relevant to examine the effect of warm-up on short races, e.g. 100 m, complementing those findings with biomechanical and physiological assessment (Study 2). Moreover, before knowing the effect of dry-land warm-up or passive methods of warm-up, one should clearly know the effects of the specific in-water warm-up.

The performance depends on the magnitude of the response determined by several components such as volume, intensity and recovery time of prior activities (Bishop *et al.*, 2003). Some changes in the characteristics of external load could influence performances but little is known about this topic and about their effects on swimming performance. Warming for about 1400 m allowed the swimmers to maintain higher SL (~4%) in the last meters of 365.8 m at 95% of maximal oxygen uptake (VO_2max), with similar values of [La^-] and heart rates (Houmard *et al.*, 1991), compared to a warm-up lower than 200 m. When testing maximal efforts, no differences were found in the 91.4 m freestyle when comparing higher volumes (~2000m vs. ~4000m) of warm-up (Arnett, 2002). However, Balilionis *et al.* (2012) have compared a 91.44 m warm-up with a usual warm-up of ~1200 m and found increased performances on 45.72 m (~1%) when the longer warm-up was used, but without physiological or biomechanical changes. Thus, the effects of implementing different warm-up volumes remain unclear, with limited biomechanical and physiological variables evaluated, and deeper analysis should be performed (Study 3).

It is known that an improperly designed warm-up protocol could have adverse effects in performance (Tomaras & MacIntosh, 2011) and the influence of volume is not the only component that remains unclear when referring to swimming performance. The intensity of warm-up could be essential. When high intensity is performed during warm-up it could lead to early fatigue and compromise subsequent performance (Houmard *et al.*, 1991). On the other hand, an extremely low intensity warm-up could not trigger the necessary adaptations for optimized performances (Mitchell & Huston, 1993). Hourmard *et al.* (1991) compared ~65% of

VO_2max of continuous swimming with an intermittent set of 4 x 45.7 m at ~95% of VO_2max and no differences were observed in heart rate, SL or $[La^-]$ in 365.8 m submaximal swimming. These results suggests no benefit of using a high-intensity set during warm-up, but limited conclusions should be made as only submaximal performances and long distances were analyzed. In fact, a high intensity set increased $[La^-]$ before and after the main task (Mitchell & Huston, 1993). Nevertheless, these same authors found increased VO_2 after the higher intensity warm-up, which could express some cardiovascular alterations that could enhance aerobic system. So, the real effects of intensity were not deeply investigated and further should be understood about the different warm-up intensities in swimming performance (Study 4). In addition, knowing that some authors claimed that warm-up may optimize performance by enhancing VO_2 kinetics (Hughson, 2009; McDonald *et al.*, 2001), it should be interesting to understand the effects of an VO_2 stimulation set instead of traditional race-pace sets.

Regarding the post-warm-up recovery, the literature demonstrated to be scarce and unclear. Most studies about warm-up in swimming used a 10 min period of recovery between warm-up and the swimming trial, and few data is known about the swimmers' performances when different recoveries are used. Zochowski *et al.* (2007) found that a 10 min recovery improved 200 m trial performances compared to a 45 min recovery. However, this 10 min is difficult to implement in a swimming competition meeting, due to the fact that the swimmers must report to a call room before the start of the race. Using higher rest periods, West *et al.* (2013) found that 200 m swimming times were better with 20 min rest instead of 45 min. Nevertheless, to the best of our knowledge, the literature only focused on the effects of different post warm-up intervals in the 200 m swimming event, and different distances might demand different recovery periods (Study 5).

Previous studies did not report variables from different scientific fields to explain the athlete's performance and hence being unable to provide a holistic understanding of the phenomenon. Considering the abovementioned, the main purpose of this thesis was to analyze the effect of warm-up on 100 m freestyle swimming performance in high-level swimmers. In addition, it was our purpose to verify the impact of different volumes, intensities and post warm-up recoveries, conducting a performance, biomechanical, physiological and psychophysiological evaluation of the swimmers.

The thesis is developed according to the following sequence:

- Chapter 2 presents a qualitative review based on the early studies regarding the warm-up and performance in competitive swimming;
- Chapter 3 shows the experimental studies developed to accomplish the main aim of this thesis:
    - Study 2 demonstrates the effects of warm-up on 100 m freestyle by comparing a warm-up situation with no warm-up activities.

- Study 3 aims to investigate the use of three different warm-up volumes on the 100 m swimming race.
- Study 4 was developed based on the previous results and aims to compare the race-pace set usually performed during warm-up with a set to elicit increase VO_2.
- Study 5 relies on the comparison of two post warm-up recoveries on the 100 m performance, trying to understand the gap time effect on performance.

Then, a general discussion of the results is obtained on the studies performed (Chapter 4), followed by the main conclusions and limitations of the thesis (Chapter 5). Some suggestions for future research are also presented (Chapter 6). To better understand the procedures, limitations and constrains, some pilot studies were performed previously for the main aim of this thesis and are presented in appendix I and appendix II.

Chapter 2. Literature review

Study 1

Warm-up and performance in competitive swimming

Abstract

Warm-up before physical activity is commonly accepted to be fundamental, and any priming practices are usually thought to optimize performance. However, specifically in swimming, studies on the effects of warm-up are scarce, which may be due to the swimming pool environment, which has a high temperature and humidity, and to the complexity of warm-up procedures. The purpose of this study was to review and summarize the different studies on how warming up affects swimming performance and to develop recommendations for improving the efficiency of warm-up before competition. Most of the main proposed effects of warm-up, such as elevated core and muscular temperatures, increased blood flow and oxygen delivery to muscle cells and higher efficiency of muscle contractions, support the hypothesis that warm-up enhances performance. However, while many researchers have reported improvements in performance after warm-up, others have found no benefits to warm-up. This lack of consensus emphasizes the need to evaluate the real effects of warm-up and optimize its design. Little is known about the effectiveness of warm-up in competitive swimming, and the variety of warm-up methods and swimming events studied makes it difficult to compare the published conclusions about the role of warm-up in swimming. Recent findings have shown that warm-up has a positive effect on the swimmer's performance, especially for distances greater than 200 m. We recommend that swimmers warm-up for a relatively moderate distance (between 1000 to 1500 m) with a proper intensity (a brief approach to race-pace velocity) and recovery time sufficient to prevent the early onset of fatigue and to allow the restoration of energy reserves (8 to 20 min).

Introduction

Warm-up routines are common practice before training and competition in almost every sport. For decades, practitioners have prescribed warm-ups to prevent injuries (*Ekstrand et al.*, 1983) and enhance the performance (De Bruyn-Prevost, 1980) of their athletes. The scientific community supports the use of warm-up, which has been reported to increase muscle temperature, stimulate the performance of muscle contraction, decrease the time to achieve peak tension and relaxation (Segal *et al.*, 1986) and reduce the viscous resistance of the muscles and joints (Wright, 1973). Additionally, the hyperthermia induced by warm-up leads to vasodilatation and increased muscle blood flow, most likely resulting in optimized aerobic function due to the higher oxygen uptake during subsequent tasks (Pearson *et al.*, 2011; Gray & Nimmo, 2001). Febbraio *et al.* (1996) suggested that muscle temperature improves the efficiency of muscle glycolysis and high-energy phosphate degradation during exercise, which may be from increasing the dependence on anaerobic metabolism. We hypothesize that priming procedures that increase the body temperature optimize both aerobic and anaerobic metabolism in energy production during exercise.

Published reports also claim that warming up via physical activity might have some effects beyond the temperature-related ones. Gray *et al.* (2002) detected a lower accumulation of muscle lactate during a 30 s sprint on a cycle ergometer after active warm-up compared to passive warm-up, despite the same starting temperature conditions. It was later confirmed that physical activity stimulates buffering capacity, maintaining the acid-base balance of the body (Beedle & Mann, 2007; Mandengue *et al.*, 2005). Theoretically, the increased heart rate after active warm-up (Andzel, 1978; Febbraio *et al.*, 1996) and the higher baseline oxygen uptake at the start of subsequent practice improve the oxygen delivery to the active muscles and potentiate the aerobic energy system (Burnley *et al.*, 2011). In addition, heavy loading activities may induce high-frequency stimulation of motor neurons (French *et al.*, 2003) for several minutes afterwards, and this enhanced motor neuron excitability can result in a considerable improvement in power production (Saez Saez de Villarreal *et al.*, 2007; Sale, 2002). The movement required for activity also reduces muscle stiffness (Proske *et al.*, 1993) and increases the range of motion of the muscles involved, possibly allowing for easier, more efficient action.

Recently, some concerns have been raised about the effectiveness of the warm-up for enhancing athletic performance and preventing injuries (Neiva *et al.*, 2011; West *et al.*, 2013; Woods *et al.*, 2007). Improvements in performance ranged from 1 to 20% in sports such as cycling (Burnley *et al.*, 2005) and running (Stewart & Sleivert, 1998) as well as in specific activities such as vertical jumping (Burkett *et al.*, 2005). Warm-up also helped athletes in team sports; players were acutely ready to perform basketball, handball and baseball skills after warm-up activities (Dumitru, 2010; Szymanski *et al.*, 2011; Thompson, 1958). Nevertheless, in other cases, performance was impaired after warm-up. The vertical jump height and gymnastic technical leap performance were decreased after static stretching exercises (Bradley *et al.*, 2007; Di Cagno *et al.*, 2010), running performance was reduced after high-intensity warm-up (Stewart & Sleivert, 1998) or after a long rest period (Andzel, 1978), and cycling performance was impaired after cyclists performed their usually long warm-up (Tomaras & MacIntosh, 2011).

Scientific research has not demonstrated the efficacy of warm-up. As a result, athletes and coaches design the warm-up routines based on their individual experiences. The combination of a large number of variables, the complexity of their relationship (e.g., volume, intensity and recovery interval) and the lack of a standardized warm-up complicate characterization of warm-up techniques (Fradkin *et al.*, 2010). For example, there is no scientific evidence of the effectiveness of warm-up in swimming, and studies have shown ambiguous effects of warm-up on swimming performance (Bobo, 1999; Mitchell & Huston, 1993; Neiva *et al.*, 2012; Robergs *et al.*, 1990). The variability of research designs (e.g., protocols, outcomes selected, swimming events, and swimmers' competitive level) makes it difficult to compare data. Therefore, the purpose of the present review is to describe the effects of warm-up in swimming performance and to recommend optimized warm-up strategies.

Literature Search

The MEDLINE, Scielo, SPORTDiscus, ScienceDirect, Scopus, Web of Science and Google Scholar databases were searched for studies that were published from January 1955 until May 2013 (including electronic publications that were available ahead of print). This review includes studies about the effects of warm-up on swimming performance, which were identified using the following key-terms, individually and/or combined: "warm-up", "warm-up effects"; "priming exercise"; "pre-exercise", "prior exercise", "warm-up and performance" and "warm-up and swimming performance". Articles were also gathered based on references from other relevant articles. Those articles with restricted full text online were found in hardcopy form in library archives.

Studies were included in the review if they fulfilled the following selection criteria: (i) the studies were written in English; (ii) they were published in a peer-reviewed journal; (iii) they contained research questions on the effects of active and/or passive warm-up in swimming; (iv) the main outcome reported was a physiological (e.g., lactate, temperature, heart rate, or rate of perceived effort), biomechanical (e.g., stroke length, stroke frequency, or force) or performance (e.g., time and velocity) measure; and (v) healthy human participants were used. Review articles (qualitative review, systematic review, and meta-analysis) were not considered.

In the initial search, 236 studies were identified. After reading the titles, 59 articles were chosen for abstract reading. Those that were clearly not relevant or did not meet inclusion criteria were eliminated. A total of 18 original research studies on the effects of warm-up on swimming were included in our final analysis (Table 1). Fifteen studies focused on active warm-up, two studies focused on passive warm-up, and the remaining study investigated both types of practices.

Studying warm-up involves a large number of variables that interact with each other and possibly condition the results. Because of the risk in separating those variables, the findings and literature limitations were analyzed after the papers had been divided up according to active warm-up and its sub-items (swim volume, intensity, recovery/rest interval, and related/non-related warm-up) and passive warm-up.

Table 1. Physiological, biomechanical and performance changes following active and/or passive warm-up in swimming.

Author	Subjects	Warm-up: Active: Volume(m)	Warm-up: Active: Intensity	Warm-up: Dry	Warm-up: Passive: Mode	Warm-up: Changes*	Post warm-up test: Rest (min)	Post warm-up test: Intervention	Post warm-up test: Test	Post warm-up test: Parameters Assessed	Post warm-up test: Main results*
Carlile (1956)	10 T (M+F)				A_1 Hot shower:8min	ND	ND	A_1vs.A_2 A_2:N	36.6m	v	v:A_1>A_2
Thompson (1958)	60 UT (M)	A_1 110 A_3 2.5min	 Moderate 75% Max	A_2 Calisthenics			5	A_1vs.A_2vs.A_4 A_3vs.A_4; A_4:N	T_1:27.4m Max T_2:5min Max	T_1:v T_2:Laps	v:A_1>A_2=A_4 Laps: A_3>A_4
DeVries (1959)	13 T (M)	A_1 457.2	 Freely	A_2 Calisthenics circuit	A_3: Massage:10min A_4: Hot Shower:6min	ND	"brief"	A_1vs.A_2vs.A_3vs. A_4vs.A_5 A_5:N	91.4m Max (Crawl,breast, fly)	Time	Time:A_1<$A_{2,3,4,5}$
Robergs *et al.* (1990)	8 T (M)	A_1 400 400 kick 4x50	 82% VO_{2max} 45% VO_{2max} 111% VO_{2max}			$[La^-]$:A_1>A_2 [H+]:A_1>A_2 HCO_3-:A_1<A_2	10	A_1vs.A_2 A_2:N	200m 120% VO_{2max} (Front crawl)	HR;pCO_2;pO_2;HCO_3-;$[La^-]$	$[La^-]$:A_1<A_2 pCo_2:A_1<A_2 HR:A_1>A_2
Houmard *et al.* (1991)	8 T (M)	A_1 4x45.7 A_2 1371.6 A_3 1188.7 4x45.7	 95% VO_{2max} 65% VO_{2max} 65% VO_{2max} 95% VO_{2max}			No	5	A_1vs.A_2vs.A_3vs. A_4 A_4:N	365.8m 95%VO_{2max} (Front crawl)	VO_2;HR;RPE; $[La^-]$;SL	HR:A_4>$A_{1,2,3}$ $[La^-]$:A_4>$A_{1,2,3}$ SL:$A_{2,3}$ >$A_{1,4}$
Mitchell and Huston (1993)	10 T (M)	A_1 366 A_2 4x46	 70% VO_{2max} 110% VO_{2max}			HR:A_1<A_2 VO_{2max}:A_1<A_2 $[La^-]$:$A_{1,3}$<A_2	5	A_1vs.A_2vs.A_3 A_3:N	T_1:183m 110%VO_{2max} T_2:TS Max (Freestyle)	$[La^-]$; HR;Time; SL;VO_{2max}	T_1: HR:A_2>A_3 $[La^-]$:A_2>$A_{1,3}$ T_2: HR:$A_{1,2}$>A_3

Table 1. Continued.

Author	Subjects	Warm-up					Post warm-up test				
		Active			Passive	Changes*	Rest (min)	Intervention	Test	Parameters Assessed	Main results*
		Volume(m)	Intensity	Dry	Mode						
Romney and Nethery (1993)	12 T (8M, 4F)	A_1 5 min 12 x 22.9 5 min	 RPE=12 Up to RP RPE=14	A_2 5 min rope 5 min calisthenics circuit 5 min rope		ND	3	A_1vs.A_2vs.A_3 A_3:N	91.4m Max (Freestyle)	Time	Time:A_1<A_3
Akamine and Taguchi (1998)	6 T (M)				A_1 Bath 36°C, CO_2 300ppm:20min A_2 Bath 36°C:20min	ND	10	A_1vs.A_2	4 min kick 80% Max	RBC;HCT; WBC;PP; Chol;TG;[La^-] HR;EMG	HCT,WBC,PP,Chol: A_1>A_2 HR:A_1<A_2 [La^-]:A_1<A_2 EMG:A_1<A_2
Bobo (1999)	23 T (ND)	A_1 731.5	 Moderate	A_2: Bench press 3x6, 50%1RM		ND	5	A_1vs.A_2vs.A_3 A_3:N	5 x 91.4m Max (I=3min) (Freestyle)	Time	No changes
Arnett (2002)	10 T (6M, 4F)	A_1 2011.7 A_2 4023.4 A_3 663.9	A_1= A_2=A_3: Moderate			BT:AM<PM	5	AM:A_1vs.A_2 PM:A_1vs.A_3 AMvs.PM	91.4m Max (Freestyle)	Time;RPE;BT	Time:$A_{2(AM)}$>$A_{1,3(PM)}$; BT:$A_{1(AM)}$<$A_{2(AM)}$, $A_{1(PM)}$, $A_{3\ (PM)}$
Zochowski *et al.* (2007)	10 T (5M, 5F)	A_1 300 6x100 10x50 100	 Easy Pull / kick Specific RP Easy			HR:R_1>R_2	R_1:10 R_2:45	R_1vs.R_2	200m Max (1^{st} technique)	HR;[La^-] RPE; Time	Time:R_1<R_2 HR:R_1>R_2

Table 1. Continued.

Author	Subjects	Warm-up					Post warm-up test				
		Active			Passive	Changes*	Rest (min)	Intervention	Test	Parameters Assessed	Main results*
		Volume(m)	Intensity	Dry	Mode						
Nepocatych *et al.* (2010)	10 Mast (4M,6F)	A_1 45.7 45.7 A_2 >457.2 A_4 A_3+A_1	 40% Max 90% Max >46m 90%Max	A_3 5x1min Upper body vibration at 22Hz		RPE:$A_5<A_{1,2}$ HR:$A_4<A_2$	3	A_1vs.A_2vs.A_5 A_2vs.A_3vs.A_4 A_5:N	45.7m Max (Freestyle)	Time;RPE;HR; SR	HR:$A_5<A_2$; $A_2>A_{3,4}$
Kilduff *et al.* (2011)	9 T (7M, 2F)	A_1 300 6x100 10x50 100	 Easy Pull / kick Specific RP Easy	A_2 3x 87% 1RM Squat		ND	8	A_1vs.A_2	15m start Max	Start time; Jump Force (PHF;PVF)	PHF:$A_1<A_2$ PVF:$A_1<A_2$
Neiva *et al.* (2011)	10 T (M)	A_1 1000	 Freely			ND	10	A_1vs.A_2 A_2:N	30s TS Max (Front crawl)	F_{max};F_{mean}; [La^-];RPE	F_{max}:$A_1>A_2$ F_{mean}:$A_1>A_2$
Neiva *et al.* (2012)	10 T (M)	A_1 1000	 Freely			ND	10	A_1vs.A_2 A_2:N	50m Max (Front crawl)	Time;[La^-]; RPE	No changes
Balilionis *et al.* (2012)	16 T (8M, 8F)	A_1 45.7 45.7 A_2 ~1200	 40% Max 90% Max Freely			HR:$A_2>A_3$ RPE:$A_2>A_{1,3}$	3	A_1vs.A_2;vs.A_3 A_3:N	45.7m Max (Freestyle)	Time;Diving distance; Reaction;RPE; HR;SR	Time:$A_1>A_2$ HR:$A_1<A_2$

Table 1. Continued.

Author	Subjects	Warm-up					Post warm-up test				
		Active			Passive	Changes*	Rest (min)	Intervention	Test	Parameters Assessed	Main results*
		Volume(m)	Intensity	Dry	Mode						
West *et al.* (2013)	8 T (4M, 4F)	A_1				Tcore:R_1>R_2	R_1:20 R_2:45	R_1vs.R_2	200m Max (Freestyle)	Tcore;[La^-]; HR;RPE;Time; SR	Time:R_1<R_2 [La^-]:R_1>R_2
		400;									
		200 pull 200 kick	HR 40 to 60 below HR_{max}								
		200 drill									
		200 IM									
		4x50 free	RP								
		200 free	Easy								
Neiva *et al.* (2013)	20 T (10M, 10F)	A_1				ND	10	A_1vs.A_2 A_2:N	100m Max (Freestyle)	Time;[La^-]; RPE;SF;DPS;SI	Time: A_1<A_2 DPS: A_1>A_2 SI: A_1>A_2
		300	Easy								
		2x100	High DPS								
		8x50	Kick/drills; RP								
		100	Easy								

AM - Morning; A_x - warm-up number; **BT** - body temperature; **Chol** - cholesterol; **DPS** - distance per stroke; **EMG** - electromyography signal; **F** - Female; F_{max} - maximal force; F_{mean} - mean force; HCO_3^- - bicarbonate; **HCT** - hematocrit; **HR** - heart rate; HR_{max} - maximal heart rate; **I** - interval; **IM** - individual medley; **[La^-]** - blood lactate concentration; **M** - Male; **Mast** - Master swimmers; **Max** - maximal; **N** - no warm-up; **ND** - not determined; pCO_2 - carbon dioxide pressure; **PHF** - peak horizontal force; **PM** - afternoon; pO_2 - oxygen pressure; **PP** - plasma protein; **ppm** - parts per million; **PVF** - peak vertical force; **R** - rest; R_1 - tested rest situation one; R_2 - tested rest situation two; **RBC** - red blood cell; **RP** - race pace; **RPE** - ratings of perceived exertion; **RM** - repetition maximum; **SI** - stroke index; **SL** - stroke length; **SR** - stroke rate; **T** - trained swimmers; T_1 - test one; T_2 - test two; **Tcore** - core temperature; **TG** - triglyceride; **TS** - tethered swim; **UT** - Untrained; ***v***- velocity; VO_2 - oxygen uptake; VO_{2max} - maximal oxygen uptake; **WBC** - white blood cell. * results are presented in the variables that were statistically significant ($p \le 0.05$)

Active Warm-Up and Swimming Performance

Active warm-up is any act of exercising, involving specific and/or non-specific body movements, with the purpose of increasing metabolic activity and heat production in preparation for an upcoming main activity (Shellock & Prentice, 1985; Woods *et al.*, 2007). Active warm-up is traditionally the preferred method used by practitioners and is the most commonly investigated type; 89% of the studies about warm-up in swimming are about active warm-up. Improvements were shown only in 67% of the twelve studies that compared the use of active warm-up with no warm-up. Five of these studies showed an improvement in performance after warm-up, and three others suggested positive effects in the physiological and biomechanical changes. The remaining studies did not find that warm-up had any effect on swimming performance (Table 1).

The first studies suggested that warm-up allowed the swimmers to go 1% faster for short distances (up to 91 m)(De Vries, 1959; Thompson, 1958). This positive influence was later confirmed for long distances, with a higher stroke length (~0.07 m) observed in the final meters of 368.5 m (Houmard *et al.*, 1991) and lower lactate concentrations (~2 mmol/l) after 200 m of intense swimming (Robergs *et al.*, 1990). There were early ideas that priming exercises are beneficial to performance, but higher peaks in the lactate concentration after 2 min of high-intensity swimming (13.66 ± 2.66 vs. 9.53 ± 2.22 mmol/l, $p \leq 0.05$) have been reported (Mitchell & Huston, 1993). Additionally, Bobo (1999) failed to find significant differences in 91.4 m performance between three conditions (exercises in the water, dry land exercises, and no warm-up). The methods used could be questioned, as performance was assessed using a set of five repetitions of 91.4 m freestyle at maximum intensity. In addition, beyond comparing the mean times of all repetitions performed, the author analyzed the best repetition performed, which is similar to a study that tested a single repetition. A recent study found that usual warm-up leads to improved 100 m swimming performance, prolonging the controversy (Neiva *et al.*, 2013).

There have been inconclusive results on a swimmer's performance for shorter distances after warm-up. One study reported that warm-up did not have any favorable effects on 50 m crawl performance (Neiva *et al.*, 2012), while participants in another study had a trend toward significantly faster times on the 45.7 m freestyle (~0.2 s, $p = 0.06$) and higher propelling force with 30 s of maximal tethered swimming (~13% for the mean force and 18% for the maximal force, $p \leq 0.05$), as reported by Balilionis *et al.* (2012) and Neiva *et al.* (2011), respectively, for warm-up . However, there were found no differences were found among the other variables measured in these studies (e.g., perceived exertion, highest post blood lactate concentration, stroke rate, dive distance and reaction time), which weakens these findings.

The effects of active warm-up depend on several components such as the volume, intensity and recovery time (Bishop, 2003a; Bishop, 2003b). Some changes in the characteristics of the external training/warm-up load could be essential to influencing the subsequent performance and the results obtained. Furthermore, dry-land movements are usually performed before swimmers enter the pool, and the effects of these movements should not be disregarded. The relevance of these presented categories and their effects on swimming performance require deeper analysis.

Dry-land Warm-Up

Dry-land warm-up is any type of active practice performed out of the water; dry-land warm-up includes calisthenics, strength/activation exercises and stretching. Swimmers often perform some sort of physical activity out of the water (e.g., arm rotation) before entering the water to activate the body. However, these exercises are used to complement and not as an alternative to the in-water warm-up. Six studies have focused on the effects of dry-land warm-up as a different type of active warm-up other than the usual in-water procedures.

Three studies have shown that the use of calisthenics exercises does not influence swimming performance compared to the no warm-up condition (De Vries, 1959; Romney & Nethery, 1993; Thompson, 1958). Although there were no statistically significant differences, the results of Romney and Nethery (1993) showed that swimmers were 0.65 s faster in the 91.4 m freestyle with dry-land warm-up than without warm-up. This difference corresponds to an increase of 1.23% in the performance, which can substantially affect a swimming race.

With regard to strength exercises, Bobo (1999) found no differences in the 91.4 m freestyle between no warm-up and bench press practice. The author claimed that the amount of weight used may not have been heavy enough to stimulate the swimmers and may have interfered with the results. In fact, Kilduff *et al.* (2011) showed no differences in the 15 m starting time after activation with loaded squats (3 x 87% of 1 maximal repetition) compared with in-water warm-up. These weight exercises with a high load can have positive effects by inducing high-frequency stimulation of motor neurons (French *et al.*, 2003), resulting in an improved rate of force production, which has already been confirmed for explosive efforts (Saez Saez de Villarreal *et al.*, 2007). Strength exercises involving large major muscle groups, with few repetitions and high loads, could better prepare swimmers for competing.

An interesting method of dry-land exercise was used by Nepocatych *et al.* (2010) in master swimmers, adapting a swim bench with an attached vibration device. This allowed the swimmers to simulate the proper swimming technique while being exposed to five sets of one-minute vibrations. The authors found no differences in the 45.7 m freestyle time between the vibrations and in-water warm-up. Although they are not easy to apply, developments could arise from this research, and new alternative warm-up procedures should be investigated and applied to higher-level swimmers.

In most swim meets, there is a considerable time interval between the in-water warm-up and the swimming event, diminishing its possible beneficial effects (West *et al.*, 2013). Moreover, some facilities do not have an extra swimming pool available, requiring swimmers to rely on alternatives to in-water warm-up. Dry-land warm-up is as a possible warm-up procedure, which is supported by some studies. It is also recommended that the whole body should be stimulated instead of focusing on specific muscle groups. To the authors' knowledge, no study on the addition of these practices to in-water warm-up has been conducted, even though it could be a method of optimizing the swimmer latency period between the warm-up and the swimming event.

Swimmers commonly use stretching exercises, but, to the best of our knowledge, no study has been conducted on the effects of stretching on swimming performance. Additionally, little attention has been given to the question of stretching as a practice that influences the injury risk. By reducing muscle strain and increasing the range of motion of joints (Ekstrand *et al.*, 1983; Hadala & Barrios, 2009), stretching is expected to reduce the resistance of the movement, allowing for easier movement that optimizes the activity and prevents muscle and joint injuries. Despite these possible benefits, pre-exercise static stretching does not produce a reduction in the risk of overuse injuries (Pope *et al.*, 2000), and it could lead to a severe loss of strength and performance impairment (Winchester *et al.,* 2008). Yet, a decrease in strength when using dynamic stretching exercises has not been demonstrated (Hough et al., 2009), suggesting that stretching may be part of a warm-up routine if these are usual practices of the swimmers. Further investigation is needed to determine the effects of stretching alone as well as in combination with other warm-up activities.

In-Water Warm-Up: the Effect of Volume

The acute effects of different warm-up volumes on swimming performance have been previously researched in four studies; two found positive effects for volumes between 1000 m and 1500 m compared to a lower volume (i.e., lower than 200 m). A higher volume (1371.6 m) allows the swimmers to maintain higher stroke length (3.76%) in the last meters of 365.8 m at ~95% of maximal oxygen uptake (VO_2max), with similar values of blood lactate concentration and heart rate (Houmard *et al.*, 1991). This was later corroborated for shorter testing distances, verifying better 45.7 m performance (1.22%) after warming up for approximately 1300 m (men: 1257 ± 160 m; women: 1314 ± 109 m) instead of a 91.44 m warm-up (Balilionis *et al.*, 2012). It is possible that the lower volume was not sufficient to cause significant metabolic changes during the performance trial. In fact, the same result was verified by Nepocatych *et al.* (2010)

in master swimmers, with no changes in the 45.7 m freestyle after two short warm-ups (91.4 m and more than 450 m).

The remaining study on the influence of warm-up volumes did not find differences in the 91.4 m freestyle when warming up for either 2011.7 m or 4023.4 m with similar intensities (Arnett, 2002). Swimmers may expend too much energy during warm-up, or they may not have enough time after warm-up to replenish their phosphocreatine and adenosine triphosphate levels, compromising the energy supply and negatively affecting their performance. For instance, swimmers traditionally complete long warm-ups, even for short races, to achieve greater water sensitivity and to be better prepared for the competitive event. However, a long duration of exercise has a higher energy consumption that can contribute to the early onset of muscle fatigue, especially for high intensities (Hawley *et al.,* 1989).

When subjected to a continuous activity at moderate intensity, the body increases its temperature and stabilizes between 10 and 20 min after the start (Bishop, 2003a). Although this time could be set as a rule of thumb, the volume of the warm-up performed before swimming competitions differs considerably. The first study on active warm-up verified that swimming for 110 m or 2.5 min (Thompson, 1958) positively affected the swimming performance. The level of the swimmers (untrained) may explain these positive results with such a light warm-up volume. With lower physical preparedness, a shorter volume is required to activate the body to the main task. A slightly longer warm-up as required for De Vries (1959) allowed verification of the improvements in the swimming performance of competitive swimmers (457 m).

Nevertheless, the volumes presented were completed in less than 10 min; this could be the reason why the following studies focused on longer warm-ups. Using the control condition of no warm-up, the 91.4 m and 100 m freestyle times and a propelling force in 30 s of tethered swimming were improved after approximately 15 min of swimming (~1000) (Neiva *et al.*, 2011; Neiva *et al.*, 2013; Romney & Nethery, 1993). Moreover, a warm-up of 1000 m reduced the changes in the acid-base balance after 200 m (2 min) of intense swimming (Robergs *et al.*, 1990).

There are some studies in which the performance was similar or even impaired after warm-up when compared to the no warm-up condition. There were no differences in the 91 m freestyle after 731.5 m of moderate swimming (Bobo, 1999) or on the 50 m front crawl after 1000 m of habitual warm-up (Neiva *et al.*, 2012). Some possible reasons for these results are the time between the warm-up and maximal swimming (not allowing a sufficient time to recover) and/or the volume and intensity of the warm-up, which most likely were not sufficient to cause desirable metabolic effects.

We propose a total warm-up volume of a 15-20 min duration (between 1000 and 1500 m) for swimming events up to 3-4 min. There is a trend toward increasing the volume of warm-up in the morning. The reasoning behind this is the need for extra body activation due to the adaptation to the circadian rhythm. However, Arnett (2002) found that the swimmers still perform better on the 91.4 m in the afternoon even when a longer warm-up (4023.4 m vs. 2011.7 m) was performed in the morning (58.48 ± 5.69 s and 56.86 ± 4.87 s, respectively; $p \leq 0.05$). This result suggests that performance is significantly higher in the late afternoon, independent of the previous warm-up volume performed.

In-Water Warm-Up: the Effect of Intensity

The two studies on the use of different warm-up intensities in swimming found no effects on performance. Houmard *et al.* (1991) were the first authors to compare the effects of two different intensities of priming-exercises on performance (~65% VO_2max of continuous swimming vs. warm-up including 4 x 45.7 m at ~95% VO_2max), and no differences were found in the heart rate, stroke length or blood lactate concentration after 365.8 m front crawl at ~95% VO_2max. Because the volume was the same in the two experimental conditions, the study did not use a specific, intensive set to optimize performance. These conditions may result in extra energy expenditure and most likely influenced the concentration of metabolites, thus impairing swimming performance. In fact, warming up at 110% VO_2max instead of 70% VO_2max led to elevated lactate concentrations (13.66 ± 2.66 vs. 9.53 ± 2.22 mmol/l, $p \leq 0.05$) after 183 m freestyle at high-intensity (Mitchell & Huston, 1993). The 5 min recovery period after warm-up could have been insufficient for reducing the residual effects of the priming exercises. The accumulation of lactate was higher after high-intensity warm-up (6.97 ± 1.97 vs. 2.27 ± 0.81 mmol/l, $p \leq 0.05$), which could have contributed to the higher values obtained after performance. Additionally, the lower volume performed during the high-intensity warm-up compared to the low-intensity warm-up did not allow a sufficient activation of the aerobic metabolism. However, the heart rate (159.9 ± 7.7 vs. 148.0 ± 9.5 bpm, $p \leq 0.05$) and VO_2max (4.18 ± 0.45 vs. 3.23 ± 0.24 l/min, $p \leq 0.05$) after the warm-up showed cardiovascular alterations that might be indicative of enhanced aerobic metabolism for the high-intensity priming exercises, regardless of the volume performed.

Despite the uncertainties about including high-intensity swimming sets in the warm-up procedures, it seems better to use high-intensity swimming sets instead of not warming up. Robergs *et al.* (1990) found that lactate concentrations after 200 m of intensive front crawl swimming were lower when the warm-up included 4x50 m at 111% VO_2max (8.7 ± 0.8 mmol/l vs. 10.9 ± 0.5 mmol/l, $p \leq 0.05$). Furthermore, including a short distance swimming set with increased intensity over the repetitions was effective for 91 m maximal freestyle (Romney & Nethery, 1993). The time performed was reduced by 0.75 s compared to when there was no previous warm-up; thus, short distances at race-pace could optimize performance. Thus, a short-distance set that is built up from low intensity to race-pace velocity in the last repetition could be used to improve subsequent performance by stimulating the energy systems that are recruited in the competitive event (Bishop, 2003a; Bishop, 2003b). Nevertheless, when high-intensity swimming is performed during warm-up, it should be used with caution to avoid the early fatigue and compromising the subsequent swimming performance.

Recovery Time After Warm-Up

Active warm-up seems to improve the performance with periods of recovery up to 20 min, mainly related to temperature mechanisms (Bishop, 2003b; West et al., 2013). The time gaps between the end of the in-water warm-up and the start of the competition/test used in the research studies were 3 min (Balilionis *et al*., 2012; Romney & Nethery, 1993), 5 min (Bobo, 1999; Mitchell & Huston, 1993), 8 min (Kilduff *et al*., 2011), and 10 min (Neiva *et al*., 2011; Neiva *et al*., 2012; Neiva *et al*., 2013; Robergs *et al*., 1990). Nevertheless, according to our knowledge, the effect of different time intervals between warm-up and the main task was only studied by Zochowski *et al*. (2007) and West *et al*. (2013). The 200 m times were 1.38% and 1.48% better with 10 min (Zochowski *et al*., 2007) and 20 min rest periods (West et al., 2013), respectively, instead of 45 min of rest. The maintenance of an elevated core temperature during shorter intervals (West et al., 2013) and the higher heart rate at the start of exercise potentially increased the baseline oxygen uptake (Zochowski *et al*., 2007) are the possible mechanisms responsible for the improved performance. In addition, the post activation potentiation effect of warm-up, which happens around the 8th min of recovery (Kilduff *et al*., 2011), possibly allowed the swimmers to start at an optimized power.

In real competition venues, it is almost impossible to take less than 8-10 min between finishing the warm-up and the swimming event. Warming up is more effective when it is sufficiently intense to activate the physiological processes that will be required in the competition event, with a recovery time that should be between 8 to 20 min, allowing for replenishment of phosphocreatine (Özyener *et al*., 2001). The literature only focuses on the effects of different intervals in the 200 m swimming event, and the various competitive distances and techniques could demand different recovery periods. Moreover, considering the studies of Saez Saez de Villarreal *et al*., (2007) it would be interesting to know how different muscle activations (e.g., using high-intensity exercises or loaded concentric actions) can extend the effects of warm-up as well as how swimmers can benefit from improved performance after a longer rest.

Passive Warm-Up and Swimming Performance

Increases in muscle and core body temperature could be achieved without physical activity by the use of external heating, such as hot showers, saunas and heated vests (Bishop, 2003a). These practices are commonly known as passive warm-up, through which the swimmers most likely benefit from the effects of temperature-related mechanisms without spending energy. A variation in the muscle temperature of 1ºC improves the muscle's contractile properties and modifies performance by 2-5% (Racinais & Oksa, 2010). Therefore, passive warm-up could be suggested as a practice for maintaining the temperature between the warm-up and the swimming event. However, heating cannot exceed the 39º C for the core temperature, as overheating negatively affects the motor drive and muscular performance (Racinais & Oksa, 2010).

Three studies examined the effects of different passive procedures on swimming performance with conflicting results. Carlile (1956) demonstrated that swimmers submitted to 8 min of a hot shower or a 10 min massage attained 1% higher swim velocity in 36.6 m than swimmers without warm-up procedures. Conversely, De Vries (1959) verified that a 10 min massage did not influence the 91.44 m performance, which was instead positively influenced by active warm-up. Thus, while the first study noted the positive influence of passive warm-up in swimming performance, there have been more studies questioning these results. The applicability of these findings should be weighed, as several decades have passed from the time when research occurred. In fact, although there are few studies about active warm-up in swimming and the findings are contradictory, the gap is even larger in regard to passive warm-up. The large range of passive procedures, the unfamiliarity with some of those techniques and a possible deviation of attention to the active warm-up, which is the most relevant form of pre-exercise, could be some of the reasons for this scarcity.

The understanding of the effects of different passive procedures is also important for optimizing swimming performance. Two different practices of passive heating were tested, and a carbonated bath at 36ºC was more effective than a normal bath at the same temperature and duration of 4 min of kicking exercise (Akamine & Taguchi, 1998). The authors proposed that this method be adopted by swimmers because it tends to reduce the lactate concentration, heart rate and electromyography response of the rectus femoris, suggesting higher muscle efficiency and less fatigue. However, the low experience level of the swimmers and the non-existence of comparison with active warm-up call into question its efficiency.

Currently, there is no evidence-based information about the effects of passive warm-up procedures in swimming performance and the unclear indications cannot support the reliably of these methods, making them uncommon. However, it is not unusual to see swimmers completely dressed up (sometimes with a jacket over a sweat suit), near starting blocks, just before starting the race. The use of external sources of heating most likely allows the swimmers to extend the effects of the active warm-up that was performed some time before. Beyond investigating the effects of passive warm-up, we should try to understand how it could be used when there is a long resting time after the active warm-up or even as a complement to active warm-up.

Effect on Different Performance Events

The Olympic competition schedule for swimming includes distances from 50 m to 1500 m in the pool and 10000 m in open-water swimming. As presented in Table 1, the swimming events performed in the pool are the main focus in warm-up related studies. Corresponding to efforts ranging from less than 30 s to more than 15 min, it is expected that these different events are stimulated by different warm-up approaches as well. Considering the studies that used a control condition (without warm-up), three of the six studies that tested swimming distances up to 50 m or the equivalent effort time presented better performance after warm-up (Carlile, 1956; Neiva *et al.*, 2011; Thompson, 1958). Some uncertainty continues on distances up to 100 m, with three of four studies showing improved performance (De Vries, 1959; Neiva *et al.*, 2013; Romney & Nethery, 1993) as well as between the 100 m and 200 m, with one of two studies mentioning lower lactate values and higher heart rate (Robergs *et al.*, 1990). Times on the distances above 200 m were improved after warm-up when considering all of the studies presented (Houmard *et al.*, 1991; Thompson, 1958). Considering that only submaximal tests were performed and mainly focused on physiological variables, longer warm-ups should be indicated when the competition distance is longer.

Researchers have focused mainly on the shorter distances, but the positive effects of warm-up seem more consistent for distances above 200 m, reinforcing the possible positive effects of aerobic metabolism stimulation during the warm-up procedures. Moreover, the positive changes in performance on distances under 200 m were lower than 1% for the time improvement, and it is unclear how much of this effect was due to warm-up. Caution has to be taken when studying any measure of performance, and, for instance, it is important to show by how much that performance measure would be expected to vary day-to-day or test-to-test. Researchers should be aware of the deficient knowledge about the effects of warm-up in the different competition distances and swimming techniques, which may be due to the existing lack of warm-up specificity.

Future Research

Some limitations were found in the literature that researched the topic covered in this review. In fact, it appears that investigations of warm-up's effects on swimming performance were not performed for a few years, resulting in a lack of research and resulting restrictions. The particular swimming pool environment, with a high temperature and humidity, and the complexity of warm-up procedures could explain why there are few studies on this topic.

Some methodological issues can be observed in the literature and should be overcome in future research. For instance, the control group or control condition in the study design sometimes did not exist, and a standard warm-up was compared with other variations of it. This methodological issue may be relevant to the analysis of the results obtained and should be considered in the possible conclusions. Additionally, the small sample sizes used in some of the studies increased the effects of chance and enhanced the ambiguity of the results.

Passive warm-up and dry-land exercises should be deepened as alternative and/or complementary practice for an active warm-up. Additionally, most of the studies focused on freestyle swimming, and a study on the warm-up effects on different techniques and swimming distances should be developed. There is a gap in the research on the influence of the different subject's ages, gender, and training status for selecting the proper warm-up. Once some of these broader issues are clarified, we can evaluate the structure and specificity of the warm-up practices.

Conclusions

Warm-up is commonly accepted as fundamental, and any priming practices are usually considered to optimize performance. Specifically in swimming and, despite some contradictory results, research tends to suggest that warm-up, more particularly the active type, has a positive effect on the swimmer's performance, especially for distances above 200 m. Additionally, the literature proposes that in-water activities are the most useful activities, but when it is not possible to do in-water warm-up, dry-land exercises can be performed as an alternative.

Dry-land warm-up should include all body segments. Strength exercises with few repetitions and high load intensities, vibration stimulation or the use of calisthenics are hypothesized to better prepare the swimmer for racing. Although there are some doubts about using these methods, some studies found promising results, with no differences in performance compared to in-water warm-up. Weight and vibration exercises are not practical to perform before a swimming event, but calisthenics can be used. Further investigation is needed to reach a consensus about the use of alternative methods of warming up and define its ideal structure in terms of the type, duration, volume, specific and/or general tasks and recovery period. Moreover, little is known about dry-land exercise for maintaining the effects of the in-water warm-up during the waiting time before the swimming race. Additionally, the use of stretching exercises is common among swimmers as a complement to the in-water warm-up, but the effects are not known and could even impair the performance. Dynamic stretches are not detrimental to performance, and a daily routine could be replicated in the warm-up procedures to prevent possible injuries.

The in-water warm-up should last for 15 to 25 min, and short intensive and specific tasks can be performed in some parts of the warm-up; there are favorable effects after short distances of progressive swimming up to the race-pace velocity. However, one should be cautious because high-intensity swimming during warm-up can be overvalued and may not be essential to performance optimization. Moreover, some studies presented standard warm-ups with exclusive lower/upper limb exercises that may achieve better activation for each body part. A swimming race is performed using the whole body and splitting stimulation of the body may not be the best way to increase the swimmer's preparedness. The use of technical drills during warm-up could increase the swimming efficiency in the first meters by the longer distance per stroke achieved (Neiva *et al.*, 2013). The recovery period after warming up should be balanced so that it is sufficient for energy replenishment and so that swimmers can benefit from the proposed effects of warm-up.

Table 2. Possible recommendations for active warm-up prior to competitive swimming

Setting	Recommendation
Main suggestions	
In-water warm-up	Volume 1,000-1,500 m
	Moderate intensity
	Drills focussing on stroke efficiency
	Short distances at race-pace
	Recovery period 8-20 min
Alternative suggestions	
Dry-land warm-up	Total body stimulation
	Calisthenics - moderate intensity
	Strength exercises - short sets, heavy loads[a]
	Vibration exercises on adapted swim bench[a]

a Hypothesized only.

Because there is a latency period between the in-water warm-up and the swimming race, passive warm-up should be considered. Despite the lack of concrete evidence, these practices could be used to maintain elevated core and muscle temperatures, which are beneficial for swimmers. Little is known about the best passive practices to implement, but passive exercise could be any method that does not elevate the temperature above 39ºC, which would otherwise impair performance.

Scientists have recently started to study the effects of warm-up on swimming performance, but numerous doubts remain. Not much is known about the structure and components of warm-up even though it is still thought to influence performance in a sport where a tenth of a second could determine success or failure. The results highlight that the volume, intensity and recovery, and specific exercises of active warm-up are complementary variables. Any change carried out in one of these characteristics leads to variations in the others, which can influence the results.

Chapter 3. Experimental Studies

Study 2

Does warm-up have a beneficial effect on 100 m freestyle?

Abstract

Purpose: The aim of this study was to investigate the effect of warm-up on 100 m swimming performance. Methods: Twenty competitive swimmers (with a training frequency of 8.0 ± 1.0 sessions per week) performed two maximal 100 m freestyle trials on separate days, with and without prior warm-up, in a counterbalanced and randomized design. The warm up distance totalled 1000 m and replicated the swimmers usual pre competition warm up strategy. Performance (time), physiological (capillary blood lactate concentrations), psychophysiological (perceived exertion) and biomechanical variables (stroke length, stroke frequency and stroke index) were assessed on both trials. Results: 100 m performance was fastest in the warm-up condition (67.15 ± 5.60 vs. 68.10 ± 5.14 s; $p = 0.01$), although three swimmers swum faster without warm-up. Critical to this was the first 50 m lap (32.10 ± 2.59 vs. 32.78 ± 2.33 s; $p < 0.01$) where the swimmers presented higher stroke length (2.06 ± 0.19 vs. 1.98 ± 0.16 m; $p = 0.04$) and swimming efficiency compared with the no warm-up condition (stroke index: 3.46 ± 0.53 vs. 3.14 ± 0.44 $m^2c^{-1}s^{-1}$; $p < 0.01$). Notwithstanding this better stroke kinematic pattern, blood lactate concentrations and perceived exertion responses were similar between trials. Conclusions: These results suggest that swimmers' usual warm-up routines lead to faster 100m freestyle swimming performance, a factor which appears to be related to better swimming efficiency in the first lap of the race. This study highlights the importance of performing swimming drills (for higher stroke length) before a maximal 100 m freestyle effort, in similar groups of swimmers.

Key words: Pre-exercise, performance, kinetics, efficiency, lactate.

Introduction

Although there is a lack of conclusive scientific evidence, the use of warm-up to enhance performance seems to be a matter of common belief and practice among coaches and athletes. In fact, the different physical exercises performed during warm-up aim to increase muscle and core temperature and, through the body's underlying mechanisms, improve performance (Bishop, 2003a; Bishop, 2003b; Gray & Nimmo, 2001; Wright & Johns, 1961). The hyperthermia resulting from physical activity increases vasodilatation and muscle blood flow, stimulating the increased aerobic energy contribution during a subsequent task (Gray & Nimmo, 2001; Pearson *et al.*, 2011). In addition, it increases the muscle glycogenolysis, glycolysis and high-energy phosphate degradation during exercise (Febbraio *et al.*, 1996). The literature also claims that warming-up via physical activity might have effects additional to the increase in temperature, particularly an elevation of the baseline of oxygen uptake (VO_2) and of the amplitude of the primary VO_2 response in the subsequent exercise (Burnley *et al.*, 2011). Nevertheless, although these metabolic responses appear to indicate a positive effect of warm-up on athletic performance, current evidence is still inconclusive (Bishop, 2003a; Bishop, 2003b).

Specifically in swimming, different physiological changes and conflicting benefits to performance have been reported. Houmard *et al.* (1991) described increments in stroke length (SL) during an intense paced 368.5 m swim, and decreased post-exercise blood lactate concentrations ($[La^-]$) with warm-up. Conversely, others (Mitchell & Huston, 1993) found that warm-up procedures did not change performance, and led to higher $[La^-]$ after a 2 min high intensity swimming trial (13.66 ± 2.66 vs. 9.53 ± 2.22 $mmol \cdot l^{-1}$). Regarding a shorter distance swimming performance, studies have shown that proper warm-up was effective in reducing 100 yds time trial by 0.44 (De Vries, 1959) and 0.75s (Romney & Nethery, 1993) compared to a bout without prior warm-up, but Bobo (1999) failed to find significant differences in 100 yds performance between three conditions (warm-up exercises in-water, in dry land, and without warm-up).

More recent research has focused on even shorter distances (50 yds and 50 m), but results are inconclusive; no favourable effects of warm-up on 50 m front crawl performance, neither in the $[La^-]$ nor perceived exertion (RPE) responses, were observed by Neiva *et al.* (2012), but Balilionis et al. (2012) reported better performances on 50 yds freestyle after a warm-up (~0.2s), although no effects on RPE and stroke frequency (SF) were detected.

Given the lack of consistent evidence about the effects of warm-up on swimming performance, the purpose of the present study was to investigate if usual warm-up procedures are beneficial to 100m freestyle swimming performance. Performance (time), biomechanical variables (SF, SL, and stroke index - SI), physiological ($[La^-]$) and psychophysiological (RPE) variables were assessed. Usual warm-up was hypothesized to positively contribute to the swimmers' response to maximal 100 m freestyle performance.

Methods

Subjects

Twenty competitive swimmers (10 males and 10 females: Age 16.0 ± 0.6 and 16.2 ± 1.14 yrs; Stature 173 ± 5.07 and 161 ± 7.04 cm; Body mass 62.3 ± 3.9 and 55.9 ± 6.3 kg, respectively) volunteered to participate in this study. The swimmers had been engaged in competitive swimming during the last 7.11 ± 1.29 years, and had a training frequency of 8.0 ± 1.0 (16.0 ± 1.5 h) sessions per week, with a training volume of 34000 ± 5400 m per week during the current season. Personal best time in the 100 m freestyle event was 64.71 ± 5.43 s which corresponds to 456.70 ± 85.91 FINA 2011 points scoring. Prior to the experiments, swimmers were informed about the study design and procedures, and an informed consent was signed. Institutional review board approval was granted, in the spirit of the Helsinki declaration.

Experimental Design

All experiments were conducted one week after the main competition of the season in a 50 m indoor swimming pool with water temperature at 27.5ºC. The swimmers performed two 100 m freestyle time trials at the maximum velocity with (WU) and without (NWU) prior warm-up, with a counterbalanced order of treatments with random assignment to order. Trials were separated by 24 h. Each swimmer performed the 100 m as an individual time trial to prevent pacing or tactics effects. Swimmers were asked to wear the swimsuits normally used during competitions.

In the WU trial, swimmers performed their usual pre-competition warm-up (Table 1), comprising 1000 m of aquatic drills, pull and kick exercises, and specific sets. After 10 min of passive rest, swimmers performed the 100 m freestyle time trial. In the NWU trial, no physical activity was allowed previous to the 100 m freestyle time trial.

Table 1. Usual warm-up protocol.

Distance	Intensity/exercise
300 m	Easy swim
2 x 100 m /15 s rest	(second faster, higher stroke length)
8 x 50 @ 1 min	- 25 m kick /25 m complete, 2x
	- 25 m drills /25 m complete, 2x
	- 25 m race-pace/25 m easy, 2x
	- 25 m race-pace/25 m easy, 2x
100 m	Easy swim

Methodology

In both the WU and NWU conditions, in-water starts were used and 100 m times for each swimmer were registered by two experienced coaches using stopwatches (Golfinho Sports MC 815, Coimbra, Portugal). The mean value of the two times was recorded for analysis. Coaches were blind as to the warm up condition of the swimmers.

Swimming velocity was determined in the middle 15 m of the swimming pool (marks were set at 20 and 35 m). The distance covered by the swimmer was divided by the time spent to cover such distance. SF was measured with a chrono-frequency meter (Golfinho Sports MC 815, Coimbra, Portugal) from three consecutive stroke cycles within the same 15 m where swimming velocity was assessed. Afterwards, SF was converted to International System Units (Hz). The velocity and SF were assessed by two different and experienced researchers, who were also blind to the swimmers' testing condition. Intraclass Correlation Coefficient (ICC) was determined for the time, velocity and SF, to ensure the accuracy of the measurement. The mean value was used for analysis. SL was estimated as the division between the velocity obtained during the 15m and the SF (Craig & Pendergast, 1979). The SI was computed as the product of the velocity of the swimmer during the 15m recorded and the corresponding SL (Costill *et al.*, 1985).

Capillary blood samples for [La^-] assessment (Accutrend Lactate®Roche, Germany) were collected from the fingertip after each maximal trial (at the first and third min of recovery) to determine its higher value. RPE were registered after each test using Borg's 6 - 20 points scale (Borg, 1998).

Statistical Analysis

Standard statistical methods were used for calculation of means and standard deviations (SD) for all variables. The normality of all distributions was verified using Shapiro-Wilks tests, and parametric statistical analysis was adopted. To compare data obtained in the two trials, Student's paired t-tests were used. Limits of agreement between the performance measured in WU and NWU were derived according to the literature (Bland & Altman, 2003). Statistical procedures were performed using SPSS 19.0 for Windows® (Chicago, IL, USA). Post hoc analysis of power ($1-\beta$) and the values of Cohen's d effect size for repeated measures (d) were accomplished using the G-Power 3.1.3 for Windows® (University of Kiel, Germany). The level of statistical significance was set at $p \leq 0.05$.

Results

Table 2 presents a comparison between the 100 m freestyle performance, the respective lap times, and the values of [La$^-$], RPE, SF, SL, and SI recorded in the first and second 50 m in the WU and NWU conditions. In the 100 m WU trial, the swimmers were 1.48 ± 2.06 % faster, with medium magnitudes of differences (d > 0.5) resulting from the large effect size (d > 0.8) noted in the first 50 m lap.

It is also possible to observe [La$^-$] higher than 10 mmol·l^{-1} and hard/very hard effort (RPE > 16) in both testing conditions. The differences verified in the second 50 m SF, in the first 50 m and second 50 m SL, and in first 50 m SI between the WU and NWU conditions ranged from a medium (0.5 < d < 0.8) to a large (d > 0.8) magnitude of the effect.

Table 2. Results for tested parameters in the 100 m trial, N = 20.

	WU	NWU	*P*	d	$1-\beta$
100 m time (s) **	67.15 ± 5.60	68.10 ± 5.14	0.01	0.69	0.99
First 50 m time (s) **	32.10 ± 2.59	32.78 ± 2.33	< 0.01	0.89	1.00
Second 50 m time (s)	35.00 ± 3.27	35.37 ± 2.98	0.07	0.44	0.76
Blood lactate concentration (mmol·l^{-1})	10.91 ± 1.75	10.28 ± 2.20	0.22	0.32	0.41
100 m rating of perceived exertion	16.90 ± 1.80	16.10 ± 1.55	0.08	0.41	0.71
Stroke frequency, first 50 m (Hz)	0.81 ± 0.07	0.80 ± 0.06	0.25	0.28	0.37
Stroke frequency, second 50 m (Hz) **	0.77 ± 0.60	0.72 ± 0.06	< 0.01	1.09	1.00
Stroke length, first 50 m (m) *	2.06 ± 0.19	1.98 ± 0.16	0.04	0.53	0.88
Stroke length, second 50 m (m) **	1.90 ± 0.18	1.99 ± 0.18	0.01	0.66	0.97
Stroke index, first 50 m (m^{2}c^{-1}s^{-1}) **	3.46 ± 0.53	3.14 ± 0.44	< 0.01	0.87	1.00
Stroke index, second 50 m (m^{2}c^{-1}s^{-1})	2.81 ± 0.46	2.89 ± 0.45	0.22	0.29	0.42

* $p \leq 0.05$ and ** $p \leq 0.01$

The individual differences between WU and NWU on the first and second 50 m laps and for the 100 m total performance are presented in Figure 1, evidencing some individual positive responses after NWU in panels A, B and C (10 %, 25% and 15%, respectively), although the mean value is positioned below zero.

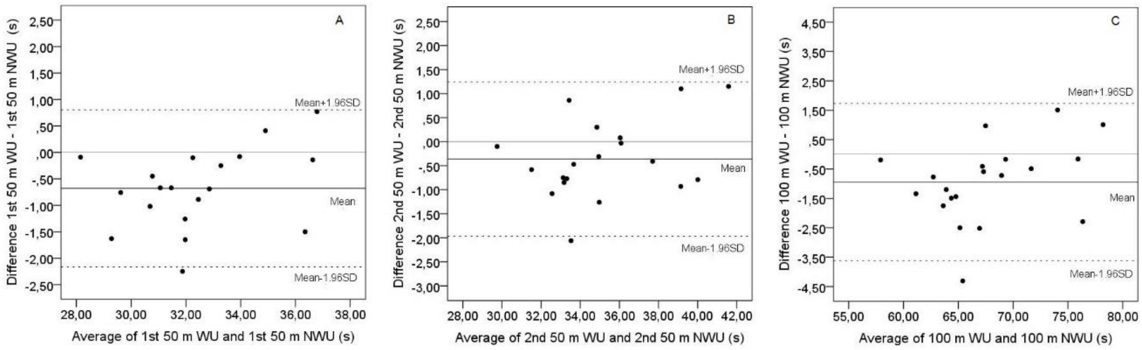

Figure 1. Bland-Altman plots representing (A) the first 50 m lap time, (B) the second 50 m lap time, and (C) 100 m total time in the 2 trial conditions, with warm-up (WU) and without warm-up (NWU). Average difference (solid line) and 95% CI (dashed lines) are indicated, N = 20.

Figure 2 presents the variation of the biomechanical variables between the 50 m laps of the 100 m maximal effort, for WU and NWU. It should be noted that the lower the value presented, the more inferior were the values obtained in the second 50 m lap. Differences were observed in the patterns of SF, SL and SI when maximal 100 m freestyle was preceded by WU or NWU.

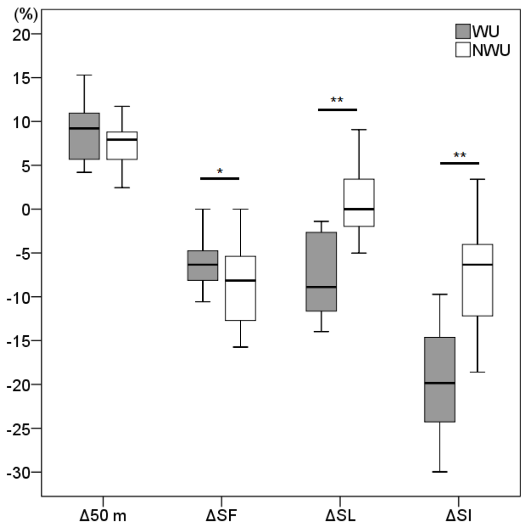

Figure 2. Comparison between the variations of the time (Δ50 m), stroke frequency (ΔSF), stroke length (ΔSL), and stroke index (ΔSI) assessed in the first and second 50 m laps of the 100 m (Δ = second – first), with warm-up (WU) and without warm-up (NWU). *$P \leq 0.01$, N = 20.

Discussion

The purpose of the current study was to investigate the effects of warm-up on maximal 100 m freestyle swimming performance. The faster times observed in the trial with prior warm-up suggest that the swimmers usual warm-up procedures have a beneficial effect on their subsequent swimming performance. Warming-up led to significant improvements in the stroke mechanics, yet the assessed physiological and psychophysiological variables did not seem to be influenced. These findings evidence the positive influence that usual warm-up may have on swimming performance, which appears to be mostly related to the swimmers' technical pattern.

Warming up before the competition is a usual practice in swimming. Its positive effect was first presented by De Vries (1959), but recent literature focusing specifically on short swimming distances demonstrated that priming exercises could impair swimming performance (Bobo, 1999; Mitchell & Huston, 1993; Neiva *et al.*, 2012). It should be noted that in most swimming competitions, there is a considerable time lapse between the in-water warm-up and the competitive event, which can negate its possible beneficial effects. Nevertheless, swimmers still compete at their maximum effort. These findings and considerations highlight the relevance of better understanding the warm-up phenomenon.

The lack of previous research assessing the effects of warm-up on maximal 100 m swimming limits the comparisons with current study results. In-water start and the lack of competitive context during the tests might explain the slightly higher final times compared to swimmers' personal bests (~2.43s) and to the literature (Stirn *et al.*, 2011; Toussaint & Beek, 1992). As the two experimental tests were performed in the same competitive environment these effects could be disregarded. Furthermore, the RPE values obtained were similar to previous studies that assessed all-out swimming performances (Balilionis *et al.*, 2012; Neiva *et al.*, 2012; Zochowski *et al.*, 2007), which could ensure the reliability of the results obtained.

Concerning the main aim of the present study, faster 100 m performances were achieved in the WU condition, those differences being mainly achieved in the first lap. According to Balilionis *et al.* (2012) it is expected that the swimmers will be faster in the 50 yds freestyle when using a regular warm-up (~1300 yds), than when using a shorter warm-up (100 yds) or when no warm-up is used (24.95 ± 1.53, 25.26 ± 1.61 and 25.19 ± 1.54s). The differences between the two conditions disappeared in the second 50 m lap, even though the observed medium effect size requires further investigation under this topic.

The results presented in Table 2 are confirmed in Figure 1 since the average difference line is farther away from zero in panels A and C than in panel B. However, the figure also illustrates individual cases in which the difference was positive, evidencing that these swimmers reacted favorably to the nonexistence of prior exercises (two in the first 50 m, five in the second 50 m and three in the total 100 m). This illustrates the individuality of swimming, as there is no clear zone in which the swimmers can be placed. Therefore swimmer individuality should be respected, and coaches should take that into account when defining their training process and determining competitive procedures.

During a 100 m swimming event the anaerobic metabolism is a substantial source of energy, leading to $[La^-]$ higher than 10 $mmol \cdot l^{-1}$ (Bonifazi *et al.*, 1993), as observed in our data. Warm-up has been proposed to maintain the acid-base balance at an appropriate level by stimulating the buffering capacity (Beedle & Mannm 2007), which was evidenced after maximal 200 m swimming: $[La^-]_{net}$ of 8.7 ± 0.85 vs. 10.9 ± 0.5 $mmol \cdot l^{-1}$ ($p < 0.05$), with and without warm-up, respectively (Robergs *et al.*, 1990). However, in the current study, $[La^-]$ levels were similar in the WU and NWU conditions, which is consistent with recent findings for short distance swimming (Neiva *et al.*, 2011; Neiva *et al.*, 2012). Possibly, different physiological variables (e.g. VO_2) are influenced to a greater extent by warm-up procedures. As the 100 m swimming performances also rely on the aerobic energy system (Capelli *et al.*, 1998), the warm-up could allow enhancing the swimmers aerobic system more than the anaerobic one.

Swimmers in general believe that warm-up is essential to attain a good performance (De Bruyn-Prevost, 1980) and, therefore, psychological beliefs could influence the perception of effort exerted. However, the observed RPE values were similar in WU and NWU conditions, as reported before (Balilionis *et al.*, 2012; Houmard *et al.*, 1991; Neiva *et al.*, 2011; Neiva *et al.*, 2012). The RPE is assumed to be influenced by the fatigue perception mainly due to the accumulation of ions of hydrogen in the active muscles as the result of the dissociation of lactic acid (Robertson *et al.*, 1986). Hence, given that $[La^-]$ values did not change between WU and NWU, it was somewhat expected that RPE would also be similar between conditions.

The faster initial meters of the 100 m freestyle in WU condition reflected the higher SL and consequently greater swimmer efficiency (evidenced by SI). Therefore, in the NWU condition it is expected that the swimmers would not be effective in the arm pull and were technically compromised (Toussaint & Beek, 1992), lowering the SL in the first 50 m lap. However, in the second 50 m lap, and once the velocity is related to SF and SL (Barbosa *et al.*, 2008), the higher SL and lower SF with NWU dissipated the differences in the time performed between conditions. In NWU, the swimmers were able to maintain the SL in the second 50 m, maybe as a consequence of the lower energy cost and velocity of the first meters, but the SF experienced a further reduction as the fatigue increased.

The variations of SF, SL and SI throughout the 100 m freestyle in the WU and NWU conditions could reflect the development of fatigue. According to Barbosa *et al.* (2008) the swimmers are able to manipulate their SL and SF to achieve a given velocity with the lowest energy cost. So, the swimmers used different kinematics patterns in the two experimental conditions to accomplish the total distance at maximum intensity according to their energetic needs.

Conclusions

The swimmers were significantly faster in the first 50 m lap of the WU trial, which led to an improvement in the 100 m overall performance. Different biomechanical patterns were observed in response to the WU and NWU conditions, suggesting that warm-up significantly influences the stroke patterns of a short swimming event. The individuality of the swimmers is also shown, enhancing the importance of an individualized approach to optimizing swimming performance.

Practical Applications

The usual warm-up performed by the swimmers was effective in optimizing 100 m freestyle swimming performance. Perhaps the greater swimming efficiency verified in the first meters suggests that the incorporation of technical drills during warm-up could be beneficial to similar groups of swimmers, specifically regarding the SL of the swimmer. Some positive responses to NWU revealed the swimmer's individuality, and this confirms the idea that warm-up procedures should be considered as an individualized approach to optimizing swimmer performance (Balilionis *et al.*, 2012). Thus, there is no single model that should be copied and adopted by all swimmers. It is fundamental to consider their biological individualities and group procedures should be handled with caution at the risk of compromising optimal performances. Possibly, swimmers and coaches need to test over several occasions to establish consistent responses to different warm-up procedures and therefore establish their own optimal warm-up. The unknown value of the variation in performance of day-to-day or test-to-test limited the understanding of the magnitude of the effects of warm-up. However, the results are clear in demonstrating a positive effect and future research is needed to better understand the ideal structure of warm-up procedures.

Study 3

The effects of different warm-up volumes on the 100 m swimming performance: a randomized crossover study

Abstract

Purpose: The aim of this study was to compare the effect of three different warm-up volumes on 100 m swimming performance. Methods: Eleven male swimmers at the national level completed 3 time trials of 100 m freestyle on separate days and after a standard warm-up (WU), a short warm-up (SWU) or a long warm-up (LWU) in a randomized sequence. All of them replicated some usual sets and drills and the WU totaled 1200 m, the SWU totaled 600 m, and the LWU totaled 1800 m. Results: The swimmers were faster after the WU (59.29s, CI 95% 57.98 to 60.61) and after the SWU (59.38s, CI 95% 57.92 to 60.84) compared with the LWU (60.18s, CI 95% 58.53 to 61.83). The second 50 m lap after the WU was performed with a higher stroke length ($d = 0.77$), stroke index ($d = 1.26$) and propelling efficiency ($d = 0.78$) than after the SWU. Both WU and SWU resulted in higher pre-trial values of blood lactate concentrations ([La^-]) compared to LWU ($d = 1.58$ and 0.74, respectively) and the testosterone/cortisol levels were increased in WU compared to LWU ($d = 0.86$). Additionally, the trial after WU caused higher [La^-] ($d \geq 0.68$) and testosterone/cortisol values compared to the LWU ($d = 0.93$). Conclusions: These results suggest that a long warm-up could impair 100 m freestyle performance. The swimmers showed higher efficiency during the race after a 1200 m warm-up, suggesting a favorable situation. It is highlighted the importance of the [La^-] and hormonal responses to each particular warm-up, possibly influencing performance and biomechanical responses during a 100 m race.

Key words: Pre-exercise, time-trial, swimmers, biomechanics, physiology.

Introduction

Warming-up before training or competition has become one of the most interesting topics for practitioners and recent research showed some positive effects on performance (Fradkin *et al.*, 2010; Neiva *et al.*, 2014a). It has been suggested that the rise in muscle temperature caused by priming exercises resulted in multiple physiological and metabolic changes that influences performance (Bishop, 2003a; Bishop 2003b). Although it is a common practice among swimmers (McGowan *et al.*, 2014), little is known about the optimal procedures that would allow an increased preparedness for a given event. The different variables and the complexity of their relationship makes it challenging to characterize the main features of the best warm-up technique. This fact may be the reason why literature found mixed results and remained a bit apart of this issue for some time (Bishop, 2003b; Fradkin *et al.*, 2010; Neiva *et al.*, 2014a).

Recently, Tomaras and MacIntosh (2011) alerted to the adverse effects that an improperly designed warm-up protocol could cause in performance. These authors verified that a traditional warm-up in cycling induced higher fatigue and impaired peak power output, compared with a shorter warm-up protocol. Similarly to cycling, in most sports the warm-up is usually performed based on the athletes and coaches experiences and perhaps it is not the best way to optimize performance. Specifically in swimming, it is suggested that the swimmers should warm-up for a relatively moderate distance (i.e.1200 m) with the proper intensity (short race-pace) and subsequent recovery time sufficient to avoid early fatigue during race (Balilionis *et al.*, 2012; Houmard *et al.*, 1991; Neiva *et al.*, 2014a). However, these recommendations were not scientifically clear and usually were followed by the suggestion for further investigation.

To the best of our knowledge, only Balilionis *et al.* (2012) have studied the effect of different warm-up volumes on maximal swimming performance. The authors compared the effects of a short (91.44 m warm-up) and a longer warm-up (~1200 m) on 45.72 m freestyle performances and found that the longer one improved the swimmers' times by 1.22%. Nevertheless, no differences were found in the perceived effort and in the biomechanical analysis during the time trial. We could infer that a lower volume was not enough to cause sufficient physiological changes or that these results could be partially influenced by the familiarization with the longer warm-up. It is clear that this study intended mostly to analyze the swimmers performance and thus limited the physiological and biomechanical analysis. Also, it was compared a usual warm-up procedure with a shorter warm-up that the swimmers were not accustomed. Thus, a possible understanding of the implementation of the different volumes of warm-up remains vague and unclear.

The warm-up could differently influence each particular race and some literature point distinct effects on the 50 or the 100 m swimming events (Balilionis *et al.*, 2012; Neiva *et al.*, 2014b).

Therefore, there is a need to investigate the impact of warm-up on longer swimming event times than literature presents. Also, few physiological and biomechanical variables were evaluated (Balilionis *et al.*, 2012) and there is a need for understanding as much variables as we can get to better know this peculiar phenomenon. The warm-up is believed to influence biomechanical variables as stroke rate and length (Houmard *et al.*, 1991; Neiva *et al.*, 2014b) and physiological variables as lactate, heart rate or temperature (West *et al.*, 2013; Zochowski *et al.*, 2007). By analyzing multiple biomechanical and physiological effects of different warm-up practices, one can increase our knowledge to the swimmers responses and to provide better recommendations. For instance, the warm-up could influence some specific stress hormones as the cortisol and testosterone. On this, research has indicated these to be related to exercise intensity and duration (Jacks *et al.*, 2002; Kraemer & Ratamess, 2005) and their relationship with the body catabolic and anabolic processes could provide some important information about the warm-up effects in the swimmers. Besides this, both pre-exercise testosterone and cortisol concentrations might condition the anaerobic metabolism and perhaps influence the 100 m swimming race (Crewther & Christian, 2010; Stupnicki *et al.*, 1995).

The current study was therefore conducted to compare the effects of three different warm-up volumes on the 100 m freestyle, in national-level swimmers. It was hypothesized that a reduced volume would not be enough to cause sufficient metabolic changes to optimize swimming performance. A secondary hypothesis was that a long warm-up would increase muscular fatigue and affect performance.

Methods

Experimental Approach to the Problem

The purpose of the current study was to evaluate the effects of a short (SWU), a standard (WU) and a long warm-up (LWU) volume on the 100 m freestyle, in high-level swimmers, in terms of performance, biomechanical, physiological and psychophysiological responses. The study followed a repeated measures design with each participant completing 3 time trials of 100 m freestyle in randomized order. Regarding the implemented warm-ups, it was verified that most studies of warm-ups protocols in competitive swimming selected volumes between 1000 and 1500m (Balilionis *et al.*, 2012; Kilduff *et al.*, 2011; Neiva *et al.*, 2014b). Based on those studies and in the knowledge of an experienced national swimming coach, it was structured a WU, comprising specific sets and drills. Using the total volume of the WU as reference (1200 m), the short warm-up (SWU) was set at 50% of the WU (600 m) and the long warm-up (LWU) an increase of 50% over the standard volume (1800 m). Moreover, the 100 m race was chosen because it is one of the most attractive swimming events and scientific evidences showed that it is affected by the usual warm-up procedures, changing some physiological and biomechanical variables compared to no warming up (Neiva *et al.*, 2014b).

Subjects

Eligible participants were all national-level swimmers with more than 6 years of competitive experience. Eleven competitive male swimmers aged 15-25 years (mean ± SD 18.09 ± 3.30 years of age, 1.78 ± 0.07 m of height, 68.46 ± 7.98 kg of body mass, 9.55 ± 2.94 years of training background) participated in this study. All swimmers had previously competed at national swimming championships finals and had completed different warm-ups during the last years. A training volume of 35,500 ± 3,605 m per week (16.01 ± 1.21 h) was performed during the current season. The personal best times in the 100 m freestyle event were 58.90 ± 2.37 s, which corresponds to 509.09 ± 63.74 FINA 2014 scoring points (long course). After local ethics board approval, ensuring compliance with the declaration of Helsinki, the participants were informed about the study procedures, and a written informed consent was signed (or parent/guardian when subjects were under 18 years old). All swimmers were asked to maintain the same training, recovery and diet routines during the days of assessment, avoiding strenuous exercise and abstaining from smoking and consuming caffeine 48 h prior to testing.

Procedures

All the procedures took place at the same time of day (morning) in a 50 m indoor swimming pool with a water temperature of 27.53 ± 0.06ºC, air temperature of 27.86 ± 0.14ºC and 61.33 ± 0.58% of humidity (measured before each test). Each swimmer was randomly assigned to one warm-up procedure (factor), and the use of competition swimsuits was allowed. The trials were performed individually to prevent pacing or tactics effects, with 48 h between the conditions tested. After arriving at the pool, the swimmers remained seated for 5 min, with the legs uncrossed, to assess baseline measurements of heart rate, cortisol, testosterone, tympanic temperature and blood lactate concentrations. Day-to-day intra-class correlation coefficients as a test of the reliability of the baseline measurements of heart rate, [La-], cortisol, testosterone, testosterone/cortisol ratio and tympanic temperature were ICC>0.90. Then, three different types of warm-up protocols were used (Table 1) with different total swimming volumes and identical intensities. Heart rate and ratings of perceived exertion (RPE) were monitored during the warm-ups to ensure the same intensity between the three conditions. After 10 min of passive rest, seated and legs uncrossed, the swimmers performed the 100 m freestyle time trial.

Table 1. Standard warm-up (WU), short warm-up (SWU) and low warm-up (LWU) protocols.

WU	SWU	LWU	Task description
300 m	150 m	500 m	Normal - breathing in the 5th stroke - Normal
4 x 100 m @ 1:50	2 x 100 m @ 1:50	6 x 100 m @ 1:50	25 m kick – 25 m increased stroke length
8 x 50 m @ 1:00	4 x 50 m @ 1:00	12 x 50 m @ 1:00	50 m drill - 50 m building up velocity - 25 m race-pace/25 m easy - 25 m race-pace/25 m easy
100 m	50 m	100 m	Easy swim

Final performance and race splits

In each trial, the swimmer was requested to set on the starting block and take off after official verbal commands and the starting signal. A timing system (OMEGA S.A. Switzerland) was used to time the 100 m trials. As a backup, time trials were also clocked with a stopwatch used by an experienced swimming coach and a video camera (Casio Exilim Ex-F1, f=30 Hz). The camera was placed at 15 m, perpendicular to lane 7 and it was used to assess the 15 m time over this distance.

Kinematics

Another camera (Casio Exilim Ex-F1, f=30 Hz) was placed poolside at the 25 m mark of the swimming pool to record the time to swim 10 m in each 50 m lap (between the 15th m and 25th m), and afterwards to determine the swimming velocity. Two different and experienced researchers assessed the stroke frequency (SF) with a stroke counter (Golfinho Sports MC 815, Coimbra, Portugal) from three consecutive stroke cycles within this 10 m. SF was converted to International System Units (Hz) for further analysis. The stroke length (SL) was calculated by dividing the velocity and the SF assessed during the 10 m (Craig & Pendergast, 1979).

Efficiency

The stroke index (SI), considered one of the swimming stroke efficiency indexes, was computed as the product of the velocity of the swimmer and the corresponding SL (Costill et al., 1985). The propelling efficiency (η_p) was also estimated by (Zamparo, 2006):

$$\eta_p = [(0.9 \cdot v)/(2\pi \cdot SF \cdot l)] \cdot 2/\pi \qquad (1)$$

where v is the swimming velocity ($m \cdot s^{-1}$), SF is the stroke frequency (Hz) and l is the arm length (m). The l is computed trigonometrically by measuring the arm length and considering the average elbow angles during the insweep of the arm pull as reported by Zamparo et al. (2005).

Metabolic, cardiovascular and psychophysiological variables

Capillary blood samples for [La$^-$] assessment (Accutrend Lactate® Roche, Germany) were collected from the fingertip after the warm-up protocol (1st min), immediately before the trial (9th min), and 3, 10, 20 and 30 min after the trial. The heart rate was assessed before, during and after each warm-up (1st min), before the trial (9th min) and during the 30 min of recovery (every min) after the swimming test (Vantage NV; Polar, Lempele, Finland). During that time, the swimmers remained seated and were not allowed to move or take off the swimsuit. Additionally, the RPE was recorded during the warm-up exercises (after each set), after the warm-up and after each test using Borg's 6 – 20-point scale (Borg, 1998).

Temperature

Tympanic temperature measurements were taken before the warm-up, after the warm-up (1 min), immediately before the trial and 1, 10, 20, and 30 min after the trial. This is a good indicator of brain temperature, which controls body temperature (Nimah *et al.*, 2006), and each swimmer's tympanic temperature was taken 3 times, and the maximal value was recorded (Braun Thermoscan IRT 4520, Germany). The thermometers had a measuring accuracy of 0.2ºC for temperatures between 32.0 and 42.0ºC.

Hormonal variables

Saliva samples were collected during the baseline evaluation, between the warm-up and trial, immediately after the 100 m and at the 30th min of recovery. The participants were seated and leaning forward, providing saliva samples using the passive drool method. Samples were collected directly through a 5 cm plastic drinking straw into 10 ml plastic screw top tubes and all samples were kept cold immediately after collection (2ºC) and then frozen (-20ºC) until they were assayed. Every collection tube was identified with numbers and letters that corresponded to each participant, warm-up procedure, and collection point. The minimum collection time was 3 min for each subject to allow for the collection of a sufficient sample volume. No drinking was allowed, and procedures were conducted at the same time of day to avoid circadian influences on performance. The salivary cortisol and salivary testosterone concentrations were determined by enzyme-linked immunosorbent assay (ELISA) using commercially available kits (Salimetrics, State College, PA, USA). The sensitivity of the kits was 0.08 nmol·l^{-1} and 3.46 pmol·l^{-1} for cortisol and testosterone, respectively. The mean intra-assay coefficients of variation were 2.43 and 3.19% for cortisol and testosterone, respectively. The mean inter-assay coefficients of variation were 1.39 and 4.73% for cortisol and testosterone, respectively.

Statistical Analysis

Standard statistical methods were used for the calculation of means, standard deviations (SD) and 95% confident intervals for all variables. The normality of all distributions was verified using Shapiro-Wilks tests. The effect of the three warm-up procedures was analyzed by an

ANOVA for repeated measures, with sphericity checked using Mauchly's test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser procedure. Post-hoc paired t-tests were run to further investigate the effect of each condition. A non-parametric Friedman test with post hoc Wilcoxon Signed-Rank test were applied whenever a normality of distributions was not found. Analysis of the Cohen's d effect size for repeated measures (d) was accomplished using the G-Power 3.1.3 for Windows® (University of Kiel, Germany) for each pair of conditions tested. An effect size 0.2 was deemed small, 0.5 medium, and 0.8 large (Cohen, 1988). The limits of agreement between the 100 m time in the three conditions were derived according to the literature (Bland & Altman, 2003). The level of statistical significance was set at $p \leq 0.05$.

Results

Acute effects of different types of warm-up stimuli

After the main task, there were no differences in the heart rate ($F_{2,20}$ = 3.08, p = 0.07) between the WU (152 ± 11 bpm), SWU (144 ± 17 bpm) and LWU (146 ± 18 bpm) and in the RPE values ($F_{2,20}$ = 3.08, p = 0.15) (13.82 ± 1.72, 13.45 ± 2.02 and 13.36 ± 1.91, respectively), reflecting the similar intensity between warm-ups. Table 2 presents a comparison between the [La^-], the heart rate, the tympanic temperature, the salivary cortisol and testosterone concentrations and their ratio after the three warm-up procedures and immediately before the trial. The conditions tested resulted in higher values of [La^-] after the WU and SWU compared with the LWU ($F_{2,20}$ = 9.41, p < 0.01), and these differences remained until the trial started ($F_{1.35,13.46}$ = 8.34, p < 0.01). Additionally, the perceived effort was higher for the WU than the SWU even though it remained very low for all of the conditions tested, and the higher tympanic temperatures were reached with the WU condition (X^2_2 = 9.80, p < 0.01). These differences caused by the different warm-up stimuli lapsed during the recovery time between the warm-up and the time trial.

Table 2. Mean ± SD values (95% confidence limits) of the physiological and psychophysiological variables after warm-up (After WUP) and before trial, N = 11.

	Standard Warm-up (WU)	Short Warm-up (SWU)	Long Warm-up (LWU)	WU vs. SWU	WU vs. LWU	SWU vs. LWU
Blood lactate (mmol·l^{-1})						
After WUP	5.52 ± 1.29 (4.65, 6.38)	5.01 ± 0.95 (4.37, 5.65)	4.01 ± 0.74 (3.56, 4.55)	d = 0.43 p = 0.19	d = 1.13 p = 0.01	d = 1.23 p < 0.01
Pre-trial	4.23 ± 0.71 (3.75, 4.70)	3.71 ± 0.86 (3.13, 4.28)	3.19 ± 0.61 (2.78, 3.60)	d = 0.47 p = 0.15	d = 1.58 p < 0.01	d = 0.74 p = 0.04
Heart rate (bpm)						
After WUP	128 ± 13 (118, 137)	118 ± 21 (103, 133)	122 ± 11 (114, 130)	d = 0.63 p = 0.08	d = 0.53 p = 0.13	d = 0.23 p = 0.48
Pre-trial	115 ± 19 (98, 133)	109 ± 17 (94, 124)	112 ± 10 (103, 121)	d = 0.32 p = 0.17	d = 0.18 p = 0.31	d = 0.17 p = 0.40
Tympanic temperature (ºC)						
After WUP	34.73 ± 0.65 (34.27, 35.19)	34.25 ± 0.29 (34.04, 34.46)	34.23 ± 0.21 (34.08, 34.38)	d = 0.65 p = 0.03	d = 0.78 p = 0.04	d = 0.11 p = 0.83
Pre-trial	36.44 ± 0.49 (36.11, 36.76)	36.26 ± 0.33 (36.04, 36.48)	36.36 ± 0.47 (36.05, 36.68)	d = 0.41 p = 0.21	d = 0.16 p = 0.64	d = 0.39 p = 0.23
Ratings of perceived exertion						
After WUP	7.91 ± 1.51 (6.89, 8.93)	6.73 ± 1.01 (6.05, 7.41)	7.36 ± 1.69 (6.23, 8.50)	d = 0.82 p = 0.02	d = 0.27 p = 0.51	d = 0.43 p = 0.17
Cortisol (nmol·l^{-1})						
After WUP	5.18 ± 2.18 (3.62, 6.74)	6.08 ± 2.54 (4.27, 7.89)	6.40 ± 3.21 (4.10, 8.70)	d = 0.36 p = 0.28	d = 0.54 p = 0.12	d = 0.10 p = 0.76
Testosterone (pmol·l^{-1})						
After WUP	330.65 ± 128.20 (238.94, 422.36)	309.40 ± 121.85 (222.24, 396.57)	278.80 ± 93.01 (212.27, 345.34)	d = 0.33 p = 0.35	d = 0.70 p = 0.06	d = 0.39 p = 0.24
Testosterone/cortisol ratio						
After WUP	68.70 ± 30.49 (46.88, 90.51)	58.68 ± 32.25 (35.61, 81.75)	49.02 ± 16.94 (36.90, 61.15)	d = 0.25 p = 0.50	d = 0.76 p = 0.02	d = 0.29 p = 0.37

Final performance and race splits

Table 3 presents the results recorded during the trial. It was shown that the 100 m time trial was different between conditions ($F_{2,20}$ = 6.57, p < 0.01). The swimmers were 1.46 ± 1.54% and 1.34 ± 1.24% faster after the WU and SWU, respectively, compared to the LWU. Additionally, the first 50 m lap time was different between conditions ($F_{2,20}$ = 4.00, p = 0.04) in opposition to the second lap that showed no differences ($F_{2,20}$ = 0.41, p = 0.67). However, this second lap showed differences in variables that are usually associated with swimming efficiency, as SL ($F_{2,20}$ = 4.15, p = 0.03), SI ($F_{2,20}$ = 5.80, p = 0.01), and η_p ($F_{2,20}$ = 4.24, p = 0.03), with higher values after the WU compared to the SWU.

Table 3 - Mean ± SD values (95% confidence limits) of the 100 and 50 m lap times, starting time (15 m), and biomechanical and efficiency variables, N = 11.

	Standard Warm-up (WU)	Short Warm-up (SWU)	Long Warm-up (LWU)	WU vs. SWU	WU vs. LWU	SWU vs. LWU
100 m time (s)	59.29 ± 1.95 (57.98, 60.61)	59.38 ± 2.18 (57.91, 60.84)	60.18 ± 2.46 (58.53, 61.83)	d = 0.09 p = 0.78	d = 0.95 p = 0.01	d = 1.12 p < 0.01
First 50 m (s)	28.04 ± 1.38 (27.12, 28.97)	28.01 ± 1.16 (27.23, 28.79)	28.64 ± 1.42 (27.69, 29.60)	d = 0.03 p = 0.91	d = 0.59 p = 0.08	d = 1.31 p < 0.01
Second 50 m (s)	31.25 ± 1.75 (30.08, 32.43)	31.37 ± 1.47 (30.38, 32.36)	31.54 ± 1.69 (30.41, 32.67)	d = 0.10 p = 0.76	d = 0.24 p = 0.41	d = 0.18 p = 0.49
15 m (s)	7.11 ± 0.37 (6.86, 7.36)	7.25 ± 0.34 (7.02, 7.48)	7.19 ± 0.36 (6.95, 7.44)	d = 1.09 p < 0.01	d = 0.68 p = 0.04	d = 0.67 p = 0.08
Stroke frequency (Hz)						
First 50 m	0.96 ± 0.08 (0.91, 1.01)	0.94 ± 0.08 (0.88, 0.99)	0.93 ± 0.09 (0.87, 0.99)	d = 0.64 p = 0.02	d = 0.73 p = 0.02	d = 0.25 p = 0.59
Second 50 m	0.76 ± 0.06 (0.72, 0.71)	0.78 ± 0.05 (0.74, 0.81)	0.76 ± 0.05 (0.72, 0.80)	d = 0.41 p = 0.40	d = 0.23 p = 0.46	d = 0.52 p = 0.18
Stroke length (m)						
First 50 m	2.21 ± 0.19 (2.08, 2.34)	2.22 ± 0.21 (2.07, 2.36)	2.27 ± 0.24 (2.10, 2.43)	d = 0.04 p = 0.89	d = 0.58 p = 0.11	d = 0.63 p = 0.07
Second 50 m	1.99 ± 0.17 (1.87, 2.10)	1.91 ± 0.17 (1.80, 2.02)	1.98 ± 0.15 (1.88, 2.08)	d = 0.77 p = 0.03	d = 0.16 p = 0.69	d = 0.58 p = 0.08
Stroke index ($m^2 \cdot c^{-1} \cdot s^{-1}$)						
First 50 m	4.68 ± 0.56 (4.31, 5.06)	4.58 ± 0.61 (4.17, 4.99)	4.76 ± 0.70 (4.29, 5.23)	d = 0.34 p = 0.28	d = 0.31 p = 0.37	d = 0.80 p = 0.03
Second 50 m	3.02 ± 0.38 (2.76, 3.27)	2.83 ± 0.37 (2.58, 3.08)	2.97 ± 0.31 (2.76, 3.17)	d = 1.26 p < 0.01	d = 0.29 p = 0.35	d = 0.62 p = 0.08
Propelling efficiency (%)						
First 50 m	35.05 ± 3.16 (32.92, 37.17)	35.11 ± 3.64 (32.67, 37.55)	35.94 ± 4.16 (33.14, 38.74)	d = 0.04 p = 0.90	d = 0.54 p = 0.10	d = 0.64 p = 0.06
Second 50 m	31.85 ± 2.53 (30.15, 33.54)	30.62 ± 2.87 (28.69, 32.55)	31.72 ± 2.41 (30.10, 33.34)	d = 0.78 p = 0.03	d = 0.12 p = 0.70	d = 0.59 p = 0.08

The individual differences between the WU, SWU and LWU for the 100 m performances are presented in Figure 1. Five swimmers were faster after the WU compared to the SWU, nine swimmers were faster after the WU compared to the LWU and ten of the swimmers were faster after the SWU compared to the LWU.

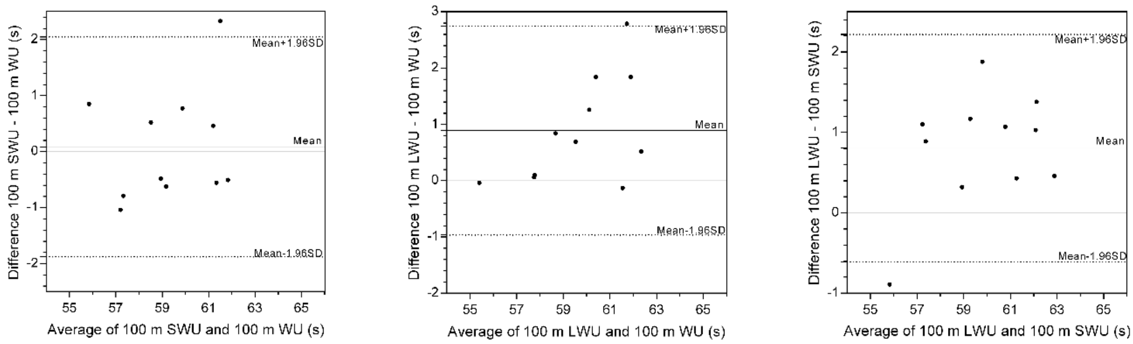

Figure 1 - Bland-Altman plots representing the 100 m time in the three trial conditions: with standard warm-up (WU), with short warm-up (SWU) and with long warm-up. Average difference line (solid line) and 95% CI (dashed lines) are indicated (n = 11)

Recovery after the trial

The three conditions tested caused different responses after the trial in the [La$^-$] values ($F_{2,20}$ = 4.41, p = 0.03), in the heart rate (X^2_2 = 6.55, p = 0.04) and in the testosterone/cortisol ratio (X^2_2 = 7.40, p = 0.03), as presented in Table 4. In the WU condition, [La$^-$] values were 1.48 ± 0.66 mmol·l^{-1} higher than with the SWU and 1.89 ± 0.82 mmol·l^{-1} higher than with the LWU. Although the salivary hormones were not different between trials, their ratio values were higher after the WU compared to the LWU.

Table 4. Mean ± SD values (95% confidence limits) of the physiological responses to the trial, N = 11.

	Standard Warm-up (WU)	Short Warm-up (SWU)	Long Warm-up (LWU)	WU vs. SWU	WU vs. LWU	SWU vs. LWU
Blood lactate (mmol·l^{-1})	12.25 ± 2.28 (10.72, 13.78)	10.77 ± 2.44 (9.13, 12.41)	10.36 ± 2.32 (8.80, 11.92)	d = 0.68 p = 0.05	d = 0.69 p = 0.04	d = 0.25 p = 0.42
Heart rate (bpm)	169 ± 9 (164, 175)	165 ± 12 (157, 173)	172 ± 10 (165, 179)	d = 0.53 p = 0.08	d = 0.24 p = 0.21	d = 0.80 p = 0.05
Ratings of perceived exertion	18.36 ± 1.21 (17.55, 19.17)	18.45 ± 0.93 (17.83, 19.08)	18.63 ± 0.81 (18.09, 19.18)	d = 0.09 p = 0.74	d = 0.24 p = 0.37	d = 0.17 p = 0.53
Tympanic temperature (ºC)	34.96 ± 0.73 (34.48, 35.45)	34.58 ± 0.45 (34.28, 34.88)	34.58 ± 0.52 (34.23, 34.93)	d = 0.48 p = 0.08	d = 0.58 p = 0.06	d = 0.00 p = 0.80
Cortisol (nmol·l^{-1})	5.01 ± 1.85 (3.69, 6.34)	5.68 ± 2.17 (4.12, 7.23)	6.37 ± 2.99 (4.23, 8.51)	d = 0.28 p = 0.40	d = 0.38 p = 0.26	d = 0.32 p = 0.33
Testosterone (pmol·l^{-1})	371.49 ± 143.35 (275.18, 467.80)	324.95 ± 101.87 (256.51, 393.39)	329.01 ± 112.14 (253.67, 404.35)	d = 0.33 p = 0.29	d = 0.36 p = 0.26	d = 0.04 p = 0.89
Testosterone/ cortisol ratio	74.55 ± 32.08 (51.60, 97.51)	61.69 ± 26.14 (43.00, 80.39)	53.66 ± 16.41 (41.91, 65.40)	d = 0.72 p = 0.09	d = 0.72 p = 0.01	d = 0.33 p = 0.45

No differences were found in tympanic temperature after 10 min ($F_{2,20}$ = 0.88, p = 0.43), 20 min ($F_{2,20}$ = 1.96, p = 0.17) and 30 min ($F_{2,20}$ = 1.02, p = 0.38) of recovery. The same effect happened with heart rate values 10 min ($F_{2,16}$ = 0.10, p = 0.91), 20 min ($F_{2,18}$ = 0.14, p = 0.88) and 30 min ($F_{2,10}$ = 1.17, p = 0.35) after finishing the time trial in the three conditions tested. However, as presented in Figure 2, [La^-] was lower after the LWU at the 20th and 30th min of recovery (7.43 ± 1.51 and 6.07 ± 1.56 mmol·l^{-1}; respectively) compared to the SWU (9.25 ± 1.49 and 7.07 ± 1.77 mmol·l^{-1}; respectively) and the WU (9.43 ± 1.54 and 7.23 ± 1.80 mmol·l^{-1}; respectively).

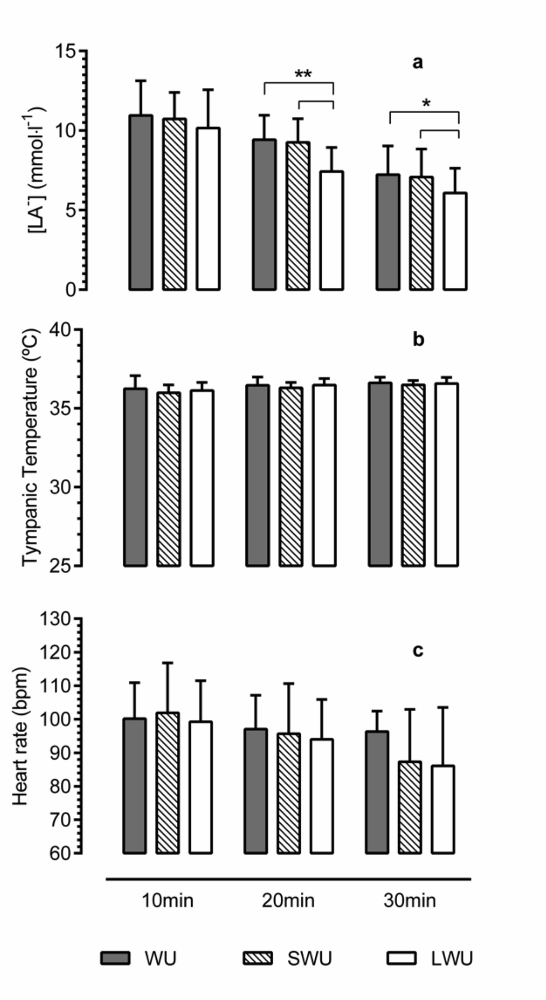

Figure 2 - Comparison between the blood lactate concentrations ([La^-]) (a), tympanic temperature (b) and heart rate (c) values, assessed during the 30 min of recovery after the 100 m, with standard warm-up (WU), short warm-up (SWU) and long warm-up (LWU). *p ≤ 0.05, **p ≤ 0.01, N = 11.

After the recovery, there were no differences in cortisol ($F_{2,20}$ = 1.10, p = 0.35), testosterone ($F_{2,20}$ = 2.05, p = 0.15) or testosterone/cortisol ratio ($F_{2,12}$ = 2.12, p = 0.17) between the WU (7.67 ± 5.20 nmol·l^{-1}, 390.32 ± 86.01 pmol·l^{-1} and 72.51 ± 46.29, respectively), SWU (6.30 ±

2.99 nmol·l^{-1}, 352.27 ± 81.47 pmol·l^{-1} and 63.52 ± 27.05, respectively) and LWU (8.19 ± 4.90 nmol·l^{-1}, 355.77 ± 105.69 pmol·l^{-1} and 55.14 ± 28.63, respectively).

Discussion

The purpose of the current study was to compare the effects of different warm-up volumes on maximal 100 m freestyle swimming performance that represents performance at the extreme-intensity domain. Our main findings could be summarized as follow: (i) the three warm-ups caused different physiological adaptations, with higher [La$^-$] values in WU and SWU and higher testosterone/cortisol levels in WU in the pre-trial momentum; (ii) the LWU resulted in impaired maximal performances, even when compared with the SWU and this did not result in different performances compared to the WU; (iii) within the conditions with better performances, different biomechanical patterns were found and the swimmers' efficiency was improved in WU during the second lap; (iv) a higher testosterone/cortisol ratio levels during recovery after trial could indicate an increased anabolic state, contributing to a faster initial recovery in WU condition.

Regarding the main aim of the present study, swimmers performed faster in the 100 m freestyle after the WU and SWU, and these differences were mainly achieved in the first 50 m lap. Furthermore, we show in Figure 1 that only one of the participants achieved a better time after the LWU compared to the SWU, with only two swimmers faster after the LWU than the WU. This individual comparison between the WU and SWU denotes the aforementioned similarity between performances (45% and 55% faster for the SWU and WU, respectively). These findings are in line with the recent approaches to warm-up that revealed a diminished power production and impaired performances after a long warm-up maybe because of increased muscle fatigue (Tomaras & MacIntosh, 2011). On the other hand, Balilionis *et al.* (2012) found better swimming times on short races (45.72 m) after a regular warm-up compared with a shorter one. However, those best results were achieved after a warm-up that was usually performed by the swimmers and comparing it to another of extremely low volume (91.44 m of total volume), perhaps insufficient to cause the necessary metabolic changes.

An interesting fact was that after the SWU, the performance of the first 15 m was impaired. It can be hypothesized that the lower volume was not sufficient to cause significant metabolic changes or that the velocity stimulus was not enough to effectively potentiate the initial power performance (Saez Saez de Villarreal *et al.*, 2007). However, these differences in the first 15 m disappeared and at the half-way point of the time trial both the WU and SWU were responsible for moderated better lap times compared to the LWU ($d \geq 0.59$). Thus, this finding should be taken into consideration based on the race strategy (e.g., if one is a quick or slow starter).

The warm-up duration also influenced the stroke mechanics of the swimmers. Too short or too long warm-ups seemed to impair the SF at the beginning of the time trial. An optimal warm-up may induce motor neuron excitability that improves the rate of force development and this helped the swimmers to attain higher SF in the first 50 m lap after the WU. Probably to compensate for the inability to increase the SF, a higher SL was used in the LWU and caused higher SI values in that lap. Moreover, our results showed that the WU resulted in increased SL, SI and η_p during the second 50 m lap, variables commonly associated with a low total energy expenditure required to displace the body over a given distance (Barbosa *et al.*, 2008). Those higher values revealed an ability of the swimmers to maintain a high swimming efficiency in the second lap after the WU compared to the SWU. The swimmers are able to readily adjust their technique and patterns of propulsive forces produced according to their constraints and contexts (Barbosa *et al.*, 2008), and perhaps an improved energy management enable the swimmers to maintain their technical ability over the time trial and optimized their biomechanical pattern (Houmard *et al.*, 1991).

The observed performances could somehow be caused by the different physiological responses to the three warm-ups tested. The swimmers reached the lower [La^-] values after the LWU. The longer time elapsed during the LWU could allow a greater recovery, and swimming at low intensities increased the stimulation of aerobic instead of anaerobic metabolism and the rate of lactate clearance (Goodwin *et al.*, 2007; Toubekis *et al.*, 2008). Also, this longer time keeping the swimmers' bodies inside water at 27ºC led to lower tympanic temperatures than WU. In the case of SWU, also with lower values of tympanic temperature compared to WU, one can speculate that it was not long enough to trigger a temperature response. Considering the importance of the body temperature effect as resultant of warm-up (Bishop, 2003a), it seemed that the relationship between the warm-up characteristics (i.e., duration, intensity, rest) and the time spent in the water could be more appropriate in the case of the WU. In addition, it should be noted that the intensity of warm-up was not different between conditions as demonstrated by the similar values of heart rate and RPE after the main task. Nevertheless, after the warm-up they performed differently, with lower RPE values after SWU compared to WU. The shorter volume and time of SWU could have influenced the swimmers to perceive lower RPE values after warming up.

The most relevant results were those verified pre-trial, influencing the homeostasis of the swimmers immediately before the race and thus the performance. It was interesting to notice that [La^-] values were higher in WU and SWU compared to LWU. Traditionally the accumulation of [La^-] and most precisely of the hydrogen ions is pointed as a major cause of muscle fatigue and impaired performance (Cairns, 2006). On both cases, our values were under the 4.70

mmol·l^{-1} and it seemed not enough to cause the different acidosis needed to influence performance, which should drop more than 0.4 pH units (Cairns, 2006). On the opposite way, one could speculate that an increase in [La$^-$] could benefited the performance. Research documented that [La$^-$] caused a greater release of oxygen from hemoglobin for working muscles, an enhancement of blood flow, and alter the neurological feedback for energy production (Darques *et al.*, 1998; Street *et al.*, 2001). These effects could emerge in an optimized aerobic stimulation during a race where this energy metabolism could contribute with 43% of the energy expenditure (Ribeiro *et al.*, 2015). Furthermore, the lactate shuttle inside muscle fibers could facilitate the use of lactate as fuel by the other muscle fibers (Gladden, 2004) and/or the acidosis resultant of glycolysis could function as a protective mechanism on potassium-depressed muscle contractions (Pederson *et al.*, 2003). The muscle force decrease known with increased potassium levels in extracellular milieu seems to be completely reestablished when lactic acid and salbutamol are added, thus suggesting a positive action of this acid on protection of muscles against fatigue (Pederson *et al.*, 2003). These effects are still controversial, however, our higher pre-trial values in WU and SWU could benefit from some of these effects and help to improve the swimmers performance.

The other physiological variable altered in pre-trial was related with the hormonal response. First, one should report that cortisol and testosterone levels corresponded to the normal range of values for men presented in the literature (Hough *et al.*, 2011; Inder *et al.*, 2012). The swimmers attained higher values of testosterone/cortisol ratio in WU compared to LWU condition, mostly because of the large magnitude of the differences found in testosterone values ($d = 0.70$). The differences found before trial between conditions tested could contribute for the improved performances on the 100 m trial in the WU condition. For instance, the higher level of testosterone responsible for the increased testosterone/cortisol ratio in WU could directly influence force production by facilitating neurotransmitter release (Nagaya & Herrera, 1995) and perhaps contributing for the higher SF in the beginning of the race. Also, the abovementioned higher efficiency found in the second 50 m lap could occur because of the delay in fatigue that research associated with an elevated acute testosterone response pre-exercise (Paton *et al.*, 2010). These suggestions could be also supported by the findings of Mujika *et al.* (1996) in a longitudinal in swimming. These authors found correlations between increases in testosterone/cortisol ratio and improvements in swimming performance during a competitive season.

The faster performances in the WU trial resulted in higher [La$^-$] values. It is known that an increase in [La$^-$] during exercise could represent an increased production and release from muscles, a decreased uptake and removal or a greater increase in production and release in comparison to uptake and removal (Goodwin *et al.*, 2007). Therefore, this increased [La$^-$] could be caused by the augmented contribution of anaerobic metabolism during the 100 m after the WU. For instance, the higher initial SF in the WU led the swimmers to spend more energy anaerobically. This is commonly associated with a higher energy cost (Barbosa *et al.*, 2008), and the use of high SF at high swimming velocities stimulates the anaerobic lactic and alactic metabolism (Termin & Pendergast, 2000).

The differences in [La$^-$] after the 100 m trial disappeared during the first 10 min of recovery, suggesting an augmented capacity of recovering in the first instants after trial in WU condition. The hormonal responses are in accordance with this hypothesis with higher testosterone/cortisol ratio levels after WU (d = 0.72). According to the literature, an increase in this variable may be related to elevated anabolic activity and a decrease may indicate a more catabolic state (Urhausen *et al.*, 1995). For instance, an augmented testosterone increases protein synthesis, while higher cortisol promotes the breakdown of muscle protein (Kraemer & Mazzetti, 2003). Thus, one could say that a faster rate of recovery from exercise exists in the first minutes, in the WU condition. In addition, this recovery could be assisted by the higher heart rate observed immediately after the trial. There are reports in the literature that the increased heart rate leads to an increased blood flow to the working muscle (Toubekis et al., 2008). This is believed to enhance lactate removal by allowing a faster distribution to the sites of removal mentioned above. Moreover, the heart rate could have been important to the increased [La$^-$] removal in the following period. In the LWU condition [La$^-$] values were lower in the 20th and 30th min of recovery, maybe because of the similar values to WU verified after the trial. Considering that there was no effects caused by testosterone/ ratio levels in LWU, heart rate alone could led to a later recovery response.

Conclusions

The swimmers were faster after the WU and SWU, suggesting that a long warm-up can impair the sprinting performance in the 100 m freestyle event. Regarding the two conditions showing better time trials, the WU showed a higher swimming efficiency and an optimized recovery in the first minutes after the trial. Immediately before the trial, [La$^-$] and testosterone/cortisol ratio were increased in WU condition and this could influenced performance and perhaps the biomechanical stroke pattern of the swimmers during the race. Also, the increased heart rate and testosterone/cortisol ratio seemed to be the main influencing factors of recovery, allowing a faster initial recovery after trial in the WU condition. These were the novel findings of this study but we also should be aware that there was a considerable inter-individual variability in the response to different warm-up designs. The counterbalanced distribution of the swimmers by the testing conditions diminished some possible day-to-day performance effects and faded some possible other effects, increasing the reliable of this study. Further investigation should be developed to understand the best condition for each swimmer and try to design a warm-up set accordingly.

Practical Applications

The results seems to suggest that high-level male swimmers should benefit from a warm-up of up to 1200 m, with an increased efficiency during the trial and faster recovery immediately after race. Furthermore, our data highlight the need for tailored and customized warm-up designs, because swimmers had different individual responses. Alternatively, if individual warm-ups are not feasible for some reason, practitioners should consider shorter distances. Coaches usually have several swimmers warming-up at the same time and individualization is difficult. However, this study alerts coaches and researchers that the use of high volume may be detrimental to swimming performance, inclusively when compared with a very short volume stimulus.

Study 4

Warm-up for sprint swimming: race-pace or aerobic stimulation? A randomized study

Abstract

Purpose: The aim of this study was to compare the effect of two different warm-up intensities on 100 m swimming performance. Methods: In a randomized design, thirteen high-level swimmers performed two 100 m freestyle time-trials on separate days either after control (CWU) or experimental warm-up (EWU). CWU included a typical race-pace set (4 x 25 m) while EWU included an aerobic set (8 x 50 m at 98–102% of the critical velocity). Cortisol, testosterone, blood lactate ($[La^-]$), oxygen uptake (VO_2), heart rate, core (Tcore and $Tcore_{net}$) and tympanic temperature, and ratings of perceived exertion (RPE) were monitored. Stroke length (SL), stroke frequency (SF), stroke index (SI), propelling efficiency (η_p) were assessed in each 50 m lap of the time trials. Results: VO_2, heart rate and $Tcore_{net}$ were higher after EWU ($p < 0.05$, $d > 0.73$), but a "very likely" positive effect was only maintained in the $Tcore_{net}$ until the trial (97%). Performance was not different between conditions ($p = 0.79$, $d = 0.07$), which was supported by the "very likely" trivial effects inferred (99%). However, EWU "possible" slowed the SF (70%), increased the SL (48%) and η_p (55%), in the first lap ($p < 0.05$, $d > 0.57$). After time trials, differences were shown by the $Tcore_{net}$ and $[La^-]_{peak}$. EWU caused moderate effects ($d > 0.56$) and "likely" positive/negative changes on $Tcore_{net}$ (84%) and $[La^-]$ (82%), respectively. Conclusions: These results suggest that both CWU and EWU have similar effects on 100 m freestyle performance but reached by different biomechanical strategies. Higher SL and efficiency in the first meters after EWU against a higher SF after CWU were observed. Physiological adaptations were mostly in the $Tcore_{net}$ being higher in EWU. The lower $[La^-]$ after trial suggests a less dependency on anaerobic metabolism in EWU.

Key words: Pre-exercise, time-trial, intensity, efficiency, lactate, hormones.

Introduction

Before a competitive event, swimmers usually engage in different activities to change their physiological status in order to optimize performance (Balilionis *et al.*, 2012; Mitchell & Huston, 1993; Neiva *et al.*, 2014a). These activities are intended to increase muscle and body temperature resulting in multiple changes like increased muscle efficiency (Segal *et al.*, 1986) increased blood flow (Pearson *et al.*, 2011), improved efficiency of muscle glycolysis and high-energy phosphate degradation during exercise (Febbraio *et al.*, 1996), and increased nerve conduction rate (Rutkove, 2001). Based on these assumptions, different routines are prescribed before racing a swim event even though there is little insight on the on possible changes on the structure of warm-up (Houmard *et al.*, 1991; Neiva *et al.*, 2014a).

The performance seems to depend on the magnitude of the response determined by intensity, duration and recovery of prior activities (Bishop *et al.*, 2003). However, these factors and their effects on swimming performance are not well known, although it is consensual the negative impact that a poorly designed warm-up may cause (Neiva *et al.*, 2014a). For instance, despite the increased publications on this topic, notably in other sports (Burnley *et al.*, 2005; Wittekind & Beneke, 2011), little information is available for one of the most popular Olympic sports, as it is competitive swimming. Houmard *et al.* (1991) compared the effects of continuous swimming at ~65% of peak oxygen uptake (VO_{2peak}) to an intermittent swimming at ~95% VO_{2peak} on 365.8 m also at 95% VO_{2peak}. No differences were found in heart rate, stroke length (SL) or blood lactate concentrations ($[La^-]$) after the trial. These results suggested no benefit of designing high-intensity sets for warm-up. Nevertheless, one should acknowledge that in this study the maximal performance adaptations were not measured and hence the real effects of intensity were not deeply investigated.

It is common practice to include race-pace sets in the pre-race warm-up (McGowan *et al.*, 2014). Anecdotal suggestions persuaded to include a short-distance swimming set at race-pace in warm-up (Mitchell & Huston, 1993; Robergs *et al.*, 1990). Unfortunately, until now, only submaximal trials were used or the experimental warm-up sets were compared to no warm-up condition and no clear evidence about specific intensities could be assigned. An interesting approach to this concern was recently reported by Wittekind and Beneke (2011) in cycling. They found that after higher intensities of warm-up reduced anaerobic glycolytic contribution during 1min of cycle ergometer might be compensated by increased aerobic stimulation. In agreement, some authors have previously reported that warm-up may optimize performance by enhancing oxygen uptake (VO_2) kinetics (Hughson, 2009; MacDonald *et al.*, 2001). A faster oxygen uptake and consequent reduced anaerobic glycolytic contribution could delay anaerobic metabolism and perhaps reduce metabolic fatigue. This VO_2 stimulation could be of particular interest when applied to sprinting events such as 100 m instead of traditional race-pace sets, and yet no insight can be found in the literature on this. Despite the short duration of the race, each energetic pathways, anaerobic and aerobic, contributes with about 50% of the total energy required, highlighting the relevance of both (Ribeiro *et al.*, 2015).

It seems critical to identify the effects of different warm-up intensities in subsequent maximal performance, and also to understand the influence on several physiological, biomechanical and psychophysiological parameters. Thus, the current study was conducted to compare the effect on performance of two different sets, one eliciting race-pace and the other the VO_2. To have a deeper understanding of the mechanisms explaining the acute response, biomechanical, physiological and psychophysiological adaptations were also assessed. It was hypothesized that performance was enhanced when race-pace sets were included in the warm-up routines, due to the stimulation of energy pathways recruited during the race, resulting in different biomechanical strategies and physiological/psychophysiological responses.

Methods

Subjects

Eligible participants were all male competitive swimmers, training at least 6 times per week and with more than 6 years of competitive experience. Thirteen high-level swimmers (mean ± SD 17.15 ± 1.52 years of age, 1.77 ± 0.07 m of height, 64.80 ± 8.58 kg of body mass, 8.20 ± 1.52 years of training background) were recruited. All had competed at junior and senior national swimming championships finals, performing different type of warm-ups over the last years. A training volume of 37,450 ± 4,950 m per week was performed during the current season (6 to 9 times per week). The personal best times in the 100 m freestyle event were 56.79 ± 2.24 s (567.85 ± 66.79 FINA 2015 scoring points in LCM). After university ethical approval, ensuring compliance with the declaration of Helsinki, the participants were informed about the study design and procedures, and a written informed consent/assent was signed (or by parent/guardian if subjects were under-age).

Procedures

The study followed a counterbalanced repeated measures design. Each participant completed 2 time trials of 100 m freestyle, in randomized order, separated by 48 h. All the procedures took place in the morning (between 8:00-12:00 am) at a 50 m indoor swimming pool with water temperature at 28.12 ± 0.09ºC, air temperature 27.95 ± 0.16ºC and 60.20 ± 0.58% of humidity (measured before each test). All swimmers were tested at the same time of the day and they were asked to maintain the same training, recovery and diet routines in the testing days, abstaining from consuming caffeine 48 h prior to testing.

After arriving at the pool, the swimmers remained seated for 5 min to assess baseline measurements of salivary cortisol, salivary testosterone, heart rate (Vantage NV; Polar, Lempele, Finland), tympanic temperature (Braun Thermoscan IRT 4520, Germany), core temperature (Tcore; CorTemp, HQ Inc, Palmetto, FL), [La^-] (Accutrend Lactate® Roche, Germany) and VO_2 ($Kb4^2$, Cosmed, Rome, Italy). Then, each swimmer was randomly assigned to one of the two warm-up protocols (Table 1), with different swimming intensities but identical volumes (1200 m). Both were prescribed with the help of an experienced national swimming coach and intended to replicate some of the specific sets and drills usually performed. The difference between the two protocols was the main set intensity. During the control (CWU) it should simulate short distance race-pace, usual among swimmers (McGowan *et al.*, 2014) and during experimental warm-up (EWU) it should elicit an increased VO_2.

EWU set was structured based on the assumptions that i) critical velocity could be 3 to 10% faster than lactate threshold and maximal lactate steady state and it leads to a progressive increase in VO_2 and [La^-] (Toubekis & Tokmakidis, 2013); ii) short duration intermittent aerobic sets results in less glycogen depletion compared with continuous sets (Billat, 2001); iii) the rest should be sufficient to maintain [La^-] levels lower than 5 $mmol \cdot l^{-1}$ as suggested by Jones *et al.* (2003). Critical velocity was calculated from the slope of the regression line between distance and time performed, combining the 50 m and the 400 m best times of the swimmers at the moment of testing, as accepted by literature (Toubekis & Tokmakidis, 2013) and a range between 98% to 102% was set for pacing the swimmers. The swimmers were familiarized with both warm-ups 48 h before the experiments.

Table 1. Warm-up protocols.

Warm-up Task	
300 m - Normal - breathing in the 5th stroke - Normal	
4 x 100 m @ 1:50 – 25 m kick – 25 m increased stroke length	
Control:	Experimental:
8 x 50 m @ 1:00	8 x 50 m @ 1:00
(50 m drill; 50 m building up velocity; 25 m race-pace/25 m easy; 25 m race-pace/25 m easy; repeat)	(All at 98% - 102% of critical velocity)
100 m - Easy swim	100 m - Easy swim

Time trial performance

After 10 min of passive rest, seated and legs uncrossed, the swimmers performed the 100 m freestyle time trial. The swimmer was requested to set on the starting block and take off after official verbal commands and the starting signal. The times were measured by a timing system

(OMEGA S.A. Switzerland) on the head wall. As a backup, time trials were also clocked with a stopwatch used by an experienced swimming coach and a video camera (Casio Exilim Ex-F1, f=30 Hz). This was placed at 15 m, perpendicular to lane 7, and it was used to assess the 15 m time over this distance.

Kinematics and efficiency

Stroke frequency (SF), SL and stroke index (SI) were determined according to the procedures used by Neiva et al. (2014b). The propelling efficiency (η_ρ) was also estimated by (Zamparo, 2006):

$$\eta_\rho = [(0.9 \cdot v)/(2\pi \cdot SF \cdot l)] \cdot 2/\pi \qquad (1)$$

where v is the swimming velocity ($m \cdot s^{-1}$), SF is the stroke frequency (Hz) and l is the arm length (m). The l is computed trigonometrically by measuring the arm length and considering the average elbow angles during the insweep of the arm pull as reported by Zamparo *et al.* (2005).

Metabolic, cardiovascular and psychophysiological variables

Capillary blood samples for [La^-] assessment were collected from the fingertip after the warm-up protocol (1 min), immediately before the trial, after the trial (3 and 6 min to obtain the highest value: $[La^-]_{peak}$) and 15min after the trial. Besides these moments, the heart rate was also assessed during the warm-up and recovery after the swimming test. Additionally, the ratings of perceived exertion (RPE; 8) were recorded during and after the warm-up, and after each trial.

Tympanic temperatures were measured before and after the warm-up, immediately before and after the trial and 15 min post trial. Each swimmer's tympanic temperature was taken 3 times, and the maximal value was recorded. The thermometers had a measuring accuracy of 0.2ºC for temperatures between 32.0 and 42.0ºC. Tcore was assessed by using a temperature sensor that was ingested in the night before, 10 h before the test (Byrne & Lim, 2006). This pill transmitted a radio signal to an external sensor (CorTemp Data Recorder, HQ Inc., Palmetto, FL), which subsequently converted the signal into digital format. To reduce possible errors of the pill position, the net values of Tcore ($Tcore_{net}$) were used to compare data results.

VO_2 was measured with a backward extrapolation technique, immediately after the trial (Costa *et al.,* 2013). The first 2s of measurement after detection were not considered due to the device adaptation to the sudden change of respiratory cycles and to oxygen uptake (Laffite *et al.*, 2004). The peak oxygen uptake (VO_{2peak}) was considered to be the mean value in the following 6s (Laffite *et al.*, 2004). Additionally, VO_2 was monitored during the post warm-up time period and after the 100 m freestyle.

Saliva samples were collected before exercise and after finishing the protocol. The participants were seated and leaning forward, providing saliva samples using the passive drool method. Samples were collected directly through a 5 cm plastic drinking straw into 10 ml plastic screw top tubes and all samples were kept cold immediately after collection (2 ºC) and then frozen (-20ºC) until they were assayed. The minimum collection time was 3 min for each subject to allow for the collection of a sufficient sample volume. The salivary cortisol and salivary testosterone concentrations were determined by enzyme-linked immunosorbent assay (ELISA) using commercially available kits (Salimetrics, State College, PA, USA). The sensitivity of the kits was 0.08 $nmol \cdot l^{-1}$ /L and 3.46 $pmol \cdot l^{-1}$ for cortisol and testosterone, respectively. The mean intra-assay coefficients of variation were 3.72 and 3.15% for cortisol and testosterone, respectively. The mean inter-assay coefficients of variation were 9.41 and 7.26% for cortisol and testosterone, respectively.

Statistical Analysis

Standard statistical methods were used for the calculation of means, standard deviations (SD) and confidence intervals. The normality of all distributions was verified using Shapiro-Wilks tests, and parametric statistical analysis was adopted. To compare data obtained in the two trials, Student's paired t-tests and Cohen's d effect size were calculated ($p \leq 0.05$). Smallest worthwhile effects were also computed to determine the likelihood that the true effect was substantially beneficial (positive), trivial, or harmful (negative). The threshold value for smallest worthwhile change was set at 0.8% for performance, whereas the other variables were set at 0.2 (Cohen's units). If both benefit and harm were calculated to be 95%, the true effect was assessed as unclear. Where clear interpretation could be made, chances of benefit or harm were assessed as follows: <0.5%, most unlikely, almost certainly not; 0.5-5%, very unlikely; 5-25%, unlikely, probably not; 25-75%, possibly; 75-95%, likely, probably; 95-99.5%, very likely; >99.5%, most likely, almost certainly (Hopkins *et al.*, 2009). The limits of agreement between the 100 m time in the three trial conditions were derived according to the literature (Bland & Altman, 2003).

Results

Baseline measures

Before the warm-ups, the physiological variables were not different between conditions. Tcore (CWU: 37.20 ± 0.33ºC vs. EWU: 37.29 ± 0.44ºC; $p = 0.50$, $d = 0.24$), tympanic temperature (CWU: 36.73 ± 0.83ºC vs. EWU: 36.76 ± 0.43ºC; $p = 0.87$, $d = 0.05$), VO_2 (CWU: 5.59 ± 0.85 $ml \cdot kg^{-1}min^{-1}$ vs. EWU: 5.63 ± 0.96 $ml \cdot kg^{-1}min^{-1}$; $p = 0.90$, $d = 0.04$), [La^-] (CWU: 2.88 ± 0.78 $mmol \cdot l^{-1}$ vs. EWU: 2.93 ± 0.56 $mmol \cdot l^{-1}$; $p = 0.85$, $d = 0.06$), salivary cortisol (CWU: 8.32 ± 3.48 $nmol \cdot l^{-1}$ vs.

EWU 9.58 ± 3.68 nmol·l^{-1}; $p = 0.11$, $d = 0.63$), testosterone (CWU: 463.60 ± 142.60 pmol·l^{-1} vs. EWU: 473.85 ± 98.33 pmol·l^{-1}; $p = 0.86$, $d = 0.06$) and testosterone/cortisol ratio (CWU: 58.11 ± 19.53 vs. EWU: 53.89 ± 19.68; $p = 0.64$, $d = 0.17$), determined the similar conditions of the two moments of procedures.

Acute responses to warm-up

The acute responses to different warm-ups are presented in Table 2. After warm-up there was an increase in VO_2, heart rate and $Tcore_{net}$ that attained higher values in EWU compared to CWU. The qualitative analysis supported this finding with large effect size for the VO_2 and strong effect sizes for the heart rate and $Tcore_{net}$. Further, a “very likely” positive effect on VO_2 and $Tcore_{net}$ and a “most likely” positive effect on heart rate were associated with EWU condition. This condition was perceived as “very likely” demanding by the effort performed by the swimmers. However, small effects were found in [La^-] and tympanic temperatures.

Before the trial, the main differences disappeared and “unclear” inferences were verified in most physiological variables. Moderate effect sizes were found in temperature (Tcore, $Tcore_{net}$ and tympanic temperature), and EWU still have a “very likely” positive effect on $Tcore_{net}$ after the 10min of rest that precedes the swim trial.

Table 2. Mean ± SD values of physiological and psychophysiological variables assessed after warm-up (Post) and before trial (Pre-trial) during control (CWU) and experimental (EWU) procedures, N = 13.

		CWU	EWU	*P*	d	Mean change (%) ± 90% CI*	Chance (%)**
Oxygen uptake ($ml \cdot kg^{-1} min^{-1}$)	Post	18.15 ± 5.40	22.84 ± 5.15	0.03	0.73	28.42 ± 25.74	95/4/1
	Pre-trial	6.58 ± 1.29	6.71 ± 1.45	0.66	0.13	1.69 ± 8.32	32/59/10
Heart rate (bpm)	Post	93 ± 13	107 ± 12	0.00	1.73	15.74 ± 5.43	100/0/0
	Pre-trial	95 ± 11	97 ± 10	0.66	0.13	1.91 ± 7.28	43/42/15
Blood lactate ($mmol \cdot l^{-1}$)	Post	3.87 ± 1.01	3.96 ± 2.23	0.88	0.04	-11.14 ± 27.90	42/27/31
	Pre-trial	2.88 ± 0.78	3.01 ± 1.36	0.68	0.11	-2.90 ± 24.20	47/35/19
Core temperature (°C)	Post	37.66 ± 0.28	37.91 ± 0.30	0.06	0.74	0.67 ± 0.57	93/5/1
	Pre-trial	37.61 ± 0.29	37.80 ± 0.35	0.28	0.40	0.49 ± 0.79	76/16/8
Core $temperature_{net}$ (°C)	Post	0.43 ± 0.28	0.62 ± 0.32	0.01	1.10	71.53 ± 76.06	97/3/0
	Pre-trial	0.36 ± 0.33	0.51 ± 0.38	0.13	0.56	21.09 ± 125.16	80/18/2
Tympanic temperature (°C)	Post	34.15 ± 0.32	33.96 ± 0.63	0.28	0.32	-0.55 ± 0.87	7/17/76
	Pre-trial	35.67 ± 0.72	35.88 ± 0.47	0.17	0.40	0.59 ± 0.73	64/34/1
Ratings of perceived exertion	Post	12.92 ± 1.55	13.92 ± 1.75	<0.01	0.87	7.52 ± 4.81	97/3/0

* where a positive % change equates to an increase in EWU condition

** presented as positive/trivial/negative.

Swim-trial

Table 3 presents the results recorded during the trial. It was shown that the 100 m time trial was not different between conditions, with a "very likely" trivial effect. Additionally, Figure 1 depicts the individual performance response to each one of the warm-ups. Out of thirteen, nine swimmers performed better after CWU and four after EWU.

Moderate effect sizes were found for some biomechanical variables. The EWU had a "possibly" negative effect on the SF over the first 50m and a "possibly" positive effect on the SL. Moreover, a "possibly" positive effect on the η_p was found in the first lap after EWU. The main physiological acute adaptations to the maximal swimming test were found to be related with $[La^-]_{peak}$ and $Tcore_{net}$, with moderate effect size and a "likely" negative or positive effect of EWU, respectively.

Table 3 – Mean ± SD values of the 100 and 50m lap times, biomechanical, physiological and psychophysiological variables assessed during control (CWU) and experimental (EWU) procedures, N=13.

	CWU	EWU	*P*	d	Mean change (%) ± 90% CI*	Chance (%)**
100 m time (s)	57.87 ± 1.84	57.83 ± 1.77	0.79	0.07	-0.07 ± 0.47	0/99/1
First 50 m (s)	27.67 ± 0.99	27.70 ± 0.95	0.30	0.31	0.45 ± 0.70	19/80/0
Second 50 m (s)	30.31 ± 1.05	30.13 ± 0.92	0.12	0.48	-0.57 ± 0.61	0/73/27
First 15m (s)	6.74 0.28	6.76 0.29	0.56	0.09	0.28 ± 0.85	14/84/2
First 50 m stroke frequency (Hz)	0.90 ± 0.07	0.88 ± 0.06	0.03	0.74	2.06 ± 1.48	0/30/70
Second 50 m stroke frequency (Hz)	0.76 ± 0.06	0.77 ± 0.06	0.48	0.30	0.85 ± 2.18	30/67/03
First 50 m stroke length(m)	2.04 ± 0.15	2.07 ± 0.14	0.05	0.57	1.65 ± 1.40	48/52/0
Second 50 m stroke length (m)	2.17 ± 0.14	2.16 ± 0.15	0.63	0.12	-0.57 ± 1.98	5/72/23
First 50 m stroke index ($m^2c^{-1}s^{-1}$)	3.70 ± 0.33	3.75 ± 0.31	0.12	0.45	1.41 ± 1.53	27/73/0
Second 50 m stroke index ($m^2c^{-1}s^{-1}$)	3.56 ± 0.25	3.54 ± 0.25	0.71	0.15	-0.38 ± 1.94	4/81/15
First 50 m propelling efficiency (%)	33.51 ± 2.68	34.11 ± 2.35	0.03	0.70	1.87 ± 1.33	55/45/0
Second 50 propelling efficiency (%)	35.82 ± 2.89	35.63 ± 3.16	0.63	0.13	-0.60 ± 1.97	3/82/15
Peak oxygen uptake ($ml \cdot kg^{-1}min^{-1}$)	50.11 ± 5.79	50.95 ± 7.41	0.63	0.15	1.30 ± 5.90	40/48/12
Heart rate (bpm)	160 ± 15	163 ± 12	0.21	0.50	1.85 ± 4.53	46/46/8
Peak blood lactate ($mmol \cdot l^{-1}$)	12.60 ± 2.50	11.58 ± 3.11	0.07	0.56	-10.05 ± 9.24	0/17/82
Core temperature (°C)	37.50 ± 0.32	37.71 ± 0.35	0.27	0.42	0.55 ± 0.89	77/16/8
Core temperature$_{net}$ (°C)	0.19 ± 0.35	0.36 ± 0.38	0.09	0.69	-20.50 ±115.00	84/14/1
Tympanic temperature (°C)	34.27 ± 0.28	34.38 ± 0.40	0.47	0.20	0.32 ± 0.79	63/23/14
Ratings of perceived exertion	18.00 ± 1.29	18.54 ± 1.20	0.01	0.82	3.04 ± 1.84	91/9/0

* where a positive % change equates to an increase in EWU condition.

** presented as positive/trivial/negative.

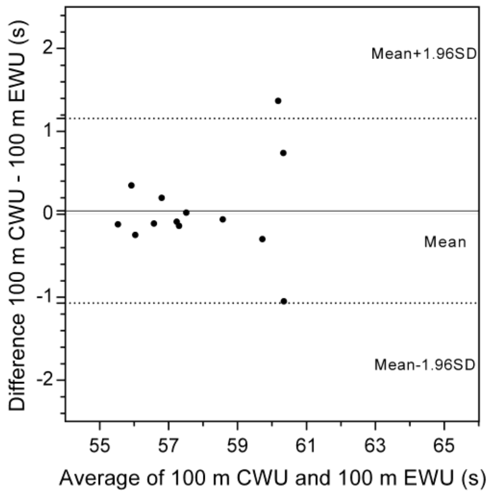

Figure 1. Bland-Altman plots representing the 100 m time in the two trial conditions: control warm-up (CWU) and experimental warm-up (EWU). Average difference line (solid line) and 95% CI (dashed lines) are indicated (N = 13).

Recovery period

Figure 2 depicts the physiological variables monitored over the recovery showing similar adaptations between conditions tested. However, the $Tcore_{net}$ after the 15 min were moderately lower in CWU compared to EWU (0.10 ± 0.35ºC vs. 0.26 ± 0.31ºC, $p = 0.06$, $d = 0.74$).

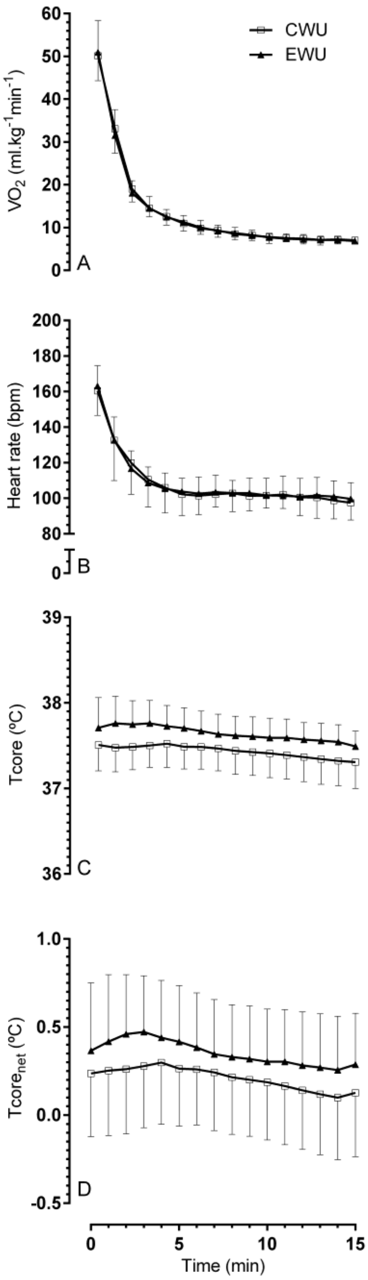

Figure 2. Comparison between the oxygen uptake (VO_2) (A), heart rate (B), Core Temperature (C) (Tcore) and its net values ($Tcore_{net}$) (D) assessed during the 15 min of recovery after the 100 m, with control warm-up (CWU) and experimental warm-up (EWU). N = 13.

Additionally, after the recovery period, [La^-] (9.15 ± 3.49 mmol·l^{-1} vs. 8.62 ± 2.41 mmol·l^{-1}; p = 0.56, d = 0.17), tympanic temperature (35.95 ± 0.74ºC vs. 35.78 ± 0.48ºC; p = 0.42, d = 0.23) and salivary hormones were not different between warm-ups. Small effect was verified in the cortisol (CWU: 10.33 ± 7.14 nmol·l^{-1} vs. EWU: 9.97 ± 4.25 nmol·l^{-1}; p = 0.89, d = 0.04), testosterone (CWU: 515.00 ± 174.72 pmol·l^{-1} vs. EWU: 476.28 ± 79.87 pmol·l^{-1}; p = 0.49, d = 0.20) and testosterone/cortisol ratio (62.70 ± 30.55 vs. EWU: 64.81 ± 49.96; p = 0.91, d = 0.03).

Discussion

The purpose of the current study was to investigate the effects of two different warm-up intensities on maximal 100 m freestyle time trial. The results showed no differences in performance between a warm-up that includes a race-pace set or a set to elicit VO_2. However, the warm-ups caused different acute adaptations. These differences disappeared during the time lag between warm-up and the time trial, resulting in similar final 100 m times. Despite similar performances, the biomechanical and physiological responses were different between trials. The efficiency was higher in the first lap of the race and, immediately after the race, $Tcore_{net}$ was higher and $[La^-]_{peak}$ was lower in EWU condition. Besides physiological adaptations, our novel finding was the adaptation of the simmers' technical pattern to each previous warm-up. Therefore, the different warm-ups seems to trigger different race strategies to attain similar times, revealing its importance for the physiological and biomechanical adjustment intended for the race.

The trivial changes found on performance between conditions were lower than 0.1% confirming the first hypotheses left by Houmard *et al.* (1991). However, those authors did not assess maximal performances and conclusions were draw based on the non-significant differences in heart rate, SL or $[La^-]$ after submaximal 385.8 m freestyle. Interestingly, our results showed different biomechanical patterns during the race. It was already showed by Neiva *et al.* (2014b) that warm-up could influence biomechanics during maximal swimming. In the current study, the swimmers were able to perform higher SF in the initial phase of the race after CWU. In contrast, higher SL values were found after EWU as well as a higher η_p in the beginning of the race. It is accepted that the swimmers are able to manipulate their SL and SF to achieve a given velocity with the lowest energy cost (Barbosa *et al.*, 2010). Consequently, those different biomechanical patterns could be the most appropriated for them in each particular moment. Also, increased motor neurons excitability by higher velocities improves the rate of force development and power production and maybe, in this particular case, the SF in CWU. The race-pace velocity was almost maximal and the critical velocity was much under that velocity. So, a different pattern could be adopted due to different stimulation (Saez Saez de Villarreal *et al.*, 2007). Hence, warm-up can be one way to trigger a given biomechanical pattern.

An interesting point of view about motor learning and warm-up was addressed by Ajemian *et al* (2010). Based on the assumption of a high learning rate of the humans to sensorimotor activity, authors suggested that the warm-up allows to recalibrate the sensorimotor network of the athletes and to restore the skills to a finely tuned state. This could justify the importance of the warm-up specificity, but also the different biomechanical patterns verified in this study. We can infer that when the swimming velocity was increased in race-pace, the SF should be higher (Pelayo *et al.*, 1996). On the contrary, SL should increase when the velocity decreases, which happened in EWU condition (Pelayo *et al.*, 1996). The main assumption here is that a within-subject comparison was carried out. Consequently, each condition could have acutely adapted the swimmers' motor skills according to the biomechanical pattern used and then replicate these during initial meters of the race.

The two warm-up procedures resulted in different acute physiological responses and increased perceived effort after EWU ("somewhat hard" vs. "light"), and this could also influence the way swimmers raced over the time trial. The higher $Tcore_{net}$ and VO_2 in EWU immediately after warm-up with no increased $[La^-]$ demonstrated that the main set succeeded in its goal of eliciting the aerobic metabolism. According to literature, one of the benefits of warm-up is the increased baseline of VO_2 in the beginning of the race, which contributes for an improved performance (Bishop, 2003). The mechanisms for this to happen are not clear, but some studies suggest altered primary oxygen uptake kinetics via shorter time constant, increased primary VO_2 amplitude or/and reduced VO_2 slow component (Wittekind & Beneke, 2011). Despite the decrease of the values during the 10 min of rest and the non-differences in VO_2 and heart rate before the trial, some of the previous effects could be promoting internal adaptations. The warm-up can change the metabolic profile of subsequent exercise by accelerating the VO_2 kinetics and diminishing the blood lactate response (Burnley *et al.*, 2005). The increased VO_2 observed after EWU may have removed some of the inertia in mitochondrial activity (Campbell-O'Sullivan *et al.*, 2002). Accordingly, the aerobic system improved its preparedness state and the oxygen could be used at a faster rate at the beginning of the exercise, diminishing the reliance on the anaerobic metabolism in this phase. So, a change in VO_2 kinetics in EWU could allow a faster response at the beginning, enabling a later increased glycolytic contribution and explaining the VO_{2peak} similarity and the different $[La^-]_{peak}$ after the trial.

Another possible explanation is the high temperature prior to the maximal bout. $Tcore_{net}$ was higher after EWU and still had a "very likely" positive effect before the trial. Speeding of overall VO_2 kinetics can occur, caused by enhanced oxygen delivery associated with increased muscle blood flow, which in turn could be associated with a temperature rise (Pearson *et al.*, 2011; Willis & Jackman, 1994). However, mixed findings have been reported, e.g., that elevated temperature had no effect on the VO_2 response (Burnley *et al.*, 2002) and therefore warrants further investigation and a closer examination of this effect.

During recovery, among the physiological variables assessed, $Tcore_{net}$ was the only that kept significant differences, with moderated higher values in EWU condition. This increased temperature could be reflected in some "discomfort" felt by the swimmers and leading to an "extremely" hard perception of the effort after trial against the "hard" effort feedback in CWU. These could even be a result of the increased VO_2 of the main set that created a greater imbalance in the homeostasis of the swimmers. It was expected that some of this impact would lead to hormonal variations between the conditions tested. Research indicates that the cortisol, testosterone and its ratio are related to the exercise intensity and duration (Jacks *et al.*, 2002;

Kochajska-Dziurowicz *et al.,* 2001) and changes in its levels could indicate an anabolic or catabolic activity within the tissues. Our findings corresponded to the normal range of men´s values reported by the literature (Hough *et al.*, 2011; Inder *et al.*, 2012); albeit no differences were observed between the two conditions, suggesting that the different warm-up intensities tested were not enough to shift the hormonal response.

Some limitations should be addressed in the present study. The swimmers were assigned in a counterbalance order to prevent some error effects. That said, we should acknowledge possible unknown variation in day-to-day performance due to outside pool daily events. Also, the study was performed in a specific race event and different events would elicit different adaptations. Finally, VO_2 kinetics and muscle temperature could have improved our understanding on the mechanistic phenomenon.

Conclusions

In conclusion, the two swimming intensities of warm-up caused no differences on 100 m freestyle performance. Nevertheless, there were some physiological changes that occur after the EWU, that were not presented after CWU. The increased $Tcore_{net}$ after warm-up until the end of the trial, the lower $[La^-]_{peak}$ after the trial and the increased swimming efficiency in the first meters of the race makes the use of an aerobic stimulation set during warm-up a viable alternative to the usual warm-up that comprises sets at higher swimming velocities (race-pace). Yet, those differences were not reflected on the performance, requiring further investigation.

Our results suggest that there is an acute learning process that could justify the different patters found during trial. This novel finding reveals the importance of the warm-up as regards to a sensorimotor adaptation to the movement and the motor skills should be performed similar to those wanted in the race. Some insights occur on the best warm-up to implement, depending of a particular race situation. Perhaps the use of the EWU structure should be applied when longer waiting periods would happen between warm-up and race, taking advantages of an increased temperature. In addition, if the race strategy depends more on a higher SF or on a higher swimming efficiency, CWU and WU should be used, respectively. In addition, we should not disregard the individual responses observed for each warm-up, highlighting the importance of a proper warm-up structure for optimized performances.

Study 5

The influence of post warm-up recovery duration on 100 m freestyle performance: a randomized crossover study

Abstract

Purpose: The aim of this study was to compare the effect of two different post warm-up recovery protocols on 100 m swimming performance.Design: Repeated measures design in randomized order of two 100 m freestyle time trials following 10 min or 20 min post warm-up recoveries. Methods: Eleven competitive male swimmers performed both trials on different days. The warm-up was the same and totalled 1,200 m. Performance (time trial), biomechanical (stroke length, stroke frequency, stroke index, propelling efficiency), physiological (blood lactate concentrations, heart rate, core and tympanic temperature), and psychophysiological (perceived effort) variables were assessed on both trials. Results: Time trial performance was faster after 10 min as opposed to 20 min recovery (58.41 ± 1.99 s vs. 59.06 ± 1.86 s, $p < 0.01$). This was supported by strong effect sizes ($d = 0.99$) and the qualitative indication of "likely" positive effects. Heart rate before trial was increased (89 ± 12 bpm vs. 82 ± 13 bpm; $p<0.01$) in the 10min condition. Further, there was a "likely" negative effect of the 20 min recovery in the pre-trial values of net core temperature and oxygen uptake. Conclusions: A 10 min post warm-up recovery period will help the swimmers to enhance the 100 m freestyle performances, compared to 20 min. The combined effects of the shorter post warm-up recovery protocol on core temperature, heart rate and oxygen uptake could be the main reasons for the improved performances.

Key words: Sports performance, pre-exercise, heart rate, temperature, oxygen.

Introduction

Warming-up before training or competition has become one of the most interesting topics for coaches, swimmers and researchers in the last few years (Balilionis *et al.*, 2012; Neiva *et al.*, 2014a; West *et al.,* 2013). Studies have described some physiological adaptations to warm-up that theoretically support a positive effect of warm-up on subsequent performance, which are mostly linked to an increase in body temperature (Bishop, 2003; Racinais & Oksa, 2010). For instance, warm-up causes faster oxygen dissociation from hemoglobin, acceleration of metabolic reactions and nerve conduction rate, and reduced muscle and joints resistance (Bishop, 2003). Besides the effects on body temperature, the priming physical activities might also exert additional effects that benefit performance, such as elevated baseline oxygen uptake (VO_2) and increased amplitude of the primary VO_2 response to subsequent exercise (Burnley *et al.,* 2011).

Specifically in swimming, only recently the evidence was gathered on warm-up positive effects. Studies have shown that swimmers were 1.5% faster at the 100 m freestyle (Neiva *et al.*, 2014b) and were able to apply 11.5% more propelling force during 30s all-out freestyle swimming after warm-up (Neiva *et al.,* 2011). Although warming up has the potential to optimize swimming performance, research on the field as only recently been focusing on the warm-up structure (Balilionis *et al.,* 2012; West *et al.,* 2013, Zochowski *et al.,* 2007). However, little attention has been given to the rest interval separating the warm-up from the main high intensity task. During this period it seems important to maintain the increased metabolic rate achieved during warm-up (McGowan *et al.*, 2015). Given that it is needed some time to accomplish all official requirements before race, it becomes critical to gather some insight about the effects of the post warm-up duration on subsequent performance.

However, the body of knowledge on the swimmers' performances when different post warm-up recoveries are used is rather scarce. Zochowski *et al.* (2007) reported that a 10 min recovery improved 200 m trial performances compared with a 45 min recovery by 1.38%. Using longer rest periods West et al. (2013) verified that 200 m swimming times were 1.48% better with 20 min rest instead of 45 min. Higher core temperature (Tcore) (West et al., 2013) and higher heart rate at the beginning of the race that potentially increased baseline oxygen uptake (Zochowski *et al.,* 2007) were the main mechanisms pointed out for improved performance following shorter intervals. Nevertheless, no evaluation of VO_2 was available and the 45 min tested in both studies could be too extensive even for a real competition venue.

To the best of our knowledge, studies to date have only focused on the effects of different post warm-up intervals in the 200 m race and different distances might demand different recovery periods. Moreover, previous studies did not report variables from different scientific fields to explain the athletes' performance, and hence being unable to provide a holistic understanding of the phenomenon. Studies focused on a few physiological parameters, disregarding hypothetical biomechanical adaptations. In addition, most studies on warm-ups used the 10 min as a standard measure, and their findings are only fully understood if we know how different recoveries influenced its effects. The current study was therefore conducted to compare the effect of two different post warm-up intervals (10 and 20 min rest) on 100 m freestyle performance. Performance, biomechanical, physiological and psychophysiological responses were investigated. It was hypothesized that the shorter recovery period would result in better swimming performances.

Methods

Eleven competitive male swimmers (age 17.36 ± 1.8 years; height 1.76 ± 0.02 m; body mass 65.7 ± 9.5 kg) took part in this study. Swimmers were eligible for the study if they competed at national level for the last 6 years. During the current season, the swimmers trained 36,390 ± 5,960 m per week, from 6 to 9 times, and their personal best time in the 100 m freestyle was 57.92 ± 2.05 s (534.36 ± 56.84 FINA 2015 scoring points). After University ethics committee approval, ensuring compliance with the declaration of Helsinki, the participants were informed about the study procedures, and written informed consent and/or assent forms obtained.

The study followed a repeated measures design. Each participant completed 2 time trials of 100 m freestyle, in randomized order, separated by 48 h. All the experiments were conducted two months after the beginning of the season, at the same time of the day (8:00–13:00 AM) in a 50 m indoor swimming pool with water temperature at 27.58 ± 0.08ºC, air temperature of 27.92 ± 0.12ºC and 60.74 ± 0.21% of humidity. The swimmers were familiarized with warm-up procedures 48hr before the experiments and they were reminded to maintain the same training, recovery and diet routines, abstaining from consuming caffeine 48 h prior to testing.

After arriving at the pool, the swimmers remained seated for 5 min to assess baseline measurements of heart rate (Vantage NV; Polar, Lempele, Finland), tympanic temperature (Braun Thermoscan IRT 4520, Germany), Tcore (CorTemp, HQ Inc, Palmetto, FL) blood lactate concentrations ([La^-]; Accutrend Lactate® Roche, Germany) and VO_2 (K4b^2, Cosmed, Rome, Italy). After that, the swimmers performed a standard warm-up with a total volume of 1,200m (Table 1), designed based on research (McGowan *et al.,* 2015; Neiva *et al.*, 2014b; Zochowski *et al.,* 2007) with the help of an experienced national swimming coach.

The main set aimed to increase the oxygen uptake to optimize the subsequent time trial performance. Critical velocity was calculated from the slope of the regression line between distance and time performed, combining the 50 m and the 400 m best times at the moment of testing (Toubekis & Tokmakidis, 2013). Heart rate, VO_2 and ratings of perceived exertion (RPE; Borg, 1998) were monitored during warm-up to ensure the same intensity between the two trials. Once swimmers finished warming-up, they were asked to remain seated for 10 or 20 min before performing the 100m time trial.

Table 1 – Standard warm-up (WU) protocol.

WU	Task description
300 m	Normal - breathing in the 5th stroke - Normal
4 x 100 m @ 1:50	25m kick - 25m increased stroke length
8 x 50 m @ 1:00	98% - 102% of critical velocity
100 m	Easy swim

The swimmer was requested to step on the starting block and take off after official verbal commands and the starting signal. The trial times were clocked by a timing system (OMEGA S.A. Switzerland), using as backup a stopwatch by a swimming coach and a video camera (Casio Exilim Ex-F1, *f*=30 Hz) placed at 15 m, perpendicular to lane 7. That same procedures and devices were also used to assess the 15 m time. Stroke frequency (SF), stroke length (SL) and stroke index (SI) were determined according to the procedures reported earlier by Neiva *et al.* (2014b) The propelling efficiency (η_ρ) was also estimated (Zamparo, 2006):

$$\eta_\rho = [(0.9 \cdot v)/(2\pi \cdot SF \cdot l)] \cdot 2/\pi \qquad (1)$$

where v is the swimming velocity ($m \cdot s^{-1}$), SF is the stroke frequency (Hz) and l is the arm length (m). The l is computed trigonometrically by measuring the arm length and considering the average elbow angles during the insweep of the arm pull as reported by Zamparo *et al.* (2005).

Capillary blood samples for [La^-] assessment were collected from the fingertip after the warm-up protocol (1 min), immediately before the trial, after the trial (3 and 6 min to obtain the highest value) and 15 min after the trial. The heart rate was also assessed over the warm-up and recovery after the time trial. Additionally, the RPE was recorded during and after the warm-up, and after each trial.

Tympanic temperatures were measured before the warm-up, after the warm-up (1 min), immediately before and after the trial and 15 min post-trial. Tcore was assessed by a temperature sensor that was ingested in the night before, 10 h before the test (Byrne & Lim, 2006). This pill transmitted a radio signal to an external sensor (CorTemp Data Recorder, HQ Inc., Palmetto, FL), which subsequently converted the signal into digital format. The net values of Tcore ($Tcore_{net}$) were selected to compare data and reducing the error for the pill position.

VO_2 was measured with a backward extrapolation technique, immediately after trial (Costa *et al.*, 2013). The first 2s of measurement after detection were not considered due to the device adaptation to the sudden change of respiratory cycles and to oxygen uptake (Laffite *et al.*, 2004). The peak oxygen uptake (VO_{2peak}) was considered to be the mean value in the following 6s (Costa *et al.*, 2013; Laffite *et al.*, 2004). Additionally, VO_2 was continually monitored during the post warm-up time period and after the 100 m freestyle.

Statistical Analysis

Standard statistical procedures were selected for the calculation of means, standard deviations (SD) and confidence intervals. The normality of all distributions was verified by Shapiro-Wilks test, and parametric statistical analysis was adopted. To compare data obtained in the two trials, Student's paired t-tests were used followed by Cohen's d effect size for repeated measures ($p \leq 0.05$). An effect size 0.2 was deemed small, 0.5 medium, and 0.8 large. Smallest worthwhile effects were also calculated to determine the likelihood that the true effect was substantially beneficial, trivial, or harmful. The threshold value for smallest worthwhile change was set at 0.8%. If both benefit and harm were calculated to be 95%, the true effect was assessed as unclear. Where clear interpretation could be made, chances of benefit or harm were assessed as follows: <0.5%, most unlikely, almost certainly not; 0.5-5%, very unlikely; 5-25%, unlikely, probably not; 25-75%, possibly; 75-95%, likely, probably; 95-99.5%, very likely; >99.5%, most likely, almost certainly (Hopkins *et al.*, 2009).

Results

The swimmers were faster in 100 m freestyle under the 10 min recovery condition (Table 2). Further, qualitative analysis supported that a 10 min recovery period is "likely" beneficial and "unlikely" trivial (80/20/0%) to 100 m swim time compared to a 20 min recovery. The reduced time-lag of recovery "likely" had a positive effect on the first 50 m lap (95/5/0%) compared to the longer recovery. Although the second 50m lap was not different between the conditions, a "possibly" beneficial effect was shown (41/59/0%) by the qualitative analysis. The swimmers showed higher SF after 10 min recovery in the first 50 m lap, with no differences in the second 50 m (small effect size). Despite the moderate effect size ($d \geq 0.39$, except for the first 50 m SI), no differences were found between conditions in the SL, SI and η_p. Physiological and psychophysiological acute responses were also similar between conditions with trivial changes (Table 2).

Table 2. Mean ± SD values of the 100 and 50 m lap times, biomechanical and efficiency variables during trial and acute responses of oxygen uptake (VO_{2peak}), heart rate, blood lactate concentrations, core (Tcore;$Tcore_{net}$) and tympanic temperatures, and ratings of perceived exertion, N=11.

	10min	20min	10-min vs. 20-min		
			Mean % change ± 90% CI*	d	*p*
100 m time (s)	58.41 ± 1.99	59.06 ± 1.86	1.12 ± 0.63	0.99	<0.01
First 50 m (s)	27.72 ± 0.92	28.15 ± 0.73	1.56 ± 0.77	1.13	<0.01
Second 50 m (s)	30.69 ± 1.27	30.91 ± 1.30	0.73 ± 0.70	0.58	0.08
15 m (s)	7.13 ± 0.33	7.26 ± 0.19	1.76 ± 1.89	0.51	0.14
First 50 m stroke frequency (Hz)	0.87 ± 0.07	0.85 ± 0.06	-3.22 ± 2.65	0.66	0.05
Second 50 m stroke frequency (Hz)	0.73 ± 0.04	0.74 ± 0.04	0.59 ± 1.75	0.23	0.47
First 50 m stroke length (m)	2.03 ± 0.17	2.07 ± 0.17	1.90 ± 2.68	0.40	0.26
Second 50 m stroke length (m)	2.19 ± 0.14	2.16 ± 0.17	-1.30 ± 1.87	0.39	0.24
First 50 m stroke index ($m^2c^-1s^{-1}$)	3.60 ± 0.37	3.61 ± 0.35	0.33 ± 2.66	0.06	0.86
Second 50 m stroke index ($m^2c^-1s^{-1}$)	3.51 ± 0.32	3.44 ± 0.38	-2.00 ± 2.21	0.49	0.14
First 50 m propelling efficiency (%)	33.88 2.45	34.55 2.34	2.01 ± 2.67	0.41	0.20
Second 50 m propelling efficiency (%)	36.55 1.91	36.10 2.37	-1.30 ± 1.87	0.36	0.26
VO_{2peak} ($ml·kg^{-1}min^{-1}$)	55.23 ± 7.03	53.67 ± 9.46	-3.42 ± 5.86	0.35	0.39
Heart rate (bpm)	173 ± 6	165 ± 11	-4.71 ± 4.52	0.75	0.10
Blood lactate ($mmol·l^{-1}$)	11.91 ± 3.82	11.32 ± 3.71	-4.89 ± 12.21	0.29	0.36
Tcore (ºC)	37.62 ± 0.38	37.49 ± 0.36	-0.34 ± 0.88	0.29	0.49
$Tcore_{net}$ (ºC)	0.68 ± 0.79	0.28 ± 0.16	-66.19 ± 12.03	0.59	0.16
Tympanic temperature (ºC)	34.79 ± 0.71	34.32 ± 0.87	-1.37 ± 1.52	0.49	0.14
Ratings of perceived exertion	18.64 ± 1.12	18.82 ± 0.98	1.02 ± 2.92	0.18	0.55

* where a positive % change equates to an increase in 20min condition

Figure 1 depicts the physiological responses to the different conditions. Baseline measures of Tcore (1A) were similar between conditions (10 min: 36.94 ± 0.86ºC vs. 20 min: 37.22 ± 0.38ºC; p = 0.27, d = 0.46; mean change ± 90%CI 0.77 ± 1.22%). Tcore highest values were recorded after warm-up (10 min: 37.67 ± 0.48ºC; 20 min: 37.76 ± 0.57ºC). These values declined during recovery and the pre-trial net values (1B) were not different between conditions (10 min: 0.73 ± 0.69ºC vs. 20 min: 0.54 ± 0.33ºC, p = 0.31, d = 0.32). Nevertheless, the 20 min condition had a "very likely" negative effect on $Tcore_{net}$ (mean change ± 90%CI: -55.29 ± 19.05%) compared with the 10 min (1/0/99%). After 15 min of recovery, the Tcore did not return to baseline values (10 min: 37.46 ± 0.33ºC; 20 min: 37.36 ± 0.39ºC). The tympanic temperature (1C) recorded no differences between conditions ($p = 0.06$, $d < 0.66$).

Baseline measures of [La^-] (1D) were similar between conditions (10min: 2.00 ± 0.81 $mmol \cdot l^{-1}$ vs. 20min: 2.14 ± 0.72 $mmol \cdot l^{-1;}$ $p = 0.15$, $d = 0.47$; mean change ± 90%CI: 8.74 ± 10.37%). [La^-] responded in the same way to warm-up (10min: 3.09 ± 2.89 $mmol \cdot l^{-1}$ vs. 20min: 3.22 ± 2.83 $mmol \cdot l^{-1}$; $p = 0.20$, $d = 0.44$; mean change ± 90%CI: 5.49 ± 8.85%) and no different values were found pre-trial (10min: 2.25 ± 1.28 $mmol \cdot l^{-1}$ vs. 20min: 2.46 ± 1.36 $mmol \cdot l^{-1}$; $p = 0.45$, $d = 0.23$; mean change ± 90%CI: 11.08 ± 29.66%) and after recovery (10min: 9.28 ± 3.63 $mmol \cdot l^{-1}$ vs. 20min: 8.28 ± 3.39$mmol \cdot l^{-1}$; $p = 0.18$, $d = 0.43$; mean change ± 90%CI: -10.89 ± 13.63%).

There were no differences in the heart rates baseline between conditions (10 min: 66 ± 7 bpm vs. 20 min: 64 ± 8 bpm; $p = 0.13$, $d = 0.49$; mean change ± 90%CI: -3.31 ± 3.64%) and the adaptations to the warm-up procedures were similar (10 min: 102 ± 14 bpm vs. 20 min: 101 ± 14 bpm; $p = 0.73$, $d = 0.40$; mean change ± 90%CI: -0.76 ± 3.64%). However, pre-trial values showed increased heart rates in the 10 min (89 ± 12 bpm) compared with the 20 min (82 ± 13 bpm; $p < 0.01$, $d = 1.07$; mean change ± 90%CI: -7.77 ± 4.03%). This could somehow reflect the almost statistically difference between VO_2 values pre-trial but with a high effect size though (10 min: 8.58 ± 1.67 $ml \cdot kg^{-1}min^{-1}$ vs. 20 min: 7.54 ± 2.45 $ml \cdot kg^{-1}min^{-1}$; $p = 0.07$, $d = 0.81$; mean change ± 90%CI: -14.08 ± 10.52%) and a "likely" negative effect of 20 min recovery on this variable (1/0/99%).

Post warm-up VO_2 was not different between conditions (10 min: 23.48 ± 6.40 $ml \cdot kg^{-1}min^{-1}$ vs. 20 min: 24.04 ± 5.24 $ml \cdot kg^{-1}min^{-1}$; $p = 0.82$, $d = 0.09$; mean change ± 90%CI: 4.03 ± 21.71%) as well as the perceived effort (10 min: 10.00 ± 1.48 vs. 20 min: 9.55 ± 1.63; $p= 0.45$; $d = 0.25$; mean change ± 90%CI: 6.73 ± 14.80%). Hence, this data ensures the similarity between the warm-up intensities and procedures.

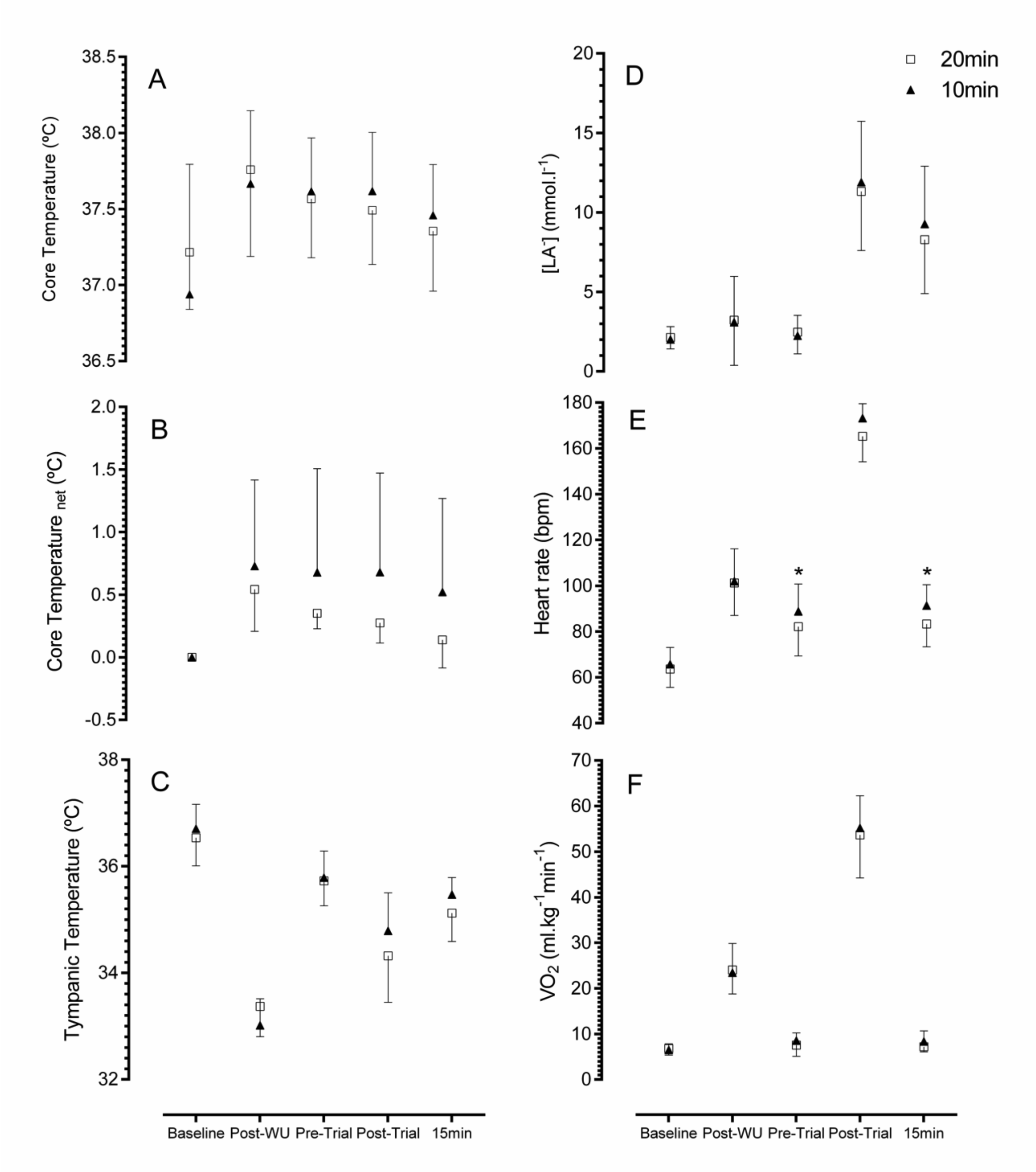

Figure 1. Physiological variables responses throughout the procedures: core temperature (A), net values of core temperature (B), tympanic temperature (C), blood lactate concentrations ([La^-]; D), heart rate (E), Oxygen uptake (VO_2; F). * Indicates difference between the two conditions assessed ($p < 0.01$). Data presented as mean ± SD (N = 11).

Discussion

The purpose of this study was to compare the 100 m freestyle performance of high-level swimmers after 10 or 20 min of post warm-up recovery. The main finding was a “likely” positive effect on swimming performance when the shorter recovery period is chosen. The swimmers were 1.12% faster after resting for 10 min instead of 20 min. This supported the hypothesis that a shorter time-lag between the warm-up and the race benefits the time trial performance. The physiological response may partially explain this finding. Although the acute adaptations in body temperature did not seem enough to justify the differences in performance, the combined effects of the shorter post warm-up interval on Tcore, heart rate, and VO_2 appeared to be associated with the faster performance observed and this is a novel finding that should be further explored.

The active warm-up in swimming seems to improve the performance after periods of recovery of 10 min (Zochowski *et al.*, 2007) and 20min (West *et al.*, 2013). However it remains to be known, which duration is the most effective to performance optimization. It is suggested that the rise in muscle and core temperature caused by priming exercises is the major contributing factor that influences performance (Bishop, 2003). At least for land-based performances, the increase in athletes' temperatures results in decreased time to achieve peak tension and relaxation (Segal *et al.*, 1985), reduced viscous resistance of the muscles and joints (Wright, 1973), increased muscle blood flow (Pearson *et al.*, 2011), improved efficiency of muscle glycolysis and high-energy phosphate degradation (Febbraio *et al.*, 1996), and increased nerve conduction rate (Rutkove & Seward, 2001).

As expected, the Tcore increased over the warm-up reaching eventually its maximal value and then started to drop until the beginning of the time trial. Before the race, the 20 min interval had a very "likely" negative effect on its net values. Therefore, the lower $Tcore_{net}$ in the 20 min condition could have influenced the swimmers performance, as a decrease in performance could be related to muscle and core temperature decline after exercitation (Mohr *et al.,* 2004). Despite not significant, tympanic temperature recorded a trend towards the highest values in the 10 min condition, supporting the $Tcore_{net}$ data. West *et al.* (2013) pinpointed that 45 min was an excessive recovery for the Tcore, explaining the negative effect on the 200 m freestyle performance. In this study, the abovementioned effects on Tcore could not alone explain the 1.12% increased performance. The heart rate and VO_2 pre-trial data could complement it, as the 10 min of extra recovery in the 20 min condition lowered these variables ~8% and ~14%, respectively. Thus, the strong effect verified in these two variables could influence the race, notably during the first few meters.

After verifying a higher heart rate before the 200 m trial in the 10 min rest compared with 45 min rest, Zochowski *et al.* (2007) hypothesized that the swimmers started the trial at a high baseline VO_2. The authors did not measure the VO_2, but our data confirmed their speculation for both heart rate and VO_2. Before their study, the warm-up was already believed to increase VO_2 and oxygen kinetics (Burnley *et al.,* 2011). However, our study was the first to provide such evidence. Higher baseline VO_2 could influence the energy provision from anaerobic sources in the first part of the race, preserving high-energy subtracts for later on the task (Burnley &

Jones, 2007), which might explain the ~0.7% faster times in the second lap in the 10 min condition compared to the 20 min.

Some of these metabolic changes could influence the biomechanical strategies of the swimmers. The better performances delivered after 10 min post warm-up period in the first 50 m lap could be the result of the higher SF. The swimmers were able to reach higher SF maybe because of an effect on motor neuron excitability that remained after the shorter post warm-up recovery (Saez Saez de Villarreal *et al.*, 2007). Also, it could be pointed out a post-activation potentiation effect that should happen by the 8th min of recovery (Kilduff *et al.*, 2011), enabling an optimized SF. This increased SF for the same efficiency (monitored by the SI and η_p) resulted in the faster 50 m lap.

The different post warm-up periods were not enough to cause differences in the [La$^-$] after the trial. Some authors may suggest that a shorter recovery induce an increase in lactate production due to a glycolytic stimulation over the trial. However, the increased VO_2 at the beginning of the trial could have stimulated the aerobic component, which has been shown to reach approximately 50% of the energy expenditure in a 100 m maximal bout (Ribeiro *et al.*, 2015). Moreover, this could hinder the glycolytic pathway. Even though we failed to observe differences in [La$^-$], VO_{2peak} and RPE, the increased heart rate after trial might suggest a higher spike of such variables at the beginning of the trial. An increased primary response would increase the oxidative metabolic contribution early in the exercise and an increase in anaerobic metabolism in the final meters (Burnley & Jones, 2007). This could be speculated to increase the heart rate response so that the swimmers could recovery easily their homeostasis. However to have a deeper insight the assessment of the VO_2 kinetics would be needed.

Although the muscle temperature could be an important variable to better understand and to complement our findings, we should not disregard the Tcore as having a great influence in performance (Bishop, 2003). Recent findings about passive heating strategies post warm-up showed that some exercitation was also needed for better performances (McGowan *et al.*, 2015; West *et al.*, 2015). Accordingly, our results suggested that temperature alone could not be responsible for the performance optimization. Therefore, researchers should consider to analyse the in-water swimming sets so that the previously mentioned effects could be extended. The lower values of VO_2 before the race in both trials lead us to speculate the existence of some physiological adaptation that may change the motor unit recruitment patterns, optimizing VO_2 immediate response during trial.

Conclusions

As a conclusion, a 10 min post warm-up recovery period will help the swimmers to enhance the 100 m freestyle performances. Swimmers should consider keeping elevated high Tcore before the race. Also, oxygen uptake seems to be positively influenced by the shorter rest, influencing notably the first meters of the race.

Practical Applications

- The beneficial effects of in-pool warm-up decrease over time and influences subsequent swimming race. It is suggested to prescribe the warm-up close to the race to benefit from all its positive effects.

- The time-lag between warm-up and race should be long enough to allow some post potentiation effect, but not so long that oxygen uptake, heart rate and core temperature effects would disappear.

- Coaches should develop methods to maintain the swimmers' warm-up temperature (e.g. passive warm-up) and perhaps some light activities could be recommended to maintain also heart rate and VO_2 above resting values before swimming race.

Chapter 4. General Discussion

The purpose of this investigation was to analyze the effect of warm-up on 100 m freestyle swimming performance in high-level swimmers. In addition, it was intended to verify the impact of different volumes, intensities and post warm-up recoveries, evaluating performance, biomechanical, physiological and psychophysiological variables. The lack of research on warm-up and its structure for competitive swimming was the starting point of our experimental research. Our findings found a beneficial effect of warm-up on 100 m freestyle performance in high-level swimmers, with increased efficiency in the first meters. With regard to warm-up design, a volume higher than 1200 m appears to impair swimming performance, but an aerobic stimulation during warm-up seemed to be a reliable alternative to usual race-pace set. Moreover, the warm-up should be performed close to the 100 m race to benefit from all the positive effects of warm-up. Our data also showed that the swimmers adapted their biomechanical stroke patterns according to each warm-up volume and intensity.

The initial work of this thesis was to conduct a review that comprised the published studies about warm-up and swimming (study 1). In the last few years the research on warm-up has been applied to several sports and physical activities. However, we observed that the knowledge about warm-up applied to swimming was limited. Active warm-up is the preferred and most applied method in swimming competition, and also, it is the most commonly investigated (~89% of the studies about warm-up in swimming). From these, less than a half of the studies that tested swimming distances up to 50 m showed better performances after warm-up (Neiva *et al.,* 2011; Thompson, 1958) and only two studies mentioned better performances in distances until 100 m (De Vries, 1959; Romney & Nethery, 1993). Our first study on the effect of warm-up on 100 m freestyle was developed after this qualitative review. However, the revision process of the review was extended implicating that our first experimental study was published (ahead of print) slightly before the conclusion of this process. Thus, this paper was included in the final version of the review, as suggested. With regard to longer distances, only submaximal evaluations were performed, but the physiological and biomechanical variables indicated beneficial effects of warm-up (Houmard *et al.,* 1991; Robergs *et al.,* 1990). Besides the limited studies, the positive effects of warm-up seemed more consistent for distances above 200 m. Moreover, even when the studies found increased performance in shorter races those effects were lower than 1%.

The effectiveness of priming exercises on subsequent performances was influenced by warm-up intensity, duration and the recovery time between the warm-up and the race. Also, not much is known about the structure of warm-up, even though it was still possible to advance with some general recommendations for coaches and swimmers. Given the abovementioned main observations, it seemed relevant to examine the effect of active warm-up on short races, with the most holistic assessment possible (study 2). The 100 m freestyle was chosen because of the lack of investigation on this race, considered one of the most attractive swimming events of the Olympic schedule (Ribeiro *et al.*, 2015). Complementarily, this race comprises important aerobic and anaerobic metabolic contribution that could allow us to better understand the effects of warm-up on this two pathways (Ribeiro *et al.*, 2015). In addition, being aware of the shortcoming on the warm-up design, different volumes and intensities of warm-up procedures and different time recoveries after warm-up were assessed to improve our knowledge about the ideal structure of warm-up.

The first experimental study developed demonstrated that swimmers were 1.5% faster on the 100 m freestyle, confirming the data of our preliminary study about propelling force (Appendix I) and the results of De Vries (1959). The swimmers were faster in the first part of the race and in the 100 m overall performance, with improvements in the stroke mechanics efficiency (evidenced by stroke index). It seemed that when there was no warm-up, the swimmers were unable to be effective in arm pull and swimming technique was comprised (Toussaint & Beek, 1992). Also, it is known that the swimmers can manipulate their SF and SL according to their energetic needs (Barbosa *et al.*, 2008), which could be different according to the conditions tested. No differences were found in $[La^-]_{peak}$ and this result led us to hypothesize that warm-up enhanced the trial performance by optimizing the swimmers' aerobic system. All these findings highlight the importance of warm-up for 100 m freestyle, denoting the importance of performing swimming drills for higher stroke length before this race. Despite the unknown value of the variation in performance day-to-day or test-to-test, the results were clear in demonstrating a positive effect of warm-up in swimming performance. Interestingly, there was an individual response to each condition tested, revealing to the coaches the importance of an individualized approach to warm-up.

Although warming up has the potential to optimize the swimming performance, the research has been only recently addressing on the warm-up structure (Balilionis *et al.*, 2012; West *et al.*, 2013). When comparing the effect of different volumes, a standard (1200 m), a shorter (600 m) and a longer one (1800 m), the standard protocol led to better performances and the longer one resulted in lower 100 m performances (study 3). Additionally, the shorter warm-up led to better 100 m times than the longer one, demonstrating the potential of this warm-up. The excess of volume during warm-up may impair the performance, in line with what had been published in cycling (Tomaras & MaCintosh, 2011). The three warm-ups caused different physiological adaptations, with higher values of $[La^-]$ after the standard warm-up or the short warm-up and higher testosterone/cortisol ratio after the standard warm-up. These increased variables in pre-trial momentum could influence performance and perhaps the biomechanical stroke pattern of the swimmers during the race. Research documented that an increase in $[La^-]$ caused a greater release of oxygen from hemoglobin for working muscles, enhancement of blood flow, and alter the neurological feedback for energy production (Darques *et al.*, 1998;

Street *et al.*, 2001). Moreover, and considering the higher [La^-] values after the race, it could be said that a 1200 m warm-up could increase both anaerobic and aerobic capacity of the swimmer during 100 m, being the most appropriated warm-up volume to apply in high-level swimmers. Also, the higher pre-trial testosterone/cortisol ratio could influence force production (Nagaya & Herrera, 1995) and fatigue delay (Paton *et al.*, 2010), perhaps contributing for the higher SF in the beginning of the race and increased efficiency in the second 50 m lap after standard warm-up. In addition, the higher heart rate and testosterone/cortisol ratio levels after trial seemed to allow a faster initial recovery in standard conditions.

The potential of the short volume warm-up abovementioned led us to consider alternatives for the optimization of the warm-up. Thus, one of the most recent attracting procedures that could be incorporated into warm-up is the post-activation potentiation. Performance improvements have been shown in explosive efforts (Gago *et al.*, 2014; Kilduff *et al.*, 2011) but there is paucity of published research on the effects of post-activation potentiation in competitive swimmers. Interesting results were published showing improvements in the start distance and in swimming velocity (Kilduff *et al.*, 2011), though no benefit from post-activation potentiation was found on 50 m compared to traditional swimming warm-up. It seems necessary to identify properly the conditioning activities and following rest intervals that prompt the potentiation in the swimmers. This is a method that could be useful for swimmers before an event and should be further investigated.

Based on the previous results, two warm-ups were designed (1200 m of total volume) with different intensities (study 4). Our main aim was to compare a race-pace set (control warm-up), a common practice before a 100 m swimming race, with a submaximal set that stimulates an increased VO_2 (experimental warm-up). Knowing that the aerobic metabolism is relevant for the 100 m freestyle (Ribeiro *et al.*, 2015), it should be interesting to find if a pre-trial increased VO_2 elicit some performance changes. No differences were found in the 100 m freestyle, which consolidate the conclusions of the studies that compared tasks of different intensities (Houmard *et al.*, 1991; Mitchell & Huston, 1993). The increased VO_2 and heart rate after the experimental warm-up disappeared during the time lag between warm-up and the race, causing no difference in performance. This data reveals that intensity could not be as influencing as expected for overall 100 m freestyle performances. However, the physiological and biomechanical responses during trials were different, which means that experimental warm-up could cause an internal adaptation time and this could be used to optimize the race strategies according to each athletes' needs. Experimental or control warm-up sets should be applied depending on the race strategy that better fits with each particular situation. Perhaps, the "VO_2 set" should be implemented when a longer waiting period would occur, taking advantage of the higher Tcore observed. If the race depends more on the higher SF in the first meters, then a race-pace set should be applied. It was also interesting to find an acute learning process to each specific set that could justify some different biomechanical patterns during trials, and this expands the possibilities for different research on warm-up.

The recovery phase after the warm-up is another main component and that was also investigated (study 5). Our results showed that a 10 min post warm-up recovery period, instead of 20 min, would help the swimmers to enhance the 100 m performances. Previous studies demonstrated that the 200 m freestyle appears to be harmed by use of recovery intervals higher than 10 min (Zochowski *et al.*, 2007) and 20 min (West *et al.*, 2013). However, of what is known, this was the first study either to compare 10 and 20 min of interval, or to study their effects on 100 m freestyle performance. The body temperature is thought to be an essential effect of warm-up and the main responsible factor for the differences in performance (West *et al.*, 2013). Nevertheless, our data suggested that temperature alone could not be responsible for the optimization of performance. The swimmers were 1.12% faster after the 10 min post warm-up, which could be explained by the combined effects of Tcore, heart rate and VO_2 before the race. Knowing that the specific in-water warm-up is performed with some time gap before the competition, it becomes critical to understand and investigate these adaptations. It seems necessary to extend the effect of warm-up, finding specific tasks to potentiate the warm-up routines, and also by optimizing the waiting time before the swimming race. Passive warm-up activities are being recently studied as a way for maintaining a warmed condition to help the swimmers to improve performance (McGowan *et al.,* 2015). These practices are suggested as a possible complement to specific in-water warm-up, but some active routines are also needed as confirmed by our results.

Finally, we should not disregard the individual responses for each warm-up, transversal to all experimental procedures. This individuality highlights the importance of a proper warm-up structure for optimized performances. If individual warm-up is not feasible, a reality that occurs in most swimming clubs, high level practitioners should consider to warm-up for a moderate or short distance (≤ 1200 m), choosing race-pace or aerobic stimulation according to race strategy and/or time-gap between warm-up and the 100 m event, trying to complete it as close as possible to the race (10 min). These warm-up components are far from being well known, but the first step has been taken and should be continued. There are several more warm-up procedures that must be accomplished to deeply understand its effects on swimming performance. Warm-up could determine the success or failure and to understand all its effects should be deepened.

Some main limitations of this thesis should be addressed:

- We should acknowledge possible unknown variation in day-to-day performance due to outside pool daily events, despite the counterbalanced distribution of the swimmers;

- These studies were performed in a specific race event and different events would elicit different adaptations;
- Muscle temperature was not measured but we should not disregard the effect of core temperature in performance;
- VO_2 kinetics during the race was not measured, as well as possible internal physiological adaptations.
- Larger samples could allow more consistent results; however, it is difficult to evaluate good level swimmers during their sport season.

Chapter 5. Overall Conclusions

The main findings of this work emphasize the importance of the warm-up and its design for the 100 m freestyle performance. Data also showed the relevance of the individualization of warm-up for optimized performances, determining some important conclusions that should guide the warm-up structure. The conclusions of the present thesis were:

i. There is a lack of research on warm-up for competitive swimming, specifically as referred to warm-up design, in the different Olympic swimming races;
ii. Warm-up is beneficial to 100 m freestyle swimming, with a faster first 50 m lap performed with greater swimming efficiency;
iii. High-level swimmers should benefit from a warm-up up to 1200 m. In addition, a 1200 m warm-up elicits higher efficiency during the race and optimizes recovery, instead of a lower volume of warm-up;
iv. Excessive warm-up volumes could impair 100 m freestyle performance;
v. Different intensities of warm-up could cause some physiological and biomechanical changes during the race although the same performance results are obtained;
vi. The use of an aerobic stimulation set is a viable alternative to the traditional race-pace set before the 100 m freestyle;
vii. The aerobic set stimulates the core temperature and should be used when there is a long time-gap between the warm-up and the race;
viii. The race-pace set stimulates the use of higher stroke frequency in the beginning of the race;
ix. The beneficial effects of in-pool warm-up decreases over time and warm-up should be performed close to the race (10 min instead of longer intervals);
x. Heart rate, VO_2 and core temperature should be the main reasons for the better results with the shortest rest able between the warm-up and the race, and these effects should be maintained as long as possible;
xi. Warm-up could have an important role in sensorimotor adaptation to the movement, with the motor skills patterns being reproduced in a similar way in the race.

Chapter 6. Suggestions for future investigations

There is a lot to know about warm-up in swimming and a few indications for possible future investigations are listed below:

- To replicate these studies but with different swimming events, to understand the warm-up effects on different distances and swimming techniques;
- To develop different in-water tasks and extend the benefits of warm-up (increased VO_2, heart rate, temperature);
- Methods as passive warm-up and dry-land exercises in swimming should be deepened as alternative and/or complementary practice for an active warm-up;
- Further investigations should be developed to understand the best condition for each swimmer and attempt to design a warm-up set accordingly;
- Some physiological variables should be investigated during the race (for example, the VO_2 kinetics; muscle temperature) or even a cellular adaptation to warm-up should be deepened (mitochondrial);
- The sensorimotor adaptation to the warm-up swimming sets needs to be further developed.

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Appendix I

The effect of warm-up on tethered front crawl swimming forces

Abstract

Purpose: This study was conducted to determine the effect of warm-up on high-intensity front crawl tethered swimming and thus to better understand possible variations in the force exerted by the swimmers. Methods: Ten male national level swimmers (mean ± SD; age 15.3 ± 0.95 years old, height: 1.73 ± 5.2 m, body mass: 64.3 ± 7.8 kg, Fat mass 8.31 ± 3.1 kg) participated in this study. After a typical competition warm-up, the subjects performed a 30 s tethered swimming all-out effort in front crawl swimming technique. The same test was repeated in the day after but performed without warming up. Capillary blood lactate concentration was assessed before and after the swimming test and the Borg ratings of perceived exertion scale was used. Results: Without a previous warm-up, the mean ± SD values of maximum and mean forces were 299.62 ± 77.56 N and 91.65 ± 14.70 N, respectively. These values were different ($p<0.05$) from the values obtained with warm-up (351.33 ± 81.85 N and 103.97 ± 19.11 N). Differences were also observed when regarding to the forces relative to body mass. However, the values of lactate net concentrations after the test performed with and without warm-up were not different (6.27 ± 2.36 $mmol \cdot l^{-1}$ and 6.18 ± 2.353 $mmol \cdot l^{-1}$) and the same occurs with the values of ratings of perceived exertion (15.90 ± 2.42 and 15.60 ± 2.27). Conclusions: These results suggest an improvement of the maximum and mean force of the swimmer on the tethered swimming due to previous warm-up.

Key words: Evaluation, strength, performance, lactate, perceived exertion.

Introduction

Warm-up procedures before competition or training are intended to assure benefits to athlete's performance (Atkinson *et al.*, 2005; Burnley *et al.*, 2002) Although there are few data available on physiological responses to the warm-up, these routines are well accepted and commonly used by athletes and their coaches (Bishop, 2003). For example, the mechanisms related to the raise of core and muscle temperature seem to be of great importance for the proposed effects of warming-up before physical activity (Asmussen & Boje, 1945). Temperature might improve performance by decreasing the viscous resistance of muscles and joints (Wright & Johns, 1961; Cavagna, 1993), increasing of nerve conduction rate and speeding of metabolic reactions, such as the muscle glycogenolysis, glycolysis and high energy phosphate degradation (Febbraio *et al.*, 1996). This temperature rise, due to the warming-up routines performed, might also contribute to increase the oxygen delivery to the muscles, via a rightward shift in the oxyhaemoglobin dissociation curve and vasodilatation of muscle blood vessels (McCutheon *et al.*, 1999). Beyond this temperature-related mechanism, warm-up seems to allow the athletes to begin subsequent tasks with an elevated baseline of VO_2, leaving more anaerobic capacity for later in the task (Febraio et al., 1996). Post activation potentiation (Sale, 2002) is also presented to be responsible for a better performance after warming-up procedures.

Despite there were several studies demonstrating improvements in performance after warming-up (Andzel, 1982; Asmussen & Boje, 1945; Atkinson *et al.*, 2005; Burnley *et al.*, 2002), there were others reporting no changes or even detrimental changes in performance (Andzel, 1982; Bruyn-Prevost & Lefebvre, 1980; Bishop *et al.*, 2001; Mitchell & Huston, 1993). Thus, there is still some inconsistency in this matter, and more studies are needed to further determine the importance of warm-up procedures, their effect in performance or even their optimal structure, especially in each sport specificity (Fradkin *et al.*, 2010). Possibly, because of the particular environment, swimming warm-up related studies are very scarce.

The main aim of the swimmers is to perform a prescribed distance in the shortest time possible, according to the rules established. In this way, the force produced by the swimmer, needed to overcome drag and to increase the swimming velocity, seems to be extremely relevant (Marinho *et al.*, 2010; Smith *et al.*, 2002). This force can be evaluated by dry-land strength and power tests (Garrido *et al.*, 2010). However, the tethered swimming is proposed to specifically assess its interaction with swimming technique (Keskinen, 1994). Full or partial tethered swimming has been recognized as a useful tool to measure the force exerted by a swimmer (Costill *et al.*, 1986; Filho & Denadai, 2008; Magel, 1970; Yeater *et al.*, 1981). This method was firstly introduced by Magel (1970), who evaluated the four swimming techniques and suggested breaststroke to have the highest values of force production. Used as an adaptation of the Wingate test (Stager & Coyle, 2005), the tethered swimming can be performed in water as a more specific ergometer. The swimmer is connected to the wall by an elastically (partial tethered) or non-elastic cable (full tethered) and produces a maximal effort, using an apparatus that measures the force produced as a biokinetic bench (Costill *et al.*, 1983) or a strain gauges system (Morouço *et al.*, 2011). This is a specific test for swimmer´s anaerobic evaluation and has been pointed as a measurement of maximum propulsive force that corresponds to the resultant force needed to overcome the resistance at maximum swimming velocity (Clarys, 1979; Keskinen, 1994).

Therefore, the aim of the current study was to compare the force exerted by the swimmer during tethered swimming with and without warming-up and to understand the effects of warm-up in the propulsive force produced by the swimmer.

Methods

Subjects

Ten male swimmers (mean ± SD; age 15.3 ± 0.95 years-old, height: 1.73 ± 5.2 m, body mass: 64.3 ± 7.8 kg, fat mass 8.31 ± 3.1 kg) participated in this study. Body mass and fat mass were assessed through a bioelectric impedance analysis method (Tanita BC 420S MA, Japan). Their training experience was of 7.2 ± 1.1 years, training from 6 to 9 times a week and all of them are national level swimmers, participating in National Championships. The participants' parents and coaches provided written informed consent to participate in this research, and the procedures were approved by the institutional review board.

Procedures

The experiments were performed in a 50 m indoor swimming pool at a water temperature of 27.5ºC. The data collection was implemented one week after the main competition (National Championships) of the season second macrocycle. Swimmers were involved in two similar protocols of tethered front crawl swimming, one executed with a previous warm-up, and another without warm-up procedures. The warm-up procedures (dry and in-water) consisted of their typical warm-up frequently performed before a competitive swimming event (total volume: 1000 m). After 10 min rest, the tethered swimming protocol was implemented. One day after, the same protocol was repeated, but without warming up.

The swimmers were wearing a belt attached to a steel cable (negligible elasticity). As the force vector in the tethered system presented a small angle to the horizontal, computing the horizontal component of force, data was corrected. A load-cell system connected to the cable was used as a measuring device, recording at 100 Hz with a measure capacity of 5000 N. The data obtained was transferred by a Globus Ergometer data acquisition system (Globus, Italy) that exported the data in ASCII format to a computer. The test started after an acoustic signal, with the swimmers in a horizontal position, with the cable fully extended. The data collection started after the first stroke cycle to avoid the inertial effect of the cable extension after the first propulsion. The swimmers swam as natural as possible during 30 s, at maximum intensity.

Additionally, capillary blood samples were collected from the fingertip before and after each tethered swimming (at the First and 3rd min of recovery) to access the higher values of blood lactate concentration ([La-]) (Accutrend Lactate®Roche, Germany). The Borg (1998) ratings of perceived exertion (RPE) scale was used to quantify exercise level of exertion after each test.

Statistics Analysis

Individual force to time F (t) curves were assessed and registered to obtain maximum force (Fmax, the highest value of force produced in first 10 s) absolute and relative values and; mean force (Fmean – average force values during the 30s test) absolute and relative values. The values of [La-]net were determined by the difference between [La-] after the test and the resting values. Standard statistical methods were used for calculation of means and standard deviations. Normality was determined by Shapiro-Wilk test. Since, the very low value of the *N* (i.e., $N < 30$) and the rejection of the null hypothesis (H_0) in the normality assessment, non-parametric procedures were adopted. In order to compare the data obtained with and without warm-up, non-parametric Wilcoxon signed rank test was used. Differences were considered significant for $p \leq 0.05$.

Results

Table 1 presents the mean ± SD values for the tethered absolute variables, namely the maximum force and mean force. Significant differences were evident for the data obtained on tethered front crawl swimming test after warm-up and without warm-up. The warm-up condition presented higher values.

Table 1. Mean ± SD values of maximum (Fmax) and mean forces (Fmean) exerted during the tethered swimming test. P-values are presented.

	No warm-up	Warm-up	*p* values
Fmax (N)	299.62 ± 77.56	351.33 ± 81.85	$p = 0.009$
Fmean (N)	91.65 ± 14.70	103.97 ± 19.11	$p = 0.005$

Fig. 1 presents relative values of the maximum and mean forces in both conditions. The body mass of the swimmers were used to determinate these relative forces, and the graphic demonstrates the differences between the values obtained (4.61 ± 0.63 $N \cdot kg^{-1}$ and 5.44 ± 0.77 $N \cdot kg^{-1}$, for Fmax without and with warm-up; 1.42 ± 0.12 $N \cdot kg^{-1}$ and 1.61± 0.13 $N \cdot kg^{-1}$ for Fmean without and with warm-up, respectively).

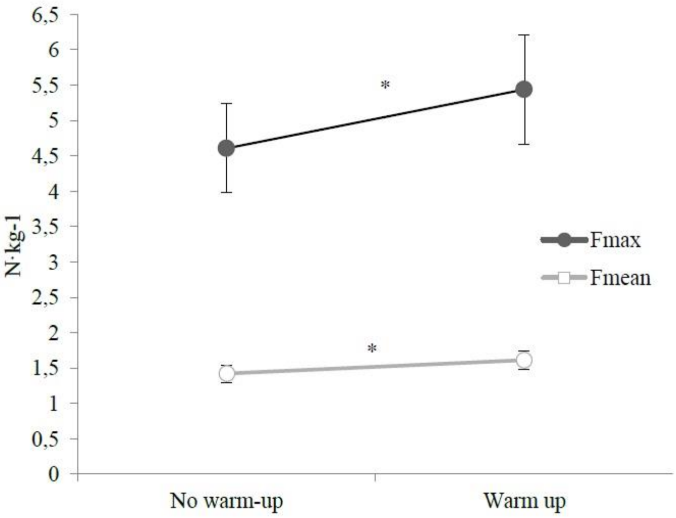

Fig. 1. Mean ± SD values of maximum (Fmax) and mean forces (Fmean) relative to the weight of the swimmers, exerted during tethered swimming test. * Represents significant differences ($p \leq 0.01$) between tests performed without warm-up and with warm-up.

Additionally, table 2 presents the mean ± SD values of the ratings of perceived exertion scale and the values of blood lactate concentration attained after the swimming test in both conditions.

Table 2. Ratings of perceived exertion scale (RPE) (mean ± SD) and difference between pre and post blood lactate concentration values ([La-]net) (mean ±SD). P-values are also presented.

	No warm-up	Warm-up	*p values*
RPE	15.90 ± 2.42	15.60 ± 2.27	*p = 0.496*
[La-]net ($mmol \cdot l^{-1}$)	6.27 ± 2.36	6.18 ± 2.35	*p = 0.767*

Discussion

The aim of this research was to investigate the effect of the warm-up in the force exerted on the tethered front crawl swimming in high-level swimmers. Main results suggest an improvement of the maximum and mean force of the swimmer on the tethered swimming due to previous warm-up.

In a broad sense, warm-up is used to increase muscle and tendon mobility, to stimulate blood flow, to increase muscle temperature and to improve coordination (Smith, 2004). Although the great importance placed in warm-up procedures by coaches and their athletes, it is a fact that their effects or even their ideal structure or type, are not well-known. Specifically in swimming, the literature is very scarce on this matter and uses different methodologies, which makes difficult the comparison between results and emphasizes the need for more researching (Fradkin *et al.,* 2010).

The tethered swimming is a methodology that allows obtaining data information related with propulsive force that swimmers can exert in their specific environment. The procedures used provide a continued measurement and recording of propelling force exerted during swimming (Mouroço *et al.,* 2011). The Fmax absolute values obtained for front crawl were higher than those presented by the specialized literature. These differences could be due to different methodology used (Keskinen, 1997) or even because our sample contained subjects from only one gender (Morouço *et al*., 2011). Higher values of Fmax relative, Fmean absolute and relative were also observed when comparing to the results obtained by Morouço *et al*. (2011). Considering the data presented by the previous authors, Fmean absolute value without warm-up was the only value of force of the current study that is similar to the literature (92.8 ± 33.7 N). Moreover, it is important to notice that the values of force obtained (absolute and relative) were higher when the swimmers performed a previous warm-up as they usually do before swimming events. When warming-up before the tethered front crawl swimming, swimmers exerted 14.72 ± 0.13% additional maximum force and 11.52 ± 0.05% additional mean force than with no warming-up (Fig. 1). These results reveal the positive effect of warm-up procedures on the propulsive forces (maximum and mean values) produced by the swimmers, suggesting the high importance of these warm-up routines.

Regarding to the ratings of perceived exertion scale, there were no differences between the two conditions of the test in the present research. This indicator is an important complement to physiological measurements, presenting strong relationships with some of these parameters. It is a measure used to quantify, monitor and assess an individual's exercise level of exertion (Borg, 1998). Despite there were no significant differences between the effort made with and without a previous warm-up, the average value of RPE obtained without warm-up appeared to be slightly higher. This suggests a tendency of a superior perceived effort by the swimmers when performing the tethered test in this condition. However, more research is needed to clarify this parameter.

The warm-up is proposed to maintain the acid-base balance at an appropriate level by stimulating the buffering capacity (Beedle *et al.,* 2007; Mandegue *et al.*, 2005). Poprzecki *et al.* (2007) presented differences in [La^-] values between the Wingate test performed with and without previous warm-up. Despite this result, in the present study the values of [La-]net obtained after the tethered swimming revealed no differences between the two conditions (no warm-up vs. warm-up). [La^-] values had been commonly used to estimate the anaerobic capacity of the athlete and the contribution of the glycolytic metabolism to exercise (di Prampero *et al.*, 1999). Considering that the values of resting [La^-] were removed to the data presented, [La^-]net values obtained confirmed the high anaerobic contribution to perform this 30 s tethered front crawl swimming test.

To the best of our knowledge, this study was the first to compare the forces exerted by the swimmers in their specific environment with and without a previous warm-up. The measurements of force production exerted in the water are a reliable method to evaluate the capacity of the swimmer to use muscular strength in effectively propulsive force (Costill *et al.*, 1986). Moreover, although tethered swimming is different from free swimming, it seems to be a better methodology to estimate propelling forces than dry-land testing protocols, based on the significant correlation between average maximum force and swimming velocity (Keskinen, 1997).

Conclusions

In conclusion, the present study revealed that the warm-up seems to improve the maximum and mean propelling forces of the swimmer in front crawl swimming technique, registering no differences in the $[La\text{-}]_{net}$ values and in the ratings of perceived exertion. The high relationships between the 30 s tethered swimming test and swimming performance (Morouço *et al.*, 2011) lead us to hypothesize a positive effect of the warm-up in performance. Nevertheless, further research is needed to continue exploring this important scope in sports performance that remains controversial and relatively unknown.

Appendix II

O efeito do aquecimento no rendimento dos 50 m de nado

The effect of warm-up in 50 m swimming performance

Abstract

Warm-up procedures are usually used by coaches and their swimmers. It is assumed that competitive performance is positively affected, but the literature regarding this matter is ambiguous. Purpose: The aim of this study was to assess the effect of typical warm-up, used by the swimmers, in the 50 m front crawl swimming performance. Methods: 10 national-level swimmers (mean ± SD, age: 15.4 ± 1.1 years, height: 1.73 ± 5.1 m, body mass: 62.3 ± 3.9 kg) swam the 50 m front crawl, at maximum velocity, after previous warm-up and without performing the same, in the day after. Capillary blood lactate concentration was assessed after the swimming test (1st and 3rd min of recovery) and the Borg ratings of perceived exertion scale were used. Results: The 50 m swimming times were not different with and without warming up (29.35 ± 1.14 s and 29.35 ± 1.41 s, respectively; $p = 0.86$). No differences were observed in lactate values (9.73 ± 1.81 mmol.l^{-1} and 9.16 ± 2.74 mmol.l^{-1}, respectively; $p = 0.68$), as well as in the ratings of perceived exertion (15.10 ± 1.20 e 14.89 ± 1.36, respectively; $p = 0.52$). Conclusions: These results suggest that the commonly warm up used by the swimmers does not cause significant changes in the 50 m front crawl swimming performance.

Key words: Swimming, activation, performance, front crawl, lactate.

Resumo

O aquecimento desportivo é uma prática habitualmente utilizada pelos treinadores e nadadores. Presume-se que o rendimento competitivo é afectado positivamente, contudo a literatura existente é pouco esclarecedora nesta matéria. Objectivo: O objectivo deste estudo foi verificar o efeito do aquecimento típico utilizado pelos nadadores no rendimento desportivo dos 50 m de nado na técnica de crol. Métodos: 10 nadadores de nível nacional (média ± dp; idade: 15.4 ± 1.1 anos, altura: 1.73 ± 5.1 m, massa corporal: 62.3 ± 3.9 kg) nadaram 50 m na técnica de crol, à velocidade máxima, com a realização prévia de aquecimento e sem a realização do mesmo, um dia após. Foram recolhidas amostras de sangue capilar para determinar a concentração de lactato após o protocolo experimental (1º e 3º min de recuperação). A escala de percepção subjectiva de esforço foi utilizada para quantificar o nível de esforço depois de cada teste. Resultados: Os tempos realizados não demonstraram ser diferentes com e sem aquecimento (29.35 ± 1.14 s e 29.35 ± 1.41 s, respectivamente; $p = 0.86$). Nestas duas condições de exercitação os valores de lactato não mostraram diferenças (9.73 ± 1.81 $mmol.l^{-1}$ e 9.16 ± 2.74 $mmol.l^{-1}$, respectivamente; $p = 0.68$) assim como os valores de percepção subjectiva de esforço (15.10 ± 1.20 e 14.89 ± 1.36, respectivamente; $p = 0.52$). Conclusões: Os resultados sugerem que o aquecimento habitualmente realizado pelos nadadores não provoca alterações de rendimento nos 50 m nadados na técnica de crol.

Palavras-chave: natação, activação, prestação, crol, lactato.

Introdução

O efeito positivo que o aquecimento tem no rendimento desportivo das tarefas subsequentes parece ser uma convicção generalizada de treinadores e seus atletas. No entanto, as evidências científicas estão longe de serem conclusivas. De entre as várias classificações, pode dizer-se que a literatura reclama duas técnicas principais de aquecimento: i) o aquecimento passivo, ii) e o aquecimento activo (Bishop, 2003). Como o próprio nome indica, esta actividade é utilizada para aumentar a temperatura intramuscular, estimulando assim a circulação sanguínea, aumentando a mobilidade muscular e articular e inclusivamente melhora a coordenação motora (Smith, 2004). Contudo, o aumento de temperatura intramuscular não parece ser o único efeito do aquecimento activo. Apesar de não detectarem diferenças na temperatura intramuscular, Gray e Nimmo (2001) verificaram uma resposta diferente nos valores de lactado durante o exercício após a realização de aquecimento activo e passivo. Isto sugere que, depois de um aquecimento activo, as diferenças observadas a nível metabólico durante um exercício de elevada intensidade podem não se dever unicamente ao aumento da temperatura intramuscular.

Para além dos mecanismos adjacentes ao aquecimento desportivo ainda estarem todavia bem conhecidos, os seus efeitos no rendimento desportivo também se apresentam algo ambíguos. Quando nos reportamos aos esforços máximos de curta duração, o aquecimento activo parece influenciar de forma positiva o rendimento no que diz respeito ao tempo de corrida (Grodjinovsky & Magel, 1970) e à máxima potência alcançada no cicloergómetro (Sargeant & Dolan, 1987). Em Natação Pura Desportiva, os estudos existentes neste capítulo são antigos e de difícil replicação. DeVries (1957) e Thompson (1958) sugeriram melhorias na velocidade de nado em distâncias curtas (até aos 91 m). Mais recentemente, Hodgson, Dochery, e Robbins (2005) sugeriram que a utilização dos mecanismos de potenciação pós-activação parecem melhorar o rendimento do nadador em esforços máximos de curta duração, como a partida e a saída até aos 15 m. Esta potenciação tem vindo a ser estudada em diversos desportos e tarefas desportivas e é definida como sendo uma alteração aguda da função do músculo após a sua activação (Hodgson *et al.*, 2005). Apesar destes efeitos positivos no rendimento em esforços máximos de curta duração, alguns estudos demonstraram que o aquecimento poderá não exercer qualquer efeito ou mesmo ser prejudicial para o posterior rendimento na tarefa (Bishop, Bonetti & Dawson, 2001; Bruyn-Prevost & Lefebvre, 1980; Mitchell & Huston, 1993).

Dada a importância que é reconhecida ao aquecimento desportivo, é surpreendente a escassez de literatura suficientemente esclarecedora sobre este tema, especificamente em natação. A utilização de diferentes metodologias e variedade de aquecimentos desportivos torna difícil a comparação entre resultados de diferentes estudos, tornado assim necessário mais e melhor pesquisa nesta área (Fradkin, Zaryn & Smoliga, 2010). Assim, com este estudo pretendeu-se verificar o efeito do aquecimento desportivo no rendimento em distâncias curtas de nado, 50 m, na técnica de crol, procurando contribuir para o melhor conhecimento dos efeitos da do aquecimento específico no rendimento em natação em esforços de curta duração.

Metodologia

Amostra

A amostra foi composta por 10 nadadores, voluntários do sexo masculino, com média de idades de 15.4 ± 1.1 anos, estatura de 1.73 ± 5.1 m, massa corporal de 62.3 ± 3.9 kg (7.37 ± 1.71 kg de massa gorda) e índice de massa corporal de 20.81 ± 1.47 kg/m^2. Os valores de massa corporal e de gordura foram obtidos pelo método de análise da impedância bioeléctrica (Tanita BC 420S, Japão). Os sujeitos da amostra são nadadores com 7.1 ± 1.1 anos de experiência, treinando entre 6 a 9 vezes por semana e todos eles com nível nacional e presença habitual nos campeonatos nacionais. Os voluntários deste estudo e seus respectivos responsáveis foram informados do propósito da pesquisa e assinaram o termo de consentimento.

Procedimentos

O protocolo experimental foi implementado numa piscina interior de 50 m, com uma temperatura de água de 27.5°C. A colecta de dados foi realizada uma semana após a competição mais relevante do 2º macrociclo da época desportiva (Campeonatos Nacionais). O procedimento experimental consistiu na realização de 50 m à velocidade máxima do nadador, na técnica de crol, com partida dentro de água e ao sinal sonoro (apito). A utilização de aquecimento prévio ou a não realização do mesmo determinou as duas condições de realização do protocolo, com 24h de diferença entre os dois momentos. Foram utilizados dois cronómetros (Seiko, Japão) para registar o tempo realizado e seus parciais. Foram ainda recolhidas amostras de sangue capilar através da punção do dedo do nadador, ao 1º e 3º minuto de recuperação, para aceder ao valor mais elevado de concentração de lactato ([La-]) (Accutrend Lactate®Roche, Germany). A escala de percepção subjectiva de esforço de Borg (1998) foi utilizada para quantificar o nível de esforço após cada teste.

Análise Estatística

Para a análise dos dados foi utilizada a análise estatística descritiva, obtendo-se valores de média e desvios-padrão, a fim de caracterizar a amostra e as variáveis obtidas. A normalidade da amostra foi verificada pelo teste de Shapiro-Wilk. Como o valor de N é baixo ($N<30$) e existe rejeição da hipótese nula ($H0$) na avaliação da normalidade da amostra, foram implementados testes não paramétricos. Para comparar os dados obtidos com e sem a realização de aquecimento, foi aplicado o teste não paramétrico de Wilcoxon (signed rank test). As diferenças foram consideradas significativas para $p \leq 0.05$.

Resultados

Na tabela 1 estão representados os valores médios dos tempos obtidos após realização dos 50 m à velocidade máxima na técnica de crol. Os valores estatísticos de p estão também representados, demonstrando não existirem diferenças entre as condições de exercitação (com e sem a realização de aquecimento).

Tabela 1. Valores médios ± desvios-padrão dos tempos realizados nos 50 m crol e seus parciais (1º e 2º 25 m) com (CA) e sem aquecimento (SA) prévio

Variável	Com Aquecimento	Sem Aquecimento	Valor de p
1º 25 m (s)	13.61 ± 0.60	13.55 ± 0.63	0.51
2º 25 m (s)	15.74 ± 0.63	15.80 ± 0.87	0.51
50 m (s)	29.35 ± 1.14	29.35 ± 1.41	0.86

Tal como podemos observar na figura 1, comparando os valores médios de concentração de lactato sanguíneo, estes não revelaram diferenças (9.73 ± 1.81 mmol/l com a realização de aquecimento prévio e 9.16 ± 2.74 mmol/l, sem a realização do mesmo; $p = 0.68$).

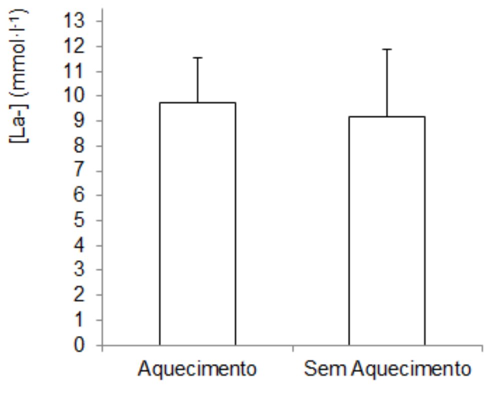

Figura 1. Representação gráfica da média e desvio padrão dos valores de concentração de lactado sanguíneo ([La-]) com e sem a realização de aquecimento.

Na figura 2 são apresentados os valores médios (e desvios-padrão) relativos à percepção subjectiva de esforço após a realização dos 50 m à velocidade máxima de nado. Os níveis de percepção de esforço obtidos demonstram que não existiram diferenças entre o teste realizado com ou sem aquecimento prévio (15.10 ± 1.20 e 14.89 ± 1.36, respectivamente; $p = 0.52$).

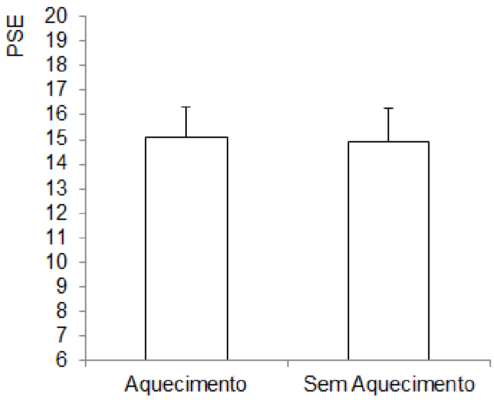

Figura 2. Representação gráfica da média e desvio-padrão dos níveis de percepção subjectiva de esforço (PSE).

Discussão

Com o presente estudo pretendeu-se examinar o efeito da realização de aquecimento desportivo no rendimento do nadador em provas curtas (50 m), na técnica de crol. Os principais resultados sugerem que os 50 m nadados na técnica de crol não são influenciados pela realização prévia de aquecimento, não se verificando diferenças nos tempos realizados, nos valores de [La-] e nos valores de percepção subjectiva de esforço.

A literatura existente sobre as alterações de rendimento em esforços dinâmicos máximos de curta duração em Natação Pura Desportiva é bastante limitada e longínqua. DeVries (1957) demonstrou que 457.20 m de aquecimento específico, teve influência positiva na velocidade em 91.44 m. Concordantemente, Thompson (1958) pode também observar uma melhoria na velocidade de nado em 27.43 m após a realização de aquecimento activo. Apesar destes factos, os dados obtidos no presente estudo mostraram-se algo distintos, não evidenciando melhorias no rendimento (Tabela 1). De facto, os tempos realizados pelos nadadores nos 50 m de nado crol mantiveram-se equivalentes nas duas condições de exercitação experimentadas. Da mesma forma, os parciais de 25 m também se mantiveram inalterados, sugerindo que o aquecimento prévio não influencia o rendimento nestas distâncias de nado para a técnica de crol. Estes dados obtidos vêm corroborar alguns estudos realizados em actividades físicas que não a natação, como corrida ou cicloergómetro (Bishop *et al.*, 2001; Bruyn-Prevost & Lefebvre, 1980; Mitchell & Huston, 1993). Estes estudos não demonstraram alterações no rendimento desportivo, podendo ser inclusivamente prejudiciais para o rendimento após a realização de aquecimento desportivo. Por exemplo, Bishop (2003) avançou com algumas explicações sobre os resultados negativos na performance, como o facto do aquecimento: i) ser de muito baixa intensidade, não causando alterações significativas no desportista; ii) ser demasiado intenso e desta forma provocando a fadiga e causando a depleção de substratos energéticos essenciais; iii) não permitir a suficiente recuperação antes do exercício. O rendimento obtido em esforços máximos de curta duração parece estar relacionado com a capacidade de utilização das moléculas de elevada energia de fosfato (Barbosa *et al*, 2009; Hirvonnen, Rehunen, Rusko & Härkönen., 1987). Assim, um aquecimento demasiado intenso ou sem o tempo de recuperação suficiente poderá levar a uma diminuição da disponibilidade destas mesmas moléculas, prejudicando o rendimento na tarefa.

Considerando que o teste realizado se aproxima dos 30 segundos de duração, em esforço máximo, a contribuição anaeróbia assume um papel fundamental para a produção total de energia utilizada (Gastin, 2001). Sendo que os valores de [La-] são normalmente utilizados para estimar a contribuição do metabolismo glicolitico para o exercício (di Prampero & Ferretti, 1999), os valores obtidos parecem realçar a preponderância da contribuição do sistema anaeróbio para satisfazer as exigências energéticas do esforço realizado. Como podemos verificar na figura 1, a inexistência de alteração nos valores de [La-] no final do teste de 50 m vem comprovar os resultados de Bruyn-Prevost e Lefebvre (1980), que não apresentaram modificações dos parâmetros fisiológicos com e sem a realização de aquecimento desportivo. No entanto, o aquecimento desportivo tem igualmente vindo a ser referido como um meio eficaz para alterar as respostas metabólicas durante um exercício subsequente, quando comparado com um grupo de controlo. Mandegue *et al.* (2005) e Beedle e Mann (2007) sugeriram que o mesmo assume um papel de manutenção do equilíbrio ácido-base num nível apropriado pela estimulação da capacidade de tamponamento e podendo assim originar uma menor acumulação de [La-]. Durante um exercício precedido de aquecimento activo, foram observadas reduções na concentração de lactato muscular e sanguíneo (Gray & Nimmo, 2001; Robergs, Pascoe, Costill & Fink, 1991). Divergindo de tais observações, as respostas metabólicas dos nadadores da nossa amostra mantiveram-se semelhantes.

No que se refere aos valores da escala de percepção subjectiva de esforço (figura 2), não foram encontradas diferenças entre as duas condições experimentais. A percepção subjectiva de esforço é uma medida utilizada para quantificar, monitorizar e avaliar o nível de esforço individual. Este é um parâmetro tido como um importante complemento às medidas fisiológicas, apresentando fortes relações com algumas delas (Borg, 1998). Robertson *et al.* (1986) sugerem que o aumento da percepção do esforço realizado seja consequência da utilização da capacidade anaeróbia. A acumulação de iões de hidrogénio presentes nos músculos activos e no sangue, resultantes da dissociação do ácido láctico em lactato e H^+, é apresentado como principal responsável pelo esforço percebido. Assim, muito embora os valores demonstrem a realização de esforços intensos, os nadadores do presente estudo não percepcionaram esforços diferentes quando realizaram ou não o aquecimento prévio. Importa referir que, embora a percepção de esforço seja uma ferramenta útil e fácil de identificar e utilizar, a confiabilidade das pontuações pode ser questionada devido ao factor de subjectividade associado.

Conclusões

Apesar das alterações que têm vindo a ser atribuídas ao aquecimento desportivo, a eficácia do mesmo no rendimento dos praticantes em tarefas de elevada intensidade ainda não foi cabalmente estabelecida. Mitchell e Huston (1993) haviam sugerido alterações insuficientes metabólicas e de rendimento que justifiquem a realização de aquecimento específico pré exercício para optimizar esforços de curta duração e elevada intensidade, facto comprovado pelo presente estudo. Verificámos não existirem alterações no rendimento bem como nos parâmetros avaliados, permitindo-nos então sugerir que o aquecimento habitualmente realizado pelos nadadores não parece influenciar as provas curtas em Natação Pura Desportiva. Contudo, mais estudos são necessários para melhor conhecer esta questão que desempenha um papel essencial no desporto e na atividade física, e que se mostra ainda controversa e relativamente desconhecida.