Acute effects of water temperature in swimming performance: a biophysical analysis

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Abstract —The aim of the present study was to explore the acute biophysical effects of different water temperatures in swimming. Ten male swimmers (28.20 ± 13.15 years old) completed two front crawl time-trials in a flume (24h rest in-between) at 18 and 26^{o} C water temperature, both without wetsuit. The speed was common at both conditions and established according to a 400 m pre-test in a 25 m swimming pool (1.28 ± 0.13m · s^{-1}). The peak oxygen uptake ($\dot{V}O_{2peak}$) maximal heart rate (HRmax), blood lactate concentrations ([La-]), energy cost (C), metabolic power ($\dot{E}$) and total energy expenditure Etot were assessed. Stroke rate (SR), stroke length (SL), stroke index (SI), propelling efficiency (η_p) and the Borg rating of perceived exertion scale (RPE) were calculated. Pair Student's t-test was computed to compare both conditions. Time endured and ($\dot{V}O_{2peak}$) were similar for 18 and 26^{o} C conditions (313.44 ± 40.10 vs 282.27 ± 58.61s; mean difference: 31.16s; 95% CI: -32.12 to 94.45s; p=0.294; 47.54 ± 7.93 vs 51.91 ± 12.49mL kg − 1 min − 1 mean difference: -4.37mL kg − 1 min − 1; 95% CI: -10.10 to 1.37s; p=0.119). However, lower [La-]peak (7.46 ± 3.33 vs 11.40 ± 1.58mmol l^{-1}; p=0.002; Cohen ‘s d: -1.42), RPE (5.10 ± 1.91 vs 7.10 ± 1.29; p=0.001; Cohen ‘s d: -1.60) and $\dot{E}$ values (1.23 ± 0.17 vs 1.41 ± 0.24; p=0.016; Cohen ‘s d: -0.94) were observed at 18^{o} C. The aerobic contribution (Aer) was higher (86.20 vs 81.90%; p=0.037; Cohen ‘s d: 0.77) and anaerobic lactic (AnL) influence lower (5.80 vs 9.82%; p=0.001; Cohen ‘s d: -1.46) when swimming at 18^{o} C, but Etot (383 ± 60 vs 397 ± 98Kj) and C (0.96 ± 0.15 vs 0.99 ± 0.25kJ m^{-1}) remained similar within conditions. Furthermore, swimming at 18 and 26^{o} C was not different from a general kinematical point of view (SR: 0.54 ± 0.04 vs 0.55 ± 0.06Hz; p=0.115; Cohen ‘s d: -0.55; SL: 2.39 ± 0.20 vs 2.32 ± 0.20m; p=0.176; Cohen ‘s d: 0.46; SI: 3.06 ± 0.53 vs 2.96 ± 0.44m^2 s^{-1}; p=0.145; Cohen ‘s d: 0.50 and η p: 47 ± 4.7 vs 48 ± 6.4%; p=0.325; Cohen ‘s d: -0.33). The tendency for lower values at 18^{o} C are not in agreement with the literature and could be affected by the reduction of the blood flow volume in cold water and also due to methodological issues, particularly the learning effect regarding the use of the flume and breathing apparatus.

Key words: Physiology, Biomechanics, Swimming flume, cold water.

1. INTRODUCTION

Open water swimming events take place in rivers, lakes and water channels (Hara & Muraoka, 2015), with wetsuits being mandatory when water temperature is < 18^{o} C and optional between 18 and 20^{o} C (http://www.fina.org). When swimming in cold water swimmers suffer a cold-shock response characterized by a 1 to 3 min hyperventilation and tachycardia besides an inspiratory gasp (Tipton, 1989). Despite that, open water swimmers should have the ability to swim long distances at 80-90% of maximal oxygen uptake ($\dot{V}O_{2max}$), requiring a high propelling efficiency and a low energy cost to maintain that intensity (Baldassarre et al., 2017).

Another recent study (Schnitzler et al., 2017) showed that maximum respiratory frequency (beats · min^{-1}) and average heart rate (HR) were higher when swimming 200 m front crawl at 10 than at 28^{o} C, and the time to reach the maximal HR (HRmax) was shorter, regardless the swimming expertise level. These results suggested that swimming after the cold-shock response required a higher energy expenditure (Etot) than at temperate conditions.

Elite open-water swimmers are anthropometrically lighter and smaller compared to the swimming pool counterparts (VanHeest et al., 2004), possessing relevant aerobic metabolic characteristics that enhances long-distance swimming performances. This study aimed to clarify swimmers physiological and technical behavior at different water temperatures, by analyzing some relevant front crawl biophysical related variables at cold and temperate water temperatures. We hypothesized that swimming at 18° C will produce an increment on physiological demands and reduce swimming efficiency comparing to performing at 26° C.

2. METHODS

2.1. Participants

Ten male swimmers 28.2 ± 13.1 years old, 175.9 ± 5.1 m of height and 72.4 ± 9.4 kg of body mass participated voluntarily in this study. All were engaged in a six to seven weekly training frequency and had 77.9 ± 11.6% of the 100 m front crawl world record as personal best. Participants provided written informed consent and the Institutional Ethical Review Board approved the study design (which has been performed according to the Code of Ethics of the World Medical Association - Declaration of Helsinki).

2.2. Design

Two front crawl time-trials in a flume (24h rest in-between) at 18 and 26° C water temperature were performed at a common speed (1.28 ± 0.13 m · s^{-1}) obtained during a 400 m pre-test in a 25 m swimming pool. All participants performed firstly the 26° C trial due to swimming flume constraints (the water temperature was lowered afterwards). They abstained taking caffeinated drinks and practicing exhausting exercise during the testing days. Before testing, an individual warm-up of 15 min of low to moderate intensity was conducted, followed by 10 min of passive rest (ensuring that previous exercise had no influence on testing performances; Bailey et al., 2009). Participants had previous experience in performing in the swimming flume.

2.3. Methodology

Respiratory and pulmonary gas-exchange variables were directly measured using the K4b2 breath-by-breath portable gas analyzer attached to an Aquatrainer® respiratory snorkel and valve systems (Cosmed, Rome, Italy; Ribeiro et al., 2016), as displayed in Fig. 1. An underwater camera (Panasonic Full-HD HX-A500, Osaka, Japan) working at 50 Hz was located on the sagittal plan of the swimmers displacement in the center of both pools (12.50 and 2.35 m in swimming pool and flume, respectively) to analyse technical variables. A 5 and 1 m long pre-calibrated spaces situated in the center of the swimming pool and swimming flume (respectively) were used as a reference for video analysis. The swimming flume (Endless Pool Elite Techno Jet Swim 7.5 HP, Aston PA, USA) was 2.4 x 4.7 m of length, with flow velocity measured at 0.30 cm depth using an FP101 flow probe (Global Water, Gold River, CA; McLean et al., 2010).

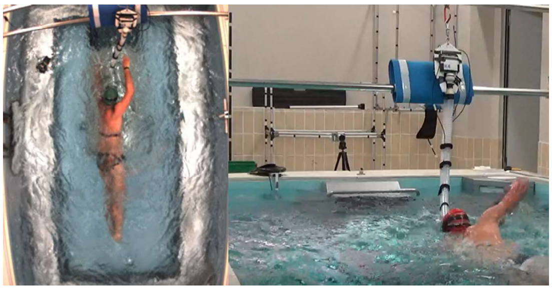

Fig. 1 Swimmer using an Aquatrainer respiratory snorkel attached to the K4b2 portable gas analyzer.

2.4. Data analysis

A mono-exponential model fitting was used for treating the ($\dot{V}O_2$) data. Etot was obtained through the addition of the net ($\dot{V}O_2$) and blood lactate concentration ([La-]) values, with energy cost (C), i.e., the energy expended to cover one-unit distance at a given speed (Baldassarre et al., 2017) determined by dividing Etot to swimming distance and metabolic power ($\dot{E}$) was computed by dividing Etot by the time endured. HR was monitored and registered trough a HR monitor system (Polar S610i, Finland), with HRmax obtained from the average of the last 30 s of the effort (the same procedure was used to obtain $\dot{V}O_{2peak}$ and the maximal respiratory exchange ratio - RER).

Capillary blood samples (25 μ L) for [La-] analysis were collected from the fingertip immediately after the trial and at the 1, 3, 5 and 7 min during the recovery period using a portable lactate analyzer (Lactate Pro, Arkray, Inc., Kyoto, Japan) to find the maximal [La-] ([La-]peak). Immediately after the trials, participants pointed out the Borg (1998) rating of perceived exertion scale (RPE).

Swimming velocity was computed in the middle of every 100 m of the 400 m pre-test to obtain the mean velocity and adjust it afterwards during the swimming flume trials. Stroke rate (SR) was obtained measuring three upper limbs cycles and subsequently stroke length (SL) and stroke index (SI) were calculated. Propelling efficiency (η_p) was estimated according with Zamparo et al. (2005) as follow:

$$\eta_p = [v \cdot 0.9/2\pi \cdot SR \cdot l) \cdot 2/\pi] \cdot 100 \quad (1)$$

where l is the distance between the shoulder and wrist during the in sweep. Reference points were drawn at the shoulders, hips and wrists to help the analysis of the technical variables.

2.5. *Statistical analysis*

Using the IBM SPSS Statistics (Version 20, IBM SPSS, Chicago, USA), pair Student's t-test was computed to compare physiological and technical variables at different water temperature conditions, and Bonferroni post hoc procedures performed to locate the pairwise differences between the means ($\alpha = 0.05$). Cohen 's d effect was calculated with the following criteria: 0 to 0.19 trivial, 0.2 to 0.59 small, 0.6 to 1.19 moderate, 1.2 to 1.99 large, 2.0 to 3.9 very large and > 4.0 nearly perfect (Hopkins, 2002).

3. RESULTS

Data concerning physiological and technical variables are presented in Table 1. Times endured in the swimming flume were similar for 18 and 26° C condition, as well as the physiological variables $\dot{V}O_{2peak}$, HRmax, RER, Etot and C. Nevertheless, [La-]peak, RPE and $\dot{E}$ were lower in the 18° C condition which explains the lower anaerobic lactic contribution (AnL) at this colder temperature. Swimming at 18 and 26° C was not different from a general kinematical point of view, with similar SR, SL and SI values, as well as regarding η_p.

4. DISCUSSION

The current study aimed to evaluate the biophysical effects of cold and temperate water temperatures (18 and 26° C, respectively) in front crawl swimming. 18° C is the temperature that swimmers have to decide whether to use or not the wetsuit in open water swimming events. We have observed a statistically non-significant difference in the swimming time although a difference of 31 s was evident between conditions. Data showed that swimming at 18° C without a wetsuit might influence the 400 m front crawl performance as lower [La-]peak, RPE and $\dot{E}$ were observed. Although, $\dot{V}O_{2peak}$, HRmax and RER did not evidence statistical differences when swimming in cold and temperate waters, a tendency for higher values were observed at 26° C (it was found ~9, 4 and ~5% differences for $\dot{V}O_{2peak}$, HRmax and RER, respectively). Technique related variables showed a similar behaviour within conditions without statistically differences found for SR, SL, SI and η_p.

These unexpected results may be due to a water temperature of 18° C not being sufficiently cold to elicit a cold-chock response. In fact, temperatures cooler than 15° C are usually utilised for this kind of studies. In addition, there is still a lack of information about the physiological responses while swimming in cold waters because the majority of the studies focus on cold water immersion after exercise rather than performing on it (see Bleakley & Davison, 2010 and Broatch et al., 2018 for a review on the topic).

Ferrara et al., (2018) investigated how muscle contraction requires less oxygen at 25° C than at 37° C. Although this study was not with humans, it could support how lower values were obtained in cold water in the current study. Besides the fact that a vasoconstriction appeared as a consequence of the cold exposure which reduced the blood flow volume (Stocks et al., 2004). As a result, [La-] production as well as AnL may have been influenced by the cold water.

Another justification for the obtained values may be related to the methodological issues, particularly the eventual learning effect regarding the use of the flume, which could induce some mechanical constraints when swimming in that pool for the first times (Espinosa et al., 2015). In fact, although swimmers had an experimental period of adaptation in the swimming flume, their technique could be affected in their first test condition (at 26°) and, in consequence, their energy requirements could be increased as confirmed by $\dot{E}$ values. The use of the Aquatrainer® snorkel (see Ribeiro et al., 2016 for a detailed description) with non-elite swimmers might also justify the obtained data.

In the future, we will try to overcome these limitations using a randomized and counterbalanced testing order and select a higher sample size with best prepared and experienced swimmers. As swimming front crawl at 18° C has a significant importance for open water (and triathlon) training and competition, future studies should also consider testing both physiological and biomechanical variables and swimming with and without a wetsuit to clarify whether its use is recommended or not with the objective of benefiting from it when its use is elective (between 18 and 20° C).

Table 1. Changes in the physiological and technical variables at 18 and at 26° C trials.

Variable	18°C	26°C	t-test (p)	Difference [95%CI]; %∆	Effect size (d)
Time endured (s)	313.44 ± 40.10	282.27 ± 58.61	0.294	31.16 [-32.12, 94.45]; -10%	0.35, Small
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	47.54 ± 7.93	51.91 ± 12.49	0.119	-4.37 [-10.10, 1.37]; 9.2%	-0.54, Small
$[La^-]_{peak}$ ($mmol \cdot l^{-1}$)	7.46 ± 3.33	11.4 ± 1.58	0.002	-3.94 [-5.92, -1.96]; 52.8%	-1.42, Large
RPE	5.10 ± 1.91	7.10 ± 1.29	0.001	-2 [-2.89, -1.11]; 39.2%	-1.60, Large
HR_{max} ($beats \cdot min^{-1}$)	164.65 ± 9.99	171.18 ± 11.61	0.081	-6.53 [-14.03, 0.98]; 4%	-0.62, Moderate
HR_{max} (%)	87.6 ± 6.3	91.1 ± 8	0.084	-3.53 [-7.64, 0.58]; 4 %	-0.61, Moderate
RER	0.98 ± 0.08	1.03 ± 0.08	0.139	-0.05 [-0.12, 0.02]; 5.3%	-0.51, Small
AnAL (kJ)	30.09 ± 3.89	30.09 ± 3.88	0.425	0.01 [-0.01, 0.02]; -0.02 kJ	0.26, Small
AnL (kJ)	22.54 ± 17.28	38.01 ± 11.14	0.001	-15.46 [-22.92, -8]; 68.6%	-1.48, Large
Aer (kJ)	330.60 ± 57.12	329.29 ± 94.81	0.971	1.32 [-78.87, 81.51]; -0.4 kJ	0.01, Trivial
AnAL (%)	8 ± 1.44	8.28 ± 3.64	0.806	-0.28 [-2.81, 2.24]; 3.5 %	-0.08, Trivial
AnL (%)	5.80 ± 4.05	9.82 ± 2.63	0.001	-4.02 [-6, -2.05]; 69.4%	-1.46, Large
Aer (%)	86.20 ± 4.69	81.9 ± 5.60	0.037	4.30 [0.32, 8.28]; -5%	0.77, Moderate
E_{tot} (kJ)	383 ± 60	397 ± 98	0.712	-14.14 [-98.15, 69.87]; 3.7%	-0.12, Trivial
$\dot{E}$ (kW)	1.23 ± 0.17	1.41 ± 0.24	0.016	-0.184 [-0.33, -0.04]; 14.6 %	-0.94, Moderate
C ($kJ \cdot m^{-1}$)	0.96 ± 0.15	0.99 ± 0.25	0.698	-0.04 [-0.25, 0.17]; 3.9%	-0.13, Trivial
SR (Hz)	0.54 ± 0.04	0.55 ± 0.06	0.115	-0.02 [-0.04, 0.01]; 3.4%	-0.55, Small
SL (m)	2.39 ± 0.20	2.32 ± 0.20	0.176	0.07 [-0.04, 0.18]; -3%	0.46, Small
SI ($m^2 \cdot s^{-1}$)	3.06 ± 0.53	2.96 ± 0.44	0.145	0.10 [-0.04, 0.24]; -3.2%	0.50, Small
η_p (%)	47 ± 4.7	48 ± 6.4	0.325	-1.07 [-3.38, 1.25]; 2.3%	-0.33, Small

Peak oxygen uptake ($\dot{V}O_{2peak}$), peak blood lactate concentrations ($[La^-]_{peak}$), Borg rating of perceived exertion scale (RPE), maximal heart rate (HR_{max}), percentage of HR_{max} ($HR_{max;}$ %), respiratory exchange ratio (RER), anaerobic alactic (AnAL), anaerobic lactic (AnL), aerobic (Aer), total energy expenditure (E_{tot}), metabolic power ($\dot{E}$), energy cost (C), stroke rate (SR), stroke length (SL), stroke index (SI), propelling efficiency (η_p).

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