Journal of Thermal Biology xxx (xxxx) 102926

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Pre-exercise skin temperature evolution is not related with 100 m front crawl performance

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ARTICLE INFO

Keywords:
Swimming
Front crawl
Warm-up
Transition phase
Infrared thermography

ABSTRACT

During the transition between warm-up and competition there is a change in core, muscle and (eventually) skin temperature that may affect swimming performance. We have aimed to assess skin temperature evolution during transition phases of different durations before a typical front crawl effort and to investigate its relationship with performance. Following a standardized warm-up, nine adolescent male swimmers performed three maximal randomized 100 m maximum front crawl trials after 10, 20 and 45 min transition phases. Skin temperature, performance (time, stroke frequency, length and index, and propelling efficiency), heart rate, lactate and perceived effort were assessed. Data showed a skin temperature log increase over time ($R^2 > 0.96$, $p < 0.01$) without differences from the 15 min with the following instants. Performance and psychophysiological variables were similar between transition phases. However, skin temperature at the end of the transition periods, i.e., just before the 100 m trials, was lower in the 10 min than the 20 and 45 min transitions (32.0 ± 0.6 vs 33.0 ± 0.4 and 33.5 ± 0.5 °C, respectively). The main finding was that no relevant relationships were observed between pre-test skin temperature and performance times ($|r| < 0.6$, $p > 0.05$) for the studied transition phases. We have concluded that transitions longer than 10 min will not present thermal changes and that, within the physiologic limits studied, pre-exercise skin temperature does not influence swimming performance.

Abbreviations

BMI	Body Mass Index
ES	Effect Sizes
HR	Heart Rate
IRT	Infrared Thermography
RPE	Rate of Perceived Exertion
SD	Standard Deviation
SF	Stroke Frequency
SL	Stroke Length
SI	Stroke Index
[La⁻]	Blood lactate concentrations
l	Arm length
η_p	Propelling efficiency
$Tmean$	Absolute average temperature
Tsk_i	Skin temperature of each region
S_i	Number of pixels defining each region
v	Swimming velocity

1. Introduction

Warming-up before a competition is fundamental to enhance sport performance (Bishop, 2003; Bobo, 1999; Neiva et al., 2014), rising

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https://doi.org/10.1016/j.jtherbio.2021.102926
Received 13 November 2020; Received in revised form 2 March 2021; Accepted 29 March 2021
0306-4565/

body temperature, blood flow, respiration rate and heart rate (HR). In addition, it reduces muscle stiffness, improves contractile performance and prepares skeletal muscles for exercise (Balilionis et al., 2012; Kilduff et al., 2013; McGowan et al., 2015). Moreover, it helps athletes to familiarize with the competition venue and, particularly for swimmers, with the swimming pool specificities (King, 1979; McGowan et al., 2016). However, warm-up routines should not induce fatigue (Balilionis et al., 2012), which might negatively influence the subsequent competitive performance.

The time gap between the warm-up end and the start of the swimming race – the transition phase – is usually quite prolonged (Kilduff et al., 2013; McGowan et al., 2016), often 30–45 min or even more (McGowan et al., 2016; West et al., 2013). In fact, in national and international meetings swimmers must be at the call room at least 20 min before the race starts (Galbraith and Willmott, 2018; McGowan et al., 2015), meaning that short transition phases are very unusual. This may mitigate the warm-up benefits, jeopardizing swimmers' performance (Galbraith and Willmott, 2018; McGowan et al., 2017; McGowan et al., 2016). It was observed that lower duration of transition phases (10–20 min vs 45 min) improved the 200 m performance by 1.38 and 1.48% respectively (West et al., 2013; Zochowski et al., 2007), and that a 10 vs 20 min transition phase leads to a 1.12% performance increment in the 100 m event (Neiva et al., 2017).

Physiologically, performance enhancement is related to higher muscle temperature, facilitating muscle metabolism, muscle fiber conduction velocity, power output and reaction times (Bishop, 2003; Galbraith and Willmott, 2018; McGowan et al., 2016). However, muscle temperature drops immediately after exercise ends (mainly during the first 15–20 min), so cancelling out the warm-up benefits (McGowan et al., 2017; Mohr et al., 2004). Skin temperature does not have the same behavior as muscle or core temperature (Jutte et al., 2001; Priego Quesada et al., 2016). In addition, and specifically in swimming, due to heat conductivity being higher in water than in air (Alexious, 2014), it has been observed that swimmers' skin temperature decreases in water despite exercise, and rises after leaving the water (Galbraith and Willmott, 2018; Novotny et al., 2015).

Body temperature changes at transition phases of different durations have previously been studied using core temperature (Neiva et al., 2017; West et al., 2013), but without examining its evolution over the course of time. Therefore, the behavior of skin temperature during these phases is still unknown. Furthermore, these authors only recorded a single measurement of the tympanic and/or central temperature, while skin temperature in a large number of body regions could provide a better picture of overall body temperature (de Andrade Fernandes et al., 2014; Priego Quesada et al., 2017).

Due to the scarcity of studies on the topic, our aim was to assess skin temperature evolution occurring between a standardized warm-up and a maximum effort 100 m front crawl, evaluating transition phases of different time durations. A further aim was to investigate whether there is a direct relationship between skin temperature and performance. We hypothesized that skin temperature would increase throughout the transition phase periods, until stabilization. And it was also expected that skin temperatures of the shorter transition phases would lead to faster 100 m front crawl exertions.

2. Methods

2.1. Participants

Nine adolescent male competitive swimmers (age 15 ± 1 years, body mass 62.3 ± 6.8 kg, height 1.74 ± 0.1 m, arm length 0.63 ± 0.04 m, BMI 20.6 ± 1.9 kg/m^2, training volume 24.6 ± 8.8 km/week, 100 m front crawl best time 59.0 ± 3.4 s and swimming experience 8 ± 3 years) voluntarily participated in the current study. Inclusion criteria were: (i) male swimmers between 14 and 18 years old; (ii) no history of serious injuries within the last 12 months; (iii) participation in regular swimming competitions; and (iv) a personal best time in the 100 m front crawl ≤ 65 s. All participants were informed about the study procedures and a written informed consent was obtained from the participants' parents or guardians. The study procedures complied with the Declaration of Helsinki and were approved by the host University Ethics Committee (code nº CEFADE 12 2020).

2.2. Procedures

Each participant completed three experimental sessions (separated by 24 h) at the same time of day in a 25 m indoor swimming pool with 28.01 ± 0.09 and 27.97 ± 1.27 °C water and air temperatures, and 57.00 ± 1.56% humidity. After a front crawl standardized 1200 m warm-up composed of 300 m (100 m usual breathing pattern, 100 m breathing in the fifth stroke and 100 m usual breathing), 4 × 100 m [2 × (25 m lower limbs actions and 25 m increased stroke length)] @ 1:50, 8 × 50 m [2 × (50 m drill, 50 m progressive speed, 25 m at 85–90% of 100 m pace and 25 m low intensity, and 25 m at 85–90% of 100 m pace with block start and 25 m low intensity)] @ 1:00 and 100 m low intensity (adapted from Neiva et al., 2014), swimmers performed a maximal 100 m front crawl trial (Fig. 1).

Each 100 m front crawl trial was performed after a 10, 20 and 45 min transition phase (in randomized order), with swimmers always wearing the same swimsuit, cap and glasses. During transition phases, participants were sat on a bench (without resting their backs) and wore the same clothing (club jacket, shorts and sports footwear). Each trial began with a dive from the starting blocks, after official verbal and auditory commands. First 15 m, each 25 m split and overall times were recorded by an experienced researcher using a manual stopwatch (3X – 100 model, Finis, Livermore, USA). Three video cameras operating at 50 Hz (Sony HDR-CX190E, Sony Electronics Inc., San Diego, USA) were placed at 7.5, 12.5 and 17.5 m perpendicular to lane 4 to cover the 25 m swimming pool and were used to confirm lap and overall times. Footage also provided data on stroke frequency, stroke length and stroke index, using Kinovea software (v 0.8.24, Free Software

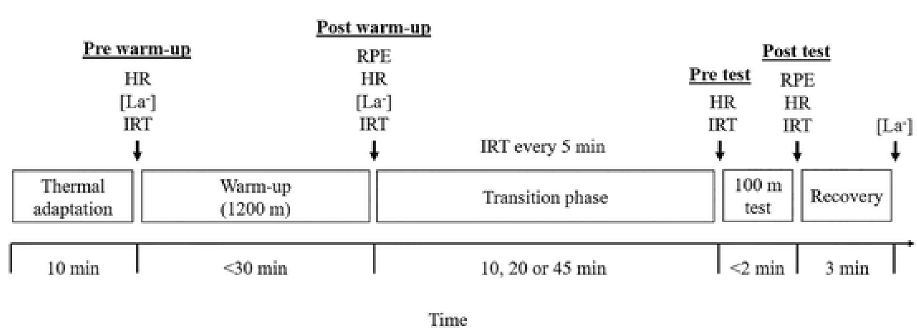

Fig. 1. Schematic representation of the experimental session design with five data collection moments being displayed. Heart rate (HR), blood lactate concentration ([La$^-$]), infrared thermography (IRT) and rate of perceived exertion (RPE).

Foundation, Boston, USA) and following Almeida-Coelho et al. (2016) procedures. Propelling efficiency (η_p) was estimated by the speed-based method using the following equation (Peterson Silveira et al., 2019):

$$\eta\rho = \frac{\upsilon}{2\pi \times SF \times l}$$

where υ is the swimming velocity (m/s), SF is the stroke frequency (Hz) and l is the arm length (m).

Skin temperature was determined using an infrared camera of a Focal Plane Array size 320 × 240 (E–60, Flir Systems Inc., Wilsonville, USA), with noise equivalent temperature difference < 50 mK and measurement uncertainty of ±2 °C or 2%. Measurements were taken perpendicular to the body region of interest in an area absent of sunlight, 5 m away from electronic equipment, electric light and people (except for the thermographer and each participant). A blackbody (BX-500 IR Infrared Calibrator, CEM, Shenzhen, China) was used to calibrate the camera and the thermographic imaging in sports and exercise medicine checklist was used to follow the protocol specificities (Moreira et al., 2017). The camera was turned on 10 min before taking the images to ensure its stabilization and positioned 4 m from the participants to frame the entire body in the screen.

Immediately after arriving at the pool, swimmers were immersed for 10 min in water, in a static position up to their neck, to measure baseline skin temperature (Domingues et al., 2017; Vardasca et al., 2017). After this acclimatization period, as well as post warm-up and each 100 m trial, swimmers were quickly dried without friction with microfiber towels (Vardasca et al., 2017). Thermal images were obtained with swimmers standing up (wearing only their swimsuit) before and after the warm-up and each 100 m front crawl trial, as well as at every 5 min of each transition phase. For that purpose, an antireflective panel was placed behind them to minimize the influence of the infrared radiation reflected in the wall (Hildebrandt et al., 2012), with the reflected temperature being measured according to the standard method ISO 18434–1:2008 (ISO, 2008) and introduced into the camera setup.

The average temperature of the thorax, abdomen, upper, dorsal and lumbar back, anterior and posterior forearm, anterior and posterior arm, anterior and posterior thigh, and anterior and posterior leg (Fig. 2) was obtained using thermography software (ThermaCam Researcher Pro 2.10 software, Flir Systems Inc., Wilsonville, USA) considering an emissivity of 0.98 (Steketee, 1973). In addition, mean skin temperature was calculated using the ratio suggested by Zaidi et al. (2007):

$$Tmean = \frac{\sum_{i=A}^{J} Tsk_i S_i}{\sum_{i=A}^{J} S_i}$$

where $Tmean$ is the absolute average temperature, Tsk_i is the skin temperature of each region (both in °C), and S_i is the number of pixels defining each region. The post warm-up and the pre and post 100 m front crawl trials delta temperatures were calculated as the difference between each instant mean skin temperature minus the corresponding pre warm-up mean value.

HR was assessed both pre and post warm-up, and 100 m front crawl trails using a HR monitor (Polar RS800CX, Polar Electro Oy, Kempele, Finland). Capillary blood samples were obtained at the same moments (plus at 3 min of the recovery period after the 100 m exertions) by a puncture at the earlobe, with blood lactate concentrations ([La⁻]) being assessed using an automated lactate analyzer (Lactate Pro 2, Kyoto, Japan). Participants were asked to rate their perceived exertion (RPE) using the 6–20 Borg (1982) scale after the warm-up and the 100 m front crawl trials.

2.3. Statistical analysis

Statistical analysis was performed using SPSS 20.0 (IBM Armonk, New York, USA) and data presented as mean ± standard deviation (SD). The distribution normality was verified by Shapiro-Wilk test and followed by a parametric statistical analysis. A one-way repeated measures ANOVA was used to compare changes in performance and psychophysiological variables between transition phases. A linear mixed model with two factors (transition phases [with 3 levels] and instant [with different levels depending on the transition phase]) was carried out to compare temperature variables. The assumptions of the linear model were evaluated by verifying the normality of the residuals. In both tests, Bonferroni *post hoc* corrections were performed to locate pairwise differences between means. Cohen's (1988) effect sizes (ES*d*) were computed and classified for pair comparisons as small (0.2–0.5), moderate (0.5–0.8) or large (>0.8). In addition, a logarithmic function of temperature vs time was adjusted (R^2) for both absolute and delta temperatures on each transition phase. Relationships between pre-test

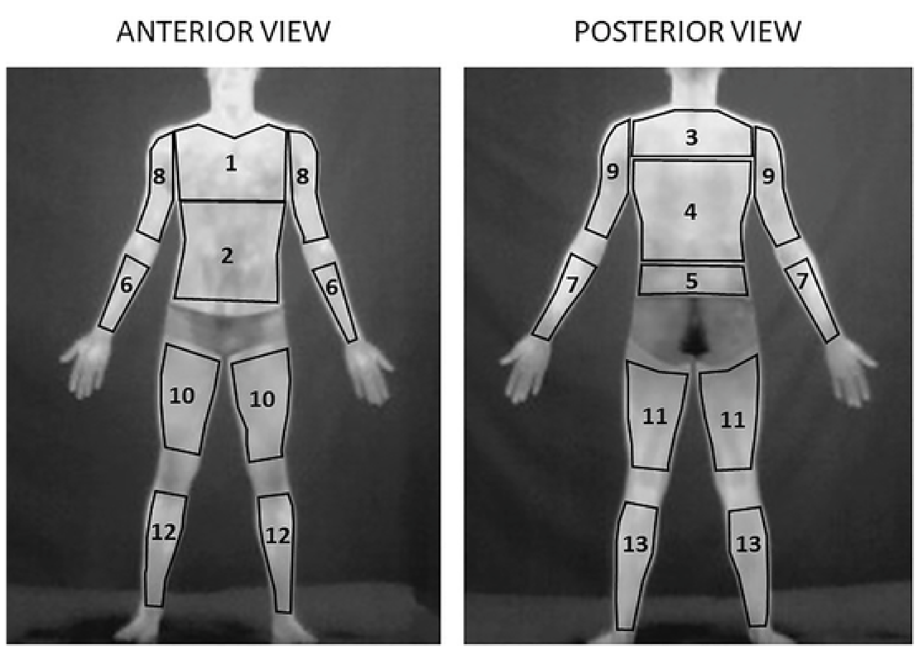

Fig. 2. Regions of interest for swimmers thermographic measurements.

temperature and swimming performance times, post-test heart rate and recovery lactate for each transition phase were analyzed through Pearson correlation coefficient and classified as weak ($0.2 < |r| < 0.5$), moderate ($0.5 \leq |r| < 0.8$) or strong ($|r| \geq 0.8$) (O'Rourke et al., 2005). Statistical significance was set at $\alpha = 0.05$.

3. Results

Fig. 3 shows the evolution of skin temperature (both in absolute and delta values) during transition phases of different durations ($F_{(23,192)} = 55.47$ and $F_{(20,168)} = 33.36$, respectively). We can observe a log increment over time ($R^2 = 1.00$, 0.98 and 0.95, for 10, 20 and 45 min transitions, respectively), with differences between 1 min vs all other instants for absolute and delta values ($p < 0.001$, ES$d > 1.6$), 5 min vs every instant from 15 min for absolute values ($p < 0.01$, ES$d > 1.4$) and from 20 min for delta values ($p < 0.001$, ES$d > 2.0$) and 10 min vs every instant from 35 min for both absolute and delta values ($p < 0.05$, ES$d > 1.5$). On comparing the different conditions studied, no differences were found for these variables.

The variables for the 100 m maximum front crawl performance at the 10, 20 and 45 min transition phases are shown in Table 1, with no differences being found in any performance variable between transition durations. Fig. 4 presents the psychophysiological and skin temperature responses in the different transition durations at the five moments of data collection. HR, [La⁻] and RPE were similar in the three transition phase durations at all measurement moments ($F_{(6,48)} = 0.88$, $\eta^2 = 0.10$; $F_{(1.6,12.6)} = 2.31$, $\eta^2 = 0.22$ and $F_{(2,16)} = 1.70$, $\eta^2 = 0.18$, respectively). However, absolute temperature before the test was lower at the 10 min transition than the 20 and 45 min transitions ($p = 0.008$, ES$d = 2.0$ and $p < 0.001$, ES$d = 2.4$, respectively). In addition, delta temperature before the test was also lower at the 10 min transition than the 45 min transition ($p = 0.001$, ES$d = 2.0$). A thermogram sequence with the four most important moments of data collection is shown in Fig. 5.

Finally, no correlation ($|r| < 0.6$, $p > 0.05$) was observed between the pre-test skin temperature (both in absolute and delta values) and 100 m front crawl times for any of the transition phases studied (Table 2). Likewise, no relationship ($|r| < 0.6$, $p > 0.05$) was found between the pre-test skin temperature and post-test heart rate (Supplementary

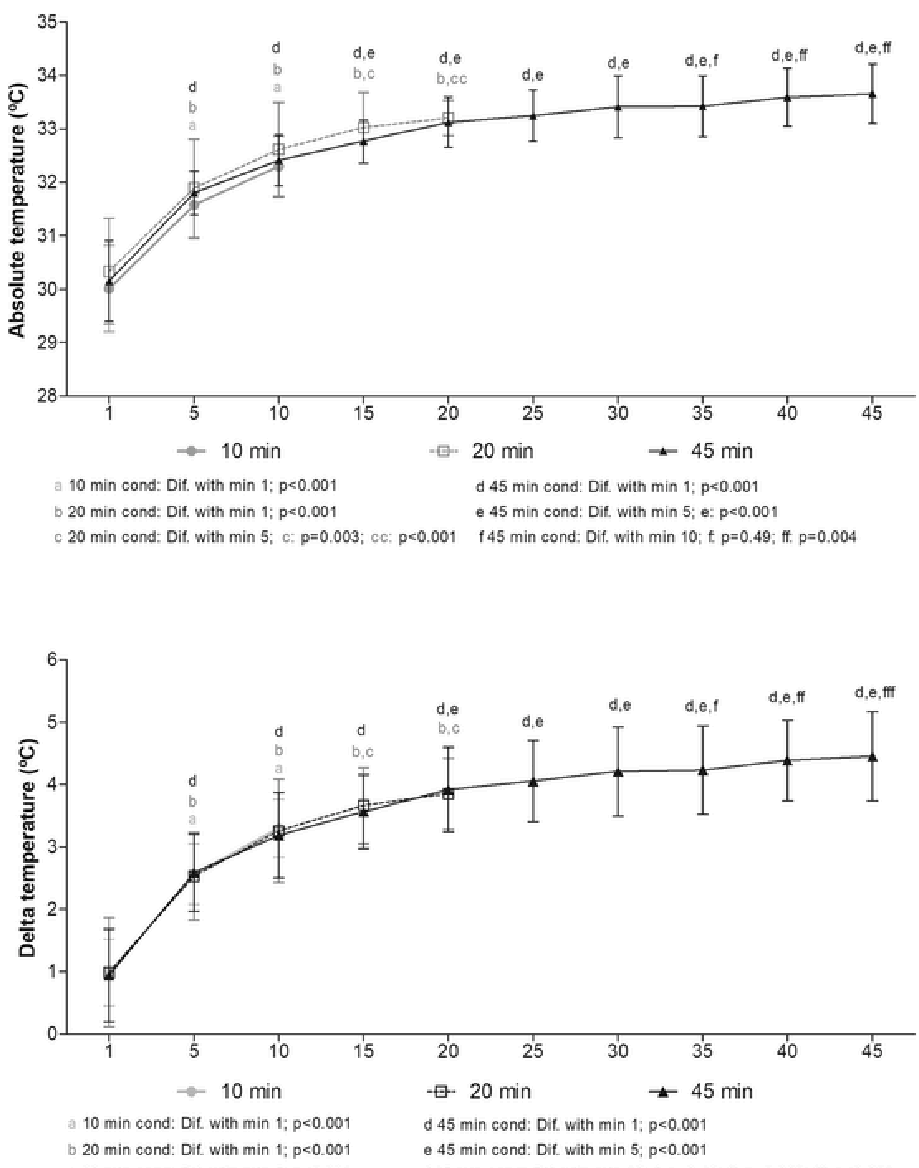

Fig. 3. Mean ± SD skin temperature evolution values throughout the three transition phases: absolute temperature (upper panel) and delta temperature (lower panel). The differences between time instants are also displayed.

Table 1
Mean ± SD values of first 15 m, each 25 m split and overall 100 m front crawl times, stroke frequency (SF), stroke length (SL), stroke index (SI) and propelling efficiency (η_p) at the different studied transition phases.

	10 min	20 min	45 min	p value	ES*d*	F (df)	η^2
First 15 m (s)	7.36 ± 0.40	7.47 ± 0.55	7.35 ± 0.41	0.16	0.2	(2,16) 2.03	0.20
1st 25 m (s)	13.93 ± 0.66	14.10 ± 0.71	13.96 ± 0.70	0.18	0.2	(6,48) 1.45	0.15
2nd 25 m (s)	15.60 ± 0.76	15.58 ± 0.77	15.54 ± 0.72	0.21	0.1		
3rd 25 m (s)	16.21 ± 0.96	16.24 ± 0.93	16.30 ± 0.98	0.21	0.1		
4th 25 m (s)	15.95 ± 1.20	15.96 ± 1.03	15.74 ± 0.94	0.50	0.1		
100 m trial (s)	61.69 ± 3.44	61.88 ± 3.27	61.54 ± 3.06	0.48	0.1	(2,16) 0.76	0.09
1st 25 m SF (Hz)	0.82 ± 0.03	0.82 ± 0.05	0.81 ± 0.04	0.69	0.3	(6,48) 0.65	0.07
2nd 25 m SF (Hz)	0.76 ± 0.05	0.75 ± 0.06	0.75 ± 0.04	0.69	0.2		
3rd 25 m SF (Hz)	0.74 ± 0.05	0.73 ± 0.05	0.74 ± 0.04	0.82	0.2		
4th 25 m SF (Hz)	0.73 ± 0.05	0.74 ± 0.05	0.75 ± 0.06	0.69	0.3		
1st 25 m SL (m)	2.12 ± 0.12	2.06 ± 0.17	2.14 ± 0.13	0.26	0.4	(6,48) 1.55	0.16
2nd 25 m SL (m)	2.09 ± 0.16	2.09 ± 0.20	2.12 ± 0.12	0.26	0.2		
3rd 25 m SL (m)	2.07 ± 0.16	2.07 ± 0.18	2.06 ± 0.18	0.18	0.1		
4th 25 m SL (m)	2.01 ± 0.16	1.96 ± 0.19	2.00 ± 0.19	0.33	0.3		
1st 25 m SI (Hz)	3.68 ± 0.35	3.50 ± 0.51	3.73 ± 0.37	0.12	0.5	(6,48) 1.40	0.15
2nd 25 m SI (Hz)	3.30 ± 0.42	3.26 ± 0.46	3.37 ± 0.35	0.50	0.3		
3rd 25 m SI (Hz)	3.18 ± 0.45	3.15 ± 0.40	3.14 ± 0.44	0.23	0.1		
4th 25 m SI (Hz)	2.98 ± 0.44	2.85 ± 0.43	2.98 ± 0.40	0.14	0.3		
1st 25 m η_p (%)	53.83 ± 2.78	52.14 ± 2.83	54.37 ± 3.58	0.26	0.7	(6,48) 1.49	0.16
2nd 25 m η_p (%)	52.96 ± 3.63	52.92 ± 3.88	53.74 ± 2.97	0.25	0.2		
3rd 25 m η_p (%)	52.39 ± 3.45	52.48 ± 3.40	52.20 ± 3.74	0.30	0.1		
4th 25 m η_p (%)	50.99 ± 3.09	49.61 ± 3.83	50.52 ± 3.19	0.40	0.4		

ESd: higher effect size observed in the paired comparisons between transition phases.

Material-Table 3). Moreover, at the 20 min transition phase, only a moderate correlation ($|r| = 0.77$, $p = 0.02$) was observed between the pre-test absolute temperature and recovery lactate (Supplementary Material-Table 4).

4. Discussion

This study analyzed skin temperature evolution during 10, 20 and 45 min transition phases that occurred between a standardized warm-up and a maximum exertion 100 m front crawl, and determined its effect on swimming performance. A temperature log increase over time (of no statistical significance between 15 min and the following instants) was observed with similar behavior (and no differences) between transition phases. In addition, no performance and psychophysiological differences were found between transition phases (only the pre-test absolute and delta skin temperature values were lower at the 10 min than the 20 and 45 min conditions). Finally, no relationship was observed between pre-test skin temperature and 100 m maximal performance times.

Warm-up routines lead to a body temperature increase, facilitating muscle metabolism and muscle fiber conduction velocity (Bishop, 2003; McGowan et al., 2016), but reductions in core temperature during transition phases (McGowan et al., 2017; Neiva et al., 2017; West et al., 2013) may mitigate its benefits, reducing athletes' performance (McGowan et al., 2017; Mohr et al., 2004). However, in swimming, the temperature of the skin decreases in the water and increases when leaving it (Domingues et al., 2017; Galbraith and Willmott, 2018; Novotny et al., 2015). It was, therefore, hypothesized that swimmers' skin temperature would increase throughout the transition phases, until stabilization. In line with our expectations, our data showed an increment of swimmers' skin temperature over time and there were no differences between the transition phases of different durations.

Previous studies have also found higher skin temperature after a 30 min transition phase but used rewarming strategies (Galbraith and Willmott, 2018; McGowan et al., 2017; McGowan et al., 2016). The skin temperature increase that we observed may be due to the fact that water heat conductivity is 25 times higher than in air (Alexious, 2014), so that water temperature equalizes body skin temperature just a few minutes after immersion. During exercise, a skin blood flow vasoconstriction is expected, which reduces heat transference between the muscle and the skin, resulting in a higher muscle and, subsequently, core temperature (Charkoudian, 2003; Tanda, 2018).

When core temperature is too high, heat dissipation mechanisms are activated increasing skin blood flow. By doing so the high-temperature gradient between the muscle and the skin causes heat transference between both tissues (Charkoudian, 2003; Tanda, 2018). For this reason, skin temperature increases and muscle temperature decreases until thermal equilibrium is reached. In addition, in the current study, skin temperature gradually returned to initial values when swimmers got out of the water after the warm-up, probably also as a consequence of the vasoconstriction reduction produced by the skin sympathetic nerve when the water cooling effect diminished (Sawasaki et al., 2001).

The current study is a pioneer in evaluating the skin temperature time course evolution during transition phases of different durations. A logarithmic growth, i.e. a fast initial increase followed by a stabilization after 10 min, was observed with no differences between 15 min and the following instants. This skin temperature behavior from the end of the warm-up until the maximum trial is similar to the rewarming process after skin cold stress application (Priego-Quesada et al., 2020; Sawasaki et al., 2001). This corroborates the water-cooling effect in swimmers' skin temperature and emphasizes the relevance of implementing future studies that aim to relate skin and core temperatures with muscle physiology under water immersion and swimming warm-up conditions.

Although better swimming performances after shorter transition phases were observed due to the maintenance of warm-up benefits (Cuenca-Fernández et al., 2019; Neiva et al., 2017; West et al., 2013), we did not detect any difference despite analyzing transition phases of different durations. Furthermore, the effect sizes between the paired comparisons were small. This lack of differences seems not to be justified by: (i) swimmers' tactics, given that 100 m exertions were similar to those described previously (Almeida-Coelho et al., 2016; Ribeiro et al., 2017) and (ii) swimmers demotivation, since they obtained good 100 m front crawl performances, presenting similar values to the literature for this particular age (Bond et al., 2015; McGowan et al., 2016) and slightly lower for swimmers of the subsequent age-group (Almeida-Coelho et al., 2016; Ribeiro et al., 2015).

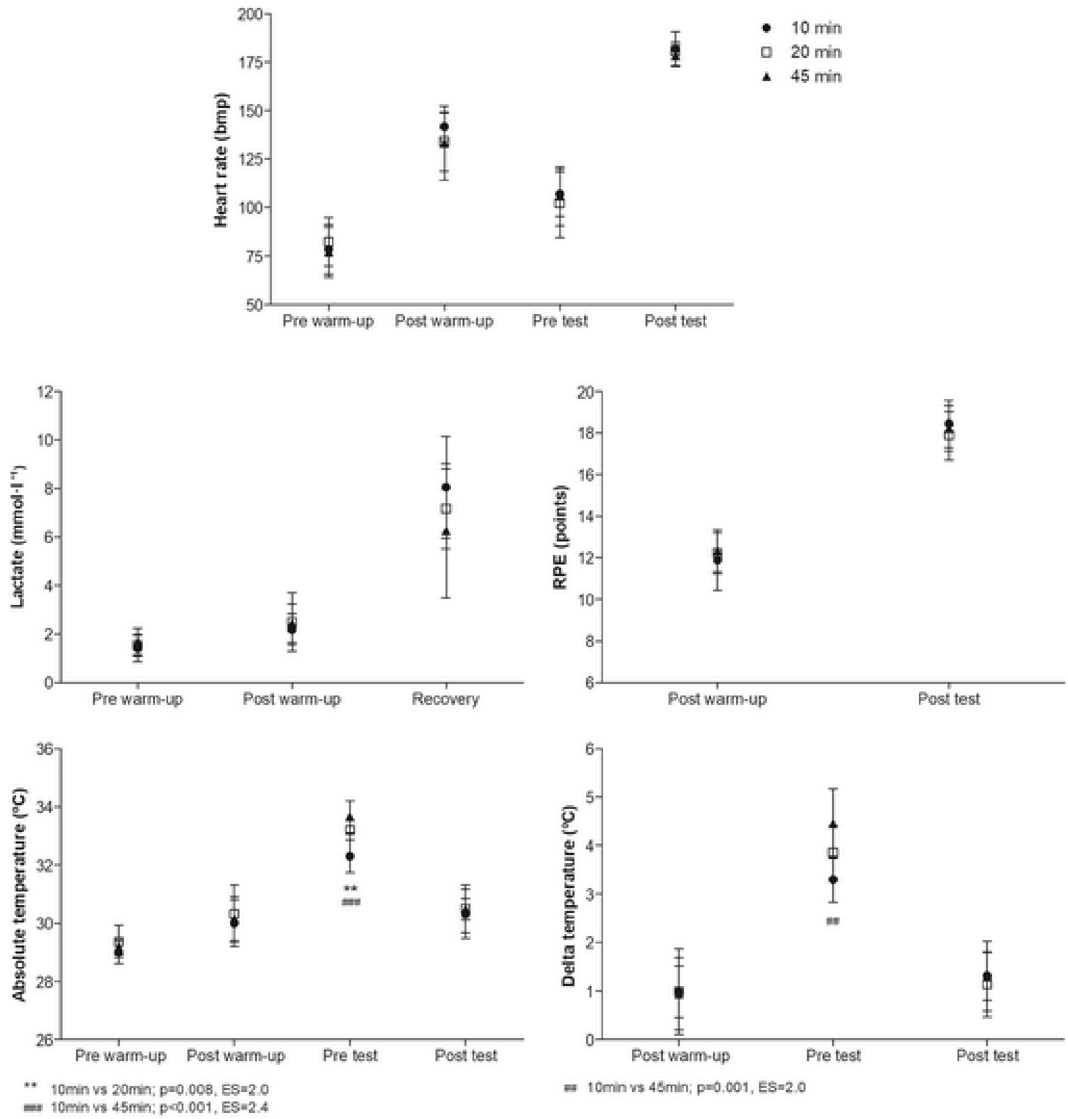

Fig. 4. Mean ± SD psychophysiological (heart rate, lactate and rate of perceived exertion - RPE) and absolute and delta skin temperature values in the different evaluation moments at the 10, 20 and 45 min transition phases.

In addition, the measured HR and [La⁻] values also evidenced that the 100 m bouts were performed at high intensity and the RPE scores indicate a very hard to extremely hard effort perception. Identical psychophysiological values have also been reported in adolescent swimmers (Lätt et al., 2010; McGowan et al., 2016; Rodríguez et al., 2016), with the not very high [La⁻] after short front crawl exertions being common due to the limited and poorly trained ability of young people to generate anaerobic energy (Ribeiro et al., 2015; Taylor et al., 2003).

Performance improvements in shorter transition phases have been attributed to lower HR values immediately before the test (Neiva et al., 2017; Zochowski et al., 2007). In the current study, the pre-test HR values among transition phases were similar, indicating that the three 100 m trials started under the same conditions and were not affected by the different durations of the transition phases. Possibly the specific characteristics of our swimmers (young swimmers with a medium competitive level and experience) might justify the data obtained. Furthermore, our swimmers could have presented better recovery capacity since they dropped from ~140 to ~100 bpm between the end of warm-up and before beginning the test regardless of the duration of the transition phase.

Muscle temperature immediately before the competitive event is also a key factor in sports performance, specifically in power-based and sprint exercise modes (Bishop, 2003; McGowan et al., 2016). Due to the physiological process of heat exchange between muscle and skin (Charkoudian, 2003; Tanda, 2018), core and skin temperatures can also be of great interest at this particular time. In the current study, the pre-test skin temperature was lower at the 10 min than the 20 and 45 min transitions. However, one previous study observed a different temperature in the shortest transition phase, in this case, finding higher values because it analyzed core temperature (West et al., 2013). These differences between transition phases could be due to the longer waiting time, as because after the warm-up both psychophysiological and temperature variables were similar, indicating that it was carried out with the same intensity in the three transition phases.

Moreover, since it has been reported an association between a smaller decline in core temperature during transition phases and swimming performance improvements (McGowan et al., 2016) has been reported, we also hypothesized that skin temperature would directly be related to subsequent performance. However, no relevant relationship was observed between temperature variables before performance and the 100 m trial for any of the three transition durations. This could be explained by the lack of differences in performance variables between the three transition phases, contrary to what is described in the literature (Neiva et al., 2017; West et al., 2013; Zochowski et al., 2007).

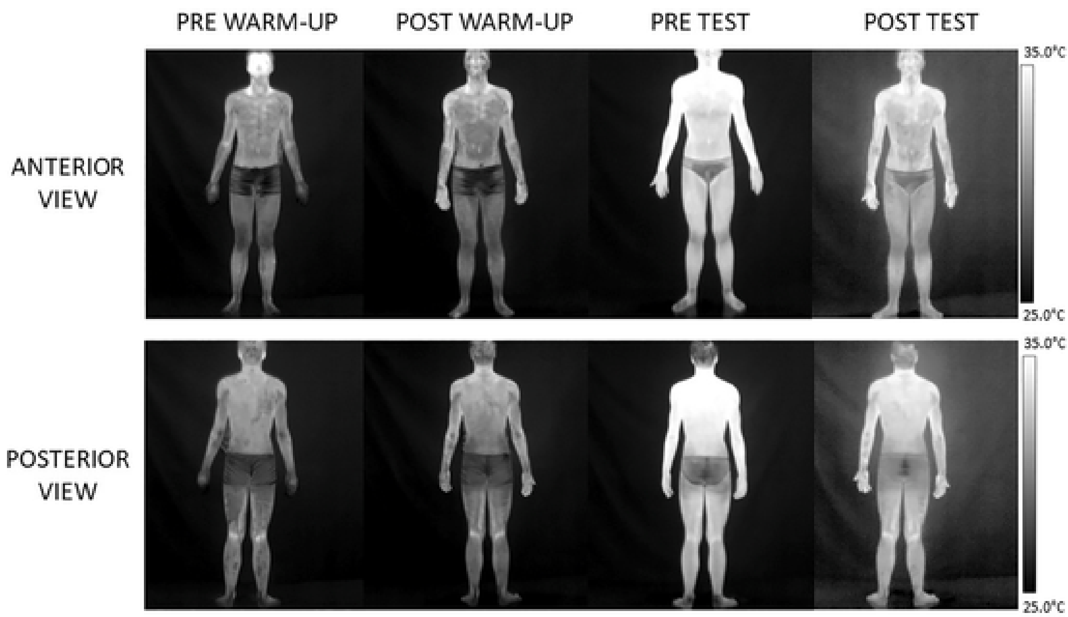

Fig. 5. Sequence of thermograms with the different evaluation moments of a swimmer.

Table 2
Relationships between pre-test skin temperature and 100 m front crawl times for the three transition phases studied.

		Absolute temperature Pre test	Delta temperature Pre test
		10 min transition phase	
100 m trial 10 min	r	0.19	−0.29
	p	0.63	0.45
		20 min transition phase	
100 m trial 20 min	r	0.57	0.63
	p	0.11	0.07
		45 min transition phase	
100 m trial 45 min	r	0.03	−0.01
	p	0.95	0.99

Similarly, no correlation was found between pre-test skin temperature and heart rate after the trial. However, recovery lactate showed a negative relationship with temperature before the test, only in the 20 min transition phase. This result could show that at higher pre-test skin temperatures (where a greater warming-up effect has been lost) lower lactate values are reached, making swimmers unable to perform with maximum effort. Nevertheless, this idea is only speculation as this relationship has not been observed in the other two transition phases. Finally, all these facts provide evidence that skin temperature is not a good predictor of short swimming events and support the idea that swimmers' determinants are multifactorial, including many more variables than just skin temperature (Lätt et al., 2010; Neiva et al., 2017; Ribeiro et al., 2017).

One limitation of the current study was that core and muscle temperatures were not measured. In fact, it would be interesting to check if they show an inverse behavior to the one displayed by skin temperature. Baseline temperature without previous adaptation to the water was also not measured, so making it impossible to compare to what extent temperature decreases in the water and recovers after the warm-up. However, the current study also presents some important strengths and practical applications related to the effect of warm-up on skin temperature and performance. Our results demonstrate, in a quantitative manner, the behavior of temperature during the transition phases by establishing the moment at which the effect of warm-up begins to fade. These results, therefore, could be compared to previous studies that have analyzed heating garments and additional warm-up exercises (Galbraith and Willmott, 2018; McGowan et al., 2016; Wilkins and Havenith, 2017), defining the moment from which these strategies would be most useful.

The small number of participants of the current study and their characteristics could also have affected the results. Future studies, therefore, should analyze a larger, older and more experienced sample, and observe skin temperature behavior whether performance differences are found between transition phases of different durations. In addition, longer tests could affect thermal behavior, so further research should carried out on that issue. Likewise, the study of the thermal map of the body, focusing on the most active muscle groups in swimming, would be worthy of analysis. Finally, it would also be interesting to study this topic specifically using female swimmers, since men and women present important physiological differences (Wardle, 2017), particularly regarding body composition, which decisively affects swimming economy (Fernandes et al., 2005).

5. Conclusions

Swimmers' skin temperature after a standard warm-up increases rapidly up to the 10 min transition phase after which it tends to stabilize. Therefore, transition phases longer than 10 min will not bring about thermal changes related to improved performance. This data suggest that skin temperature is not a good predictor of performance in short swimming events in adolescent swimmers.

Acknowledgements

We are grateful to swimmers and coaches from Clube de Natação de Valongo for their voluntary participation in this study, and to academics for their collaboration during data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2021.102926.

Funding

The work of IJP was supported by the Ministry of Science, Innovation and Universities of the Spanish Government (FPU 14/05626).

Declaration of interest statement

The authors report no conflict of interest.

References

Alexious, S., 2014. The effect of water temperature on the human body and the swimming effort. Biology of Exercise 10 (2), 9–23.

Almeida-Coelho, J., Fernandes, R.J., Vilas-Boas, J.P., 2016. Metabolic and technical changes in swimmers during a 100-m all-out front crawl. Trends in Sport Sciences 23 (4), 177–183.

Balilionis, G., Nepocatych, S., Ellis, C.M., Richardson, M.T., Neggers, Y.H., Bishop, P.A., 2012. Effects of different types of warm-up on swimming performance, reaction time, and dive distance. J. Strength Condit Res. 26 (12), 3297–3303.

Bishop, D., 2003. Warm up II: performance changes following active warm up and how to structure the warm up. Sports Med. 33 (7), 483–498. https://doi.org/10.2165/00007256-200333070-00002.

Bobo, M., 1999. The effect of selected types of warm-up on swimming performance. Int. Sports J. 3 (2), 37–43.

Bond, D., Goodson, L., Oxford, S.W., Nevill, A.M., Duncan, M.J., 2015. The association between anthropometric variables, functional movement screen scores and 100 m freestyle swimming performance in youth swimmers. Sports 3 (1), 1–11.

Borg, G.A., 1982. Psychophysical bases of perceived exertion. Med. Sci. Sports Exerc. 14 (5), 377–381.

Charkoudian, N., 2003. Skin blood flow in adult human thermoregulation: how it works, when it does not, and why. Mayo Clin. Proc. 78 (5), 603–612.

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences (second ed.). Routledge. https://doi.org/10.4324/9780203771587

Cuenca-Fernández, F., López-Contreras, G., Mourão, L., de Jesus, K., de Jesus, K., Zacca, R., Vilas-Boas, J.P., Fernandes, R.J., Arellano, R., 2019. Eccentric flywheel post-activation potentiation influences swimming start performance kinetics. J. Sports Sci. 37 (4), 443–451.

de Andrade Fernandes, A., dos Santos Amorim, P.R., Brito, C.J., de Moura, A.G., Moreira, D.G., Costa, C.M.A., Sillero-Quintana, M., Marins, J.C.B., 2014. Measuring skin temperature before, during and after exercise: a comparison of thermocouples and infrared thermography. Physiol. Meas. 35 (2), 189.

Domingues, A. S., Barbosa, F., Seixas, A., Borgonovo-Santos, M., Pereira, E. M., Vardasca, R., Gabriel, J., Fernandes, R. J., & Vilas-Boas, J. P. (2017). Infrared thermography in swimming: thermal characterization of swimming technique. In Innovative Research in Thermal Imaging for Biology and Medicine (pp. 199–219). IGI Global.

Fernandes, R., Billat, V., Cruz, A., Colaço, P., Cardoso, C., Vilas-Boas, J.P., 2005. Has gender any effect on the relationship between time limit at VO (2) max velocity and swimming economy?. J. Hum. Mov. Stud. 49, 127–148.

Galbraith, A., Willmott, A., 2018. Transition phase clothing strategies and their effect on body temperature and 100-m swimming performance. Eur. J. Sport Sci. 18 (2), 182–189.

Hildebrandt, C., Zeilberger, K., Ring, E.F.J., Raschner, C., 2012. The application of medical infrared thermography in sports medicine. Ultrasound 10, 2.

Jutte, L.S., Merrick, M.A., Ingersoll, C.D., Edwards, J.E., 2001. The relationship between intramuscular temperature, skin temperature, and adipose thickness during cryotherapy and rewarming. Arch. Phys. Med. Rehabil. 82 (6), 845–850.

Kilduff, L.P., Finn, C.V., Baker, J.S., Cook, C.J., West, D.J., 2013. Preconditioning strategies to enhance physical performance on the day of competition. Int. J. Sports Physiol. Perform. 8 (6), 677–681.

King, A., 1979. The relative effects of various warm-up procedures on 50 meter times of trained, competitive swimmers. J. Phys. Educ. 7 (3), 22–24.

Lätt, E., Jürimäe, J., Mäestu, J., Purge, P., Rämson, R., Haljaste, K., Keskinen, K. L., Rodriguez, F.A., Jürimäe, T., 2010. Physiological, biomechanical and anthropometrical predictors of sprint swimming performance in adolescent swimmers. J. Sports Sci. Med. 9 (3), 398.

McGowan, C.J., Pyne, D.B., Raglin, J.S., Thompson, K.G., Rattray, B., 2016a. Current warm-up practices and contemporary issues faced by elite swimming coaches. J. Strength Condit Res. 30 (12), 3471–3480.

McGowan, C.J., Pyne, D.B., Thompson, K.G., Raglin, J.S., Osborne, M., Rattray, B., 2017. Elite sprint swimming performance is enhanced by completion of additional warm-up activities. J. Sports Sci. 35 (15), 1493–1499.

McGowan, C.J., Pyne, D.B., Thompson, K.G., Rattray, B., 2015. Warm-up strategies for sport and exercise: mechanisms and applications. Sports Med. 45 (11), 1523–1546.

McGowan, C.J., Thompson, K.G., Pyne, D.B., Raglin, J.S., Rattray, B., 2016b. Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance. J. Sci. Med. Sport 19 (4), 354–358.

Mohr, M., Krustrup, P., Nybo, L., Nielsen, J.J., Bangsbo, J., 2004. Muscle temperature and sprint performance during soccer matches–beneficial effect of re-warm-up at half-time. Scand. J. Med. Sci. Sports 14 (3), 156–162.

Moreira, D.G., Costello, J., Brito, C.J., Sillero-Quintana, M., 2017. A checklist for measuring skin temperature with infrared thermography in sports and exercise medicine. Thermology International 27 (4), 136–138.

Neiva, H.P., Marques, M.C., Barbosa, T.M., Izquierdo, M., Viana, J.L., Marinho, D.A., 2017. Effects of 10 min vs. 20 min passive rest after warm-up on 100 m freestyle time-trial performance: a randomized crossover study. J. Sci. Med. Sport 20 (1), 81–86.

Neiva, H.P., Marques, M.C., Fernandes, R.J., Viana, J.L., Barbosa, T.M., Marinho, D.A., 2014. Does warm-up have a beneficial effect on 100-m freestyle?. Int. J. Sports Physiol. Perform. 9 (1), 145–150.

Novotny, J.A.N., Rybarova, S., Zacha, D., Bernacikova, M., Ramadan, W.A., 2015. The influence of breaststroke swimming on the muscle activity of young men in thermographic imaging. Acta Bioeng. Biomech. 17 (2), 121–129.

O'Rourke, N., Hatcher, L., & Stepanski, E. J. (2005). A Step-by-step Approach to Using SAS for Univariate & Multivariate Statistics. SAS institute.

Peterson Silveira, R., Soares, S.M., Zacca, R., Alves, F.B., Fernandes, R.J., Castro, F.A. de S., Vilas-Boas, J.P., 2019. A biophysical analysis on the arm stroke efficiency in front crawl swimming: comparing methods and determining the main performance predictors. Int. J. Environ. Res. Publ. Health 16 (23), 4715.

Priego Quesada, J. I., Kunzler, M. R., & Carpes, F. P. (2017). Methodological aspects of infrared thermography in human assessment. In Application of Infrared Thermography in Sports Science (pp. 49–79). Springer.

Priego Quesada, J.I., Martínez, N., Palmer, R.S., Psikuta, A., Annaheim, S., Rossi, R.M., Corberán, J.M., de Anda, R.M.C.O., Pérez-Soriano, P., 2016. Effects of the cycling workload on core and local skin temperatures. Exp. Therm. Fluid Sci. 77, 91–99.

Priego-Quesada, J.I., Pérez-Guarner, A., Gandia-Soriano, A., Oficial-Casado, F., Galindo, C., de Anda, R.M.C.O., Pineiro-Ramos, J.D., Sánchez-Illana, Á., Kuligowski, J., Barbosa, M.A.G., 2020. Effect of a marathon on skin temperature response after a cold-stress test and its relationship with perceptive, performance, and oxidative-stress biomarkers. Int. J. Sports Physiol. Perform. 1, 1–9.

Ribeiro, J., Figueiredo, P., Sousa, A., Monteiro, J., Pelarigo, J., Vilas-Boas, J.P., Toussaint, H.M., Fernandes, R.F., 2015. VO2 kinetics and metabolic contributions during full and upper body extreme swimming intensity. Eur. J. Appl. Physiol. 115 (5), 1117–1124. https://doi.org/10.1007/s00421-014-3093-5.

Ribeiro, J., Figueiredo, P., Morais, S., Alves, F., Toussaint, H., Vilas-Boas, J.P., Fernandes, R.J., 2017. Biomechanics, energetics and coordination during extreme swimming intensity: effect of performance level. J. Sports Sci. 35 (16), 1614–1621.

Rodríguez, F.A., Lätt, E., Jürimäe, J., Maestu, J., Purge, P., Rämson, R., Haljaste, K., Keskinen, K.L., Jürimäe, T., 2016. VO2 kinetics in all-out arm stroke, leg kick and whole stroke front crawl 100-m swimming. Int. J. Sports Med. 37 (3), 191–196.

Sawasaki, N., Iwase, S., Mano, T., 2001. Effect of skin sympathetic response to local or systemic cold exposure on thermoregulatory functions in humans. Auton. Neurosci. 87 (2–3), 274–281.

Steketee, J., 1973. Spectral emissivity of skin and pericardium. Phys. Med. Biol. 18 (5), 686.

Tanda, G., 2018. Total body skin temperature of runners during treadmill exercise. J. Therm. Anal. Calorim. 131 (2), 1967–1977.

Taylor, S., MacLaren, D., Stratton, G., & Lees, A. (2003). The Effects of Age, Maturation and Growth on Tethered Swimming Performance. Biomechanics and Medicine in Swimming IX. Saint-Étienne, 2003b, 185–190.

Vardasca, R., Seixas, A., Gabriel, J., & Vilas-Boas, J. (2017). Infrared thermography in water sports. In Application of Infrared Thermography in Sports Science (pp. 137–157). Springer.

Wardle, S., 2017. Sex differences in thermoregulation: implications for physical performance. J. Sci. Med. Sport 20, S16.

West, D.J., Dietzig, B.M., Bracken, R.M., Cunningham, D.J., Crewther, B.T., Cook, C.J., Kilduff, L.P., 2013. Influence of post-warm-up recovery time on swim performance in international swimmers. J. Sci. Med. Sport 16 (2), 172–176.

Wilkins, E.L., Havenith, G., 2017. External heating garments used post-warm-up improve upper body power and elite sprint swimming performance. Proc. Inst. Mech. Eng. P J. Sports Eng. Technol. 231 (2), 91–101.

Zaidi, H., Fohanno, S., Polidori, G., Taiar, R., 2007. The influence of swimming type on the skin-temperature maps of a competitive swimmer from infrared thermography. Acta Bioeng. Biomech. 9 (1), 47.

Zochowski, T., Johnson, E., Sleivert, G.G., 2007. Effects of varying post-warm-up recovery time on 200-m time-trial swim performance. Int. J. Sports Physiol. Perform. 2 (2), 201–211.