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Training in hot water immersion improved exercise performance in hot and humid conditions in recreational athletes - a randomized controlled trial

G Helmer ¹, M Laurent ², J Rubio ^{2 3}, C Duflos ⁴, M Hayot ⁵, J Myzia ⁵, C Hedon ⁵, F Gouzi ⁵, R Candau ², S Racinais ^{2 3}, M Julia ^{3 6}

¹ PhyMedExp, INSERM, CNRS, CHRU Montpellier, Montpellier University, Montpellier, France. g-helmer@chu-montpellier.fr.

² DMEM. Montpellier University, INRAE, Montpellier, France.

³ CREPS Montpellier Font-Romeu, Montpellier, France.

⁴ Clinical Research and Epidemiology Unit, Montpellier University Hospital, Univ Montpellier, Montpellier, France.

⁵ PhyMedExp, INSERM, CNRS, CHRU Montpellier, Montpellier University, Montpellier, France.

⁶ Department of Physical Medicine and Rehabilitation, Sport Medicine Federation, CHRU Montpellier, Montpellier University, Montpellier, France.

Keywords:

Acclimation; Athletes; Core temperature; Hot water exercise; Performance; Skin temperature.

E-mail:

G. Helmer

g-helmer@chu-montpellier.fr

Abstract

Background and objective:

Heat acclimation is a common strategy for athlete preparing to compete in the heat. It is generally obtained by exercising in a hot environment, (e.g. environmental chambers) but passive exposure to hot water has also been shown to induce acclimation. Thus, combining exercise in hot water could be an innovative method to enhance performance in hot environments.

Methods:

In this prospective randomized controlled trial, two groups of 12 participants (22 males/2 females) underwent 10 aerobic training sessions on an underwater bike in either hot (35 °C- hot water acclimation, HWA) or temperate (25 °C, control, CON) water. Two to three days before and after intervention participants performed a 30-min time trial, in a hot and humid environment (T° : 38.4 ± 1.4 °C, Relative Humidity: $45.3 \pm 6.9\%$), as well as a cardiac echography, a blood analysis and a cardiopulmonary exercise test ($\dot{V}O_{2max}$) in temperate ambient conditions.

Results:

The distance covered during the time trial in the heat increased depending on group ($p = 0.024$) with an increase of 1.1[+ 0.7, + 1.4]km in HWA ($p < .001$) and 0.5[+ 0.1, + 0.8]km in CON ($p = 0.009$). As well as power output ($p = 0.096$) improved more in the HWA vs. CON group (+ 27W in HWA and + 13W in CON). However, no difference between groups was observed regarding changes in physiological parameters during the time trial in the heat (core and skin temperature, sweat rate) or across the tests and measures in temperate environments (plasma volume, heart rate, $\dot{V}O_{2max}$).

Conclusion:

Exercise on a bike in hot water improves performance in hot and humid conditions but does not induce change physiological parameters in ambient conditions.

Clinicaltrials:

gov Identifier: NCT05727774.

Introduction

Exercising in hot and/or humid ambient conditions induces a thermal stress leading to a cardiorespiratory stress and a reduction in performance (Racinais et al. 2015).

However, repeated heat exposures trigger specific adaptations called heat acclimation (in cases of artificial exposures) or heat acclimatization (in case of natural exposures) (Tyler et al. 2016). Those adaptations include an increase in sweat rate, a reduction in resting and exercising core and skin temperature, an increase in plasma volume and ultimately allow a reduction in cardiovascular strain and an increase in endurance performance in the heat (Racinais et al. 2015; Lorenzo et al. 210). Heat acclimation is actually considered as the most important countermeasures that athletes should adopt before competing in the heat to protect their health and performance (Racinais et al. 2015, 2023). Current recommendations include to complete a period of heat acclimation prior to competing or operating in the heat, which requires to repeat exercise sessions in the heat (typically 5–14 sessions of 60-min) allowing central core and skin temperature to elevate and to initiate perfuse sweating (Racinais et al. 2015; Taylor 2014).

While athletes can perform training camps in hot countries to gain heat acclimation, this poses financial and logistical challenges that may impact the preparation of the athletes (Racinais and Périard 2020). As such, numerous athletes aim for heat acclimation using various methods ranging from active to passive heat exposures (Daanen et al. 2018). While current training methods requires to exercise in hot air, passive methods often rely on hot water immersions as water is a better thermal conductor than air, which means better heat transfer to the body (Thermal conductivity: Air 0.026W/m/K at 25°) and Water 0.6089W/m/K at 26,85 °C) (Leçon. 2025).

For example, passive immersion in hot water acts on cellular signaling pathways that induce adaptive mechanisms similar to those observed during aerobic exercise in heat (Cullen et al. 2020). Thus, hot water immersion protocols after exercise have shown evidence of acclimation, with improved performance in hot, humid environments (McIntyre et al. 2021; Greenfield et al. 2021), including reductions in resting and heat-exercise T_{c} , as well as exercise T_{sk} (Zurawlew et al. 2018). Moreover, hot water immersion stimulates peripheral sweating in response to the increase of the skin temperature the thermoregulatory response is modulated by the high thermal conductivity and hydrostatic pressure of water (Nadel 1984).

A downside of using hot water immersion for passive heat acclimation is the need to use water temperature of 42 °C (Daanen et al. 2018) which is the upper limit tolerable. While such passive exposure may benefit athlete unable to train (Dablainville et al. 2025), combining cycling with hot water immersion would allow to reduce the external thermal stimulus as the athletes will already be producing metabolic heat (Daanen et al. 2018). Indeed, heat exposure might potentiate the adaptations elicited by physical exercise— a concept previously raised in the literature (Cullen et al. 2020). In this context, only one study has investigated the effects of the combination of aerobic training and hot water exposure on adaptation to exercise in a hot environment (Young et al. 1995). The authors found no changes in the lactate accumulation of training at 35 °C, or at skin and core temperature, compared with training in cold water. While the chronic adaptation to exercising in hot water was not investigated in that study, it demonstrated the safety of cycling in hot water at 35 °C.

Thus, the first aim of the current study was to compare the effect of aerobic immersion training in hot thermal water (35 °C) versus training in temperate thermal water (25°C). While it was hypothesized that performance would be improved during a cycle time in hot and humid conditions (environmental chamber at 38 °C and 50% humidity), the underlying physiological adaptations were uncertain. Indeed, on one hand, the combination of hot water immersion and aerobic exercise could exert a synergistic effect and lead to larger acclimation, but, on the other hand, hot water immersion could interfere in the sweating responses one of the main acclimation responses (Nadel ER. 1984; Flouris and Schlader. 2015). Secondary aims were to characterise the improvements in aerobic fitness in temperate ambient conditions maximal aerobic power (MAP) and $\dot{V}O_2\text{max}$ during an incremental test on a cycloergometer in neutral conditions.

Methods

Participants

This prospective randomized controlled study was conducted in line with the Declaration of Helsinki and the European guidelines for good clinical practice and was preregistered in www.clinicaltrials.gov (ClinicalTrials.gov Identifier: NCT05727774). Volunteers provided written informed consent to participate in the study (Ethics Committee No. 2022-A01631-42). Inclusion criteria were as follows: age between 18 and 50 years, cyclists or triathletes. Both men and women could be included.

The tests took place between February and March in Montpellier (France) and no participant was to have been exposed to hot conditions in the 2 months preceding the start of testing. Participants were asked to restrict alcohol and caffeine intake in the 12 h prior to each test. Participants were free to follow their training outside the protocol. The training load of the participants outside the training protocol was calculated based on the declaration of the participants: duration of the sessions * intensity perceived by the participants (RPE).

A G*Power analysis (Version 3.1.9.7) determined that 20 subjects in total were needed to determine performance effects on a similar protocol 17 using an effect size of 0.6, power of 0.8 and alpha risk of 0.05.

From February 2023 to March 2023, after screening, 24 participants who gave written informed consent to take part in the study were randomized. 23 completed the study as one patient in the hot-water acclimation (HWA) group discontinued the study due to an acute bronchitis before the post-test (Fig. 1). Subjects in both groups were similar in terms of age, gender, $\dot{V}O_2\text{max}$, and Pmax. (Table 1).

Central randomization stratified for $\dot{V}O_2\text{max}$ and gender was performed after the inclusion test to force comparability of the 2 groups on these parameters. Participants were not aware of the study hypothesis and the investigators and methodologist were blinded during outcomes assessment and statistical analysis.

Fig. 1 Study participant flow-chart

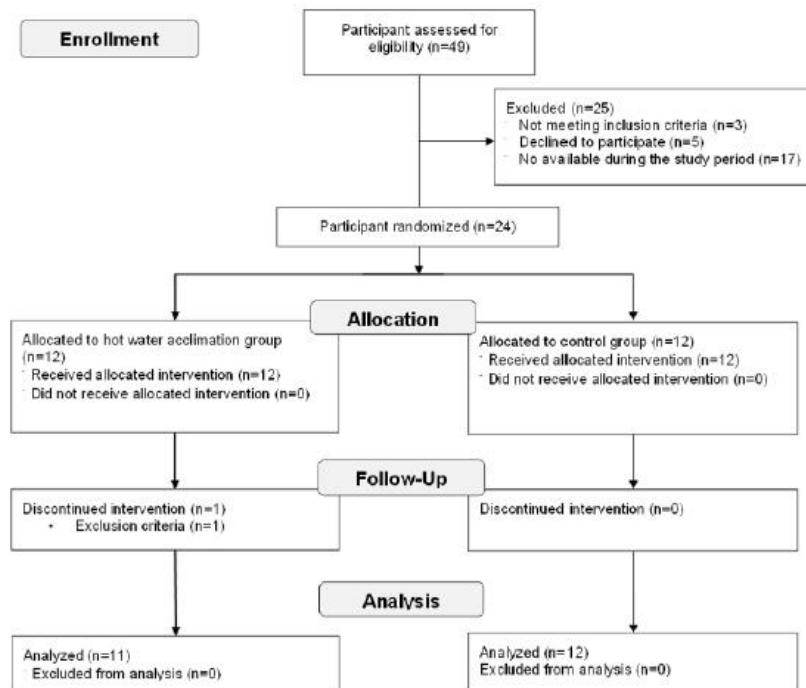


Table 1 Characteristics of participants

	HWA (35°C) n = 12	CON (25°C) n = 12	Difference 35°/25° (IC 95%)
Sex, F n / H n	1/11	1/11	
Age (years)	33.58 ± 13.61	32.67 ± 11.62	0.92 (– 9.8; 11.63)
Height (cm)	174.96 ± 5.86	178.29 ± 4.92	– 3.33 (– 7.91; 1.25)
Hemoglobin (g/dL)	14.31 ± 0.72	14.70 ± 0.92	– 0.39 (– 1.09; 0.31)
V̇O ₂ max (ml/min/kg)	47.53 ± 9.20	44.02 ± 7.40	3.52 (– 3.55; 10.58)
Aerobic maximal power AMP (watts)	289.58 ± 27.01	304.58 ± 65.90	– 15 (– 58.93; 28.93)
Maximal heart rate (bpm)	181.58 ± 7.46	179.33 ± 10.10	2.25 (– 5.27; 9.77)
Power@VT1 (watts)	189.17 ± 27.12	175.42 ± 42.40	13.75 (– 16.38; 43.88)
Heart rate@VT1 (bpm)	145.17 ± 10.69	141.17 ± 21.32	4 (– 10.58; 18.58)
LVEF (%)	66.96 ± 2.69	66.62 ± 4.66	0.35 (– 3.04; 3.73)
Index cardiac output (l/min/m ²)	3.35 ± 0.80	3.30 ± 0.63	0.05 (– 0.59; 0.7)

Study protocol

The study was a prospective, randomized, controlled, open-label study comparing recreational athletes' performance before and after experimental or control intervention. Participants trained for 10 sessions of 60-min over a 2-week period. Training consisted of cycling underwater with the body immersed up to the waist and the water temperature for warm-water acclimation (HWA) set at 35 °C, while the water temperature for the control group (CON) was set at 25 °C. Participants completed the sessions at the same time of day to minimise any effect of the circadian rhythm.

The training started 3 to 5 days after the pre-test. The protocol was identical for both groups, with the 10 training sessions carried out in thermal water (Thermes de Balarucles- Bains, Balaruc-les-Bains, France), but the water temperature differed between the group (Fig. 2). Each workout was performed on an INOBIKE 8 aquabike (Water□ex, Rousset, France) immersed up to the waist and consisted of 60 min of aquabike at a heart rate corresponding to the first ventilatory threshold (VT1) + 10% (PolarH10, Polar, Kimpele, Finland). Each VT1 was determined during a cardiopulmonary exercise test (CPET) before the training program. Participants were free to drink during training sessions.

Primary outcome

The primary outcome of the study was the gain in distance covered in the time trial between the pre-intervention test and the post-intervention test.

Tests and Measures

Tests in hot environment

A time trial was performed in a hot environmental room (38.4 ± 1.4 °C, $45.3 \pm 6.9\%$ Relative Humidity (RH)). The task was to complete the longest possible distance over 30 min on a cycloergometer (Nucleus Wattbike, Nottingham, England). Participants could freely adjust their pedalling cadence and the ergometer resistance. During the test, participants had access to test information (elapsed time, distance covered, average power, cadence). Heart rate was measured continuously at 1 Hz (Polar H10, Kimpele, Finland) to determine average heart rate over the duration of the test. Rectal temperature (T_{re}) was measured continuously by eCelsius capsules (BodyCap, Hérouville, France). Skin temperature (T_{sk}) was measured continuously using 4 sensors placed on the pectoral, upper arm, thigh and shin. Skin temperature was calculated as per Ramanathan weighted average (Davie and Amoore 2010; Ramanathan 1964). Sweat sodium concentration was measured after the test as the average of 2 measurements using a LAQUAtwin ionometer (HORIBA, Kyoto, Japan). Sweat rate was estimated during time trials from the pre- and post-exercise body weight and difference corrected for water intake (Vogt and Metz 1968). The water consumption was ad libitum. At the end of the test, distance covered, average heart rate and average power were collected from the ergo-cycle.

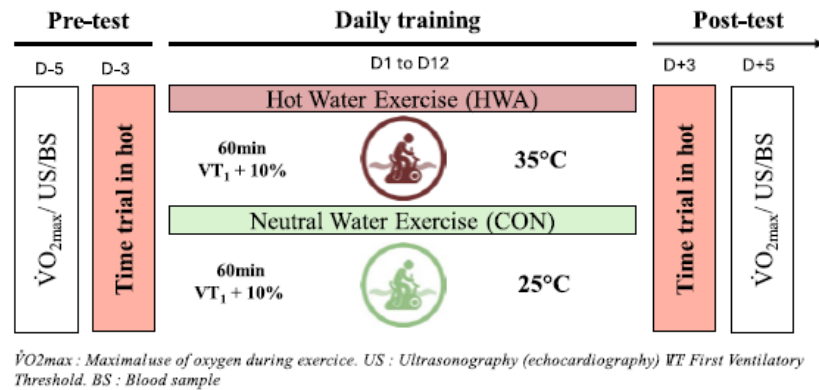
Tests in neutral environment

Venous blood analysis

A venous blood sample was collected from the arm of the participants by a nurse of the hospital. There was at rest, before the first cardiopulmonary exercise test and they did the same after the protocol in the same conditions. There were two types of tube (one EDTA tube for the haematological parameters and one dry tube for the ionogram, Vacutainer ®, BD, Canada).

The goal was to study variations in haemoglobin, haematocrit and mean corpuscular volume (Analyser XN-9100®, Sysmex, France).

Fig. 2 Study design. $\dot{V}O_{2max}$ Maximal use of oxygen during exercise, *US* Ultrasonography (echocardiography), *FVT* First ventilator threshold, *BS* blood sample



Transthoracic echocardiography

Echocardiographic images were obtained at rest, lying down, using a commercially available ultrasound system (Vivid S70®, GE Healthcare, Chicago, Illinois, USA). Images, recorded with five ECG-triggered cardiac cycles, were analysed offline using EchoPac 205 software (GE Healthcare, Chicago, Illinois, USA), averaging data from three cardiac cycles to assess standard echocardiographic parameters and myocardial work. This involved integrating the left ventricle global longitudinal strain and intra-left ventricle pressure, estimated non-invasively from brachial systemic blood pressure measurements, taken just before echocardiography (Russell et al. 2012).

Cardiopulmonary exercise test

Participants performed a cardiopulmonary exercise test (CPET) on an electromagnetically braked cycle ergometer (Ergoline Bosch 500, Ergoline) connected to a breath-by-breath device (COSMED Quark cardiopulmonary exercise testing, COSMED) for oxygen consumption ($\dot{V}O_{2max}$) and carbon dioxide production ($\dot{V}CO_2$) measurements. The laboratory temperature averaged 23 °C. The theoretical maximal oxygen output ($\dot{V}O_{2max}$) was calculated for all patients using Wasserman equations including sex, age, height and weight.

The test was performed according to international standards. Briefly, after a 3-min constant load warm-up corresponding to 20% of the targeted maximal workload, the load was progressively increased every minute by 10% of the targeted maximal workload, until the patient's exhaustion. During the exercise test, heart rate, ECG, blood pressure, and transcutaneous oxygen saturation were monitored. In addition, the subject's muscle weariness was recorded every minute using a VAS scale graded from 0 to 10. Maximality criteria had to match the international guidelines. Maximal power output was the maximal workload sustainable, and $\dot{V}O_{2max}$ was the mean value during the last 20 s of the test. The 1st ventilatory threshold (VT_1) was identified on the basis of the agreement between two blinded physicians, using the following criteria: increase in ventilation ($\dot{V}E$), $\dot{V}CO_2/\dot{V}O_2$ slope, ventilatory equivalents ($\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$) slopes 22.

Statistical analysis

All continuous variables were expressed as mean \pm standard deviation (SD) if normally distributed, or as median [interquartile range: 25 – 75%] if not. Baseline and post-intervention characteristics were compared using Student *t*-test if normally distributed and Wilcoxon if not. The main analysis was conducted on the intention to treat (ITT) population, which means all participants who passed the randomization, by comparing the means between the groups for the primary endpoint (change in distance covered during the 30-min time trial) using a rank test (Wilcoxon Mann–Whitney). Sensitivity analysis used a linear mixed model and included a potential confounding factor. Association between primary outcome changes and baseline characteristics, as well as intervention characteristics and physiological changes, were assessed using Pearson or Spearman rank order correlations, depending on the data distribution. The significance level was set at $p < 0.05$. Statistical analyses were performed using R software (version 4.2.2).

Results

Daily training

The average outdoor temperature was 8 °C over the whole training period, while the indoor ambient temperature during the training period was 23.5 ± 3.2 °C. Water temperature during the training sessions was significantly different between both HWA and CON groups (35.6 ± 0.9 °C vs. 24.7 ± 1.7 °C; $p = 0.05$, respectively). Temperature increased significantly more during the session in the HWA group than the CON group ($+ 1.4 \pm 0.3$ °C and $+ 1.0 \pm 0.5$ °C; $p = 0.029$, respectively) (Fig. 3). Moreover, the time spent above 38.5 °C was significantly higher in the HWA group than in the CON group (18.4 ± 11.9 min vs. 5.0 ± 10.0 min, $p = 0.018$), as assessed during the last training session.

The percentage of target heart rate achieved session (VT1 + 10%) was similar in both groups (91.1% for the HWA group and 93.5% for the control group) (Fig. 3 and 4).

All participants completed a minimum of 9 training sessions. Only 3 sessions were missed by 3 different participants (2 participants in the control group and 1 participant in the HWA group). Participants training load outside of the study was similar in both groups (CON and HWA) throughout the protocol (1581 ± 1405 vs. 1498 ± 1373 ; $p = 0.800$).

Heat time-trial

The distance covered also increased ($p < 0.001$) depending on group ($p = 0.024$) with an increase of 1.1[+ 0.7, +1.4] km in HWA ($p < 0.001$) and 0.5[+ 0.1, + 0.8]km in CON ($p = 0.009$). As such, the average power output during the time-trial increased from pre to post training ($p < 0.001$) depending on group ($p = 0.037$), with the HWA group improving by 27[+ 17, + 37]W ($p < 0.001$) and the CON group by 13[+ 3, + 22]W ($p = 0.009$) (Fig. 4). Improvements in average power output and distance were observed in the absence of significant changes in rating of perceived exertion (RPE), sweat loss, sweat sodium concentration, skin temperature, or rectal temperature (all $p > 0.05$).

Fig. 3 Temporal evolution of mean rectal temperature during the first and last training sessions in both HWA and CON groups. Time in minutes and temperature in C

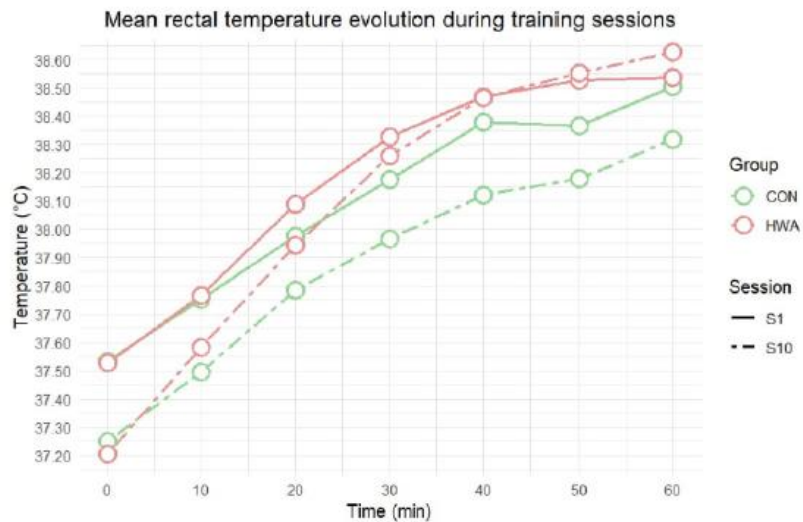
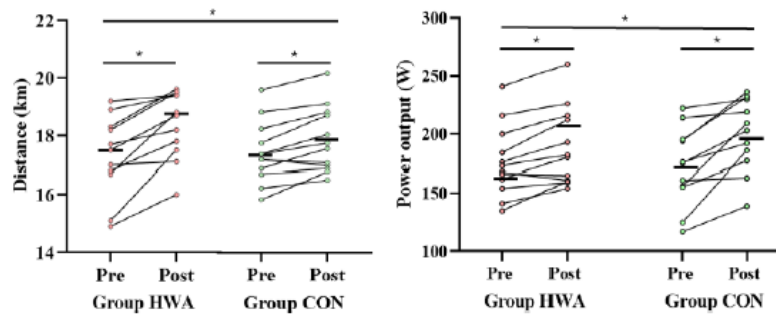


Fig. 4 Effect of cycling training sessions in hot (HWA) or neutral water (CON) on a 30 min time trial in hot and humid conditions. (distance in km, power output in watts) Bars represent the median of each test; circles represent individual participant distance



Specifically, the skin temperature increased between the pre and post training in both the CON and HWA groups. In the CON group, skin temperature increased by + 1.38 [0.66; 1.96]°C, whereas in the HWA group, the increase was + 2.17 [1.86; 2.53]°C ($p < 0.06$).

However, average HR during the heat time trial decreased pre to post training ($p = 0.005$) depending on group ($p = 0.012$), as average HR remained stable in the HWA group (- 1[- 5, + 4]bpm, $p = 0.809$) but decreased in the CON group (-9[-14,-5]bpm, $p < 0.001$).

Adaptations in neutral conditions

During the CPET, the VO_{2max} did not change from pre to post training ($p = 0.599$) irrespective of group ($p = 0.580$). The P_{max} increased from pre to post training (16[+ 7, + 24] W, $p = 0.001$) irrespective of group ($p = 0.476$). The HR_{max} at the end of the test decreased from pre to post training (- 3[- 5, - 1]bpm, $p = 0.006$) irrespective of group ($p = 0.895$). At the first ventilatory threshold (VT1), power between HWA and CON did not change before (185 [167–210]W vs 172.5 [147.5–183.75]W; $p = 0.22$) and after (177.5 [150–202.5]W vs 182.50 [170–202.5]W $p = 0.76$) the training program.

Haematocrit and total blood protein concentration changes before and after the intervention were not significantly different between HWA and CON group ($+ 0.24 \pm 1.74\%$ vs. $- 0.20 \pm 1.26\%$, $p = 0.66$, respectively and $+ 0.33 \pm 2.39$ g/L vs. 0.25 ± 3.05 g/L, $p = 0.77$, respectively). Moreover, echocardiography assessments did not reveal a significant difference regarding cardiac remodelling, function and work parameters was found between groups on (supplemental Table 2).

Table 2 Echocardiography data

Difference in LVEF (%) between post and pre training				
Mean (\pm SD)	0.88 (\pm 4.97)	0.47 (\pm 5.11)	1.28 (\pm 5.03)	0.81 ($-$ 3.7;5.32)
Median (25% ; 75%)	1.50 ($-$ 2.05 ; 5.30)	0.40 ($-$ 3.90 ; 4.50)	2.00 ($-$ 0.80 ; 5.50)	0.6 ($-$ 3.7;5.6)
[Minimum ; Maximum]	[$-$ 8.00 ; 7.60]	[$-$ 6.90 ; 7.60]	[$-$ 8.00 ; 7.40]	
Missing	2	1	1	
Difference in global longitudinal LVstrain (%) between post and pre training				
Mean (\pm SD)	$-$ 1.29 (\pm 1.60)	$-$ 1.80 (\pm 1.45)	$-$ 0.82 (\pm 1.65)	0.98 ($-$ 0.44;2.41)
Median (25% ; 75%)	$-$ 1.50 ($-$ 2.60 ; -0.60)	$-$ 1.60 ($-$ 2.95 ; -1.03)	$-$ 1.40 ($-$ 2.10 ; 0.55)	0.95 ($-$ 0.6;2.5)
[Minimum ; Maximum]	[$-$ 4.00 ; 1.70]	[$-$ 4.00 ; 1.00]	[$-$ 2.80 ; 1.70]	
Missing	3	2	1	
Difference in indexed cardiac output (l/min/m2) between post and pre training				
Mean (\pm SD)	$-$ 0.30 (\pm 0.78)	$-$ 0.26 (\pm 0.83)	$-$ 0.34 (\pm 0.76)	$-$ 0.08 ($-$ 0.78;0.63)
Median (25% ; 75%)	$-$ 0.26 ($-$ 0.66 ; 0.21)	$-$ 0.14 ($-$ 0.77 ; 0.15)	$-$ 0.42 ($-$ 0.61 ; 0.12)	$-$ 0.13 ($-$ 0.72;0.69)
[Minimum ; Maximum]	[$-$ 1.70 ; 1.32]	[$-$ 1.70 ; 1.32]	[$-$ 1.69 ; 1.01]	
Missing	2	1	1	

Discussion

This current study sought to compare the effects of 10 sessions of training in hot water (HWA) and temperate water (CON) on performance in a time trial under hot and humid conditions. Exercise training in hot water immersion induced a significant improvement in exercise performance in a hot and humid environment compared to training in neutral water immersion. Yet, changes in heart rate at VT1, central core and skin temperature, sweat rate, hematocrit, as well as exercise capacity in a neutral environment were not significantly different between hot and neutral water training groups.

Performance improvement in hot conditions

The study's primary outcome which was the change of the distance covered during a 30 min time trial in hot and humid condition improved more in the HWA group $+ 1.1[+ 0.7, + 1.4]$ km in HWA ($+ 8\%$) than in the CON group $+ 0.5[+ 0.1, + 0.8]$ km indicating an adaptation in the heat thanks to hot water immersion,

In addition, the tendency for a higher improvement in weight-adjusted average power performance in the HWA vs. CON group confirms the higher gain in performance.

This performance improvement could not be related to differences in baseline characteristics and fitness of the subjects, as randomization has led to a minimal difference in terms of $\dot{V}O_2$ max and gender between HWA and CON groups. Moreover, the improved performance was confirmed by the significant difference between the two groups after adjustment on gender and $\dot{V}O_2$ max. Altogether, the gains in distance and power observed in our study align

with various studies on acclimation in hot and humid conditions (Racinais et al. 2015; Lorenzo et al. 2010; Kirby et al. 2023).

This study showed that training in warm water allows to increase performance in hot ambient conditions. While it was conceivable that the combination of hot water and exercise stressors could lead to antagonistic or even adverse effects, our findings do not support this assumption. Moreover, this could be an accessible and practical option for training prior to competitions in hot environments. Training in water reduces joint stress and therefore the risk of injury, so this could be a way to increase training volume without the risk of injury (Kim et al. 2010).

Our study showed that an adaptation to the heat is possible in the absence of changes in physiological parameters of acclimation. Water immersion has an interesting characteristic in that it leads to an inability to thermolysis by sweating.

Physiological adaptation

In our study, we were not able to show significant changes in any of the parameters classically associated with acclimation in hot environment.

We did not find any change in sweat rate and sodium concentration in sweat during the time trial before and after the ten sessions of training in both groups. Indeed, an increase in sweat rate and a decrease in sweat sodium concentration was expected on the basis of training and heat acclimation studies, which have been shown to enhance sweating efficiency and sweat composition changes (Takamata et al. 2001). However, this lack of sweat adaptation to hot water training acclimation could be attributed to the aquatic environment (Eichna et al. 1950). Indeed, physiological studies have previously shown the inhibitory effect of water immersion on sweat, as well as the potential impact of gravity and pressure, that are modified in water immersion on sweating mechanisms (Physiological. 2024; Postural influences on sweating. 2024). Altogether, training in hot water could have blunted the adaptation of sweating during hot water exercise and leading to a lack of skin and core temperature increase during the 30-min time trial in hot environment. These results are in line with previous acclimation studies in swimmers/divers. Indeed, swimming in warm water 60 min/ day on 7 days in 33 °C did not alter performance, plasma volume expansion, HR reduction, resting T_{re} or sudomotor function versus 28 °C (Bradford et al. 2015).

We showed that both rectal temperature (T_{re}) and skin (T_{sk}) temperature increased during the time trial over 38,5 °C in hot conditions in HWA and CON groups. This is in line with the literature that shows an increase in both T_{re} and T_{sk} when competing in heat (Racinais et al. 2015; Mohr et al. 2012; Racinais et al. xxxx). Although skin temperature (T_{sk}) was not directly measured during training sessions in this study, it is plausible to assume an elevation occurred during hot-water immersion, consistent with the findings of previous studies (Thermal regulation. 2025). An increase in T_{sk} reduce the core-to-skin temperature gradient ($T_{core} - T_{sk}$) thereby compromising heat dissipation and augmenting cardiovascular strain through increased skin blood flow. As participants trained at a fixed target heart rate, potentially attenuating the overall training load. Consequently, it can be hypothesized that the physiological benefits observed in this study could have been even greater if participants had been allowed to train at a higher heart rate to compensate for the cardiovascular effects of hot-water exposure.

During training sessions, exercise intensity was monitored to target the HR of the subject 's $VT1 + 10\%$. However, the mean HR during the time trial following the intervention did not differ between groups, although a reduction in mean HR could have been expected given the nature of the training modality. Moreover, early studies suggest that heat acclimation attenuates cardiovascular strain, which could result in a reduction of mean heart rate in hot environments due to improved thermoregulatory adaptations.(Macdonald and Wyndham 1950; Eichna et al. 1950; Périard et al. 2011).

Interestingly, performance was improved by immersion in warm water in the absence of adaptation of sweat rate and haematological parameters. This improvement may be explained by a phenomenon of habituation to exercise, often found in studies of performance in cold environments, but which seems to be the case in our study.

The optimal temperature for muscle function is close to $40^{\circ}C$ so immersion of the lower limbs during moderate power exercise certainly allows us to get closer to the optimal temperature for muscle function and determine adaptations than is possible with moderate exercise in water at neutral temperature in our study.

This should be assessed in future acclimation studies investigating the impact and physiological adaptations of acclimation in hot water immersion. Otherwise, the safety of such intervention is indeed confirmed by our study, showing the stability of the parameters measured by echocardiography between pre- and post-training, and the lack of adverse effects or discomfort, as previously reported (Tyler et al. 2016; Young et al. 1995).

Perspectives

This study showed that training in warm water allows to increase performance in hot ambient conditions. Training in water reduces joint stress and therefore the risk of injury, so this could a way to increase training volume without the risk of injury (Kim et al. 2010). The decision to combine cycling with hot water immersion, as opposed to evaluating passive immersion alone, was based on the hypothesis that heat exposure might potentiate the adaptations elicited by physical exercise—a concept previously raised in the literature (Cullen et al. 2020). While it was conceivable that the combination of hot water and exercise stressors could lead to antagonistic or even adverse effects, our findings do not support this assumption. Rather, the results indicate that hot water cycling allow for an increase in performance in hot ambient conditions, suggesting a possible synergistic effect between exercise and heat exposure (Zurawlew et al. 2016), although the physiological underlying mechanisms remain to be clarified.

Future research should further investigate the underlying physiological mechanisms responsible for this synergy or exploring the dose–response relationship between exercise intensity, immersion temperature, and duration could help to optimize hot water training protocols for both athletic performance and potential therapeutic applications as for rehabilitation of thermal cure patients, most of whom are elderly and vulnerable to the heat (Quitmann et al. 2024).

Conclusion

This study examined changes in performance in hot and humid conditions during a cycloergometer time trial after ten aerobic training sessions in hot thermal water versus neutral thermal water. The study showed that participants who trained in hot water performed better in hot and humid conditions than those in the control group. In terms of physiological acclimation parameters, there were no significant changes between the two groups, in either the warm or neutral environment. Likely related to the fact that training in an aquatic environment may have affected sweating. This study suggests interesting prospects for the future physical preparation of recreational athletes prior to competition in hot environments, or for elderly patients, who make up a large proportion of thermal cure patients.

Author contributions

MJ conceived and designed the research. ML, GH, JR, FG, MH, JM conducted experiments. CH conducted echocardiography. SR and RC contributed new reagents or analytical tools. CD and SR analyzed data. GH and ML wrote the manuscript. All authors read and approved the manuscript.

Data availability

The raw data is not stored on an online server. We cannot provide a link to access the data.

Declarations

Conflict of interest None declared.

References

American Thoracic Society (2003) American college of chest physicians ATS/ACCP statement on cardiopulmonary exercise testing. *Am J Respir Crit Care Med.* 167(2):211–277. [https:// doi. org/ 10.1164/ rccm. 167.2. 211](https://doi.org/10.1164/rccm.167.2.211)

Bradford CD, Lucas SJE, Gerrard DF, Cotter JD (2015) Swimming in warm water is ineffective in heat acclimation and is non-ergogenic for swimmers. *Scandinavian Med Sci Sports* 25(S1):277–286. [https:// doi. org/ 10. 1111/ sms. 12351](https://doi.org/10.1111/sms.12351)

Candau R, Iorga B, Travers F, Barman T, Lionne C (2003) At physiological temperatures the atpase rates of shortening soleus and psoas myofibrils are similar. *Biophys J* 85(5):3132–3141

Cullen T, Clarke ND, Hill M et al (2020) The health benefits of passive heating and aerobic exercise: to what extent do the mechanisms overlap? *J Appl Physiol.* 129(6):1304–1309. [https:// doi. org/ 10.1152/ jappphysiol. 00608. 2020](https://doi.org/10.1152/jappphysiol.00608.2020)

Daanen HAM, Racinais S, Périard JD (2018) Heat acclimation decay and re-induction: a systematic review and meta-analysis. *Sports Med* 48(2):409–430. [https:// doi. org/ 10. 1007/ s40279- 017- 0808-x](https://doi.org/10.1007/s40279-017-0808-x)

Dablainville V, Mornas A, Normand-Gravier T et al (2025) Muscle regeneration is improved by hot water immersion but unchanged by cold following a simulated musculoskeletal injury in humans. *J Physiol*. <https://doi.org/10.1113/JP287777>

Davie A, Amoore J (2010) Best practice in the measurement of body temperature. *Nurs Standard* 24:42–49. <https://doi.org/10.7748/ns2010.06.24.42.42.c7850>

Eichna LW, Park CR, Nelson N, Horvath SM, Palmes ED (1950) Thermal regulation during acclimatization in a hot, dry (desert type) environment. *Am J Physiol-Leg Content* 163(3):585–597. <https://doi.org/10.1152/ajplegacy.1950.163.3.585>

Flouris AD, Schlader ZJ (2015) Human behavioral thermoregulation during exercise in the heat. *Scand J Med Sci Sports* 25(Suppl1):52–64. <https://doi.org/10.1111/sms.12349>

Greenfield AM, Pereira FG, Boyer WR, Apkarian MR, Kuennen MR, Gillum TL (2021) Short-term hot water immersion results in substantial thermal strain and partial heat acclimation; comparisons with heat-exercise exposures. *J Therm Biol* 97:102898. <https://doi.org/10.1016/j.jtherbio.2021.102898>

Kim E, Kim T, Kang H, Lee J, Childers MK (2010) Aquatic versus land-based exercises as early functional rehabilitation for elite athletes with acute lower extremity ligament injury: a pilot study. *PM R* 2(8):703–712. <https://doi.org/10.1016/j.pmrj.2010.03.012>

Kirby NV, Lucas SJE, Lucas RAI (2019) Nine-, but not four-days heat acclimation improves self-paced endurance performance in females. *Front Physiol*. <https://doi.org/10.3389/fphys.2019.00539>

Leçon 11 - Température, conduction, convection et chaleur latente. Accessed April 9, 2025. http://www.atmo.arizona.edu/students/courselinks/spring13/atmo170a1s1/online_course/week_4/lect11_temperature_conduction_convection_latent_heat.html

Lorenzo S, Halliwill JR, Sawka MN, Minson CT (2010) Heat acclimation improves exercise performance. *J Appl Physiol* 109(4):1140–1147. <https://doi.org/10.1152/jappphysiol.00495.2010>

MacDONALD DKC, Wyndham CH (1950) Heat transfer in man. *J Appl Physiol* 3(6):342–364. <https://doi.org/10.1152/jappphysiol.1950.3.6.342>

McIntyre RD, Zurawlew MJ, Oliver SJ, Cox AT, Mee JA, Walsh NP (2021) A comparison of heat acclimation by post-exercise hot water immersion and exercise in the heat. *J Sci Med Sport* 24(8):729–734. <https://doi.org/10.1016/j.jsams.2021.05.008>

Mohr M, Nybo L, Grantham J, Racinais S (2012) Physiological responses and physical performance during football in the heat. *PLoS ONE*. 7(6):e39202. <https://doi.org/10.1371/journal.pone.0039202>

Nadel ER (1984) Energy exchanges in water. *Undersea Biomed Res* 11(2):149–158

Périard JD, Cramer MN, Chapman PG, Caillaud C, Thompson MW (2011) Cardiovascular strain impairs prolonged self-paced exercise in the heat. *Exp Physiol* 96(2):134–144. <https://doi.org/10.1113/expphysiol.2010.054213>

Physiological Response to Water Immersion | Sports Medicine. Accessed July 5, 2024. <https://link.springer.com/article/https://doi.org/10.2165/00007256-200636090-00003>

Postural influences on sweating: exploring the effects of gravity and pressure | Extreme Physiology & Medicine | Full Text. Accessed July 5, 2024. <https://extremephysiolmed.biomedcentral.com/articles/https://doi.org/10.1186/2046-7648-4-S1-A154>

Quitmann C, Herrmann A, Koschemann V (2024) Heat health risks for the elderly. *MMW Fortschr Med* 166(11):41–45. <https://doi.org/10.1007/s15006-024-3957-5>

Racinais S, Périard JD (2020) Benefits of heat re-acclimation in the lead-up to the Tokyo Olympics. *Br J Sports Med* 54(16):945–946. <https://doi.org/10.1136/bjsports-2020-102299>

Racinais S, Périard JD, Karlsen A, Nybo L (2015) Effect of heat and Med Sci Sports Exerc 47(3):601–606. <https://doi.org/10.1249/MSS.0000000000000428>

Racinais S, Moussay S, Nichols D et al (2019) Core temperature up to 41.5°C during the UCI road cycling world championships in the heat. *Br J Sports Med*. 53(7):426–429. <https://doi.org/10.1136/bjsports-2018-099881>

Racinais S, Hosokawa Y, Akama T et al (2023) IOC consensus statement on recommendations and regulations for sport events in the heat. *Br J Sports Med* 57(1):8–25. <https://doi.org/10.1136/bjsports-2022-105942>

Ramanathan NL (1964) A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 19:531–533. <https://doi.org/10.1152/jappl.1964.19.3.531>

Russell K, Eriksen M, Aaberge L et al (2012) A novel clinical method for quantification of regional left ventricular pressure-strain loop area: a non-invasive index of myocardial work. *Eur Heart J* 33(6):724–733. <https://doi.org/10.1093/eurheartj/ehs016>

Takamata A, Yoshida T, Nishida N, Morimoto T (2001) Relationship of osmotic inhibition in thermoregulatory responses and sweat sodium concentration in humans. *Am J Physiol Regul Integr Comp Physiol* 280(3):R623–629. <https://doi.org/10.1152/ajpregu.2001.280.3.R623>

Taylor NAS (2014) Human Heat Adaptation. In: Terjung R (ed) *Comprehensive Physiology*, 1st edn. Wiley, Amsterdam, pp 325–365. <https://doi.org/10.1002/cphy.c130022>

Thermal regulation of man exercising during water immersion. Portal de Periódicos da CAPES. Accessed June 13, 2025. https://www.periodicos.capes.gov.br/index.php/acervo/busca_dor.html?task=detalhes&id=W2244958157

Tyler CJ, Reeve T, Hodges GJ, Cheung SS (2016) The Effects of heat adaptation on physiology, perception and exercise performance in the heat: a meta-analysis. *Sports Med* 46(11):1699–1724. <https://doi.org/10.1007/s40279-016-0538-5>

Vogt JJ, Metz B (1968) Nomogrammes De Prédiction Du Débit Sudoral Requis Ou De La Durée-Limite D'exposition En Fonction Des Caractéristiques Physiques D'une Ambiance Thermique. *Le Travail Humain* 31(1/2):175–179

Young AJ, Sawka MN, Levine L et al (1995) Metabolic and thermal adaptations from endurance training in hot or cold water. *J Appl Physiol* 78(3):793–801. <https://doi.org/10.1152/jappl.1995.78.3.793>

Zurawlew MJ, Walsh NP, Fortes MB, Potter C (2016) Post-exercise hot water immersion induces heat acclimation and improves endurance exercise performance in the heat. *Scand J Med Sci Sports* 26(7):745–754. <https://doi.org/10.1111/sms.12638>

Zurawlew MJ, Mee JA, Walsh NP (2018) Post-exercise hot water immersion elicits heat acclimation adaptations in endurance trained and recreationally active individuals. *Front Physiol* 9:1824. <https://doi.org/10.3389/fphys.2018.01824>

Conflict of interest statement

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References

1. American Thoracic Society (2003) American college of chest physicians ATS/ACCP statement on cardiopulmonary exercise testing. *Am J Respir Crit Care Med.* 167(2):211–277. <https://doi.org/10.1164/rccm.167.2.211> - DOI
2. Bradford CD, Lucas SJE, Gerrard DF, Cotter JD (2015) Swimming in warm water is ineffective in heat acclimation and is non-ergogenic for swimmers. *Scandinavian Med Sci Sports* 25(S1):277–286. <https://doi.org/10.1111/sms.12351> - DOI
3. Candau R, Iorga B, Travers F, Barman T, Lionne C (2003) At physiological temperatures the atpase rates of shortening soleus and psoas myofibrils are similar. *Biophys J* 85(5):3132–3141 - PubMed - PMC
4. Cullen T, Clarke ND, Hill M et al (2020) The health benefits of passive heating and aerobic exercise: to what extent do the mechanisms overlap? *J Appl Physiol.* 129(6):1304–1309. <https://doi.org/10.1152/jappphysiol.00608.2020> - DOI - PubMed
5. Daanen HAM, Racinais S, Périard JD (2018) Heat acclimation decay and re-induction: a systematic review and meta-analysis. *Sports Med* 48(2):409–430. <https://doi.org/10.1007/s40279-017-0808-x> - DOI - PubMed
6. Dablainville V, Mornas A, Normand-Gravier T et al (2025) Muscle regeneration is improved by hot water immersion but unchanged by cold following a simulated musculoskeletal injury in humans. *J Physiol.* <https://doi.org/10.1113/JP287777> - DOI - PubMed
7. Davie A, Amooore J (2010) Best practice in the measurement of body temperature. *Nurs Standard* 24:42–49. <https://doi.org/10.7748/ns2010.06.24.42.42.c7850> - DOI
8. Eichna LW, Park CR, Nelson N, Horvath SM, Palmes ED (1950) Thermal regulation during acclimatization in a hot, dry (desert type) environment. *Am J Physiol-Leg Content* 163(3):585–597. <https://doi.org/10.1152/ajplegacy.1950.163.3.585> - DOI
9. Flouris AD, Schlader ZJ (2015) Human behavioral thermoregulation during exercise in the heat. *Scand J Med Sci Sports* 25(Suppl 1):52–64. <https://doi.org/10.1111/sms.12349> - DOI - PubMed
10. Greenfield AM, Pereira FG, Boyer WR, Apkarian MR, Kuennen MR, Gillum TL (2021) Short-term hot water immersion results in substantial thermal strain and partial heat acclimation; comparisons with heat-exercise exposures. *J Therm Biol* 97:102898. <https://doi.org/10.1016/j.jtherbio.2021.102898> - DOI - PubMed
11. Kim E, Kim T, Kang H, Lee J, Childers MK (2010) Aquatic versus land-based exercises as early functional rehabilitation for elite athletes with acute lower extremity ligament injury: a pilot study. *PM R* 2(8):703–712. <https://doi.org/10.1016/j.pmrj.2010.03.012> - DOI - PubMed
12. Kirby NV, Lucas SJE, Lucas RAI (2019) Nine-, but not four-days heat acclimation improves self-paced endurance performance in females. *Front Physiol.* <https://doi.org/10.3389/fphys.2019.00539> - DOI - PubMed - PMC
13. Leçon 11 - Température, conduction, convection et chaleur latente. Accessed April 9, 2025. <http://www.atmo.arizona.edu/students/courselinks/spring13/atmo170a1s1/on...>
14. Lorenzo S, Halliwill JR, Sawka MN, Minson CT (2010) Heat acclimation improves exercise performance. *J Appl Physiol* 109(4):1140–1147. <https://doi.org/10.1152/jappphysiol.00495.2010> - DOI - PubMed - PMC
15. MacDONALD DKC, Wyndham CH (1950) Heat transfer in man. *J Appl Physiol* 3(6):342–364. <https://doi.org/10.1152/jappl.1950.3.6.342> - DOI - PubMed

16. McIntyre RD, Zurawlew MJ, Oliver SJ, Cox AT, Mee JA, Walsh NP (2021) A comparison of heat acclimation by post-exercise hot water immersion and exercise in the heat. *J Sci Med Sport* 24(8):729–734. <https://doi.org/10.1016/j.jsams.2021.05.008> - DOI - PubMed
17. Mohr M, Nybo L, Grantham J, Racinais S (2012) Physiological responses and physical performance during football in the heat. *PLoS ONE*. 7(6):e39202. <https://doi.org/10.1371/journal.pone.0039202> - DOI - PubMed - PMC
18. Nadel ER (1984) Energy exchanges in water. *Undersea Biomed Res* 11(2):149–158 - PubMed
19. Périard JD, Cramer MN, Chapman PG, Caillaud C, Thompson MW (2011) Cardiovascular strain impairs prolonged self-paced exercise in the heat. *Exp Physiol* 96(2):134–144. <https://doi.org/10.1113/expphysiol.2010.054213> - DOI - PubMed
20. Physiological Response to Water Immersion | Sports Medicine. Accessed July 5, 2024. <https://link.springer.com/article/> <https://doi.org/10.2165/00007256-200636090-00003>
21. Postural influences on sweating: exploring the effects of gravity and pressure | Extreme Physiology & Medicine | Full Text. Accessed July 5, 2024. <https://extremephysiolmed.biomedcentral.com/articles/> <https://doi.org/10.1186/2046-7648-4-S1-A154>
22. Quitmann C, Herrmann A, Koschemann V (2024) Heat health risks for the elderly. *MMW Fortschr Med* 166(11):41–45. <https://doi.org/10.1007/s15006-024-3957-5> - DOI - PubMed
23. Racinais S, Périard JD (2020) Benefits of heat re-acclimation in the lead-up to the Tokyo Olympics. *Br J Sports Med* 54(16):945–946. <https://doi.org/10.1136/bjsports-2020-102299> - DOI - PubMed
24. Racinais S, Périard JD, Karlsen A, Nybo L (2015) Effect of heat and heat acclimatization on cycling time trial performance and pacing. *Med Sci Sports Exerc* 47(3):601–606. <https://doi.org/10.1249/MSS.0000000000000428> - DOI - PubMed - PMC
25. Racinais S, Moussay S, Nichols D et al (2019) Core temperature up to 41.5°C during the UCI road cycling world championships in the heat. *Br J Sports Med*. 53(7):426–429. <https://doi.org/10.1136/bjsports-2018-099881> - DOI - PubMed
26. Racinais S, Hosokawa Y, Akama T et al (2023) IOC consensus statement on recommendations and regulations for sport events in the heat. *Br J Sports Med* 57(1):8–25. <https://doi.org/10.1136/bjsports-2022-105942> - DOI - PubMed
27. Ramanathan NL (1964) A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 19:531–533. <https://doi.org/10.1152/jappl.1964.19.3.531> - DOI - PubMed
28. Russell K, Eriksen M, Aaberge L et al (2012) A novel clinical method for quantification of regional left ventricular pressure-strain loop area: a non-invasive index of myocardial work. *Eur Heart J* 33(6):724–733. <https://doi.org/10.1093/eurheartj/ehs016> - DOI - PubMed - PMC
29. Takamata A, Yoshida T, Nishida N, Morimoto T (2001) Relationship of osmotic inhibition in thermoregulatory responses and sweat sodium concentration in humans. *Am J Physiol Regul Integr Comp Physiol* 280(3):R623–629. <https://doi.org/10.1152/ajpregu.2001.280.3.R623> - DOI - PubMed
30. Taylor NAS (2014) Human Heat Adaptation. In: Terjung R (ed) *Comprehensive Physiology*, 1st edn. Wiley, Amsterdam, pp 325–365. <https://doi.org/10.1002/cphy.c130022> - DOI

31. Thermal regulation of man exercising during water immersion. Portal de Periódicos da CAPES. Accessed June 13, 2025. <https://www.periodicos.capes.gov.br/index.php/acervo/buscaador.html?task=...>
32. Tyler CJ, Reeve T, Hodges GJ, Cheung SS (2016) The Effects of heat adaptation on physiology, perception and exercise performance in the heat: a meta-analysis. *Sports Med* 46(11):1699–1724. <https://doi.org/10.1007/s40279-016-0538-5> - DOI - PubMed
33. Vogt JJ, Metz B (1968) Nomogrammes De Prédiction Du Débit Sudoral Requis Ou De La Durée-Limite D'exposition En Fonction Des Caractéristiques Physiques D'une Ambiance Thermique. *Le Travail Humain* 31(1/2):175–179
34. Young AJ, Sawka MN, Levine L et al (1995) Metabolic and thermal adaptations from endurance training in hot or cold water. *J Appl Physiol* 78(3):793–801. <https://doi.org/10.1152/jappl.1995.78.3.793> - DOI - PubMed
35. Zurawlew MJ, Walsh NP, Fortes MB, Potter C (2016) Post-exercise hot water immersion induces heat acclimation and improves endurance exercise performance in the heat. *Scand J Med Sci Sports* 26(7):745–754. <https://doi.org/10.1111/sms.12638> - DOI - PubMed
- 36.
37. Zurawlew MJ, Mee JA, Walsh NP (2018) Post-exercise hot water immersion elicits heat acclimation adaptations in endurance trained and recreationally active individuals. *Front Physiol* 9:1824. <https://doi.org/10.3389/fphys.2018.01824> - DOI - PubMed - PMC