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Combined Active and Passive Isothermic Heating Leads to Similar Core Temperature Compared With Exercise Alone

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Context: The training stress of heat acclimatization optimizing exercise performance in a hot environment can be demanding.

Objective: This study evaluated the efficiency of different single heating protocols to elevate core temperature.

Design: Nonrandomized controlled trial.

Setting: Laboratory.

Patients or Other Participants: Ten male participants (age = 25 ± 3 years) performed 4 different 60-minute heating strategies at least 1 week apart.

Interventions: Sixty minutes passive heating (PAS), 30 minutes active heating using a high-intensity bike protocol (HIBP) in a hot environment with 30 minutes passive heating (EH-PAS), 60 minutes HIBP in a hot environment (EH), or 60 minutes HIBP at room temperature (EM).

Main Outcome Measure(s): Body core temperature and heart rate.

Results: The highest peak gastrointestinal temperature occurred in EH-PAS (39.1 ± 0.4°C), followed by EH (38.9 ± 0.3°C), EM (38.4 ± 0.3°C), and PAS (38.1 ± 0.5°C). The average heart rate, measured as a control for intensity, was not different between exercise strategies (EH-PAS = 142 ± 12.3 beats per minute [bpm], EH = 146 ± 9.7 bpm, and EM = 142 ± 13.3 bpm; $P > .05$), but was different for PAS (98 ± 15.2 bpm; $P < .05$).

Conclusions: Adding passive heating to a shorter exercise protocol can be just as effective in keeping core temperature elevated as exercise in the heat alone during a 60-minute session. Therefore, a single-bout combination of exercise and passive heating may result in a similar body temperature induction compared with exercise heat stress alone.

Key Words: acclimation, body temperature, heart rate, extreme heat, work performance

Key Points

- Different heat-acclimatization protocols have been suggested to increase heat stress in addition to normal training load.
- Beyond adding exercise in the heat alone, passive heating and a combination of exercise and passive heating have been suggested.
- This study showed that exercise with or without passive heating was more effective in reaching a body core temperature ≥38.5°C than passive heating alone.

Heat stress is affected by a combination of environmental conditions (eg, temperature, humidity, and solar radiation), type and amount of physical activity, and clothing worn.[1] When heat stress is paired with higher work rates, physiological strain and perceived exertion increase,[2] where strain is represented by a rise in core, skin, and brain temperatures.[3] Further, these stressful conditions lead to increased heart rate (HR) and breathing rate and to altered muscle metabolism, which result in fatigue while limiting power output.[4] As a result, the cardiovascular system is challenged by heat, directing blood flow to the periphery to cool the body, though in turn not efficiently delivering oxygen.[5,6] Simplified, when exposed to extreme heat during activity, the body slows down, and therefore a person may be exposed to higher environmental temperatures for more extended periods to achieve the same output compared with exercising in moderate environmental conditions.[7]

Exertional heat illnesses (EHIs) are the second leading cause of exertional injury, right behind cardiac-related events, yet they are preventable.[8] To prevent EHI,[9] heat acclimatization may help increase athlete safety and exercise performance through physiological adaptations.[10] In addition to seasonal adaptation to warmer conditions (ie, heat acclimatization) that occurs automatically, to a certain extent, over time when exposed to heat, both occupational workers and competitive athletes use heat-acclimation strategies to optimize their adaptation to the heat, aiming to optimize (work) performance.[11]

Physiological adaptations to heat include changes in core temperature and skin temperature (Tsk), higher sweat rate, less electrolyte loss, higher skin blood flow, and overall improved thermal comfort.[12] Aside from natural acclimatization as a result of being exposed during warmer temperatures during the spring and summer, heat adaptation can specifically be accelerated by heat-acclimation strategies.[11] These include strategies to increase body core temperature, for example by self-paced exercise and constant work rate exercise in a warm environment, controlled intensity exercise, controlled hyperthermia (through passive or active heating), or passive heating (eg, postexercise to maintain core temperature).[11] These acclimation strategies aim to temporarily increase or maintain body core temperature $\geq$38.5°C for at least 1 hour a day over a 6- to 21-day period.[12] To be effective, it is advised that heat acclimation should be added to normal training, increasing the total exercise workload and resulting in additional fatigue. Hence, there is interest in including passive heating strategies in addition to exercise in the heat to reduce overall stress on the body.[13]

We have noted that when controlled hyperthermia is applied as part of a training program, it may be difficult for athletes to reach the suggested core temperature threshold of 38.5°C consistently over multiple days.[14] As such, a combination of active and passive heating may be an effective strategy to stimulate a core temperature rise while reducing the additional exercise workload. Although exercise in the heat is the most effective method for developing heat acclimation,[12] passive heat exposure may also result in some adaptations toward pulmonary ventilation[15] and physiological symptoms of acclimation including reduced body core temperature, physiological stress index scores, and HR, as well as increased sweat rate,[16] but information regarding the magnitude of performance change, as well as the perceptual responses to passive heating protocols, is limited.[13] To date, researchers have compared passive heating (ie, hot-water immersion or sauna bathing) with exercise-based heat acclimation[17–19] or active heating via exercise followed by sauna visits vs exercise alone,[20,21] but to our knowledge, none have compared the acute single-bout short-term impact on body core temperature of more than 2 different heating strategies within a single study. Therefore, we aimed to assess if a combination of exercise and passive heating could elevate core temperature in a similar way to exercise alone in a hot environment, while also assessing the impact of passive heating alone, as well as exercise in a thermoneutral environment. Heart rate, a measurement that is normally available to most athletes in an applied setting, was measured to control for work intensity. Ultimately, the combination of exercise and passive heating should result in a lower energy expenditure and therefore be more efficient. This strategy would offer a more practical solution for athletes and those being physically active in the (extreme) heat, while allowing them to consistently reach a targeted core temperature of 38.5°C and reducing the amount of additional exercise activity needed to sustain an elevated body core temperature.

METHODS

Study Design

The research design was a nonrandomized controlled crossover field study. We evaluated 4 heating strategies for feasibility and efficacy of bringing the body's core temperature to 38.5°C in a field setting. Each participant completed all 60-minute interventions in the same order within a 5-week period, at least 1 week apart, in September 2020 to October 2020 in Phoenix, Arizona. As solar heat was used to create a hot environment, and temperature was slowly declining during the study period, randomization of heating interventions was not possible. To allow for standardization of the temperatures within each intervention, all measurements for a single heating protocol were collected in the same week. Therefore, the study started the first test week with a 60-minute passive heating protocol in a solar-heated tent (PAS), followed in week 2 with 30-minute active heating using a high-intensity bike protocol (HIBP) combined with 30-minute PAS (EH-PAS), followed in week 3 with 60 minutes active heating using HIBP in a hot environment in a solar-heated tent (EH), and finally, in week 4 participants performed 60-minute active heating using HIBP at room temperature (EM). Participants performed each condition only once, in a consecutive order. The main outcome was a change in body core temperature during each 60-minute heating intervention, and HR and hydration status were assessed as control variables.

Participants

A total of 10 self-reported healthy, nonsmoking, uninjured, active (training 5–10 hours per week), male athletes between 18 and 30 years old were recruited via Arizona State University club sports and by word of mouth. Participants were screened for fitness using the Physical Activity Readiness Questionnaire and for contraindications to use a body core temperature sensor capsule. Participants read and signed informed consent. The study was conducted in accordance with the Declaration of Helsinki and approved by the Western Institutional Review Board (#20193446).[22]

Procedures

Participants were instructed to ingest a body core temperature sensor capsule at least 3 hours before each trial to allow passage from the stomach into the intestine, but preferably the previous day before going to sleep to ensure that the temperature reading of the capsule would not interfere with fluid intake during the heating interventions.[23] See the Measurements section for all sensor specifications and use. Once at our research facility, the sensor was synchronized with a monitor to allow reading of core temperature data in real time, and it was checked if fluid intake did not directly interfere with the internal temperature reading. In the 2 cases when core temperature readings were affected by fluid intake, the participant was rescheduled on the next available testing day. Then, participants provided a urine sample, completely emptying their bladder. Before the start of each trial, seminude pre-exercise body mass was collected followed by application of an HR monitor strap and Tsk sensors. Passive or active heating interventions then began. At the end of each trial, a second urine sample was collected, followed by a second seminude postexercise body mass. Participant height was measured at the last start of the last trial to the nearest 0.1 cm using a stadiometer (Portable Stadiometer, Seca GmbH & Co KG).

Heating Interventions. Interventions were separated by 1 week to minimize the effect of having a cumulative heat-acclimation effect over time. Separating heat-acclimation sessions by a week or more has been suggested to have no adaptation effects on HR, rectal temperature, Tsk, oxygen

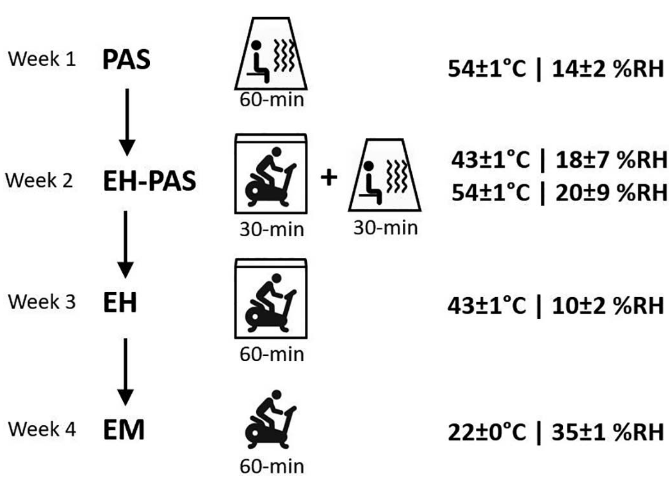

Figure 1. Heating interventions in a fixed order with temperature (°C) and relative humidity (% RH), including passive heating (PAS), exercise in the heat and passive heating (EH-PAS), exercise in the heat (EH), and exercise in moderate conditions (EM).

volume, and total sweat loss.[24] Clothing was standardized: participants performed the interventions in the same athletic gear (ie, long training pants and T-shirt). Additionally, every time participants exercised on the bike they wore a watertight coverall on top of their athletic gear, to shield for potential differences in airflow during conditions; it also served as a method to create a similar microenvironment between each of the separate heating intervention sessions.

Exercise Protocol. The HIBP was performed on a stationary spinning bike (RevMaster Classic, Greg Lemond) not allowing for measuring wattages; HR was measured as a marker to control for work intensity.[25] Participants were instructed to bike at a self-selected resistance at 80 to 90 rpm for 2 minutes, followed by 5 to 10 two-minute, high-intensity "sprints" at 100 rpm with a higher resistance, followed by 2 minutes of relative rest at 80 to 90 rpm for the first part of the 30 minutes of exercise, as described earlier in a publication from our lab.[14] After reaching a target core temperature of 38.5°C to 39.5°C, participants were instructed to keep a constant work pace to maintain their body core temperature within the target for the remaining duration of the intervention.

Intervention Sessions. During each weekly visit to the lab, participants performed one of the following 60-minute interventions in a fixed order, as shown in Figure 1:

1. *60-minute PAS:* This intervention consisted of sitting in a solar-heated restroom tent (Wakeman Pop Up Pod; Trademark Global LCC) at an air temperature of approximately 54°C. Participants remained seated in this small tent for 60 minutes.
2. *30-minute EH and 30-minute PAS:* This heating intervention consisted of performing the HIBP for 30 minutes in a solar-heated confined-space tent (Allegro Manhole Utility Shelter; Allegro Industries) at approximately 43°C, followed by 30 minutes of PAS at a temperature of approximately 54°C. To ensure that the confined-space tent air temperature remained consistent around approximately 43°C, the space was ventilated with a ventilator (High Velocity Heavy Duty Floor Fan 20 Inch, Deluxe Simple Deluxe, Duarte, CA, USA).
3. *Exercise in a hot environment:* The EH intervention consisted of performing the HIBP for 60 minutes in the solar-heated confined-space tent at approximately 43°C, similar to the protocol described in EH-PAS.
4. *Exercise in a moderate environment:* The EM intervention consisted of performing the HIBP indoors for 60 minutes at approximately 22°C room temperature.

Measurements

Physiological Measurements. For all physiological measurements, the baseline was determined on the average of all measurements taken for each instrument within 30 seconds before the start of the intervention. The average was based on all consecutive measurements for each instrument during the full intervention. Finally, the highest value measured was presented as the peak, and the increment (Δ) was calculated as peak minus baseline.

Gastrointestinal Temperature. A portable telemetry system (E-Celsius; BodyCAP) for temperature sensor capsule, with an accuracy of ±0.2°C, was used to measure gastrointestinal temperature (Tgi) at 15-second intervals.

Skin Temperature. Wireless temperature sensors (iButton DS1 + 2L; Dallas Semiconductor Corp), with an accuracy of ±0.5°C and a resolution of 0.0625°C, were used to measure Tsk at 20-second intervals.[26] Sensors at 4 locations (neck, right shoulder, and right shin, all with a 0.28 weighted coefficient, and left hand with a coefficient of 0.16 to calculate weighted Tsk outcome) as suggested per International Organization for Standardization protocol, held in place at the skin using Opsite transparent film (Opsite Flexigrid; Smith & Nephew Medical Limited).[27]

Heart Rate. Participants wore an elastic chest strap device (Bioharness-3; Zephyr Technology), measuring HR in beats per minute (bpm) at 1-second intervals.

Hydration. ***Fluid Intake.*** Participants were allowed to drink ad libitum water stored at room temperature (22°C) throughout all heating interventions. All bottles for fluid consumption were measured before and after consumption in grams with 0.1-g accuracy using a precision scale (PT 1400; Sartorius AG) within 30 minutes before the start of and 15 minutes after each test or training session.

Body Mass. Measurements in kilograms were performed seminude in dry underwear after voiding before and after each intervention at a body-weight scale (896 Digital Scale; SecaGmbH & Co KG).

Urine Volume and Urinalysis. Participants provided an all-out urine sample before and after each intervention, and the weight of each sample (as equivalent of volume, in which 1 g was assumed to be equal to 1 mL) was determined using a precision scale. A total of 30 mL was transferred in a test tube to measure urine specific gravity (USG) at a standard sample temperature of 20°C (4410 PAL-10S Digital "Pocket" Urine SG Refractometer; ATAGO).

Sweat Rate. Sweat rate (mL/h) was calculated as a combination of fluid intake, body mass change, and urine volume using the following formula[28]:

$$\text{Sweat rate (mL/h)} = \frac{(\text{Pre-exercise Body Mass} - \text{Postexercise Body Mass} + \text{Fluid Intake} - \text{Urine Output})}{\text{Exercise Duration}}$$

Environmental Conditions. During each intervention, the ambient temperature and relative humidity of each testing condition were logged every minute (Kestrel 5400 Heat Stress Tracker with wind vane; Nielsen-Kellerman). After this, saturated vapor pressure, $0.61365\frac{(17.502 \times T_{air})}{(240.97 + T_{air})}$, and actual vapor pressure, $0.61365\frac{(17.502 \times T_{dp})}{(240.97 + T_{dp})}$, were calculated to measure the moisture of the environment using the previous formulas, where T_{air} is ambient air temperature (°C) and T_{dp} is dew point temperature (°C).[29]

Statistical Analysis

The majority of data were normally distributed, and results are presented as mean ± SD (except for body mass and body mass index). Primary outcomes were Tgi and HR at baseline, peak, increment, and average for the 60-minute interventions (slope and time increments per 10 minutes). These primary outcomes were also assessed in 30-minute increments to determine differences between mixed EH-PAS and the other interventions. Further, averages were reported for Tsk, hydration status, and environmental conditions. Finally, the time to reach the average group core body temperature of 38.5°C per 10-minute interval was reported for each intervention. Differences between interventions were assessed using repeated-measures analyses of variance or their nonparametric counterparts followed by pairwise comparisons. Significance was set for $P \leq .05$.

RESULTS

A total of 10 male participants (24.5 ± 3.4 years, body height of 180.0 ± 11.1 cm, and a median body mass of 84.5 kg (interquartile range, 73.9–95.1) and body mass index 25.5 (interquartile range, 15.4–36.6), completed all 4 heating interventions. The group consisted of club athletes (n = 5), a member of the Army Reserve Officer Training Corps (n = 1), and other recreational athletes (n = 4). All athletes self-reported being healthy and free from injuries while having a normal training load of 5 to 10 hours per week.

As shown in the Table, Tgi (ranging from 37.1°C ± 0.5°C to 37.3°C ± 0.3°C, $P = .37$) and HR (ranging from 73.0 ± 31.1 bpm to 86 ± 24.5 bpm, $P = .28$) were not significantly different at baseline, but Tsk was significantly lower during EM (32.7°C ± 0.73°C) in comparison with the other interventions in a hot environment (ranging from 33.5°C ± 1.2°C to 34.7°C ± 0.6°C, $P = .004$).

The heating interventions resulted in significant differences for average, increment, and peak Tgi, HR, and Tsk ($P < .001$), but pairwise comparison showed that EH-PAS and EH resulted in higher Tgi levels compared with PAS and EM. For example, the highest peak Tgi was for EH-PAS with 39.1 ± 0.4°C, followed by EH with 38.9 ± 0.3°C.

The outcomes for HR (independent from average and increment) were not significantly different for EH-PAS, EH, and EM but were significantly lower for PAS. Finally, average, increment, and peak Tsk were significantly higher in PAS interventions (PAS and EH-PAS) compared with EH and EM ($P < .05$).

No difference was reported for pre-exercise USG on each test day, with participants coming in well hydrated with average USG values per day ranging from 1.011 ± 0.008 to 1.013 ± 0.009. Sweat rate ($P < .001$) and body mass change ($P < .002$) differed among conditions, showing the largest loss during exercise in the heat. Although not significantly different, fluid intake tended to be higher during exercise in the heat ($P = .07$).

Environmental conditions were significantly different between heating facilities PAS vs EH vs EM (with 53.8°C ± 1.1°C for PAS, 43.3°C ± 1.1°C and 54.0°C ± 2.3°C for EH-PAS, 42.8°C ± 1.4°C for EH, and 22.4°C ± 0.4°C for EM), but the conditions between PAS and EH-PAS were not significantly different ($P > .05$). In addition, there was no significant difference between temperature for exercise in the heat for EH-PAS and EH ($P > .05$). For the EH condition, there were small differences between testing days for EH-PAS and EH in relative humidity and vapor pressure ($P < .05$), but because of the coverall induced microclimate, likely no differences were experienced on total body level.

As shown in Figure 2, peak Tgi was not significantly different between EH-PAS and EH, but peak Tgi values for EH-PAS and EH were different from those for PAS and EM. The peak HR was not different among the conditions involving exercise (ie, EH-PAS, EH, and EM), but HR was lower for PAS.

Figure 3 shows that the average core temperature had a similar trajectory in 10-minute bouts for EH-PAS and EH, finishing above 38.5°C. It also shows that, on average, during EM, participants could not increase their core temperature above 38.4 ± 0.3°C, and during PAS, participants could on average not exceed 38.1 ± 0.5°C, measured toward the end of the intervention around the 50- and 60-minute marks, respectively. For the other interventions it took 40 minutes before the average group core body temperature for EH-PAS (38.6 ± 0.3°C) and EH (38.5 ± 0.4°C) interventions reached ≥38.5°C, and during the last 20 minutes of EH-PAS and EH temperatures still increased. Significant differences between the exercise protocols and PAS were found after 20 minutes, and after 30 minutes and beyond, both EH-PAS and EH were significantly different from PAS and EM ($P < .05$).

The average HR significantly differed for all exercise protocols vs PAS at 10 minutes and beyond ($P < .05$). The average HR for EH-PAS, EH, and EM showed a similar pattern for the first 30 minutes; after that, EH-PAS significantly dropped as exercise was stopped and as participants underwent PAS, whereas both EH and EM dropped minimally in the second half of the 60 minutes of exercise. The work rate (ie, biking rpm and resistance) for EH was stabilized and/or adjusted as participants reached their targeted Tgi to stabilize core temperature around 38.5°C, whereas the work rate for EM dropped as they were not able to sustain the work while not being close to their targeted Tgi.

DISCUSSION

All heating interventions resulted in a significant rise in body core temperature, yet the most effective core temperature rise occurred in the EH and EH-PAS trials. Participants began each test day well hydrated, and exercise protocols were standardized effectively based on the HR data as a marker for exercise intensity, showing no differences between the exercise portions of the interventions. The

Table. Physiological Outcomes, Hydration Markers, and Environmental Conditions Presented as Mean ± SD for Different Interventions and Significant Differences[a]

	Condition				
	PAS	EH-PAS	EH	EM	P
Core temperature, °C					
Baseline	37.3 ± 0.3	37.3 ± 0.2	37.3 ± 0.2	37.1 ± 0.5	.37[b]
Average	37.5 ± 0.4[d,e]	38.2 ± 0.2[c,f]	38.2 ± 0.1[c]	37.9 ± 0.2[d]	<.001
Increment	0.8 ± 0.2[d,e]	1.8 ± 0.6[c]	1.6 ± 0.5[c]	1.3 ± 0.6	<.001
Peak	38.1 ± 0.5[d]	39.1 ± 0.4[c,f]	38.9 ± 0.3[f]	38.4 ± 0.3[d,e]	<.001
Heart rate, bpm					
Baseline	73 ± 13.1	86 ± 24.5	79 ± 15.6	80 ± 20.9	.28
Average	98 ± 15.2[d,e,f]	142 ± 12.3[c]	146 ± 9.7[c]	142 ± 13.3[c]	<.001
Increment	60 ± 15.9[d,e,f]	101 ± 29.8[c]	102.6 ± 14.4[c]	94 ± 22.5[c]	<.001
Peak	134 ± 20.5[d,e,f]	186 ± 9.7[c,f]	181 ± 9.1[c]	174 ± 12.8[c,d]	<.001[b]
Skin temperature, °C					
Baseline	33.5 ± 1.2	34.7 ± 0.6[f]	34.4 ± 0.6[f]	32.7 ± 0.7[d,e]	.004
Average	39.1 ± 0.3[d,e,f]	38.2 ± 0.5[c,e,f]	36.8 ± 0.5[c,d,f]	33.8 ± 0.5[c,d,e]	<.001
Increment	6.7 ± 1.5[e,f]	5.4 ± 0.9[e,f]	3.60 ± 0.6[c,d,f]	2.17 ± 0.6[c,d,e]	<.001
Peak	40.3 ± 0.6[e,f]	40.1 ± 0.7[e,f]	38.0 ± 0.4[c,d,f]	34.9 ± 0.7[c,d,e]	<.001
Hydration markers					
Pre-exercise USG	1.012 ± 0.008	1.011 ± 0.010	1.013 ± 0.009	1.011 ± 0.008	.81
Sweat rate, mL/h	1071 ± 551[d,e]	1737 ± 416[c,f]	1698 ± 657[c]	1289 ± 298[d]	<.001
Fluid intake, mL	747 ± 802	1084 ± 750	1020 ± 837	563 ± 604	.07
Body mass change, %	0.38 ± 0.36[d,e,f]	0.92 ± 0.59[c]	1.16 ± 0.81[c]	0.92 ± 0.60[c]	.002[g]
Environmental conditions					
Ambient temperature, °C	53.8 ± 1.1[e,f,h]	Tent 1: 43.3 ± 1.1[c,f,i] Tent 2: 54.0 ± 2.3[e,f,h]	42.8 ± 1.4[c,f,i]	22.4 ± 0.4[c,e,h,i]	<.001[a]
Relative humidity, %	13.5 ± 2.2[e,f]	Tent 1: 18.3 ± 6.6[e,f] Tent 2: 20.4 ± 9.2[f]	10.0 ± 1.8[c,f,h]	34.7 ± 0.5[c,e,h,i]	<.001[a]
Saturation vapor pressure, kPa	15.3 ± 1.0[e,f,h]	Tent 1: 9.0 ± 0.6[c,f,i] Tent 2: 15.4 ± 1.7[e,f,h]	8.7 ± 0.7[c,f,i]	2.7 ± 0.1[c,e,h,i]	<.001[a]
Actual vapor pressure, kPa	2.0 ± 0.3[e,f,h]	Tent 1: 1.3 ± 0.2[c,e,f,i] Tent 2: 2.3 ± 0.4[e,f,h]	0.8 ± 0.1[c,h,i]	2.7 ± 0.1[c,e,h,i]	<.001[a]

Abbreviations: bpm, beats per minute; EH, exercise in the heat; EH-PAS, exercise in the heat + passive heating; EM, exercise in moderate conditions; PAS, passive heating; USG, urine specific gravity.

[a] All interventions lasted 60 minutes. Differences between interventions were assessed using repeated-measures analysis of variance; $P < .05$, with post hoc Bonferroni correction. Due to a technical error, skin temperature and core temperature data were lost on day 1; therefore, PAS data (day 1) for core temperature were based on n = 7 and skin temperature on n = 5.

[b] Greenhouse-Geisser used with P value set at .05.

[c] Different from PAS.

[d] Different from EH-PAS.

[e] Different from EH.

[f] Different from EM.

[g] Repeated-measures analysis of variance with P value set at .05.

[h] Different from tent 1 of EH-PAS environment.

[i] Different from tent 2 of EH-PAS environment.

results confirmed that a combination of exercise and passive heating can help reach and exceed a targeted core temperature of 38.5°C, similar to exercise in the heat, whereas exercise in moderate conditions or passive heating alone did not result in an average peak core body temperature ≥38.5°C.

The selection of the EH-PAS intervention matches earlier research investigating the long-term impact of PAS on heat acclimation.[21,30] In addition to previous studies performing 30 to 40 minutes of hot-water immersion as part of a multiple-day heat-acclimation protocol, our study is the first to compare the efficiency of single bouts of heating strategies (ie, passive heating alone, exercise and passive heating, exercise in the heat, and exercise in moderate conditions) regarding their suitability for reaching a body core temperature of 38.5°C.[17–19] This finding is important, as a heat-acclimation program may be burdensome, specifically because when adaptations develop workload needs to be increased to maintain an effective elevation of body temperature throughout the heat-acclimation period.[25] A 16-day combined exercise and passive heating acclimation program showed reduced external work while maintaining a similar response on body core temperature in comparison with exercise in the heat alone.[31] However, that study did not provide a breakdown of core temperature for individual days and segments of the heating strategy.[31] The current study showed that when core temperature increases enough in the first half of the intervention through exercise, passive heating in warm conditions can sustain the elevated core temperature for at least one more half hour. Although our study does not address the impact of a combined exercise and passive heating acclimation program for 6 to 21 days, as suggested in the literature,[12] it confirms that passive heating after repeated sprint exercise is effective in reaching a targeted core temperature of 38.5°C.[32]

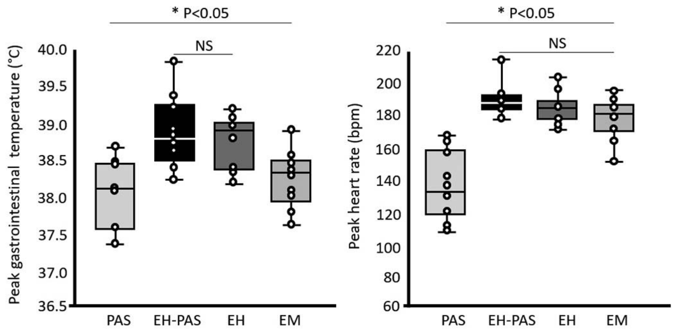

Figure 2. Box plots with peak gastrointestinal temperature and heart rate per heating intervention with median, interquartile range, and whiskers representing minimum–maximum. Significance, indicated by an asterisk, was set at *P* < .05. Passive heating (PAS), exercise in the heat + passive heating (EH-PAS), exercise in the heat (EH), and exercise in moderate conditions (EM), with all interventions lasting 60 minutes.

The literature describing the impact of passive heating can be broken down into passive heating alone vs passive heating before or after exercise in a warm or thermoneutral environment.[13] The most commonly investigated passive heating strategies are the use of sauna bathing,[21,33–35] a sauna suit,[36] or hot water immersion,[19,31,32] but a limitation within the existing literature is that many heat-acclimation programs focus on the pretest and posttest but do not measure the actual isothermic response during the acclimation sessions. When comparing our 4 interventions in the current study, EH and EH-PAS methods resulted in similar outcomes, and the actual increment from baseline to target body core temperature was achieved during the exercise protocol after 40 minutes. The following 20 minutes of passive heating after exercise allowed for maintaining this elevated body core temperature throughout the rest of the protocol, whereas in the other trials (ie, PAS alone and EM), group averages did not meet or exceed the targeted core temperature that should prompt heat acclimation.[12] At the same time, a review on passive heating strategies showed that the evidence for the magnitude of combined exercise and passive heating on performance change is limited.[13] Although our study cannot provide performance-related evidence, our study adds to the literature, revealing that passive heating alone in a warm environment, at a temperature approximately 54°C with 14% relative humidity during 60 minutes, was not as effective in raising core temperature as including exercise in the heat within the 60-minute heating period, with a Tgi peak stalling around approximately 38°C. Other authors, following an isothermic approach reporting physiological data per session, were able to report similar findings. One study used a sauna suit with a 44°C warm-water infusion, showing a very effective core temperature increase toward 38°C in 60 minutes, similar to the data in the current study (38.1 ± 0.5°C), while being exposed to a 53.8 ± 1.1°C ambient temperature.[36] Importantly, it took up to 120 minutes wearing the sauna suit to reach a body core temperature of 38.5°C, showing the limitation of passive heating alone to increase body core temperature. As such, passive heating alone in a hot and dry environment (ie, sauna) is probably less effective than exercise and passive heating combined. When performing consecutive days of isothermic heat acclimation, studies have shown that groups can meet an average core temperature ≥38.5°C during multiple sessions,[14,37] but the cumulative time participants are exposed to ≥38.5°C can be limited to approximately 30% to 40% of the total workout.[38,39] The current study, with its core temperatures and HR values during the first 30 minutes of the heating protocol, shows very similar average and peak values, as found previously.[14,37] Overall, we show that with an intensive biking protocol in the heat, it will take at least half an hour to reach a core temperature of 38.5°C, after which passive heating can help to maintain core temperature without having to complete any extra physical work.

To control for exercise intensity (as output from the generated revolutions per minute and self-selected bike resistance), this study measured HR, which we used as a proxy marker to quantify workload during heat acclimation.[40] Our results showed very similar average HR values for all our exercise- and passive heating–based protocols. This similarity is in contrast with previous research in which HR was not measured during exercise itself when a combined exercise and passive heating intervention was performed.[21,30]

The differences in environmental conditions between trials were planned as part of the study design, as we aimed to have different ambient temperatures between PAS, heated exercise, and exercise in moderate conditions. More importantly, the environmental conditions were stable within each

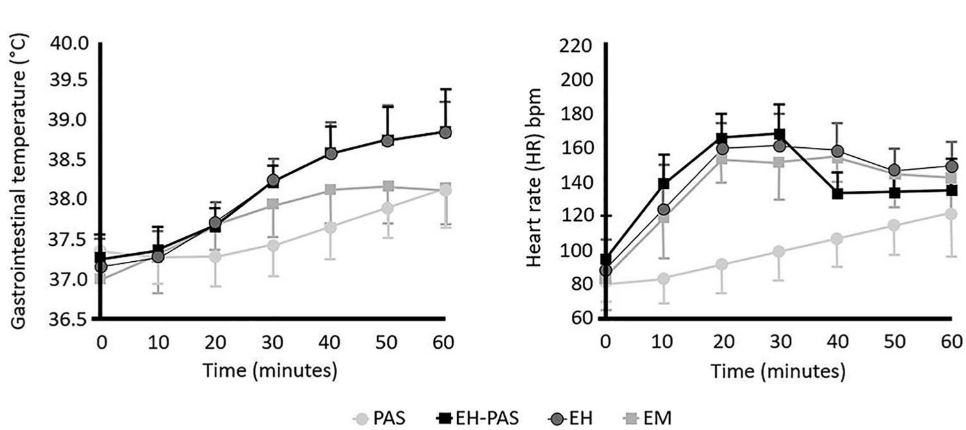

Figure 3. Average ± SD for core temperature and heart rate per heating intervention at baseline and 10-minute marks. Passive heating (PAS), exercise in the heat + passive heating (EH-PAS), exercise in the heat (EH), and exercise in moderate conditions (EM), with all interventions lasting 60 minutes.

of the individual strategies and comparable when strategies overlapped, such as the PAS in PAS and EH-PAS and the exercise in hot conditions in EH-PAS and EH. Baseline hydration suggested a good hydration status, and then followed a similar pattern between trials, as expected, resulting in elevated sweat rates and fluid intake during hot exercise conditions while still staying within acceptable limits to not impair exercise performance during testing.[41]

Being a field-based trial, we had to be able to control for potential changes in environmental conditions within and between heating strategies. One concern was the difference in airflow during exercise testing, as a fan was used for ventilation to keep the ambient temperature in the solar-heated tent stable. Therefore, we used impermeable plastic coverall suits that would help to block the impact of intermittent airflow on the body, while also allowing us to create a similar microclimate for each of the participants during each of the exercise conditions.[15,42] The suits helped to reduce sweat evaporation, and as such they created a more standardized environment. Further, these suits should encourage a rise in body core temperature by limiting sweat evaporation, and as such, the skin cannot be cooled effectively.[43]

The practical application of this study lies in showing the higher efficiency of a protocol combining exercise and passive heating. This finding could be beneficial for various populations, such as service members, firefighters, or other occupational professionals working in hot environments, as well as athletes who require proper thermoregulation.[44] Especially when there is limited time to adjust to a new (hot) environment while also being mentally and physically prepared for any scenario, a more efficient heat-acclimation protocol can be critical.[45] As heat acclimation normally comes with performing extra work on top of the regular activity,[12] less work could also mean less risk of injury related to heat illness.[46] Finally, for example, high school athletes (including American football athletes) experience elevated risk for EHI during the preseason, which begins in summer.[46] The body's ability to thermoregulate is limited when wearing additional protection, such as padding and helmets.[47,48] More efficient heat-acclimation protocols, including a combination of exercise and passive heating, may help to prepare these populations for physical activity in the heat. The optimal way for passive heating to effectively raise core temperature (ie, pre-exercise or postexercise activity in the heat) should be further investigated, yet at least 1 study using hot water immersion before or after exercise showed that the actual duration of Tgi $\geq$38.5°C during the exercise intervention was substantially longer in the group who were immersed in the 30 minutes before exercise in 40°C water.[32]

Clear strengths of this study are comparing multiple heating strategies within one study, while continuously measuring body temperature markers and controlling for HR. We also demonstrated that with limited resources, one can organize reasonable, effective, field-based heat-acclimation facilities with comparable environmental conditions, while including participants starting in stable conditions (ie, not significant differences in baseline body temperature and hydration status). Overall, it is important to acknowledge that protective heat acclimatization could benefit from gradually increasing exercise in the heat. In addition, passive heating may initiate, add to, and supplement current heat acclimatization for preventing EHI, protecting cardiovascular system, and boosting performance, but passive heating alone likely will not raise body core temperature toward the body core temperature levels suggested by the literature.

This research also presents some limitations. This study was set up to show that isothermic heat-acclimation strategies could be performed in an applied. Participants served as their own controls, but we were not able to randomize heating strategies as this field study relied on the hot weather conditions in the US Southwest; therefore, it was considered more important to have identical environmental conditions within each heating intervention than to allow for randomization. As a result of COVID-19–related delays, the study was performed in early fall, resulting in a hot outdoor environment that would substantially cool off during the 4-week study period, hence also eliminating the option to include female participants while reasonably controlling for their menstrual cycle, for which more time would have been needed. As the passive heating interventions were using solar-heated tents, we decided to schedule consecutive participant testing for each heating strategy within 5 to 10 days. This allowed for stable conditions within each of the 4 heating strategies, as shown by our results, but therefore randomization was not possible. At the same time, interventions were separated by at least 1 week to ensure no actual heat acclimation would take place over time,[24] while we aimed to investigate the impact on core temperature elevation efficiency and not on the actual impact of the method on heat acclimatization. Furthermore, it is likely that participants were acclimated to the heat to some extent, because it took place in the fall when it was still warm outside, but no significant difference was found for baseline temperatures throughout the study. In addition, our research group earlier showed that physiological parameters as part of a short heat-acclimation protocol can be improved in (partially) heat-acclimated recreative athletes.[14] Not including females can be seen as a strong limitation, especially because it was recently shown that there was no difference in sex response for core temperature variability.[49,50] Therefore, generalization of our conclusions toward females should be done with caution.

Many heat-acclimation studies have been performed in cold or thermoneutral conditions, but because this study took place at the end of summer in the hot US Southwest,[51] it is likely that participants were already acclimatized to the heat to some extent; however we showed earlier that heat acclimation can still influence physiological body processes.[14] Although the study standardized the exercise protocol, including a prescribed revolutions per minute, we did not measure the actual output in terms of wattage. Instead we controlled for HR, which has been suggested to be a good marker for meeting heat-acclimatization program work intensity.[52] Finally, an additional limitation to this study is that some data on core temperature and Tsk were lost due to technology errors, which primarily occurred on day 1 during PAS; therefore, body core temperature data were available for only 7 participants for this measurement.

In conclusion, although each of the heating interventions resulted in an increase in body core temperature, a combination of exercise and passive heating may result in a similar body temperature induction compared with exercise heat stress alone. Exercise in the heat with or without passive heating allows athletes to reach a higher body core temperature within 60 minutes than exercise in moderate environmental conditions or passive heating alone.

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