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Effectiveness of Short-Term Heat Acclimation on Intermittent Sprint Performance in the Heat with Moderately Trained Males

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Abstract

Purpose: Effectiveness of short-term heat acclimation (STHA), over 5 days (permissive dehydration), on intermittent heat stress test (HST) with males.

Methods: Ten moderately trained males (mean [SD] age 25.6 [8.9] years; stature 180.7 [5.6] cm; body mass 83.2 [10.8] kg; and $\dot{V}O_{2\,max}$ 45.3 [6.5] mL kg^{-1} min^{-1}) participated. The HST was 9 × 5 minutes (45 minutes) of intermittent exercise based on professional soccer players. One week apart, HST1 versus HST (11.0℃, 50% RH) as a reliability trial and HST3 in 31.0℃, 50% RH were completed. Then 90 minutes of dehydration, STHA (no fluid intake), for 5 consecutive days (39.5℃, 60% RH), using controlled hyperthermia (~rectal temperature [T_{re}] 38.5℃). HST4 within one week after STHA. Blood plasma constituents: percent plasma volume (%PV), aldosterone, total protein, albumin, electrolytes, cortisol, and HSP70. Data analysis reported as mean differences with 95% confidence intervals (95% CI) and Cohen's *d* effect size.

Results: Post STHA, there was a decrease of −0.20℃ in T_{re} at 45 minutes in the HST (95% CI −0.40 to −0.05℃; P = 0.03; d = −0.56), mean skin temperature (−0.80; −1.30 to −0.30℃; P = 0.007; d = −1.46), and mean body temperature (−0.30; −0.50 to −0.10℃, P = 0.01; d = −0.75). Cardiac frequency decreased (−3; −5 to −1 b min^{-1}; P = 0.01; d = −0.20) and %PV increased (7.3; 0.9 to 13.7%; P = 0.03; d = 0.59). Mean peak power increased ($P < 0.05$) across sprints 7, 8, and 9. Time to exhaustion increased (167; −15 to 350 s; P = 0.06; d = 0.63).

Conclusion: STHA (5 days) with dehydration, using controlled hyperthermia technique, is effective for physiological adaptations during intermittent exercise in the heat, with moderately trained males.

Keywords: intermittent, males, dehydration, fluid regulation, plasma volume

Abbreviations

f_c	Cardiac frequency [b min^{-1}]
$\dot{Q}$	Cardiac output [L min^{-1}]
HST	Heat stress test
$[HSP70/TP]_p$	Plasma heat shock protein 70 corrected for total protein
$\dot{V}O_{2\,max}$	Maximum oxygen uptake [L min^{-1} or mL kg^{-1} min^{-1}]
$\bar{T}_b$	Mean body temperature [℃]
MPO	Mean power output
$\bar{T}_{sk}$	Mean skin temperature [℃]
$\dot{V}O_2$	Oxygen consumption [L min^{-1} or mL kg^{-1} min^{-1}]
$\dot{V}O_{2\,peak}$	Peak oxygen uptake [L min^{-1} or mL kg^{-1} min^{-1}]
%PV	Percentage plasma volume [%]
$[alb]_p$	Plasma albumin [mg mL^{-1}]
$[aldo]_p$	Plasma aldosterone [pg mL^{-1}]
$[cortisol]_p$	Plasma cortisol [ug dL^{-1}]
$[Na^+]_p$	Plasma sodium [mmol L^{-1}]
$[TP]_p$	Plasma total protein [mg mL^{-1}]
T_{re}	Rectal temperature [℃]

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RH Relative humidity [%]
STHA Short-term heat acclimation
$color_u$ Urine color [units]
osm_u Urine osmolality [mOsm kg]
SG_u Urine specific gravity [units]

Introduction

Exercising in hot conditions induces thermoregulatory and physiological strain that can impair exercise endurance and exercise capacity and reduce optimal performance (Chalmers et al., 2014; Racinais et al., 2015). The thermoregulatory responses associated with acute exercise in the heat include: elevated rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), and mean body temperature ($\bar{T}_b$); increased exercising cardiac frequency (f_c); rate of perceived exertion (RPE); thermal comfort; increased thirst and water loss leading to dehydration (Chalmers et al., 2014; Guy et al., 2015; Racinais et al., 2015). It is well established that repetition of heat stress exposure facilitates adaptations to the heat (Garrett et al., 2009) and this can take up to 14 days for complete adaptation of cardiovascular and sudomotor systems (Racinais et al., 2015). However, it had been shown that 75% of physiological adaptations occur within 4–6 days (Garrett et al., 2011). However, the majority of the studies investigating the effect of heat acclimation on performance have tended to use protocols of a fixed work intensity, continuous exercise, long-term duration (>7 days) and hydration. Therefore, the aims of this study were to investigate the effectiveness of short-term heat acclimation (STHA) for 5 days, using the controlled hyperthermia technique with no fluid intake, on intermittent exercise in a hot environment.

Methods of Heat Acclimation

Repetitive heat exposure has been well established in facilitating heat adaption and improving performance in the heat. The major benefits of heat acclimation have been well defined and can be short (<7 days), medium (8–14 days) or longer term (>15 days) in duration (Garrett et al., 2011). The physiological responses before and after heat acclimation are dependent on the length of exposure to heat stress conditions, with complete cardiovascular and sudomotor adaptation occurring after 14 days of heat exposure (Racinais et al., 2015). However, long-term acclimation is not always feasible (Gibson et al., 2014), particularly for athletes competing in other countries because of time or financial restrictions. Therefore, STHA is beneficial for those looking to be acclimatized in the shortest time possible.

There are different methods that can be used for the heat acclimation protocol, which include constant work rate, self-regulated work rate, and the controlled hyperthermia technique (Taylor, 2000). The controlled hyperthermia technique involves exercising to elevate and maintain T_{re} above the sweating threshold; this ensures equal thermal strain on each participant. The controlled hyperthermia technique has been shown to provide a more complete heat adaptation than both the constant and self-regulated work-rate methods (Taylor, 2000). The level of heat acclimation can be influenced by two factors: level of fitness and hydration status of the individual (Cheung & McLellan, 1998). Aerobically fit individuals possess similar attributes to heat acclimated individuals. Cheung and McLellan (1998) demonstrated that highly trained individuals are more capable of tolerating high levels of heat stress compared to untrained individuals, with lower resting and higher end exercise T_{re} than untrained individuals. Endurance trained individuals have been shown to adapt more rapidly to heat acclimation than those with low or moderate fitness levels (Cheung & McLellan, 1998).

There are fundamentally three models in which active heat acclimation can be achieved: (i) constant work rate, (ii) self-regulated exercise, and (iii) the controlled hyperthermia or isothermic technique (Taylor & Cotter, 2006). The controlled hyperthermia technique has been postulated to provide greater heat adaptation than the constant work-rate and self-regulated work-rate methodologies. This technique is proposed on the basis that core temperature elevation is a key consideration for successful heat acclimation associated with high skin temperature and sweating response, as exercise alone is not a sufficient stimulus for adaptation (Hessemer et al., 1986). In contrast, there has been evidence to demonstrate that isothermic and fixed intensity heat acclimation methods induce similar heat adaptation in the short and long term. However, it is suggested that controlled hyperthermia is a more efficient and practical method for heat adaptation, especially for athletes tapering before competition (Gibson et al., 2015).

The addition of a permissive dehydration stimulus, that is, restricting fluid intake during acclimation, has received attention in the literature (Akerman et al., 2016) and with a female cohort (Kirby et al., 2019). However, the benefits of permissive dehydration have not been reported universally (Neal et al., 2016). In our previous work using a male cohort (Garrett et al., 2014), permissive dehydration during acclimation was shown to improve the fluid regulatory mechanisms by improving the reabsorption of water and Na^+ resulting in PV expansion. This indicated that the adaptive response may be enhanced rather than impaired by dehydration acclimation and this work had a euhydration control. Furthermore, we have demonstrated that the use of permissive dehydration with short-term heat acclimation (5 days) provides heat adaptation for moderately (Garrett et al., 2009) and highly trained (Garrett et al., 2012) individuals. Furthermore, it has demonstrated effectiveness with moderately trained females during intermittent exercise (Garrett et al., 2019).

High Intensity Interval Training (HITT)

There is no one accepted definition of HIIT. Instead multiple authors have attempted to define this inherently varied form of exercise training (Gibala & McGee, 2008). A broad definition of HIIT is a form of exercise training that incorporates repeated short bouts of intense exercise separated by similar length bouts of low-intensity or no exercise; these intense bouts of exercise are usually completed a number of times in a single training session. There are many forms of HIIT each utilizing different intensities, durations, and modes of exercise. Sprint interval training is a common form of HIIT, characterized by repeated bouts of "all out" sprints. Common HIIT protocols, including sprint interval training, generally consist of Wingate style supramaximal "all out" sprints, which involve an individual cycling at a maximal effort for a short duration (Gibala & McGee, 2008). Protocols vary between studies, but usually involve multiple (two to seven) all out, 30-second sprints separated by 4 minutes of active recovery (Astorino et al., 2012; Bayati et al., 2011; Burgomaster et al., 2005; Garcia et al., 2016). A similarity between studies is the reliance on supramaximal exercise.

The time of each interval is another common variable that is manipulated. The duration of intervals usually begins at 30 seconds up to a maximum of 4 minutes with studies using a range in between. Protocols utilizing even shorter durations have been reported, but the literature seems to predominately use durations equal to, or above 30 seconds. Duration and intensity of intervals commonly have an inverse relation, where researchers choose shorter durations incorporating higher intensities and vice versa. In effect, researchers attempt to find the optimum balance between the length and intensity of intervals.

Intermittent exercise can be defined as short periods of moderate and/or strenuous exercise, with short intervals of recovery (Kraning II & Gonzalez, 1991). Intermittent exercise and steady-rate exercise use different metabolic processes to support the activity (Drust et al., 2000). They compared an intermittent exercise protocol with steady-rate exercise, with the same mean exercise intensity (12 km h^{-1}) in 18℃, 54% RH with seven male university soccer players. Both the intermittent and steady-state exercise protocols lasted ~46 minutes. Physiological strain, mean energy expenditure, f_c, $\dot{V}O_2$, T_{re}, and sweat production were similar between the two types of exercise. However, there was a large effect size for f_c between the two modes of exercise, suggesting intermittent exercise may create a greater demand on the cardiovascular system than steady-rate exercise when performed at the same overall mean exercise intensity.

Team Sports

Team sports are intermittent in nature and involve bouts of high and low exercise intensities; performance of specific skills and sporadic patterns of movements may be included with these changes (Drust et al., 2007). Team sports, like soccer, are primarily aerobic sports and include frequent bouts of activity (Bangsbo, 1993). The intensity and duration of the activity vary greatly and tend to be followed by a recovery period where activity is light or with no activity (Drust et al., 2007). The movements and skills involved in a team sport (tackling, maintaining possession, and passing, kicking, and throwing of a ball) contribute to this erratic activity profile (Carling et al., 2006).

Drust et al. (2000) designed a laboratory protocol, using a motorized treadmill, to simulate the activity in a soccer game. All data were based on motion analysis developed historically (Reilly & Thomas, 1976) for professional soccer players. The protocol was originally based on one half of a match (45 minutes); however, this was later adapted to simulate a full match (90 minutes) (Drust et al., 2007). The protocol includes periods of rest, walking, jogging, cruising, and sprinting, all in proportion to those observed in match-play, and also incorporates a 15-minute rest, to imitate the half-time period of a soccer game (Drust et al., 2007).

Intermittent shuttle running, most commonly the Loughborough Intermittent Shuttle Run Test (LIST) (Magalhães et al., 2010; Saunders et al., 2012), has been used to simulate the activity pattern of soccer and can be performed in a sports hall. The LIST protocol involves 75 minutes of intermittent activity, split into 3 × 15-minute blocks separated by a 3-minute rest period. Each block of exercise includes walking, low- and high-speed running (55% and 95% $\dot{V}O_{2\,max}$, respectively), sprinting, and short static recovery (4 seconds) (Nicholas et al., 2000). This is then followed by ~10 minute test to exhaustion, requiring participants to run intermittently at 55% and 95% $\dot{V}O_{2\,max}$, with intensity changing every 20 m (Nicholas et al., 2000). The LIST protocol has been adapted for other team sports and females by Sunderland and Nevill (2005) who investigated the effect of heat on both high-intensity running and skill performance in field hockey players. Therefore, the aims of the present study were to investigate the effectiveness of STHA for 5 days, using the controlled hyperthermia technique with no fluid intake, on intermittent exercise in a hot environment with moderately trained males.

Methods

Experimental Design and Overview

Ten moderately trained male participants undertook a 5-day STHA regime, with no fluid replenishment (DEH) during each daily acclimation session. Participants' thermoregulatory, cardiovascular, and fluid-regulatory statuses were measured at rest and in response to an intermittent, exercising heat stress test (HST) in thermoneutral conditions (HST1 versus HST2; 11℃, 50% RH) as a reliability trial. This was followed by an intervention trial of the HST a week before and after the second day following the DEH acclimation regime to ensure one day of rest (HST3 versus HST4; 31℃, 50% RH). Participants were asked to refrain from strenuous exercise immediately before and 24 hours prior to each HST, as it has been demonstrated that lower resting core temperature contributes to reduced physiological strain during acclimation (Kampmann et al., 2008). A food diary was used by participants to follow a consistent food intake. They were asked to refrain from caffeine and alcohol consumption 12 hours before all testing procedures. A general overview of the STHA protocol for the moderately trained males is shown in Figure 1.

Participants

Participants were 10 male, British/European, team sport games players and volunteers from the University of Hull (Table 1). Therefore, all participants were involved with intermittent activity in a sporting context. Participants completed pre-exercise medical questionnaires and informed consent to participate in the study, indicating that all participants were deemed to be in good health. The study had ethical approval (No. 1314214) from the University of Hull ethics committee.

Experimental Standardization

All participants were fully informed of all experimental procedures (orally and written). Prior to experimental testing, participants completed pre-exercise medical questionnaires and informed consents. All participants were previously unacclimated to the heat and this study was completed outside the British summertime to minimize seasonal acclimatization effects. To minimize circadian rhythm affects, HSTs and acclimations occurred at the same time of day. It is recognized that resting T_{re} is an adaptive response sensitive to the time of day of heat exposure (Shido et al., 1999) and the time of the day of heat exposure has to be controlled (Buono et al., 1998). The laboratory was at sea level (~760 mmHg atmospheric pressure). All participants had limited experience using treadmills in a gymnasium or laboratory environment.

Short-Term Heat Acclimation

The STHA protocol consisted of five consecutive days' heat exposure (39.5℃, 60% RH) for 90 minutes a day, using the controlled hyperthermia technique with permissive dehydration. Participants cycled (Monark 824E, Monark Exercise AB, Varberg, Sweden) against a self-selected resistance at 60 rpm aiming to attain a T_{re} of 38.5℃, as quickly as possible and maintained for the 90 minutes of exposure by regular adjustment of workload. Elevation of T_{re} to the same point during heat exposure aimed to increase workload progressively during the week. Plasma concentrations of fluid-regulatory hormone (aldosterone [aldosterone]$_p$), electrolytes (Na^+, K^+, and Cl^-), proteins (total protein [TP]$_p$; albumin [alb]$_p$), heat shock protein 70 corrected for total protein [HSP70/TP]$_p$, and cortisol [cortisol]$_p$ and percentage change in plasma volume (%PV) were measured at rest and end of acclimation bouts on day one and day five of acclimation. Time (minutes) to

Table 1
Mean ± SD of the personal characteristics for the 10 participants.

Age (years)	25.6 ± 8.9
Height (cm)	180.7 ± 5.6
Body mass (kg)	83.2 ± 10.8
Body mass index (units)	25.4 ± 3.2
$\dot{V}O_{2\,max}$ (mL kg^{-1} min^{-1})	45.3 ± 6.5
Resting $\dot{Q}$ (L min^{-1})	6.1 ± 1.8

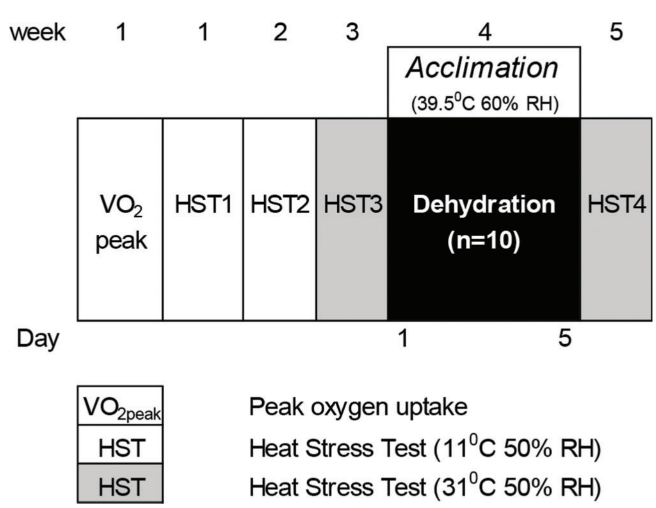

Figure 1. Schematic model of the STHA protocol for moderately trained males.

T_{re} of 38.5℃ and work (kJ) were recorded on each day of acclimation.

Urinary measures

Urine samples were obtained before and after day one and day five of acclimation. Using fresh urine samples, urine specific gravity and urine color were measured using a calibrated refractometer (Uricon-N, urine specific gravity refractometer, Atago Co., Tokyo, Japan) and urine color chart (Armstrong et al., 1994, 1998), respectively. Urine volume was recorded and urine osmolality was analyzed after the experiment.

Blood measures

Plasma for the measurement of the fluid regulatory hormone aldosterone (200 μL) was stored using chilled K-EDTA tubes (1.6 mg mL^{-1}). Measurement of aldosterone used the Coat-A Count aldosterone procedure (DPC's), which is based upon human serum calibrators, ^{125}I tracer and aldosterone antibody-coated tubes. The tube was decanted and counted in a gamma counter. The sample concentration was then determined from calibration standards (25–1200 pg mL^{-1}) and control samples, using a standard curve. The intra-assay coefficient of variation was 8.8% for duplicate measures and all samples for a given individual were analyzed within the same assay. Plasma Na^+, K^+, and Cl^- were analyzed using duplicate colorometric analysis (Cobas Mira Plus, New Jersey, USA). HSP70 enzyme-linked immunosorbent assay analysis was used to determine inducible, plasma heat shock protein concentration response, as described previously (Njemini et al., 2003).

Changes in the concentration of hemoglobin [Hb] and hematocrit [Hct] were used to determine the relative change in plasma volume described by Dill & Costill (1974). Venous blood samples (5 mL) were taken from an antecubital vein (Vacutainer Precision Glide 21-gauge needle, Becton Dickinson Vacutainer Systems) by phlebotomy without stasis and immediately analyzed—in sexplicate—for [Hb] (Willoughby et al., 2002) (using a model OSM3, Radiometer, Copenhagen, Denmark) and [Hct] (using a microhematocrit centrifuge [Hawksley, UK] and a microcapillary reader [Damon/IEC Division, MA, USA]). The percentage change in plasma volume was analyzed from day one to five of the acclimation regime and during HSTs and calculated using a mathematical equation (Dill & Costill, 1974).

Aerobic Fitness Testing

Participants performed an incremental ramp exercise test to volitional exhaustion on a treadmill (h/p/Cosmos, Model Pulsar 3p, Traunstein, Germany), for determination of peak oxygen uptake ($\dot{V}O_{2\,peak}$) and velocities for individualization of the HSTs. This procedure involved a starting velocity of 5 km h^{-1} with workload increments of 0.1 km h^{-1} every 6 s (1 km h^{-1} min^{-1}), until volitional exhaustion. Breath-by-breath expired air was collected via a metabolic cart system (Cortex Metalyzer 3B, Cortex Biophysic, Leipzig, Germany). Participants' RPE (Borg, 1982) and f_c (Polar FS1, Polar Electro, OY, Finland) were recorded every minute. All participants were given verbal encouragement in the latter stages of the incremental test in order to attain maximal performance.

Heat Stress Test

The HST took place in an environmental chamber (Type SSR 60-20H, Design Environment, Gwent, Wales) set to ambient temperature of 11℃, 50% RH for the reliability trial (HST1 versus HST2) and 31℃, 50% RH for the intervention study (HST3 versus HST4).

Pre-exercise urine, blood measure (%PV), and resting cardiac output (Innocor, Innovision, Odense, Denmark) were taken prior to entering the chamber. The HST consisted of 9 × 5-minute blocks of intermittent exercise on a treadmill set at 0% incline (Pulsar 3p, h/p/Cosmos, Traunstein, Germany) and cycle ergometer for a sprint performance test (Wattbike Ltd, Nottingham, UK). Participants then went on to perform a test to exhaustion on the treadmill. The exercise intensities used in the intermittent protocol were based upon the match-play characteristics of professional footballers (Drust et al., 2007). Each 5-minute block consisted of intermittent treadmill running, as presented in Table 2. Sprint characteristics, peak power output (PPO), mean power output (MPO), and time to exhaustion were used as sprint and endurance performance measures.

The HST was performed in thermoneutral conditions (HST1 versus HST2; 11℃, 50% RH) as a reliability trial followed by the intervention trial. The HST was the week before and after the second day following the dehydration acclimation regime to ensure one day of rest (HST3 versus HST4; 31℃, 50% RH). The post-acclimation HST4 was performed within a week of the final acclimation day to prevent the decay of acclimation (Garrett et al., 2009).

Body temperature

Core body temperature was measured using a rectal thermistor (U thermistor, Grant Instruments Ltd, Cambridge,

Table 2
Speed intensities and durations for the 45-minute (9 × 5-minute) intermittent performance HST.

Speed (km h^{-1})	**Duration (s)**
0	30
6	60
12	180
15	30
Maximal sprint (cycle)	6

UK) inserted to a depth of 10 cm beyond the anal sphincter. Skin temperature was measured using skin thermistors (Type EUS-U-V5-V2, Grant Instruments Ltd, Cambridge, UK) placed on four, left-sided sites: chest, bicep, thigh, and calf, secured using micropore tape. Mean skin temperature ($\bar{T}_{sk}$) and mean body temperature ($\bar{T}_b$) were calculated as follows:

$\bar{T}_{sk} = 0.3T_{\text{chest}} + 0.3T_{\text{bicep}} + 0.2T_{\text{thigh}} + 0.2T_{\text{calf}}$ (Ramanathan, 1964)

$\bar{T}_b = 0.9T_r + 0.1\bar{T}_{sk}$ (Sawka et al., 1996)

Temperature data were recorded at 1-minute intervals on a portable data logger (2020 series data logger, Grant Instruments Ltd, Cambridge, UK).

Data analysis

Where a statistical difference was observed in primary outcomes, the stress response of dependent measures in STHA and HSTs were analyzed for normal distribution by using the Shapiro–Wilk and the Brown–Forsythe tests determining equal variance. Where data were normally distributed, two-way repeated measures ANOVA was used to determine differences between pre- and post-HSTs and pairwise multiple comparison procedures were analyzed using post-hoc Bonferroni correction *t*-tests where appropriate. The changes in thermal and blood markers on day one and day five of acclimation were analyzed using paired *t*-tests. Data are reported for ten moderately trained males unless otherwise stated. Where appropriate, data are reported as mean differences ± SD with 95% confidence intervals (95% CI) and the magnitude of effect using Cohen's *d* effect sizes (where 0.2–0.59, small; 0.6–1.19, moderate; 1.2–1.99, large; 2.0–4.0, very large). The relationship (*r*) within variables has been calculated using the Pearson product moment correlation. The reliability of dependent measures is presented as the CoV (95% CI) and SE (95% CI).

Results

All ten participants completed the 5-day STHA protocol and eight the HSTs (HST1, HST2, HST3, and HST4). HST1 versus HST2 was a reliability trial taken one week apart with no intervention. HST3 versus HST4 was with the STHA (5-day) intervention.

Short-Term Heat Acclimation

Thermal stress and strain

Thermal stress and strain from days one and five of heat acclimation are presented in Table 3. Measures of ambient temperature (T_a) and RH indicated that the thermal stress was similar on days one and five of acclimation. The thermal strain was consistent between days illustrated by rectal temperature (T_{re}) response, but mean cardiac frequency (f_c) was lower on day 5 and this was close to significance (P = 0.06). Time to 38.5℃ was longer on day five than on day one (Table 3; P = 0.04).

Body mass and color_u significantly decreased from rest to the end of exercise on day one. On day five, body mass decreased.

Urinary measures

To determine hydration status, measures of urine specific gravity (SG_u), urine color (color_u), urine osmolality (Osm_u), and body mass on days one and five of acclimation are shown in Table 4.

The percentage change of blood measures, time to 38.5℃, and work on the first day (day 1) to the last day (day 5) of dehydration acclimation after 90 minutes of heat exposure are presented in Table 5. There was a consistent increase from rest to end exposure with limited difference on day one versus day five acclimation for $[TP]_p$, $[alb]_p$, $[aldo]_p$, $[Na^+]_p$, and $[HSP70/TP]_p$. In contrast, the stress hormone response of $[\text{cortisol}]_p$ increased on day one but decreased by day five (P = 0.005), with an increase in exercise time to 38.5℃ (P = 0.04; n = 10).

Blood measurements

Blood measures, time to 38.5℃ and work on the first day (day 1) to the last day (day 5) of dehydration acclimation after 90 minutes of heat exposure are presented in Table 5.

Table 3
Thermal stress and strain on the first day (day 1) and last day (day 5) of STHA.

	Day 1	Day 5	*P*-value
T_a (℃)	39.7 ± 0.2	39.7 ± 0.2	0.19
RH (%)	61.0 ± 1.3	60.1 ± 1.2	0.42
Mean f_c (b min^{-1})	133 ± 19	123 ± 16	0.06
Mean T_{re} (℃)	38.29 ± 0.46	38.30 ± 0.47	0.46
Time to T_{re} of 38.5℃ (min)	31.50 ± 6.62	36.62 ± 9.24	**0.05**
Work (kJ)	24.77 ± 7.18	28.70 ± 6.65	0.11
Body mass change (%)	−2.0 ± 0.7	−2.5 ± 0.6	**0.03**
%PV change	−5.9 ± 0.7	−2.2 ± 0.3	0.14

Note. Ambient temperature (T_a), RH, cardiac frequency (f_c), rectal temperature (T_{re}), time to T_{re} of 38.5℃, and work determined on days one and five of acclimation undertaken with permissive dehydration. Data presented as mean ± SD for ten male participants. Significant differences are shown in bold.

Table 4
Urinary measures of hydration (color$_u$, Osm$_u$, SG$_u$) and nude body mass, at rest and end-exercise, on days one and five of STHA.

	Day 1: rest	Day 1: 90 minutes	*P*-value	Day 5: rest	Day 5: 90 minutes	*P*-value
Color$_u$ (units)	2 ± 1	4 ± 2	**0.005**	3 ± 2	4 ± 2	0.14
Osm$_u$ (mOsm kg^{-1})	479 ± 145	449 ± 161	0.59	390 ± 245	375 ± 253	0.82
SG$_u$ (units)	1.002 ± 0.005	1.015 ± 0.003	0.21	1.006 ± 0.008	1.007 ± 0.005	0.68
Body mass (kg)	62.3 ± 8.7	61.2 ± 8.6	**0.005**	62.5 ± 8.8	61.4 ± 8.7	**0.005**

Note. Data presented as mean ± SD for ten male participants. Significant differences (rest to 90 minutes) presented in bold.

Reliability Study

HST1 versus HST2 was a reliability trial taken one week apart with no intervention in 11℃, 50% RH. Table 6 presents the reliability of rectal temperature, mean body temperature, and mean skin temperature at rest and end-exercise. Table 7 presents the reliability of exercise performance measures of MPO, PPO, and time to exhaustion. Data are presented for eight male participants. Low seven-day measurement errors (CoVs and SEs) were recorded for all temperature measures (T_{re}, $\bar{T}_{sk}$, and $\bar{T}_b$) and performance measures (PPO, MPO, and time to exhaustion), indicating that the measurements of these variables in the HST were reliable.

Intervention Study

Measurements were taken at rest and at end of exercise in HSTs. Data are presented for eight male participants unless otherwise stated. The pre-HST3 trial took place one week before the STHA (5 days), with dehydration intervention in 31℃, 50% RH. The post-HST4 trial occurred within 7 days of the last acclimation bout.

Body temperatures

Figure 2 shows the mean ± SD rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), and mean body temperature ($\bar{T}_b$) pre (HST3) to post (HST4) acclimation in hot conditions (31℃, 50% RH; $n = 8$). There was a reduction at 45 minutes for T_{re} (−0.20; 95% CI −0.40 to −0.05℃; $P = 0.03$; $d = -0.56$: small), $\bar{T}_{sk}$ (−0.80; −1.30 to −0.30℃; $P = 0.007$; $d = -1.46$: large), and $\bar{T}_b$ (−0.30; −0.50 to −0.10℃; $P = 0.01$; $d = -0.75$: moderate).

Cardiac frequency (f_c) and percentage change in plasma volume (%PV)

Pre (HST3) versus post (HST4) STHA cardiac frequency (−5; −7 to −2 b min^{-1}; $P = 0.01$; $d = -0.20$: small) was reduced at 45 minutes and there was an increase in %PV (7.3; 0.9 to 13.7%; $P = 0.03$; $d = 0.59$: moderate).

Psychophysiological measures

There was limited change in thermal comfort (−0.5; −1 to 0; $P = 0.17$; $d = 0.15$: small) and thermal sensation (0; −1 to 1; $P = 0.28$; $d = 0.25$: small) at 45 minutes. However, RPE decreased at 45 minutes (−2; −3 to −1 units; $P = 0.01$; $d = -0.56$: small) pre (HST3) versus post (HST4) STHA.

Repeated sprint performance and time to exhaustion trial

MPO was measured across all nine, 6-second maximal sprints in the 45-minute protocol (Figure 3).

The MPO increased ($P < 0.05$) across sprints 7 (111; 25 to 197 W; $d = 0.93$: moderate), 8 (87; −8 to 182 W; $d = 0.52$: small), and 9 (240; 9 to 489 W; $d = 0.77$: moderate). A tendency for increased time to exhaustion was observed in seven of the eight participants (167; −15 to 350 s; $P = 0.06$; $d = 0.63$: moderate).

Discussion

Effectiveness of STHA

There were physiological adaptations from short-term (5-day) heat acclimation with no fluid acclimation, using the controlled hyperthermia technique, reducing cardiovascular strain during intermittent exercise and enhancing repeated sprint capacity and endurance performance. These adaptations included lower end-exercise f_c, T_{re}, $\bar{T}_{sk}$, and $\bar{T}_b$ and increased %PV (Garrett et al., 2009). The cardiovascular stability was due to increased heat loss rather than lower heat content (~resting core temperature), at the time of day of HSTs. This concurs with previous work that used permissive dehydration but with continuous exercise (Garrett et al., 2014), and furthermore, using untrained males (Turk & Worsley, 1974; Weller & Harrison, 2001); moderately trained (Garrett et al., 2009) and highly trained (Garrett et al., 2012) males; and intermittent exercise with moderately trained females (Garrett et al., 2019).

Adaptation to Exercise in the Heat

Low seven-day measurement errors (CoVs and SEs) were recorded for all temperature measures (T_{re}, $\bar{T}_{sk}$, and $\bar{T}_b$; Table 6) and performance measures (PPO, MPO, and time to exhaustion; Table 7), indicating that the measurements of these variables used in the HST were reliable.

The post-acclimation HST4 was performed within a week of the final acclimation day to prevent the decay of acclimation (Garrett et al., 2009). The present results obtained using a moderately trained male cohort, undergoing STHA of daily controlled hyperthermia with

Table 5
Percentage changes of blood measures, time to 38.5℃, and work on the first day (day 1) to the last day (day 5) of dehydration acclimation after 90 minutes of heat exposure.

	$[TP]_p$ (mg mL^{-1})	$[alb]_p$ (mg mL^{-1})	$[aldo]_p$ (pg mL^{-1})	$[Na+]_p$ (mmol L^{-1})	$[HSP70/TP]_p$ (mg ng^{-1})	$[cortisol]_p$ (ug dL^{-1})	%PV (%)	Time to 38.5℃ (min)	Work (kJ)
Day one acclimation									
Rest	87.6 ± 10.2	45.0 ± 1.4	198 ± 223	128 ± 2	0.14 ± 0.10	184 ± 60			
End	97.5 ± 21.8	48.2 ± 2.7	587 ± 359	130 ± 1	0.14 ± 0.12	281 ± 67	−5.9 ± 0.7	31.5 ± 6.6	24.77 ± 7.18
Change (%)	10	7	66	2	0	35			
Day five acclimation									
Rest	88.1 ± 12.0	45.4 ± 2.5	360 ± 426	120 ± 2	0.14 ± 0.11	185 ± 53			
End	94.2 ± 18.3	49.7 ± 1.0	762 ± 532	130 ± 2	0.15 ± 0.13	181 ± 67*	−2.2 ± 0.3	36.6 ± 9.3*	28.70 ± 6.65
Change (%)	7	9	53	8	7	−2	−4	14	14

Note. Data are mean ± SD for ten moderately trained males.
*Significant difference ($P < 0.05$); day 1 versus day 5 acclimation.

dehydration, demonstrated that the participants experienced substantial adaptation to the heat, as indicated by the characteristic features of acclimation. A decrease in T_{re} by −0.2℃ (Figure 2; top panel), $\bar{T}_{sk}$ by −0.8℃ (Figure 2; middle panel), and $\bar{T}_b$ by −0.30 (Figure 2; lower panel) was observed. We have previously reported similar body temperature measures using the hyperthermia control technique with male (Garrett et al., 2012, 2009, 2014) and female (Garrett et al., 2019) participants. Furthermore, a key adaptation is a reduction in $\bar{T}_b$ for a given exercise workload (Brade et al., 2013; Garrett et al., 2012; Sunderland et al., 2008). The decrease in $\bar{T}_b$ and $\bar{T}_{sk}$ at the end of exercise in hot conditions observed in this study is similar to that reported in other studies (Racinais et al., 2015; Taylor, 2000). The lower $\bar{T}_b$ and $\bar{T}_{sk}$ observed in the present study is likely indicative of more effective evaporative cooling (Gagnon & Kenny, 2012). A redistribution of sweat to the limbs has been suggested to result in greater post-acclimation evaporative heat loss (Hofler, 1968; Regan et al., 1996; Shvartz et al., 1979). However, this has not always been shown to be the case (Cotter et al., 1997). It has been suggested that if sweat glands can adapt it is those farthest from their maximal sweat capacity that will undergo the greatest adaptation, such as the forearm (Patterson et al., 2004b). In the present study, sweat rate was measured as a function of body mass loss during the each HST and therefore conclusions regarding local sweat rate cannot be made.

End-exercise f_c decreased by 5 b min^{-1}. Increased cardiovascular stability is recognized as one of the most rapidly occurring adaptations to heat and thus one of the quickest to decay (Garrett et al., 2009, 2011). There was an increase in %PV by 7.3 and this range was variable (0.9 to 13.7%). However, previous research suggests large variability in PV expansion ranging from 3 to 27% (Garrett et al., 2014; Nielsen et al., 1993; Patterson et al., 2004a, 2014). Increased resting albumin concentration (Table 5) likely increased colloid-osmotic pressure (Yang et al., 1998). Previous research suggests that intravascular fluid expansion resulting from such increases in colloid-osmotic pressure (Senay, 1979; Senay et al., 1976) explains a majority of PV expansion (Goto et al., 2010).

Fluid regulation response to repeated heat stress

In the present study, participants experienced the same thermal load which is the basis of using the controlled hyperthermia technique for heat acclimation (Taylor, 2000). Individuals' hydration status was reflected on day five of acclimation by total body water; after dehydration acclimation the participants experienced a mild hypohydration of ~2% body mass (Table 3). This is similar to the imposed hypohydration administered by Judelson and colleagues (2008), who reported a modification in the hormonal and metabolic response to resistance exercise, influencing the post-exercise circulatory milieu (Judelson

Table 6
Reliability of rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), and mean body temperature ($\bar{T}_b$) at rest and end-exercise.

Dependent variable	*n*	CoV (95% CI)	SE (95% Cl)	*r*
T_{re} rest	8	0.2 (0.1 to 0.4)	0.04 (0.04 to 0.2℃)	0.88
T_{re} end-exercise	8	0.5 (0.3 to 1.1)	−0.06 (−0.04 to 0.05℃)	0.66
$\bar{T}_{sk}$ rest	8	4.0 (2.7 to 8.4)	−0.21 (−1.91 to 0.7℃)	0.97
$\bar{T}_{sk}$ end-exercise	8	3.5 (2.3 to 7.4)	−1.4 (0.8 to 0.5℃)	0.78
$\bar{T}_b$ rest	8	0.3 (0.2 to 0.7)	−0.06 (−0.3 to −0.03℃)	0.87
$\bar{T}_b$ end-exercise	8	0.6 (0.4 to 1.2)	−0.06 (−0.05 to 0.06℃)	0.96

Note. CoV (95% CI): coefficient of variation and 95% confidence interval; SE (95% CI): standard error and 95% confidence interval; *r*: Pearson product moment correlation.

Table 7
Reliability of performance measures (mean power output, peak power output) and time to exhaustion in the reliability trial.

Dependent variable	*n*	CoV (95% CI)	SE (95% Cl)	*r*
Mean power output	8	2.5 (1.7 to 4.9)	8.44 (−7.8 to 31.1 W)	0.83
Peak power output	8	2.9 (2.0 to 5.8)	12.4 (−27.6 to 29.6 W)	0.71
Time to exhaustion	8	7.8 (5.3 to 17.1)	1.98 (−15.1 to 26.4 s)	0.96

Note. CoV (95% CI): coefficient of variation and 95% confidence interval; SE (95% CI): standard error and 95% confidence interval; *r*: Pearson product moment correlation.

et al., 2008). Furthermore, the transient osmolality and volume effects of hypohydration incur fluid-regulatory responses that could partially mediate the hypervolemia and improved fluid-regulatory efficiency that is observed with training (Merry et al., 2010, 2008) provided that nutritive substrates are available and ingested following the conditioning bouts (Okazaki et al., 2009b, 2009a). Therefore, we suggest that the increased physiological strain of restricted fluid replenishment during dehydration acclimation may have resulted in adaptation of the fluid-regulatory system (Akerman et al., 2016) and this concurs with our previous work on this potential mechanistic response (Garrett et al., 2014).

Stress hormone response

In the present study, the time to reach 38.5℃ significantly increased (14%) from days 1 to 5, resulting in an associated increase in work (14%; Table 3). Time to 38.5℃ was consistent in comparison with previous studies using male cohorts (Garrett et al., 2012, 2009, 2014; Neal et al., 2015). The stress hormone cortisol significantly increased during acclimation on day 1 but not on day 5. A greater time to 38.5℃ and more work completed indicate a heat-adaptive response (Table 5). This agrees with previous observations suggesting heat acclimation reduces cortisol levels during exercise in the heat (Armstrong et al., 1989; Francesconi et al., 1983), but such findings are not universal (Finberg & Berlyne, 1977; Sunderland et al., 2008). In response to hot–wet (35℃, 79% RH) and hot–dry (49℃, 20% RH) exercise before and after acclimation in both euhydrated and hypohydrated conditions, Francesconi et al (1983) observed that hypohydration in a pre-acclimated state significantly increased plasma cortisol levels. This effect was significantly attenuated post-acclimation especially in the hot–wet condition (Francesconi et al., 1983). Therefore, in the present study, improved fluid dynamics could have played a significant role in the reduction in plasma cortisol concentration.

Repeated Sprint Performance and Time to Exhaustion Trial

The majority of research on the effectiveness of heat acclimation has tended to use continuous/endurance-based protocols (Garrett et al., 2011). The present study investigated the effect of STHA on intermittent exercise performance and demonstrated an increase in MPO across maximal sprints after STHA of 5 days (Figure 3). From a practical and applied perspective, an improvement in sprint dynamics is a valuable asset in team sport situations. Work rates during team sports matches are largely determined by the playing style of the opposing team and individuals (Ozgunen et al., 2010). The ability to maintain repeated sprint performance can determine when a games player gets to the ball first and outruns the opposition. The improved sprint dynamics observed in the current study may be efficient to achieve these goals in a game situation. Secondly, the time to exhaustion trial was close to significance with seven of the eight participants improving, indicating an increase in endurance performance after STHA (Garrett et al., 2009).

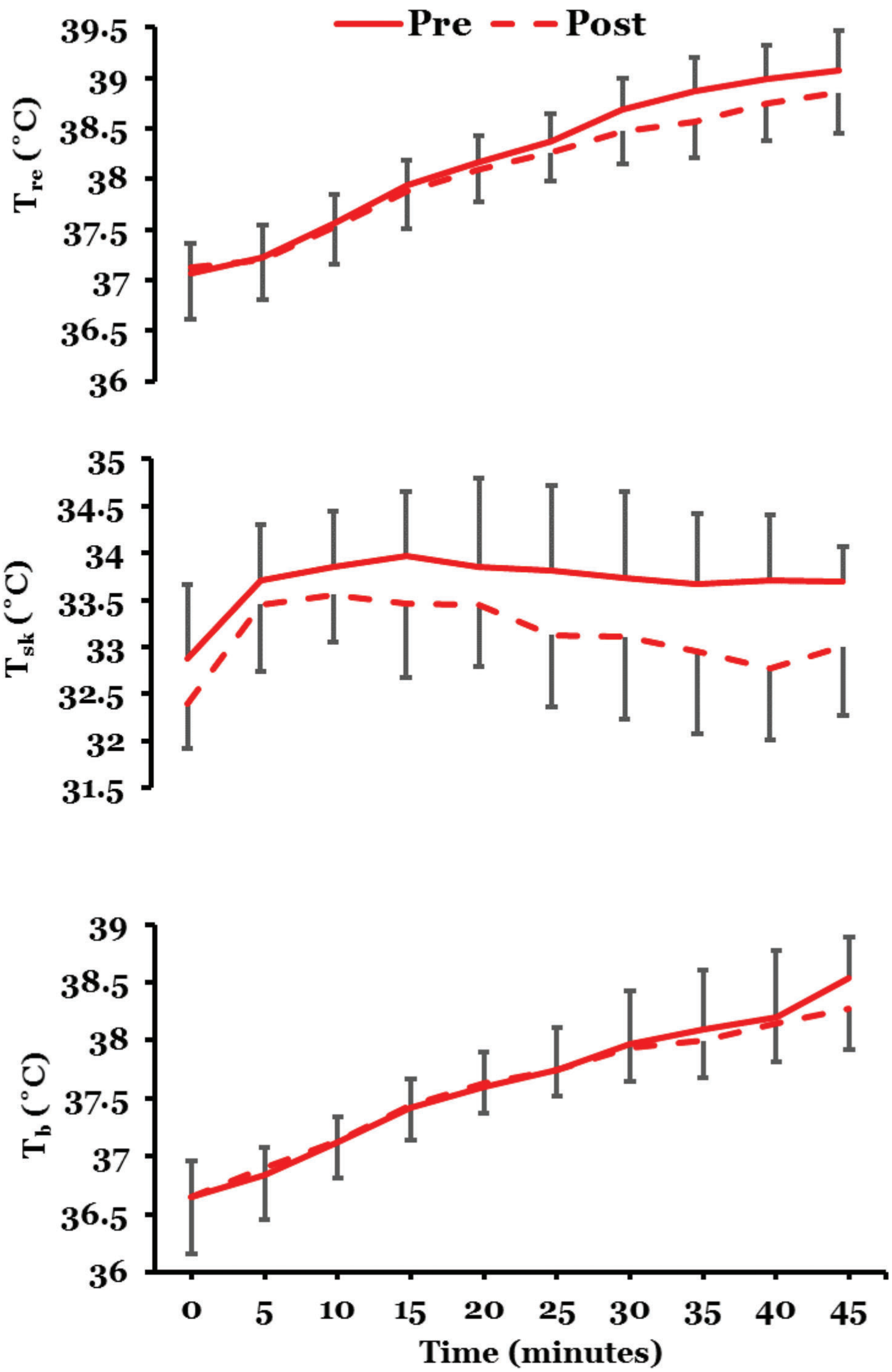

Figure 2. Mean ± SD rectal temperature (T_{re}) (upper panel), mean skin temperature ($\bar{T}_{sk}$) (middle panel), and mean body temperature ($\bar{T}_b$) (lower panel) pre (HST3) versus post (HST4) STHA in hot conditions (31℃, 50% RH; $n = 8$).

Limitations and Future Directions of Research

The key limitation is that we have used a relatively small sample size of male participants due to the time involved with the experimentation. However, we have recently published work using the same acclimation protocol from this work but with a female cohort (Garrett et al, 2019). This work investigated the effectiveness of STHA, over 5 days (permissive dehydration), on an intermittent sprint exercise protocol with females, controlling for menstrual cycle phase. This work suggested that the adaptive responses in a female cohort were of a similar magnitude

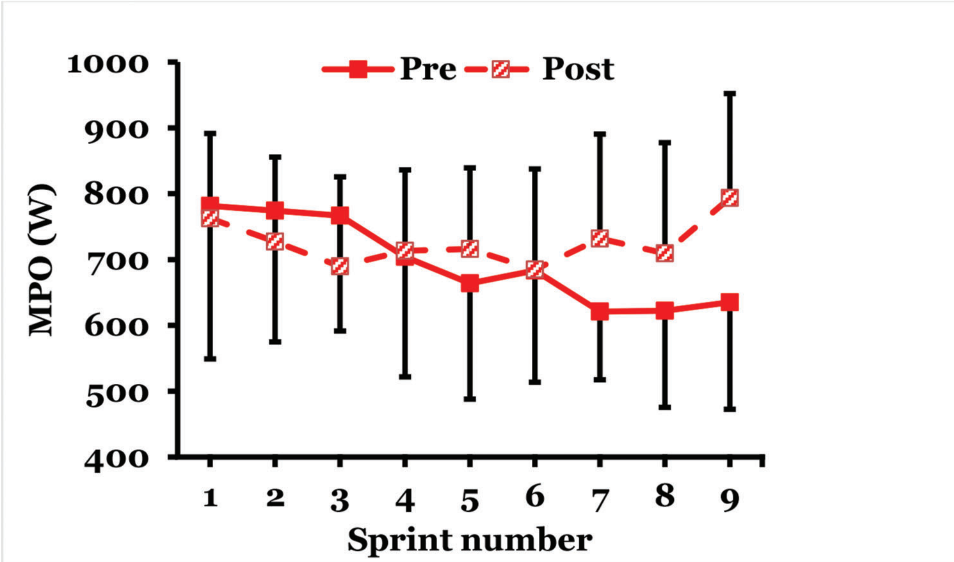

Figure 3. Mean ± SD of MPO in maximal sprint performance pre (HST3) versus post (HST4) STHA in hot conditions (31℃, 50% RH; $n = 8$).

to those of the present study with male participants, enhancing thermoregulation and cardiovascular stability during intermittent exercise in the heat.

For future directions, a comparative study of males versus females using the same STHA protocols may add to the limited information on females. Secondly, as information is limited on the physiological mechanisms of fluid regulation in males and females, a comparison of euhydration versus dehydration STHA may provide a greater understanding of this area. To the authors' knowledge, our earlier work (Garrett et al., 2014) is the only study to have done this and with male participants only.

Conclusion

In summary, this work has established the effectiveness of STHA for 5 days, using the controlled hyperthermia technique with no fluid intake (Garrett et al., 2009, 2012, 2014, 2019), on intermittent activity in hot environments with a moderately trained, male cohort. This study suggests these methods of heat acclimation in a male cohort enhance thermoregulation and cardiovascular stability during intermittent exercise in the heat. Such improvements allow performance enhancements, increased thermal comfort, and may provide protection from exertional heat-related illnesses associated with exercise performance. This work has used STHA and intermittent activity in the preparation for sport. The authors suggest that it will have wider implications for other ergonomic activities, such as military engagements in the heat and the work of the fire service.

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