

Short-Term Heat Acclimation Training Improves Physical Performance: A Systematic Review, and Exploration of Physiological Adaptations and Application for Team Sports

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Abstract

Background Studies have demonstrated that longer-term heat acclimation training (≥ 8 heat exposures) improves physical performance. The physiological adaptations gained through short-term heat acclimation (STHA) training suggest that physical performance can be enhanced within a brief timeframe.

Objective The aim of this systematic review was to determine if STHA training (≤ 7 heat exposures) can improve physical performance in healthy adults.

Data Sources MEDLINE, PubMed, and SPORTDiscusTM databases were searched for available literature.

Study Selection Studies were included if they met the following criteria: STHA intervention, performance measure outcome, apparently healthy participants, adult participants (≥ 18 years of age), primary data, and human participants.

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Study Appraisal A modified McMaster critical appraisal tool determined the level of bias in each included study.

Results Eight papers met the inclusion criteria. Studies varied from having a low to a high risk of bias. The review identified aerobic-based tests of performance benefit from STHA training. Peak anaerobic power efforts have not been demonstrated to improve.

Limitations At the review level, this systematic review did not include tolerance time exercise tests; however, certain professions may be interested in this type of exercise (e.g. fire-fighters). At the outcome level, the review was limited by the moderate level of bias that exists in the field. Only two randomized controlled trials were included. Furthermore, a limited number of studies could be identified (eight), and only one of these articles focused on women participants.

Conclusions The review identified that aerobic-based tests of performance benefit from STHA training. This is possibly through a number of cardiovascular, thermoregulatory, and metabolic adaptations improving the perception of effort and fatigue through a reduction in anaerobic energy release and elevation of the anaerobic threshold. These results should be viewed with caution due to the level of available evidence, and the limited number of papers that met the inclusion criteria of the review. STHA training can be applied in the team-sport environment during a range of instances within the competitive season. A mixed high-intensity protocol may only require five sessions with a duration of 60 min to potentially improve aerobic-based performance in trained athletes.

1 Introduction

Sporting events in hot and humid environmental conditions pose a great environmental challenge to maintaining

the optimal performance of an athlete [1]. Submaximal exercise in hot ambient conditions challenges the cardiovascular system to meet thermoregulatory demands without compromising metabolic and circulatory demands. Thermoregulation can be compromised during prolonged submaximal exercise by competing circulatory and metabolic requirements that result in a rise in core temperature (T_c) and associated fatigue [2]. Many major team-sport events in the near future are scheduled in potentially hot and/or humid ambient conditions, such as the 2014 Soccer World Cup and 2016 Olympics in Brazil, 2015 Cricket World Cup in Australia/New Zealand, and the 2022 Soccer World Cup in Qatar. Hence, the effects of acute and chronic heat exposure on physical performance are significant factors in the management and preparation of athletes.

1.1 Heat Acclimation/Acclimatization Training

Through repeated heat stress exposure, the heat acclimation (response to a controlled environment setting) or acclimatization (response to naturally occurring environment) (both abbreviated to HA in the current paper) process facilitates adaptations that enhance cardiovascular, thermoregulatory, metabolic, and perceptual function during exercise, improving the exercise capacity of an individual [3, 4]. Garrett and colleagues [3] defined the process of HA as taking place across three time periods, broadly categorized as short-term heat acclimation (STHA) (≤ 7 exposures) [5–15], medium-term heat acclimation (MTHA) (8–14 exposures) [15–20], and long-term heat acclimation (LTHA) (≥ 15 exposures) [21–23]. Traditionally, HA training protocols have consisted of at least ten exposures, which is often considered the point at which full HA is usually obtained [24]. However, as little as four heat training sessions have been reported to confer partial HA [12].

In order to obtain partial or full HA, most athletes use repeated bouts of exercise in hot conditions. Recently, athletes have sought HA training as an ergogenic aid with the intent of enhancing physical performance in both hot and temperate conditions [9, 12, 16]. HA training studies of longer duration (at least eight heat exposures) have demonstrated improved physical performance in hot conditions, such as enhanced peak power output [19], time-to-exhaustion [25], and tolerance time [17]. Furthermore, improved maximal oxygen consumption ($\dot{V}O_{2\max}$) [16], time-trial performance [16], power at lactate threshold [16], and 400-m swimming time [26] have been observed in temperate conditions. Thus, it seems apparent that physical performance can be improved in hot and temperate conditions following longer-term HA training.

1.2 Adaptations from Short-Term Heat Acclimation (STHA)

In brief, previous research has identified numerous common physiological and molecular adaptations that are developed within seven heat exposures. Cardiovascular system adaptations include plasma volume expansion [7, 9, 14, 19, 21, 27, 28] and a reduced heart rate response to submaximal exercise [7–10, 12–14, 29]. Thermoregulatory adaptations include decreased T_c response to exercise [5, 7, 12–14, 17], increased skin blood flow for a given T_c [14, 30], decreased T_c threshold for cutaneous vasodilation [14, 30–32], and decreased T_c threshold for the onset of sweating [29, 30, 32, 33]. The primary metabolic adaptation is attenuated carbohydrate metabolism [10, 13]. Finally, perceptual adaptations include enhanced thermal comfort [10, 12].

1.3 Team-Sport Players

Field team-sport (Australian football, soccer, and rugby are used as examples throughout the review) players require not only superior skills, but also pronounced endurance, muscular strength and power, speed, acceleration, repeat-sprint ability, and flexibility [34, 35]. Competitive matches are characterized by players covering a large distance at a submaximal running speed, interspersed with high-intensity activity and unpredictable rest intervals [34–36]. For example, Wisbey et al. [37] reported nomadic Australian football players to undertake an average of 248 accelerations (over 4 km/h in 1 s) and 89 running surges (above 18 km/h) during a competitive match. Gabbett and colleagues [38] provided an insight into the intermittent demands of rugby league players. Players undertake repeat high-intensity efforts (defined as three or more high-intensity running efforts and/or tackle efforts with < 21 s between efforts) ranging from one every 4.8 min (hit-up forwards) to one every 9.1 min (outside backs) [38].

HA training has traditionally been undertaken by athletes from individual sports; however, coaches and sport scientists are now increasingly examining the implementation of HA training for team-sport players. Training for team-sport events requires an extensive multifactorial approach, including endurance, skill, tactical, and resistance training [35]. Many team-sport competitions are played in hot environments, often requiring teams to complete inter-continental travel. A brief STHA training protocol may induce partial HA for players preparing for hot competition, and potentially improve physical performance. A STHA training protocol may also provide the opportunity for team-sport players in temperate regions to achieve physiological adaptations that are not usually developed to the same magnitude in cooler climates.

Moreover, skill and endurance training can concurrently be targeted during a STHA protocol.

Narrative reviews have provided valuable updates on the field of HA research [3, 4, 24, 26, 39, 40], primarily examining the physiological and molecular changes. However, no systematic reviews are available, nor has the effect of STHA training upon physical performance seen extensive review. The primary aim of the current systematic review was to investigate the effects of STHA training upon physical performance in healthy adults. Further, the review summarized the possible mechanisms of any potential physical performance changes and the application of STHA training for team-sport players.

2 Methods

2.1 Data Sources

MEDLINE, PubMed, and SPORTDiscusTM databases were searched for available literature from their respective inception through to September 2013. The search strategy included the following keywords: ‘acclimation’, ‘acclimatization’, ‘short-term’, ‘short term’, ‘heat’, ‘performance’, ‘athletic performance’, ‘training’. The relevant subject headings were used in isolation and in combination in each database. The complete MEDLINE search strategy is provided in the Electronic Supplementary Material (ESM) S1. Searches were limited to ‘English language’ and ‘humans’ only. The references of all relevant articles were pearled for further articles.

2.2 Study Selection

One reviewer scanned all of the titles for duplicates. Two independent reviewers screened the titles and abstracts to determine the relevance of each article. Results of this process were compared between the two independent reviewers. Following initial screening, the full text of relevant studies were retrieved and reviewed independently by the same two reviewers. Only published peer-reviewed studies were included in the analysis. Studies were retained if they met the following criteria: STHA intervention (seven or fewer total heat exercise exposures before physical performance testing), performance measure outcome, apparently healthy participants, adult participants (≥ 18 years of age), primary data, and human participants. The criteria for ‘seven or fewer total separate heat exercise exposures before physical performance testing’ included testing sessions in hot conditions that were either undertaken < 5 days prior to the first designated HA training session, or prior to the post-HA physical performance testing. If it was unclear whether a pre-testing session

occurred in hot conditions within 5 days before the beginning of the HA protocol, the pre-test was not identified as a heat exposure. In the event that studies randomised the order of participant distribution into two different post-testing sessions for the purpose of separate physical performance (as defined by the current review) data analysis, these tests were classed as one heat exposure. Since the review aimed to examine the performance change in an athletic population, studies were excluded if participants were required to exercise in occupational safety equipment (e.g. protective suits) during testing or training sessions. There were no selection criteria for the total heat exposure time during an STHA intervention.

2.3 Outcome Measures

Any measure used to detect a change in physical performance based upon pre- and post-intervention testing was examined. The definition of a performance test was ‘any physical test that elicits a maximum intensity effort within a defined time, distance, repetition, or end-point’. A special point of interest in relation to the HA research field is that the chosen definition does not incorporate submaximal intensity testing to fatigue/biological safety-point (i.e. a tolerance time test). Results of these tests can inherently be prone to variability [41], due to the subjective nature of finishing the test. To determine the effectiveness of STHA training upon physical performance, a combination of means comparison (statistical significance $p < 0.05$) and effect sizes (Cohen’s d [≥ 0.2 small, ≥ 0.5 moderate, ≥ 0.8 large]) were used [42]. Within-group effect sizes were calculated using Cohen’s d if the data were not provided (the average of the standard deviation [SD] for the pre-test and post-test scores were used if the SD of the change score was not provided) [42].

2.4 Risk of Bias Assessment and Data Extraction

Two reviewers independently assessed the risk of bias of included studies using a modified version of the McMaster critical review form in quantitative studies [43]. The critical appraisal tool is outlined in the ESM S2. The critical appraisal tool of the current study retains six categories from the McMaster tool, whilst the additional category explores the processes of controlling and randomization within studies.

For all the eligible studies, data extraction was independently completed by two reviewers using a customized data extraction form. Data extraction included participant characteristics such as sex, number of participants, sport participation, the training protocol, the dosage of heat exposures, the change in test score of a performance measure, the environmental conditions during performance testing, a statistical indicator of the change in performance (i.e.

Table 1 Characteristics of the heat intervention training group in the included studies

References	Participants	Training protocol	Training conditions	Number of heat exposures	Total duration of heat training (min)	Performance test conditions
Brade et al. [5]	10 moderately trained male team-sport players	Repeated cycling for 3 min at 80 % maximum power output for 32–48 min	35 °C, 60 % RH	5 intermittent training exposures over 10 days	200	Hot (35.2 °C, 57.8 % RH)
Chen et al. [6]	7 male badminton and table tennis athletes (total of 14 participants in the study)	25–45 min of cycling below and above the ventilatory threshold	38.4 °C, 52.0 % RH	5 consecutive days (+ pre-test exposure)	175	Hot (38.4 °C, 52.0 % RH) Temperate (24.1 °C, 51.5 % RH)
Garrett et al. [7]	8 elite male rowers	90 min of rowing at T_{re} of 38.5 °C	39.5 °C, 60.0 % RH	5 consecutive days (+ pre-test exposure)	450	Hot (35 °C, 60 % RH)
Buchheit et al. [9]	15 well-trained male soccer players	Routine soccer training	40.4 °C, 23.8 % RH ^a	7 consecutive days	510	Temperate (20.6 °C, 55.0 % RH)
Petersen et al. [10]	6 trained male cricketers (total of 12 participants in the study)	30–45 min of repeat sprint cycling	30.1 °C, 61.0 % RH	4 consecutive days (+ pre-test exposure)	150	Temperate (24 °C, 48 % RH)
Brazaitis and Skurvydas [11]	13 healthy male and female participants (total of 25 participants in the study)	45 min passive heating of lower body by water immersion	Water: 44 °C Room: 23 °C, 40 % RH	7 intermittent training days	315	Temperate (23 °C, 40 % RH)
Sunderland et al. [12]	6 well-trained female hockey players (total of 17 participants in the study)	30–45 min of the Loughborough intermittent shuttle run test	30 °C, 24 % RH	4 intermittent training exposures over 10 days	150	Hot (30.5 °C, 27.0 % RH)
Febbraio et al. [13]	13 endurance trained males	90 min of cycling at 50 % $\dot{V}O_{2max}$	40 °C, 20 % RH	7 consecutive days	630	Hot (40 °C, 20 % RH)

RH relative humidity, T_{re} rectal temperature, $\dot{V}O_{2max}$ maximal oxygen consumption

^a Average environmental conditions during heat exposure

statistical significance, effect size). The interpretation of effect sizes was based upon the methods used by included papers. Any disagreements regarding risk of bias or data extraction were resolved through discussion, or if necessary, through consultation with a third independent reviewer.

3 Results

3.1 Study Description

An initial literature search yielded 545 records following the removal of duplicate titles, of which 354 were excluded during title scanning due to relevance. A total of 191 articles were screened, with 19 of these assessed for eligibility. Eleven articles were excluded, with the primary reasons being no inclusion of an STHA training protocol (six), no examination of a performance outcome (four), and no inclusion of adult participants (one). Finally, eight studies were included for final data synthesis (Table 1). The screening and review process is shown in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram (Fig. 1).

3.2 Risk of Bias of Included Studies

The risk of bias of each included study was examined using a modified McMaster critical appraisal tool. The results are reported in Table 2. Studies most commonly lost points for not being controlled [5, 7, 9, 13], which demonstrated a consistent source of bias in this research field. It is

interesting to note that only two randomized controlled trials were included [6, 10]. The other category in which studies commonly lost points was for not reporting if the performance outcome variables were valid and/or reliable [5, 10, 11, 13]. Reporting these parameters would help to further strengthen the confidence in outcome results.

3.3 Results of Individual Studies

Maximum tests using either progressive increments to fatigue, or aerobic-based time trial tests may be enhanced following STHA training [5, 7, 9, 12]. Despite these improvements, $\dot{V}O_{2\max}$ has yet to be shown to significantly increase [6, 13]. Peak anaerobic power efforts do not appear to be enhanced following STHA training [5, 11, 12]. In assessing the evidence, it is important to note the methodological characteristics of the included studies that may influence the results (outlined in Tables 1, 3). These include testing conditions, humidity, sex of participants, frequency of heat training sessions, and the training level of participants. These factors are discussed in Sect. 4.1.

3.4 Level of Evidence Provided by Included Studies

The National Health and Medical Research Council (NHMRC) guidelines were used to assess the level of evidence provided by studies that were included in this systematic review. For each category, a full explanation for the score can be found in ESM S3. The overall grade of recommendation reflects the strength of the evidence provided by the included studies. A score of 'C' was given to

Fig. 1 A PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow chart outlining the identification and inclusion processes of the review

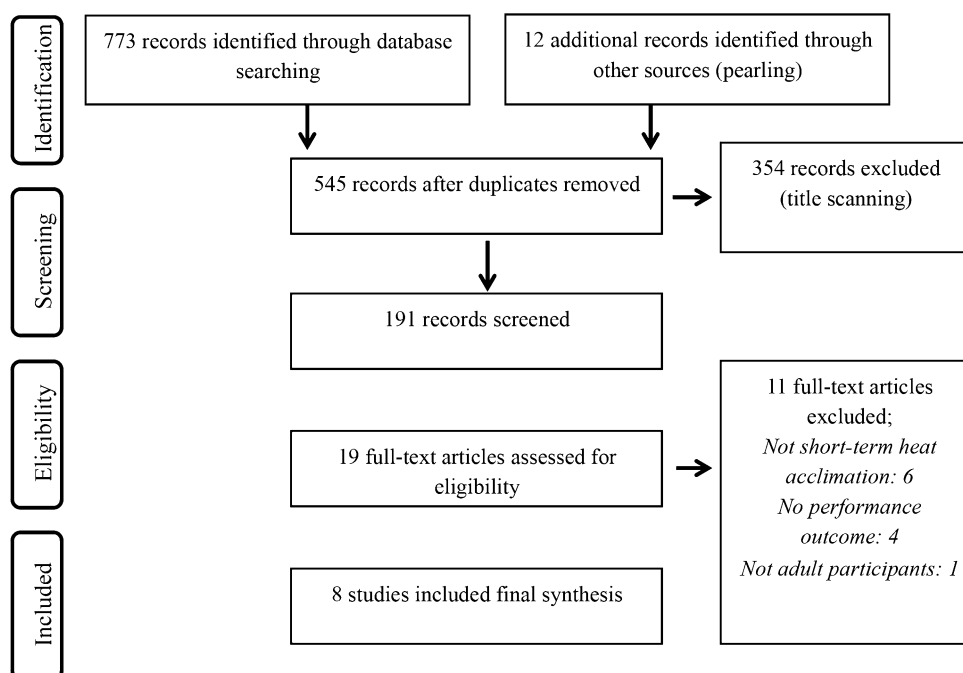


Table 2 Risk of bias for included studies

References	Study purpose (1)	Study design (2) ^a	Sample (1)	Reliability and validity (1)	Intervention (1)	Statistical analysis (1)	Conclusions (1)	Total (/8)
Brade et al. [5]	Y	N/N	Y	N	Y	Y	N	4
Chen et al. [6]	Y	Y/Y	Y	N	Y	Y	Y	7
Garrett et al. [7]	Y	N/N	Y	Y	N	Y	Y	5
Buchheit et al. [9]	Y	N/N	Y	Y	Y	Y	Y	6
Petersen et al. [10]	Y	Y/Y	Y	N	Y	Y	Y	7
Brazaitis and Skurvydas [11]	Y	Y/N	Y	N	Y	Y	Y	6
Sunderland et al. [12]	Y	Y/N	Y	Y	Y	Y	Y	7
Febbraio et al. [13]	Y	N/N	N	N	Y	Y	Y	4

Y yes, N no

^a The 'study design' section covers a maximum score of two points. The first point indicates that the study was a controlled study. A second point is awarded if the study was a randomized controlled trial

the body of evidence, which implies “body of evidence provides some support for recommendation(s) but care should be taken in its application” (Table 4).

4 Discussion

The primary aim of this systematic review was to investigate the effects of STHA training upon physical performance. The review identified that aerobic-based tests of performance are improved following STHA training [5–7, 9, 12]. This is possibly through a number of cardiovascular, thermoregulatory, and metabolic adaptations improving the perception of effort and fatigue through a reduction in anaerobic energy release and elevation of the anaerobic threshold. A progressive maximum exercise test might increase in duration [5–7, 9, 12], but $\dot{V}O_{2\max}$ has yet to be shown to significantly increase [6, 13]. Peak anaerobic power efforts do not appear to be enhanced [5, 11, 12]. There appears to be no plausible physiological or biomechanical reason for a change in rate-limiting variables affecting peak-power outcomes following STHA training. No studies demonstrated significant detrimental effects of STHA training upon physical performance. Collectively, these results should be viewed with caution due to the level of available evidence and the limited number of studies that met the inclusion criteria of the review. Further, the review discusses the underlying mechanisms associated with the changes in physical performance and the application of STHA training for team-sport players.

4.1 Change in Physical Performance Following STHA

4.1.1 STHA Training Improves Physical Performance in Hot Playing Conditions

Intuitively, the greatest benefit of STHA training upon physical performance should be evident in hot

conditions. Prolonged, predominantly aerobic-based, activity can be significantly improved under hot testing conditions [6, 7, 12]. Chen et al. [6] observed a significant increase in the time-to-exhaustion at maximal intensity; however, $\dot{V}O_{2\max}$ was not concurrently improved. Speculatively, this may support the suggestion that the lactate threshold is enhanced following STHA training. Only a brief duration of STHA training may be required to improve physical performance in hot conditions, with three studies demonstrating an improvement in aerobic-based performance following up to 200 min of heat training [5, 6, 12]. Even though Brade et al. [5] did not observe a significant enhancement in ‘total work’ ($J \cdot kg^{-1}$) during a repeat-sprint exercise test, the observed change demonstrated a moderate effect size. This suggests that the study may have been underpowered to observe a statistically significant effect. It is interesting to note that post-test sessions in the study by Chen et al. [6] occurred within 24 h of the final HA exposure, indicating that fatigue could have impacted the results. Daanen and colleagues [17] did not observe a change in resting T_c during 12 days of HA training; however, resting T_c significantly decreased by 0.4 °C following a 72-h recovery period. The authors concluded that a recovery period following HA protocols may be required to allow athletes to recover from the strain of training [17]. Further comparison of the duration of heat exposure between studies is problematic because the outcomes of studies may largely depend on the mode of exercise (see Sect. 4.3.1). Equivocal data suggest that physical performance can be improved in temperate testing conditions following STHA training [6, 9–11]. The physiological adaptations from STHA appear relevant to both hot and temperate playing conditions. Nonetheless, the current results suggest that the performance changes following STHA training are most evident in hot playing conditions.

Table 3 The results from studies that met the inclusion criteria

References	Performance test	Performance measure 1	Mean performance change $\pm$ SD/ ^a CL ^b (effect size)	Performance measure 2	Mean performance change $\pm$ SD/ ^a CL ^b (effect size)
Brade et al. [5]	Repeat sprint cycle test	Work ($\text{J} \cdot \text{kg}^{-1}$) during 1st half of test	$\uparrow 4.8 \pm 1.0$ % ^b (NS) ($d = 0.56$)	Peak power ($\text{W} \cdot \text{kg}^{-1}$) during 1st half of test	$\uparrow 3.0 \pm 0.8$ % ^b (NS) ($d = 0.31$)
		Work ($\text{J} \cdot \text{kg}^{-1}$) during 2nd half of test	$\uparrow 4.4 \pm 1.1$ % ^b (NS) ($d = 0.73$)	Peak power ($\text{W} \cdot \text{kg}^{-1}$) during 2nd half of test	$\uparrow 3.8 \pm 0.9$ % ^b (NS) ($d = 0.46$)
Chen et al. [6]	$\dot{V}O_{2\text{max}}$ test	$\dot{V}O_{2\text{max}}$	Temperature: $\downarrow 1.5$ % (NS) ($d = 0.14$) Hot: $\uparrow 2.1$ % (NS) ($d = 0.15$)	Time to exhaustion (at maximal intensity)	Temperature: $\uparrow 4.6$ % (NS) ($d = 0.36$) Hot: $\uparrow 6.6$ %* ($d = 0.47$)
Garrett et al. [7]	2-km rowing time-trial	Total time (s)	$\uparrow 1.5$ %* ($d = 0.33$)		
Buchheit et al. [9]	Yo-yo intermittent recovery test I	Total distance (m)	$\uparrow 7 \pm 9$ % ^{a*} ($d = 0.45$)		
Petersen et al. [10]	Repeat sprint run test ($6 \times [3 \times 17.68 \text{ m}]$)	Total time (s)	$\uparrow 0.4$ % (NS) ($d = 0.08$)		
Brazaitis and Skurvydas [11]	MVC test of knee extensors	MVC peak torque (N·m)	NS change		
Sunderland et al. [12]	Loughborough intermittent shuttle test	Total distance (m)	$\uparrow 33$ %* total distance ($d = 0.65$)	Sprint efforts (s) 1st set sprint 2nd set sprint 3rd set sprint	$\downarrow 0.4$ % (NS) ($d = 0.05$) $\downarrow 0.7$ % (NS) ($d = 0.10$) $\downarrow 1.0$ % (NS) ($d = 0.22$)
Febbraio et al. [13]	$\dot{V}O_{2\text{max}}$ test	$\dot{V}O_{2\text{max}}$	$\downarrow 2.3$ % (NS) ($d = 0.09$)		

* statistically significant ($p < 0.05$), NS not significant ($p > 0.05$), d Cohen's d effect size, ^aSD standard deviation, ^bCL 90 % confidence limits, $\dot{V}O_{2\text{max}}$ maximal oxygen consumption, MVC maximal voluntary contraction, $\uparrow$ positive (improvement) change, $\downarrow$ negative (decrease) change

Table 4 Summary of National Health and Medical Research Council level of evidence for included studies

Assessing the body of evidence	Score
Volume of evidence	C
Consistency	B
Clinical impact	B
Generalizability	B
Applicability	B
Grade of recommendation	C

4.1.2 STHA Training in Dry and Moderate Humidity Conditions Can Improve Physical Performance

The level of humidity during heat training sessions has the potential to influence the adaptive process for individuals [4]. For example, Taylor and Cotter [4] reported that a greater adaptation in sweat rate occurs after training in hot-humid conditions rather than hot-dry conditions. No studies have examined the physical performance changes following STHA training in high-humidity (70–100 % relative humidity [RH]). Two of the three STHA training studies in dry-heat (0–39 % RH) [9, 12], and three of the five studies in moderate humidity (40–69 % RH) [5–7], observed a significantly enhanced physical performance measure. The dry-heat studies demonstrated improved physical performance in both temperate [9] and hot [12] conditions. Studies undertaken in moderate humidity have only demonstrated enhanced performance in hot conditions [5–7]. However, for the purpose of future studies, there seems to be no plausible reason to suggest that physical performance changes following humid STHA training are less transferable to temperate conditions than those gained from dry-heat STHA.

4.1.3 STHA Training Improves Physical Performance Changes by Sex

Evidence suggests that STHA training can improve the physical performance of men [5–7, 9]; however, only one study has examined the effects of STHA training upon physical performance in a cohort of women. Similar to studies in men, Sunderland and colleagues [12] observed improvements in an aerobic-based performance test, but not anaerobic-based maximal efforts following STHA training. This study recorded the lowest risk of bias (7/8) for all the included studies according to the modified McMaster scale, strengthening confidence in the findings of the study.

4.1.4 Both Consecutive Day and Intermittent Day STHA Training Can Improve Physical Performance

Traditionally, HA training protocols have consisted of daily heat exposures. This removes the uncertainty of whether

participants will optimally adapt to intermittent heat stress training days, in which individuals are removed from the stimulant for extended periods of time in between sessions. Gill and Sleivert [20] observed that a consecutive-day MTHA protocol was more effective for inducing HA than an intermittent-day protocol. However, consecutive-day heat training sessions are often impractical for team-sport participants. Three of the five STHA training studies that used consecutive-day protocols observed a significantly enhanced physical performance measure [6, 7, 9]. These performance enhancements were seen in both temperate [9] and hot [6, 7] conditions. Two of the three studies that used intermittent-day training noted improved physical performance, but were only tested in hot conditions [5, 12]. This suggests that both consecutive-day and intermittent training day protocols (usually no more than 72 h in between exposures) can be effectively implemented to enhance physical performance, although the effects of intermittent STHA training day protocols on performance in temperate conditions remains unknown.

4.1.5 STHA Training Improves the Physical Performance of Highly Trained Athletes

Since highly trained athletes are the population most often in demand of HA training, it is worthwhile to examine the change in physical performance outcomes among this group. The participants in three STHA training studies were classified as ‘highly trained’ [7, 9, 13]. Two studies observed an improvement in aerobic performance [7, 9], while the remaining study [13] did not identify a significant change in $\dot{V}O_{2\max}$. Even though highly trained athletes may have less adaptive potential and display many partially developed HA adaptations [3], evidence suggests that STHA training can be an effective modality for improving aerobic performance in this population. In two studies, Garrett et al. [7, 8] observed similar changes in cardiac frequency, T_{c} , and plasma volume expansion for moderately and highly trained athletes following 5 days of controlled hyperthermia HA training.

4.2 The Mechanisms for an Enhancement of Physical Performance

The current review suggests that STHA training might be an effective modality for improving aerobic-based tests of performance. The underlying mechanisms that could be contributing towards a change in physical performance can broadly be identified into four categories: cardiovascular system, thermoregulation, altered metabolism, and perceptual changes. For the benefit of a broader discussion, STHA papers cited in Sects. 4.2 and 4.3 fall under the definition provided by Garrett et al. [3], rather than the STHA definition used as one of the inclusion criteria for the former systematic review.

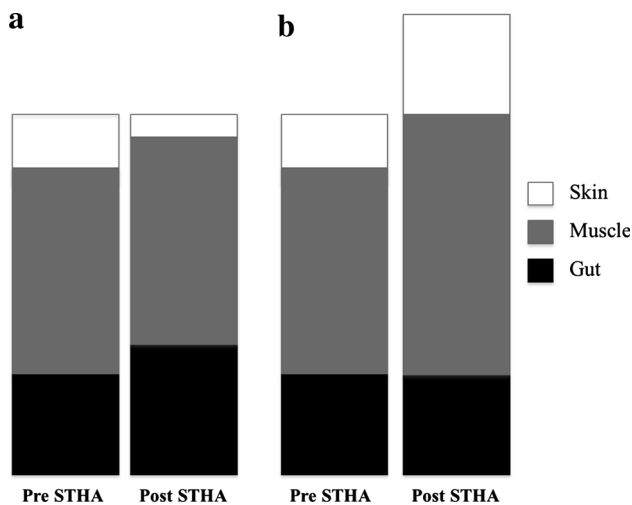


Fig. 2 Possible changes in cardiac output (the height of each tube), and blood distribution to the skin, muscle, and gut following short-term heat acclimation training (a) at an absolute exercise intensity (e.g. 15 km/h; pre-heat acclimation core temperature of 38.0 °C and post-heat acclimation core temperature of 37.7 °C); (b) at a relative exercise intensity (e.g. 60 % maximum oxygen consumption; core temperature of 38.0 °C). *STHA* short-term heat acclimation

4.2.1 Cardiovascular System

4.2.1.1 Circulatory Adjustments Plasma volume expansion is an early occurring adaptation to heat stress. It typically occurs within the first 3–6 days of repeated heat exposures [3, 24, 44], but with considerable variability in the magnitude of change (usually between +4.5 and +15 % [7, 9, 14, 19, 21, 27, 28]). Buchheit et al. [9] identified that the reduction in exercising heart rate was ‘moderately-to-largely’ related to plasma volume expansion following STHA. Patterson et al. [21] suggests that the expansion of the extracellular fluid compartment primarily accounts for the increase in plasma volume. The expansion of plasma volume plays a multifaceted role in cardiovascular stability, thermoregulation, and fluid regulatory adaptations following STHA training, but is a transient process and can return to baseline levels once the heat stimulus has been removed for 1 week following STHA [8].

Based upon evidence from MTHA studies [16, 45], it is reasonable to suggest that cardiac output may increase at a given relative exercise intensity following STHA training (Fig. 2b). Interestingly, muscle blood flow for a given absolute exercise intensity may not change following STHA training (Fig. 2a). This evidence is derived from HA protocols of longer duration, which have failed to show significant changes in leg blood flow at a comparable absolute submaximal exercise intensity [45–47]. Intuitively, due to the associated reduction in the T_c response to exercise [5, 7, 12–14, 17] and the greater physical performance capacity following STHA [5–7, 9, 12], muscle

blood flow for a relative exercise intensity may be increased (Fig. 2b).

4.2.1.2 Reduced Heart Rate Response to Exercise The significant reduction of heart rate following STHA training usually occurs within the first 3–6 days of heat training [24]. STHA training research has demonstrated a lowering of both resting heart rate [6, 11, 14, 29, 32] and exercising heart rate at the same absolute intensity (commonly 6–10 %) [6–10, 12–14, 29]. Interestingly, Garrett and colleagues [7] demonstrated an extensive (7.5 %) reduction in the end-exercise heart rate of highly trained rowers following a permissive dehydration (~2 %) STHA protocol. Since the adaptive potential of these athletes may have been limited, this method warrants further consideration.

The mechanism for a reduced heart rate response to exercise is multifactorial in nature. In brief, first, an increase in stroke volume (mediated by plasma volume expansion and enhanced venous tone) allows the cardiovascular system to service metabolic, cardiovascular, and thermoregulatory demands with fewer heart beats [9, 48–51]. Convertino [49] demonstrated a 1 % increase in plasma volume resulted in a 1 % reduction in exercising heart rate of healthy males. However, Garrett et al. [8] demonstrated that the plasma volume adaptation to STHA training decayed at a faster rate than the heart rate adaptation. This indicates that plasma volume expansion following STHA may not be solely responsible for the increased cardiovascular stability [8]. Second, research from animal models suggests that central mechanisms through improved mechanics (i.e. increased compliance, better preservation of high-energy phosphorous compounds) may facilitate a reduction in heart rate following HA [52, 53]. Third, Hodge and colleagues [54] observed plasma norepinephrine concentration during exercise to be significantly reduced within three HA sessions. The authors report a high correlation between the reduction in end-exercise heart rate and plasma norepinephrine concentration, suggesting that reduced sympathetic nervous activity may play a role in attenuating the heart rate response to exercise following HA [54].

4.2.1.3 Fluid Regulatory Adaptations There remains conflicting results regarding fluid regulatory adaptations due to the variations in hydration protocols for participants in previous STHA training research. Evidence suggests that STHA training is a catalyst for the conservation of plasma sodium [21], potassium [21], aldosterone [7], albumin [8, 21], and the associated water retention. This is supported by reduced exercise sweat sodium [10, 27], potassium [10], and chloride ion concentrations in sweat [10]. To further stress fluid homeostasis and optimize fluid regulatory

adaptations, Garrett and colleagues [3] recommended permissive dehydration during HA training.

4.2.1.4 The Impact of Cardiovascular Adaptations upon Performance by Team-Sport Players: Hydration Edwards and colleagues [55] examined the effect of restricting fluid intake during a 45-min soccer match upon the subsequent performance in the yo-yo intermittent recovery test. The performance of dehydrated players (1.5–2 %) in the running test was significantly impaired compared with players who were permitted fluid intake. The authors could not discern whether the decrement in performance was related to cardiovascular limitations or the negative psychological associations derived from a greater perception of effort in a dehydrated state [55]. Edwards and Noakes [56] suggest that fluid loss acts as a subconscious physiological stimulus for the conscious feelings of fatigue and thirst in soccer players. In this model, players pace themselves by modifying their match behavior to avoid failure of any peripheral physiological systems [56]. McGregor et al. [57] observed soccer skill performance to significantly decline in players who were denied fluid ingestion during strenuous exercise. At the peripheral level, plasma volume expansion and fluid regulatory adaptations following STHA training enables greater maintenance of fluid from the vascular compartment [7, 58, 59]. Sunderland and colleagues [12] demonstrated a trend for a reduced perceived thirst in well trained hockey players following 4 days of heat training. It is reasonable to suggest that the cardiovascular adaptations following STHA training may reduce the relative exercise intensity and promote greater maintenance of fluid, which in turn positively influences the perception of effort and fatigue [60, 61].

4.2.2 Enhanced Thermoregulation

Enhanced regulation of T_c is a rapidly occurring adaptation, often developing within four to eight HA training sessions [24]. STHA training can reduce T_c at rest by approximately 0.2 °C [11, 14, 29, 31, 32] and at the same absolute exercise intensity [5, 7, 12–14, 17]. Enhanced T_c maintenance is achieved through adaptations in evaporative and convective heat dissipation.

4.2.2.1 Evaporative Cooling: Sweat Rate Change Following STHA Sweating adaptations following HA training enhance evaporative cooling [24]. Sweat rate (usually measured as $\text{mg}\cdot\text{cm}^{-1}\cdot\text{min}^{-1}$) and total sweat loss (kg) has commonly been reported to remain unchanged at an absolute and relative exercise intensity in a range of humidity conditions following STHA (Table 5). Armstrong and Maresh [24] suggested that at least eight heat exposures are required to produce a plateau in the sweat rate adaptation. Sweat sensitivity (ml per 1 °C rise in T_c) has generally been reported to remain constant [29, 30, 32, 33, 62], or in some cases, increase [5, 63]. The current evidence suggests that sweat rate may increase towards the end of a seven day HA training program, but most people may require more extensive exposure.

4.2.2.2 Evaporative Cooling: STHA Reduces the Core Temperature Threshold for the Onset of Sweating STHA training enhances evaporative cooling by decreasing the T_c and mean body temperature (usually calculated using T_c [$\times 0.8$] and mean skin temperature [$\times 0.2$] [16]) threshold for the onset of sweating by 0.15–0.29 °C [29, 30, 32, 33,

Table 5 Change in sweat rate/total sweat loss following short-term heat acclimation

Study	Training conditions	Change in sweat rate/total sweat loss
Brade et al. [5]	35 °C, 60 % RH	↔
Chen et al. [6]	38 °C, 52 % RH	↔
Racinais et al. [27]	38–43 °C, 12–30 % RH	↑
Brazaitis and Skurvydas [11]	Passive water (44 °C) immersion	↑
Petersen et al. [10]	30 °C, 60 % RH	↔
Patterson et al. [33]	40 °C, 60 % RH	↑
Cotter et al. [29]	39 °C, 59 % RH	↔
Nielsen et al. [46]	35 °C, 87 % RH	↔
Aoyagi et al. [15]	40 °C, 30 % RH	↔ ^a /↑ ^b
Aoyagi et al. [64]	40 °C, 30 % RH	↔ ^a /↑ ^b
Hessemer et al. [32]	55 °C, 20 % RH	↔
Shvartz et al. [63]	40 °C, 20 % RH	↔

RH relative humidity, ↑ % increase, ↔ unchanged

^a reported in military protective equipment

^b reported in nuclear, biological, and chemical (NBC) suit

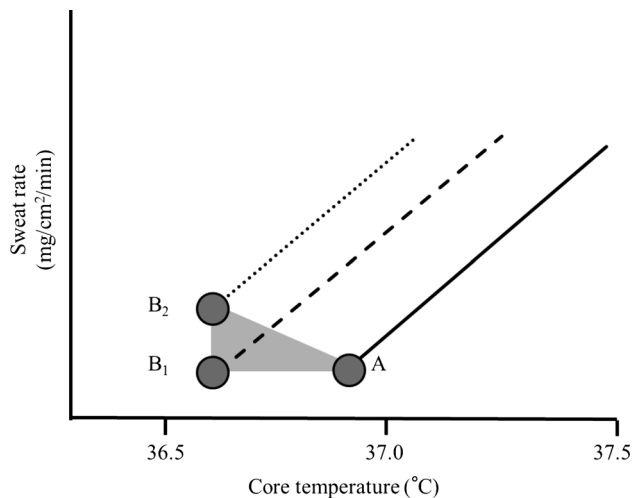


Fig. 3 Representation of the sweat response and adaptation following short-term heat acclimation. Each grey circle identifies the commencement of sweating due to exercise. Point A (continuous line) represents the sweat response (curve) to graded exercise of an athlete not acclimated to the heat. Short-term heat acclimation training can result in a parallel shift of the response (curve) to the left (point B₁ [broken line]). This indicates a lower core temperature threshold for the onset of sweating, but no adaptation in sweat rate has occurred. In a few instances, this may be accompanied by an upward shift of the individuals' sweat response (curve) to exercise to point B₂ (dotted line), indicating the adaptation of an increased sweat rate to exercise and a lower core temperature threshold for sweating. The precise relocation of the sweat response (curve) from point A in response to acclimation, will in general, traverse through the grey triangle to either point B₁ or point B₂ (indicated by the grey-shaded triangle). This may relate to a multitude of factors such as training status, heat acclimation exercise protocol, and environmental conditions during heat acclimation

62]. This is supported by evidence from MTHA studies [65–68] and has been demonstrated to occur in the absence of enhanced sweat rate/total sweat loss [5, 29, 63]. This adaptation is supported by evidence demonstrating that the T_c threshold for cutaneous vasodilation decreases [14, 30–32, 46], which closely mirrors the T_c sweat threshold [69]. Figure 3 summarizes the possible change in the sweat response to exercise following STHA training.

4.2.2.3 Convective Cooling: STHA Enhances Cutaneous Vasodilation for a Given T_c Skin blood flow is a critical component of convective heat transfer. Skin blood flow for a given T_c is increased following STHA training [14, 30] (Fig. 2b), which is supported by evidence from MTHA training studies [67, 70]. The STHA-induced hypervolemia helps maintain central blood volume, reducing the vasoconstrictor influence upon skin blood flow [45, 71, 72]. Skin blood flow is also positively influenced by a reduction in mean arterial pressure following STHA training [14]. Due to the lower T_c response to exercise following STHA training [5, 7, 12–14, 17], skin blood flow for a given

absolute exercise intensity is reduced, facilitating less disruption to other vascular beds (Fig. 2a). Chen et al. [6] demonstrated a 100 % reduction in skin blood flow to the active leg during cycle exercise in hot conditions at 240 W following STHA training. Some authors have reported the sensitivity (slope) of the association between cutaneous vasodilation and T_c to remain constant [30, 67], or increase [14, 70] following STHA training.

4.2.2.4 Convective Cooling: STHA Reduces the Core Temperature Threshold for Cutaneous Vasodilation STHA training lowers the thermoregulatory threshold for cutaneous vasodilation [14, 30–32]. Following 6 days of exercise HA training, Fujii et al. [14] demonstrated a 0.4 °C (36.8–36.4 °C) reduction in the forearm vascular conductance temperature–threshold relationship. Likewise, Yamazaki and Hamasaki [30] also reported the esophageal threshold temperature for forearm cutaneous vascular conductance to be 0.15 °C lower (37.02–36.87 °C) following 6 days of HA training. Although the precise mechanism is debated, the expansion of blood/plasma volume following exercise training may initiate active vasodilation at a lower T_c [73]. Numerous authors have speculated that the reduction in the T_c threshold for cutaneous vasodilation is coupled with the reduction in resting T_c [14, 30, 31, 46], suggesting that while the threshold may be lowered, the gains remain the same.

4.2.2.5 Convective Cooling: Unchanged Skin Temperature Following STHA training, exercising skin temperature has been reported to increase [10], decrease [5, 63], or remain unchanged [5, 6, 14, 27, 29]. HA protocols of longer duration (at least eight exposures) have consistently reported skin temperature to be lowered [16, 17, 33, 45, 46]. Tentatively, skin temperature does not consistently decrease following STHA training due to the variability of sweat rate adaptations following STHA training. The inconsistency in skin temperature changes following STHA training has meant that the core-to-skin gradient has been reported to increase [63, 74] or decrease [74, 75]. Following longer-term HA training, the core-to-skin gradient has generally been reported to increase [16, 20, 50, 76], reducing skin blood flow requirements for a given workload [16]. Skin temperature and core-to-skin gradient changes may largely be dependent upon the duration and frequency of the STHA training protocol.

4.2.2.6 Implications of Improved Thermoregulation upon Team-Sport Performance: Pacing Strategies The ability to repeatedly outrun and chase opponents, and ‘find space’ is fundamental to successful performance in field team-sports. Austin et al. [77] observed 70 % of all repeated

high-intensity bouts in rugby league to occur within 5 min prior to a try being scored, illustrating the importance of high-quality running. At the central level, hyperthermia reduces motor drive [78]. Aughey et al. [79] and Duffield et al. [80] suggest that anticipatory pacing strategies based upon thermal load influence the running capacity of Australian football players. Improving the perception of thermal load may enhance subsequent running performance, especially in the latter stages of each half when it is difficult to effectively cool players [79]. The lowering of exercising T_c may be particularly relevant for the pacing strategies of athletes who require extensive protective equipment, which diminishes the potential for heat dissipation. At the peripheral level, in comparison with normal skin temperature and T_c , high body temperature during maximal exercise is associated with accelerated declines in cardiac output and mean arterial pressure [81]. As a whole, improvement of intermittent running performance may relate to enhanced thermoregulatory processes blunting the T_c response to exercise following STHA training [5, 7, 12–14, 17].

4.2.3 Altered Metabolism

4.2.3.1 Attenuated Carbohydrate Metabolism The increased reliance upon carbohydrates as a fuel source during exercise in the heat appears to partially attenuate during the development of HA [13, 47, 82–84]. Limited evidence is available on the changes in metabolism during STHA. Reduced lactate accumulation, respiratory exchange ratio, blood glucose concentration, and less depletion of glycogen from type I fibers at a given absolute exercise intensity have been reported following STHA [10–13]. Interestingly, Sunderland and colleagues [12] demonstrated a trend for an increased blood lactate concentration at the end of a repeat-sprint performance test following STHA. Since the finish time for the test was based upon a maximal subjective exhaustive effort by the participants, this could relate to the higher exercise volume that the well trained hockey players could achieve following the intervention [12].

4.2.3.2 Improved Metabolic Rate Fujii and colleagues [14] reported the aerobic metabolic rate (indicated by oxygen consumption) to be significantly reduced by <5.2 % during a moderate-intensity cycling exercise heat test following STHA training. Furthermore, two other STHA training studies found a trend for reduced $\dot{V}O_2$ at a given absolute exercise intensity following STHA [13, 63]. These findings are supported by HA studies of longer duration [82, 85, 86]. A lower whole-body metabolic rate would decrease metabolic heat production, reducing T_c and hence, thermoregulatory

and cardiovascular demands [85, 87]. Houmard and colleagues [85] suggest this is a contributing factor to improved heat tolerance. The reduction in heart rate [7–10, 12–14, 29] and ventilation [14] at an absolute workload post-acclimation would support the apparent decrease in oxygen demand.

4.2.3.3 Implications of Altered Metabolism upon Team-Sport Performance: Attenuated Carbohydrate The limited available evidence suggests that carbohydrate metabolism is decreased at a given absolute exercise intensity following STHA [13, 14, 63]. Krstrup et al. [88] suggests that a reduced glycogen level in muscle fibers is associated with fatigue at the end of a soccer match. Furthermore, the shooting ability of soccer players may be compromised with low glycogen stores [89]. Therefore, less depletion of glycogen from type I fibers following STHA training may lessen fatigue and positively influence performance [13]. Decreasing lactate accumulation inhibits metabolic acidosis, preserving contractile machinery (i.e. Ca^{2+} kinetics fatigue, affecting the excitation-contraction coupling) and adenosine triphosphate production from glycolysis (phosphofructokinase and phosphorylase inhibition) [90]. At the central level, decreasing lactate accumulation positively influences the perception of fatigue and effort [60, 61].

4.2.4 Perceptual Changes during Exercise

4.2.4.1 Changes in the Rating of Perceived Exertion Evidence is conflicting in regards to the changes in perceived exercise exertion following STHA training. Armstrong and Maresh [24] suggested the rating of perceived exertion (RPE) to be decreased following three to six repeated heat exposures, mirroring the reduction in a number of related physiological stress markers (heart rate, T_c , and thermal comfort [91]). Pandolf et al. [92] monitored the day-to-day changes in RPE over the course of nine HA training sessions and reported the adaptation to begin to plateau on the seventh day in fit soldiers. Castle and colleagues [19] reported RPE to significantly decrease in hot conditions by the third day for moderately trained males. Despite reductions in markers of physiological stress, numerous authors have failed to observe a significant change in RPE following STHA training [5, 14, 29]. However, this could relate to the tests in which RPE was collected. Some studies required participants to intermittently exercise at a maximal effort during testing, rather than a constant absolute intensity [5, 14]. This subjective and relative nature of a maximal effort could limit a change in RPE. Some longer-term HA studies have also failed to demonstrate a lowered RPE [16, 93].

4.2.4.2 Enhanced Thermal Comfort and Sensation Significant improvements in thermal comfort [10, 12, 17] and sensation [10, 19] have been reported following STHA training. This is supported by evidence from longer-term heat exposure training [17, 19]. Thermal comfort and sensation may link with a multitude of factors, but primarily driven by deep body (core) and peripheral (skin) temperature. Enhancing thermal comfort (associated with a lower T_{c} following STHA training [5, 7, 12–14, 17]) may improve the perception of effort and fatigue [12, 60], especially in hot conditions. As discussed in Sect. 4.2.2.6, an improvement in perceived thermal load could improve match running performance [79].

4.3 Applying STHA Training to Team-Sport Players

4.3.1 Duration and Type of STHA Sessions

Garrett and colleagues [3] provided a framework by which to define short- (seven or fewer exposures) and medium-term (8–14 days) HA interventions, although the total heat exposure time within these frameworks needs to be considered. Since a range of team-sport athletes require an individualized training approach, it is difficult to define a total heat exposure time by which to broadly define STHA training. Table 6 demonstrates the methodology of a sample of compensable STHA and MTHA studies, which the duration and environmental conditions were standardized among all participants. The STHA studies identified in Table 6 had a mean of 5.8 ± 1.2 heat exposures and duration of 72.7 min per session. The total duration of a STHA protocol should be based upon the type of training. High-intensity HA protocols that mimic typical competition demands may require shorter duration sessions. Alternatively, moderate-intensity HA sessions that might complement regular training may require longer-duration sessions.

Taylor and Cotter [4] recommend that HA session exposures for sports that have relatively short events (<2 h) be of at least equal duration to competition. Training for team-sport requires a time-consuming multifactorial approach [35], meaning that it is often not possible for teams that are based in temperate regions to devote an equal time to heat training. The critical factor during HA training is raising the T_{c} of the athlete (usually not higher than 39.5 °C for safety reasons) [100]. It must be considered that each training session requires a ‘warming period’, in which the initial heat exposure raises the T_{c} to an elevated level [100]. A minimum of 25–30 min per HA session has been reported in the STHA literature [6, 10, 12]. Using previous studies as a guide (Table 6), and the results from the current review, we propose that a mixed high-intensity protocol for trained athletes may require five

sessions with a duration of 60 min to potentially improve aerobic-based performance in hot and temperate environmental conditions. On average, a moderate-intensity protocol for trained athletes may require six sessions with a duration of 90 min to potentially improve aerobic-based performance in hot and temperate conditions. However, shorter protocols may also succeed in conferring partial HA and improving physical performance [5, 6, 12].

Passive HA (e.g. water immersion, rest) is an alternative method to exercise-heat training (e.g. running, cycling, rowing) for inducing acclimation. For example, Brazaitis and Skurvydas [11] required participants to undertake immersion in water set at 44 °C for 45 min. Participants in the study by Shido and colleagues [65] were instructed to rest and were exposed to ambient temperature of 46 °C and RH of 20 % for 4 h each day over 9–10 consecutive days. Rectal temperature was significantly lowered following both HA protocols [11, 65]. However, exercise heat training is more relevant to team-sport players than passive HA because it is specific to the demands of competition and stimulates acclimation to a greater extent [101].

4.3.2 Timing of STHA Training

STHA training could be used throughout the course of a competitive year to either prepare, improve, or maintain physical performance. First, STHA training could be used as a pre-season preparation tool for winter team-sports players who complete heavy training during summer by helping transition players into the rigors of regular training in hot conditions. Second, STHA could be used as a preparatory tool for players prior to competition in hot environments. This could be achieved within the 2 weeks prior to competition and may help limit the deleterious effects of hot conditions upon aerobic-based performance in comparison with cool conditions [16]. Third, STHA may act as a physical performance ‘booster’ during the in-season phase of competition. Since STHA requires a limited commitment, this could be relevant during periods in which teams have extended breaks between matches. Finally, STHA training could be used during the in-season phase as a taper tool when training volume decreases immediately prior to a tournament. Mujika [102] suggests that low training volume and high-intensity activity during a taper phase could improve the physical performance of team-sport players during competition. In this instance, a brief high-intensity STHA training protocol (e.g. four sessions of 45 min) may provide an effective method for performance maintenance before a major tournament (e.g. Soccer World Cup) or at the transition between pre-season training and in-season competition [103, 104]. Despite the intuitive application of high-intensity HA training as a taper tool, a potential caveat is still the uncertainty of how this will

Table 6 The methodology of a sample of compensable short-term ($n = 13$) and medium-term ($n = 12$) heat acclimation studies since 1980

	Number of exposures	Total duration of heat exposure (min)	Ambient temperature (°C)	Relative humidity (%)
Short-term heat acclimation studies				
<i>High intensity</i>				
Brade et al. [5]	5	200	35	60
Chen et al. [6]	5	175	38.4	52
Buchheit et al. [9]	7	510	40.4 ^a	23.8 ^a
Petersen et al. [10]	4	150	30.1	61
Sunderland et al. [12]	4	150	30	24
Best et al. [94]	6	360	35	40
Dawson et al. [95]	7	560	34.3	65
<i>Low and moderate intensity</i>				
Garrett et al. [7]	5	450	39.5	60
Fujii et al. [14]	6	660	37	50
Brazaitis and Skurvydas [11]	7	315	NA	NA
Garrett et al. [8]	5	450	39.5	60
Buono et al. [31]	7	840	35	75
Febbraio et al. [13]	7	630	40	20
Mean	5.8 (± 1.2)	419.2 (± 219.2)	36.2 (± 3.6)	49.2 (± 18.2)
Medium-term heat acclimation studies				
<i>High intensity</i>				
Gill and Sleivert [20]	10	300	38	70
<i>Low and moderate intensity</i>				
Hodge et al. [54]	8	720	35.3	40.2
Lorenzo et al. [16]	10	1,000	40	30
Chinevere et al. [96]	10	1,000	45	20
Weller et al. [18]	10	1,100	46.1	17.9
Buono et al. [97]	10	900	39.3 ^a	46.7 ^a
Regan et al. [76]	10	600	38.2	39.7
Pandolf et al. [93]	10	1,100	49	20
Kirwan et al. [47]	8	720	39.6	29.2
Young et al. [82]	9	1,080	49	20
Horstman and Christensen [98]	11	1,320	45	13.5 ^b
Shapiro et al. [99]	10	1,200	40	30
Mean	9.7 (± 0.9)	920.0 (± 287.4)	42.0 (± 4.6)	31.4 (± 15.9)

NA not applicable

^a Where day-specific data regarding ambient temperature and relative humidity were supplied, these values were averaged to provide an overall study mean

^b Calculated from dry-bulb temperature and wet-bulb temperature

affect performance during competition [103, 104]. It is important to consider the rate of decay in adaptations from HA training when implementing a protocol. Garrett and colleagues [3] provided a review of the rate of decay in physiological adaptations gained from HA training. The authors indicate there is no clear consensus concerning the decay of adaptations [3].

An important timing consideration for HA training is the time of day. Shido and colleagues [65] identified that the adaptations related to HA were more prominent during the

same time of day in which the heat exposures occurred. This suggests that the timing of HA sessions should be planned in accordance with anticipated competition or training times. Furthermore, the frequency of heat training must also be considered. Traditionally, HA training protocols have used a consecutive-day approach, although the phase of season will be the main determinant for training frequency. A heat-training stimulus on consecutive days may be effective in obtaining quicker HA than intermittent-training days [20], though fatigue and hydration levels

must be closely monitored. As demonstrated in Sect. 4.1.4 of the current review, STHA training on intermittent days can also potentially improve physical performance. Training sessions are usually separated by no more than 72 h during an intermittent-day protocol.

4.3.3 Environmental Conditions during the STHA Protocol

The environmental conditions during an STHA protocol should either mimic the anticipated climate during competition, or provide a challenging training stimulus without endangering athlete health. The sample of compensable STHA studies in Table 6 demonstrate that STHA training typically occurs between 35–40 °C and 20–60 % RH, which still allows athletes to complete quality mixed high-intensity training [5, 6, 9]. Athletes may be required to consume fluid ad libitum in highly stressful training conditions (high ambient temperature and humidity) to maintain biological safety and performance. Although permissive dehydration (~2 %) might independently facilitate further HA through increased fluid-electrolyte retention, plasma volume expansion, and cardiovascular response to heat stress [4, 8]. Garrett et al. [3] provided a review of permissive dehydration during HA.

4.3.4 Considerations Following Short-Term Heat Acclimation

As discussed in Sect. 4.1 of the current manuscript, practitioners should be aware that STHA training has not been demonstrated to improve maximal anaerobic efforts [5, 11, 12]. Equally, evidence suggests that STHA is not significantly detrimental for maximal anaerobic efforts [5, 11, 12]. An improved sweat response to exercise usually develops after seven heat exposures, although some athletes may develop the adaptation following STHA protocols (Sect. 4.2.2.1) [24]. An increased sweat rate is advantageous for heat dissipation in dry environmental conditions; however, an increased fluid loss may increase the risk of dehydration in humid environmental conditions where heat dissipation through sweating is diminished [105]. This is still an important consideration, even in the face of a higher plasma volume content following STHA training [7, 9, 14, 19, 21, 27, 28]. Therefore, HA athletes require adequate hydration strategies.

4.4 Limitations

At the review level, this systematic review did not include tolerance time exercise tests, involving participants exercising at a sub-maximal intensity until voluntary exhaustion. As previously stated, these types of tests can be inherently prone to a high level of variability since factors

such as boredom and motivation contribute to the final outcome [41]. However, certain professions may be interested in this type of exercise (e.g. fire-fighters). Performance in tolerance time tests has previously been shown to improve following STHA training [6, 63, 106]. The review also excluded papers that contained valid performance tests and included seven or fewer designated HA training sessions if participants experienced a total of more than seven exercise heat training exposures before post-testing [14, 15, 64, 85, 95]. This was usually due to studies implementing one or more heat stress tests before final physical performance testing. With the exception of one study [14], these papers did not demonstrate a significant change in $\dot{V}O_{2\max}/\dot{V}O_{2\text{peak}}$ [15, 64, 85, 95]. A recommendation for defining STHA studies is provided in Sect. 4.5. At the outcome level, the review was limited by the moderate level of bias that exists in the field, since only two randomized controlled trials were included. Furthermore, a limited number of studies could be identified (eight), and only one of these articles focused on women participants.

4.5 Recommendations for Future Research

Previous findings have indicated promising results that STHA training can improve physical performance in both hot and temperate climatic conditions. To advance the field of knowledge, there are specific aspects that should be addressed. We propose that the definition for STHA remain consistent with the description provided by Garrett et al. [3]; however, testing or familiarization sessions in hot conditions should be classified as a heat exposure if they occur within 5 days of the designated HA training protocol. Barnett and Maughan [107] demonstrated that adaptations from HA training did not develop when heat exposure sessions are separated by 1 week (≤ 7 days). An interesting proposition that requires further attention is the potential for sporting teams who predominantly play competitive matches in temperate conditions to use STHA as a means for enhancing physical performance in cool conditions. Only the research of Sunderland and colleagues [12] has examined the effects of STHA training upon physical performance in a cohort of women. The response to heat stress is similar to that in men; however, some adaptations may vary due to the natural variations in particular physiological and anatomical measures [108]. For example, women tend to have a larger surface area/mass ratio than men, influencing external heat dissipation strategies [108]. Further research into the effects of STHA in women is encouraged to explore these sex differences. A paucity of literature has examined the concept of combining heat and altitude training. Recent evidence suggests that the benefits of heat training may decay at a slower rate during a 'live-high train-low in the heat' protocol [109]. Takeno and

co-workers [70] examined the slope of forearm vascular conductance/esophageal temperature relationship following training in a warm high-altitude (30 °C; 2,000 m), warm low-altitude (30 °C; 610 m), cool high-altitude (20 °C; 2,000 m), or cool low-altitude (20 °C; 610 m) environment. The greatest thermoregulatory adaptation was evident in the warm high-altitude group [70]. This promising area of research warrants further attention.

5 Conclusion

This systematic review has highlighted the potential for improvement in aerobic-based tests of performance following STHA training. This is possibly through a number of cardiovascular, thermoregulatory, and metabolic adaptations improving the perception of effort and fatigue through a reduction in anaerobic energy release and elevation of the anaerobic threshold. However, peak anaerobic power efforts do not appear to be enhanced. These results should be viewed with caution due to the level of available evidence, and the limited number of studies that met the inclusion criteria of the review. STHA training can be applied in the team-sport environment during a range of instances within the competitive season. A mixed high-intensity protocol for trained athletes may require five sessions with a duration of 60 min to potentially improve aerobic-based performance in hot and temperate environmental conditions.

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References

- Maughan RJ, Shirreffs SM, Ozgüven KT, et al. Living, training and playing in the heat: challenges to the football player and strategies for coping with environmental extremes. *Scand J Med Sci Sports*. 2010;20(Suppl 3):117–24.
- González-Alonso J, Crandall CG, Johnson JM. The cardiovascular challenge of exercising in the heat. *J Physiol (Lond)*. 2008;586(1):45–53.
- Garrett A, Rehrer N, Patterson M. Induction and decay of short-term heat acclimation in moderately and highly trained athletes. *Sports Med*. 2011;41(9):757–71.
- Taylor N, Cotter J. Heat adaptation: guidelines for the optimisation of human performance. *Int Sportsmed J*. 2006;7(1):33–57.
- Brade C, Dawson B, Wallman K. Effect of precooling and acclimation on repeat-sprint performance in heat. *J Sports Sci*. 2013;31(7):779–86.
- Chen T-I, Tsai P-H, Lin J-H, et al. Effect of short-term heat acclimation on endurance time and skin blood flow in trained athletes. *Open Access J Sports Med*. 2013;4:161–70.
- Garrett A, Creasy R, Rehrer N, et al. Effectiveness of short-term heat acclimation for highly trained athletes. *Eur J Appl Physiol*. 2012;112:1827–37.
- Garrett A, Goossens N, Rehrer N, et al. Induction and decay of short-term heat acclimation. *Eur J Appl Physiol*. 2009;107(6):659–70.
- Buchheit M, Voss S, Nybo L, et al. Physiological and performance adaptations to an in-season soccer camp in the heat: associations with heart rate and heart rate variability. *Scand J Med Sci Sports*. 2011;21(6):e477–85.
- Petersen C, Portus M, Pyne D, et al. Partial heat acclimation in cricketers using a 4-day high intensity cycling protocol. *Int J Sports Physiol Perform*. 2010;5(4):535–45.
- Brazaitis M, Skurvydas A. Heat acclimation does not reduce the impact of hyperthermia on central fatigue. *Eur J Appl Physiol*. 2010;109(4):771–8.
- Sunderland C, Morris J, Nevill M. A heat acclimation protocol for team sports. *Br J Sports Med*. 2008;42(5):327–33.
- Febbraio M, Snow R, Hargreaves M, et al. Muscle metabolism during exercise and heat stress in trained men: effect of acclimation. *J Appl Physiol*. 1994;76(2):589–97.
- Fujii N, Honda Y, Ogawa T, et al. Short-term exercise-heat acclimation enhances skin vasodilation but not hyperthermic hyperpnea in humans exercising in a hot environment. *Eur J Appl Physiol*. 2012;112(1):295–307.
- Aoyagi Y, McLellan T, Shephard R. Effects of 6 versus 12 days of heat acclimation on heat tolerance in lightly exercising men wearing protective clothing. *Eur J Appl Physiol*. 1995;71(2–3):187–96.
- Lorenzo S, Halliwill J, Sawka M, et al. Heat acclimation improves exercise performance. *J Appl Physiol*. 2010;109(4):1140–7.
- Daanen HAM, Jonkman AG, Layden JD, et al. Optimising the acquisition and retention of heat acclimation. *Int J Sports Med*. 2011;32(11):822–8.
- Weller AS, Linnane DM, Jonkman AG, et al. Quantification of the decay and re-induction of heat acclimation in dry-heat following 12 and 26 days without exposure to heat stress. *Eur J Appl Physiol*. 2007;102(1):57–66.
- Castle P, Mackenzie R, Maxwell N, et al. Heat acclimation improves intermittent sprinting in the heat but additional pre-cooling offers no further ergogenic effect. *J Sports Sci*. 2011;29(11):1125–34.
- Gill N, Sleivert G. Effect of daily versus intermittent exposure on heat acclimation. *Aviat Space Environ Med*. 2001;72(4):385–90.
- Patterson M, Stocks JM, Taylor N. Sustained and generalized extracellular fluid expansion following heat acclimation. *J Physiol (Lond)*. 2004;559(1):327–34.
- Höfler W. Changes in regional distribution of sweating during acclimatization to heat. *J Appl Physiol*. 1968;25(5):503–6.
- Fox R, Goldsmith R, Hampton I, Lewis H. The nature of the increase in sweating capacity produced by heat acclimatization. *J Physiol*. 1964;171:368–76.
- Armstrong LW, Maresh CM. The induction and decay of heat acclimatisation in trained athletes. *Sports Med*. 1991;12(5):302–12.
- Burk A, Timpmann S, Kreegipuu K, et al. Effects of heat acclimation on endurance capacity and prolactin response to exercise in the heat. *Eur J Appl Physiol*. 2012;112(12):4091–101.
- Hue O, Antoine-Jonville S, Sara F. The effect of 8 days of training in tropical environment on performance in neutral climate in swimmers. *Int J Sports Med*. 2007;28(1):48–52.
- Racinais S, Mohr M, Buchheit M, et al. Individual responses to short-term heat acclimatisation as predictors of football performance in a hot, dry environment. *Br J Sports Med*. 2012;46(11):810–5.
- Wyndham CH, Benade AJ, Williams CG, et al. Changes in central circulation and body fluid spaces during acclimatization to heat. *J Appl Physiol*. 1968;25(5):586–93.

29. Cotter J, Patterson M, Taylor N. Sweat distribution before and after repeated heat exposure. *Eur J Appl Physiol.* 1997;76(2):181–6.
30. Yamazaki F, Hamasaki K. Heat acclimation increases skin vasodilation and sweating but not cardiac baroreflex responses in heat-stressed humans. *J Appl Physiol.* 2003;95(4):1567–74.
31. Buono MJ, Heaney JH, Canine KM. Acclimation to humid heat lowers resting core temperature. *Am J Physiol.* 1998;274(5 Pt 2):R1295–9.
32. Hessemer V, Zeh A, Bruck K. Effects of passive heat adaptation and moderate sweatless conditioning on responses to cold and heat. *Eur J Appl Physiol.* 1986;55(3):281–9.
33. Patterson MJ, Stocks JM, Taylor NA. Humid heat acclimation does not elicit a preferential sweat redistribution toward the limbs. *Am J Physiol Regul Integr Comp Physiol.* 2004;286(3):R512–8.
34. Gray AJ, Jenkins DG. Match analysis and the physiological demands of Australian football. *Sports Med.* 2010;40(4):347–60.
35. Gabbett T, King T, Jenkins D. Applied physiology of rugby league. *Sports Med.* 2008;38(2):119–38.
36. Carling C, Bloomfield J, Nelsen L, et al. The role of motion analysis in elite soccer: contemporary performance measurement techniques and work rate data. *Sports Med.* 2008;38(10):839–62.
37. Wisbey B, Montgomery PG, Pyne DB, et al. Quantifying movement demands of AFL football using GPS tracking. *J Sci Med Sport.* 2010;13(5):531–6.
38. Gabbett TJ, Jenkins DG, Abernethy B. Physical demands of professional rugby league training and competition using microtechnology. *J Sci Med Sport.* 2012;15(1):80–6.
39. Pandolf KB. Time course of heat acclimation and its decay. *Int J Sports Med.* 1998;19(Suppl. 2):S157–60.
40. Cedaro R. Environmental factors and exercise performance: a review. 1. Heat and acclimatization. *Excel.* 1992;8:61–72.
41. Hopkins WG, Schabert EJ, Hawley JA. Reliability of power in physical performance tests. *Sports Med.* 2001;31(3):211–34.
42. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale: Lawrence Erlbaum Associates; 1988.
43. Law M, Stewart D, Pollock N, et al. Guidelines for critical review form—quantitative studies. McMaster University: Occupational Therapy Evidence-Based Practice Research Group; 1998. <http://www.srs-mcmaster.ca/Portals/20/pdf/ebp/quantreview.pdf>. Accessed 17 Aug 2012.
44. Senay LC, Mitchell D, Wyndham CH. Acclimatization in a hot, humid environment: body fluid adjustments. *J Appl Physiol.* 1976;40(5):786–96.
45. Nielsen B, Hales J, Strange S, et al. Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *J Physiol (Lond).* 1993;460:467–85.
46. Nielsen B, Strange S, Christensen N, et al. Acute and adaptive responses in humans to exercise in a warm, humid environment. *Pflugers Arch.* 1997;434(1):49–56.
47. Kirwan JP, Costill DL, Kuipers H. Substrate utilization in leg muscle of men after heat acclimation. *J Appl Physiol.* 1987;63(1):31–5.
48. Fortney SM, Nadel ER, Wenger CB, et al. Effect of acute alterations of blood volume on circulatory performance in humans. *J Appl Physiol Respir Environ Exerc Physiol.* 1981;50(2):292–8.
49. Convertino VA. Heart rate and sweat rate responses associated with exercise-induced hypervolemia. *Med Sci Sports Exerc.* 1983;15(1):77–82.
50. Rowell LB, Kraning KK II, Kennedy JW, et al. Central circulatory responses to work in dry heat before and after acclimatization. *J Appl Physiol.* 1967;22(3):509–18.
51. Wyndham CH, Rogers GG, Senay LC, et al. Acclimatization in a hot, humid environment: cardiovascular adjustments. *J Appl Physiol.* 1976;40(5):779–85.
52. Levi E, Vivi A, Hasin Y, et al. Heat acclimation improves cardiac mechanics and metabolic performance during ischemia and reperfusion. *J Appl Physiol.* 1993;75(2):833–9.
53. Horowitz M, Shimoni Y, Parnes S, et al. Heat acclimation: cardiac performance of isolated rat heart. *J Appl Physiol.* 1986;60(1):9–13.
54. Hodge D, Jones D, Martinez R, et al. Time course of the attenuation of sympathetic nervous activity during active heat acclimation. *Auton Neurosci.* 2013;177(2):101–3.
55. Edwards AM, Mann ME, Marfell-Jones MJ, et al. Influence of moderate dehydration on soccer performance: physiological responses to 45 min of outdoor match-play and the immediate subsequent performance of sport-specific and mental concentration tests. *Br J Sports Med.* 2007;41(6):385–91.
56. Edwards AM, Noakes TD. Dehydration: cause of fatigue or sign of pacing in elite soccer? *Sports Med.* 2009;39(1):1–13.
57. McGregor SJ, Nicholas CW, Lakomy HKA, et al. The influence of intermittent high-intensity shuttle running and fluid ingestion on the performance of a soccer skill. *J Sports Sci.* 1999;17(11):895–903.
58. Nadel ER, Cafarelli E, Roberts MF, et al. Circulatory regulation during exercise in different ambient temperatures. *J Appl Physiol.* 1979;46(3):430–7.
59. Finberg J, Berlyne G. Modification of renin and aldosterone response to heat by acclimatization in man. *J Appl Physiol Respir Environ Exerc Physiol.* 1977;42(4):554–8.
60. Noakes TD, St Clair Gibson A, Lambert EV. From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *Br J Sports Med.* 2005;39(2):120–4.
61. Noakes T. The central governor model of exercise regulation applied to the marathon. *Sports Med.* 2007;37(4–5):374–7.
62. Gonzalez RR, Pandolf KB, Gagge AP. Heat acclimation and decline in sweating during humidity transients. *J Appl Physiol.* 1974;36(4):419–25.
63. Shvartz E, Benor D, Saar E. Acclimatization to severe dry heat by brief exposures to humid heat. *Ergonomics.* 1972;15(5):563–71.
64. Aoyagi Y, McLellan T, Shephard R. Effects of training and acclimation on heat tolerance in exercising men wearing protective clothing. *Eur J Appl Physiol.* 1994;68(3):234–45.
65. Shido O, Sugimoto N, Tanabe M, et al. Core temperature and sweating onset in humans acclimated to heat given at a fixed daily time. *Am J Physiol.* 1999;276:R1095–101.
66. Armstrong CG, Kenney WL. Effects of age and acclimation on responses to passive heat exposure. *J Appl Physiol.* 1993;75(5):2162–7.
67. Roberts MF, Wenger CB, Stolwijk JAJ, et al. Skin blood flow and sweating changes following exercise training and heat acclimation. *J Appl Physiol Respir Environ Exerc Physiol.* 1977;43(1):133–7.
68. Nadel ER, Pandolf KB, Roberts MF, et al. Mechanisms of thermal acclimation to exercise and heat. *J Appl Physiol.* 1974;37(4):515–20.
69. Inoue Y, Shibasaki M, Hirata K, et al. Relationship between skin blood flow and sweating rate, and age related regional differences. *Eur J Appl Physiol.* 1998;79(1):17–23.
70. Takeno Y, Kamijo YI, Nose H. Thermoregulatory and aerobic changes after endurance training in a hypobaric hypoxic and warm environment. *J Appl Physiol.* 2001;91(4):1520–8.
71. Fortney SM, Vroman NB, Beckett WS, et al. Effect of exercise hemoconcentration and hyperosmolality on exercise responses. *J Appl Physiol.* 1988;65(2):519–24.
72. Convertino VA. Blood volume: its adaptation to endurance training. *Med Sci Sports Exerc.* 1991;23(12):1338–48.

73. Simmons GH, Wong BJ, Holowatz LA, et al. Changes in the control of skin blood flow with exercise training: where do cutaneous vascular adaptations fit in? *Exp Physiol*. 2011;96(9):822–8.
74. Shvartz E, Saar E, Meyerstein N, et al. A comparison of three methods of acclimatization to dry heat. *J Appl Physiol*. 1973;34(2):214–9.
75. Piwonka RW, Robinson S. Acclimatization of highly trained men to work in severe heat. *J Appl Physiol*. 1967;22(1):9–12.
76. Regan JM, Macfarlane DJ, Taylor NAS. An evaluation of the role of skin temperature during heat adaptation. *Acta Physiol Scand*. 1996;158(4):365–75.
77. Austin DJ, Gabbett TJ, Jenkins DJ. Repeated high-intensity exercise in a professional rugby league. *J Strength Cond Res*. 2011;25(7):1898–904.
78. Thomas MM, Cheung SS, Elder GC, et al. Voluntary muscle activation is impaired by core temperature rather than local muscle temperature. *J Appl Physiol*. 2006;100(4):1361–9.
79. Aughey RJ, Goodman CA, McKenna MJ. Greater chance of high core temperatures with modified pacing strategy during team sport in the heat. *J Sci Med Sport*. 2014;17(1):113–8.
80. Duffield R, Coutts AJ, Quinn J. Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. *J Strength Cond Res*. 2009;23(4):1238–44.
81. González-Alonso J, Calbet JAL. Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation*. 2003;107(6):824–30.
82. Young AJ, Sawka MN, Levine L. Skeletal muscle metabolism during exercise is influenced by heat acclimation. *J Appl Physiol*. 1985;59(6):1929–35.
83. Febbraio MA. Alterations in energy metabolism during exercise and heat stress. *Sports Med*. 2001;31(1):47–59.
84. King DS, Costill DL, Fink WJ, et al. Muscle metabolism during exercise in the heat in unacclimatized and acclimatized humans. *J Appl Physiol*. 1985;59(5):1350–4.
85. Houmard J, Costill D, Davis J, et al. The influence of exercise intensity on heat acclimation in trained subjects. *Med Sci Sports Exerc*. 1990;22(5):615–20.
86. Sawka MN, Pandolf KB, Avellini BA, et al. Does heat acclimation lower the rate of metabolism elicited by muscular exercise? *Aviat Space Environ Med*. 1983;54(1):27–31.
87. Givoni B, Goldman RF. Predicting rectal temperature response to work, environment, and clothing. *J Appl Physiol*. 1972;32(6):812–22.
88. Krstrup P, Mohr M, Steensberg A, et al. Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med Sci Sports Exerc*. 2006;38(6):1165–74.
89. Ali A, Williams C, Nicholas CW, et al. The influence of carbohydrate-electrolyte ingestion on soccer skill performance. *Med Sci Sports Exerc*. 2007;39(11):1969–76.
90. Spriet LL, Lindinger MI, McKelvie RS, et al. Muscle glycogenolysis and H⁺ concentration during maximal intermittent cycling. *J Appl Physiol*. 1989;66(1):8–13.
91. Aoyagi Y, McLellan TM, Shephard RJ. Interactions of physical training and heat acclimation. The thermophysiology of exercising in a hot climate. *Sports Med*. 1997;23(3):173–210.
92. Pandolf KB, Burse RL, Goldman RF. Role of physical fitness in heat acclimatization, decay and reinduction. *Ergonomics*. 1977;20(4):399–408.
93. Pandolf KB, Cadarette BS, Sawka MN, et al. Thermoregulatory responses of middle-aged and young men during dry-heat acclimation. *J Appl Physiol*. 1988;65(1):65–71.
94. Best S, Thompson M, Caillaud C, et al. Exercise-heat acclimation in young and older trained cyclists. *J Sci Med Sport*. 2013 Oct 31 [Epub ahead of print].
95. Dawson B, Pyke FS, Morton AR. Improvements in heat tolerance induced by interval running training in the heat and in sweat clothing in cool conditions. *J Sports Sci*. 1989;7(3):189–203.
96. Chinevere TD, Kenefick RW, Cheuvront SN, et al. Effect of heat acclimation on sweat minerals. *Med Sci Sports Exerc*. 2008;40(5):886–91.
97. Buono MJ, Ball KD, Kolkhorst FW. Sodium ion concentration vs. sweat rate relationship in humans. *J Appl Physiol*. 2007;103(3):990–4.
98. Horstman D, Christensen E. Acclimatization to dry heat: active men vs. active women. *J Appl Physiol Respir Environ Exerc Physiol*. 1982;52(4):825–31.
99. Shapiro Y, Hubbard R, Kimbrough C, et al. Physiological and hematologic responses to summer and winter dry-heat acclimation. *J Appl Physiol Respir Environ Exerc Physiol*. 1981;50(4):792–8.
100. Taylor N. Principles and practices of heat adaptation. *J Hum Environ Syst*. 2000;4(1):11–22.
101. Pandolf K, Sawka M, Gonzalez R. Human performance physiology and environmental medicine at terrestrial extremes. United States of America: Benchmark Press Inc.; 1988.
102. Mujika I. Intense training: The key to optimal performance before and during the taper. *Scand J Med Sci Sports*. 2010;20(Suppl 2):24–31.
103. Le Meur Y, Hausswirth C, Mujika I. Tapering for competition: a review. *Sci Sports*. 2012;27(2):77–87.
104. Pyne DB, Mujika I, Reilly T. Peaking for optimal performance: research limitations and future directions. *J Sports Sci*. 2009;27(3):195–202.
105. Montain SJ, Sawka MN, Cadarette BS, et al. Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate. *J Appl Physiol*. 1994;77(1):216–22.
106. Aoyagi Y, McLellan T, Shephard R. Effects of endurance training and heat acclimation on psychological strain in exercising men wearing protective clothing. *Ergonomics*. 1998;41(3):328–57.
107. Barnett A, Maughan R. Response of unacclimatized males to repeated weekly bouts of exercise in the heat. *Br J Sports Med*. 1993;27(1):39–44.
108. Fein JT, Haymes EM, Buskirk ER. Effects of daily and intermittent exposures on heat acclimation of women. *Int J Biometeorol*. 1975;19(1):41–52.
109. Buchheit M, Racinais S, Bilsborough J, et al. Adding heat to the live-high train-low altitude model: a practical insight from professional football. *Br J Sports Med*. 2013;47(Suppl 1):i59–69.

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