©Journal of Sports Science and Medicine (2019) **18,** 316-326
http://www.jssm.org

Review article

Physiological Responses to Heat Acclimation: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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Abstract
The aim of this meta-analysis was to evaluate the effectiveness of heat acclimatization (HA) on time trial (TT) performance, maximum oxygen uptake (VO_{2max}), exercise heart rate (HR_E), time trials heart rate (HR_{TT}), maximal heart rate (HR_M), core temperature (T_C), mean skin temperature (T_S), thermal comfort (T_{Comf}), plasma volume (PV), blood lactate concentration and rate of perceived exertion (RPE). Cochrane-CENTRAL, EMBASE, CINAHL and PubMed databases and reference lists of included studies were searched for randomized controlled trials that investigated the efficacy of HA in athletes. Data were then extracted from the entered studies for analyses. A total of 11 randomised controlled trials (215 participants; mean age, 26.09 years; 91% men) were included after screening of 508 titles and abstracts and 19 full-text articles. The pooled standard mean difference (SMD) between the HA and non-HA groups were 0.50 (95% CI: 0.03 to 0.97, p = 0.04) for TT performance and 1 (95% CI: 1 to 2, p = 0.007) for HR_{TT}. The pooled mean difference (MD) between the HA and non-HA groups were -7 (95% CI: -13 to -1, p = 0.03) for HR_M. The changes in T_{Comf} and RPE were too small to be meaningful. There were no significant differences between the HA and non-HA groups for VO_{2max}, HR_E, T_C, T_S, PV and blood lactate concentration (all p > 0.05). This meta-analysis implies that HA may improve tolerance to discomfort during heat exposure, but may not necessarily improve the associated physiological markers of improved performance.

Key words: Performance, heart rate, thermal comfort, rate of perceived exertion.

Introduction

Hot and humid ambient environments affect the human physiological response to physical activity (No and Kwak, 2016; Tucker et al., 2004), and exercise-induced increases in core temperature (T_C) and increased ambient temperature result in premature fatigue and loss of athletic performance (Al-Nawaiseh et al., 2013). Muscle and skin blood flow (Sawka et al., 2011), aerobic capacity (Tucker et al., 2004), early onset of anaerobic threshold (Tyka et al., 2009), stimulation and accumulation of stress hormones (Jones et al., 2010), increased anaerobic glycolysis, increased use of intramuscular glycogen and lactate accumulation (Tan et al., 2018), are all factors associated with increased body temperature during exercise. However, competitive athletes compete in a variety of environmental conditions, which emphasizes the importance of reducing the potential adverse effects of a hot environment on athletic performance (Al-Nawaiseh et al., 2013). Heat acclimatization (HA) has been undertaken by endurance athletes to enhance tolerance and exercise performance in hot conditions (Guy et al., 2016; Périard et al., 2015a). Generally, HA has been undertaken at sub-maximal intensities during exposure to elevated temperature and/or humidity (Taylor, 2014; Tyler et al., 2016). Some of these studies have reported beneficial responses, such as decreases in heart rate (HR), T_C and skin temperatures (T_S) (Brade et al., 2013).

Alterations in critical physiological parameters such as increased plasma volume (PV), reduced exercise HR (HR_E) (Kelly et al., 2016; Sawka et al., 2011), lower resting and exercise T_C (Sawka et al., 2011; Tyler et al., 2016), and improved maximal cardiac output (Sawka et al., 1985; Shvartz et al., 1977), can all lead to increased performance (Guy et al., 2016) via short and medium duration HA programs. These adaptations could be beneficial for consequent performance in the heat, as well as in the cold, where possible fluid loss may be considerable (Corbett et al., 2014). The apparent dose-response to HA proposes that 15 days or more is required to optimize performance (Guy et al., 2015). Nevertheless, PV, HR and T_C adjustments can take place as quickly as four days, and sustained thermal adaptation needs to be maintained by regular exertional exposure to hot climates (Weller et al., 2007).

Numerous elite sporting competitions are programmed in geographical locations that involve exposure to hot and humid environments, such as the 2020 Tokyo Olympics and 2022 Qatar World Cup. Hence, it is essential that athletes should be readied for such competitions, especially those who live and exercise in cold environments or are unaccustomed to heat stress (Milne and Shaw, 2008).

A previous meta-analysis on HA efficacy was conducted (Tyler et al., 2016), but only included investigations up until February 2016 and also included non-randomized, controlled trials. Additional randomized controlled trials (RCTs) have since been published, and this argues in favor of carrying out an updated meta-analysis. This update includes data pooling for several outcomes that were previously not carried out because of insufficient outcome data. The aim of this meta-analysis was to update previous pooled analyses, using only level 1 (RCT) evidence, on outcome measures relating to thermoregulatory adaptations attributed to HA with athletic performance in RCTs.

Methods

Search strategy

This systematic review and meta-analysis has been reported using the PRISMA guidelines (Liberati et al., 2009). Accordingly, using a PubMed search strategy (1966 to Nov

Received: 29 January 2019 / Accepted: 10 April 2019 / Published (online): 01 June 2019

1, 2018), we identified relevant articles by the following keywords: "acclimation", "acclimatization", "heat", "acclimation and performance", "temperature", "exercise training in heat". Then, after the initial screening, the references of all studies based on the inclusion and exclusion criteria were examined to find additional studies.

Study selection

Two reviewers separately looked at the titles and read the abstracts and filtered relevant articles to be included. The four-phase (identifying, screening, qualification and inclusion) method identified were used in the PRISMA report to diminish the number of primary search results.

Inclusion/exclusion criteria

Study design: full text articles of controlled trials and RCTs of heat exercise training of natural and artificial HA, excluding review articles, conference abstracts and study protocols.

Comparison intervention: study protocols that used heat training (HOT) with thermo-neutral training (NEUTRAL), in a pre-post design, excluding the studies on acute interventions (e.g., single-session interventions) and also water immersion interventions.

Population: Men and women (age ≥ 18 years) who identified as triathletes, runners, endurance athletes, cyclists or team sport athletes from both elite and sub elite competitive levels.

Publications: English language manuscripts published in specialised English journals.

Outcome measures

The outcome measurements of this meta-analysis were;

Time trial (TT) performance (in seconds): in included studies TT performance were measured with the test of maximal leg cycle exercise test (time to reach exhaustion), 5 km TT performance, 20-km cycling, and running 3 km TT on a motorized treadmill.

Maximum oxygen uptake (VO_{2max} in ml/kg/min), Exercise (HR_E), time trials (HR_{TT}) and maximal heart rate (HR_M).

Core (T_C) and mean skin temperature (T_S): in included studies T_C was measured in the rectal (Guy et al., 2016; Lorenzo et al., 2010; Sunderland et al., 2008; Willmott et al., 2016), gastrointestinal (Chalmers et al., 2016; Petersen et al., 2010; Schmit et al., 2018), and oesophageal (Nielsen et al., 1993) sites. In addition, end exercise values (Lorenzo et al., 2010; Nielsen et al., 1993) and also delta temperature from pre-post values (Chalmers et al., 2016; Guy et al., 2016; Petersen et al., 2010; Schmit et al., 2018; Willmott et al., 2016) were used for T_C and T_S in included studies.

Thermal comfort (T_{Comf}): in included studies T_{Comf} was determined according to the 5-point scale, 8-point scale or a 10-point scale.

Plasma volume (PV in percent): change in PV (%) was estimated using the method of Dill and Costill 1974 or PV was calculated from body mass by the equation of Sawka et al 1992.

Blood lactate (mmol.L).

Rate of perceived exertion (RPE): in included studies RPE was measured using the Borg and Kaijser 2006 scales.

Statistical analysis

For all included studies, we summarized the effect size for any outcome by measuring the mean difference between the heat and neutral condition from before and after the intervention. If multiple articles were published from the same dataset then we checked the data in order to avoid using the same results for the same outcome measure on more than one occasion. Results were analyzed by weighted mean difference (MD), if the measurement method or reporting was identical. For outcomes using different measurement or reporting techniques a standardized mean difference (SMD) was used. All analyses were conducted using Review Manager 5.3 (The Nordic Cochrane Centre, Copenhagen, Denmark). Extracted outcome data employed were change in the mean ± SD. In studies that reported SE data, these were converted to SD. A random-effects inverse variance was employed. When a standardized mean difference (SMD) was used the guideline for commentary was used (Cohen, 1988), with 0.2 described as small, 0.5 medium and 0.8 as large. Where an article contained a control group and more than one HA group, we separately labelled each HA groups and adjusted the sample size of the control group according to the number of HA groups. We presented meta-analysis using forest plots and applied a 5% level of significance to describe the significance of results.

Heterogeneity: To evaluate the heterogeneity among the studies, the I^2 statistic was employed, with values > 50% showing substantial heterogeneity (Higgins et al., 2003). The risk of publication bias was assessed using the Egger plot (Egger et al., 1997). Any analysis of heterogeneity depends on the number of trials included in a meta-analysis, which is generally small, and this limits the statistical power of the test. We therefore based evidence of asymmetry on $P<0.1$, and we present intercepts with 90% confidence intervals.

Study quality: Study quality and reporting was assessed using the validated TESTEX scale (Table 1) (Smart et al., 2015). This is a validated 15-point scale which evaluates quality of the study (5 points maximum) and reporting (10 points maximum). A study with a TESETX quality score of less than 10 was deemed of low quality.

Results

Study characteristics

Figure 1 displays the selection process employed to include manuscripts in our meta-analysis. Of 617 possibly associated articles reclaimed from the search, 113 were animal studies and a further 489 were excluded by title or abstract, leaving 19 full text articles. A further 4 were excluded as duplicate studies, two more were excluded as they used immersion water protocol and 2 used an acute protocol, leaving 11 studies for the meta-analysis.

Table 1. Study quality assessment of included studies using the tool for the assessment of study quality in exercise (TESTEX).

Study	Eligibility Criteria specified	Randomisation Details Specified	Allocation concealed	Groups similar at baseline	Assessors blinded	Outcomes measures assessed >85% participants	Intention to treat analysis	Reporting between group statistical comparison	Point measures & measures of variability	Activity monitoring in control group	Relative exercise intensity constant	Exercise volume & Energy expenditure	Overall TESTEX (/15)
Chalmers 2016	1	0	0	1	0	3	1	2	1	1	0	1	11
Chen 2013	1	1	0	1	0	2	0	2	1	1	0	1	10
Guy 2016	1	1	0	1	0	2	0	2	1	1	1	0	10
Karlsen 2015	1	0	0	1	0	2	0	2	1	1	0	1	9
Kelly 2016	1	1	0	0	0	2	0	2	1	1	0	1	9
Lorenzo 2010	1	1	0	1	0	2	0	2	1	1	0	1	10
Nielsen 1993	1	0	0	1	0	3	1	2	1	1	0	1	11
Peterson 2010	1	1	0	1	0	2	0	2	1	1	0	1	10
Schmit 2017	1	1	0	1	0	2	0	2	1	1	0	0	9
Sunderland 2007	1	0	0	1	0	2	0	2	1	1	0	1	9
Willmott 2016	1	1	0	1	0	2	0	2	1	1	1	0	10

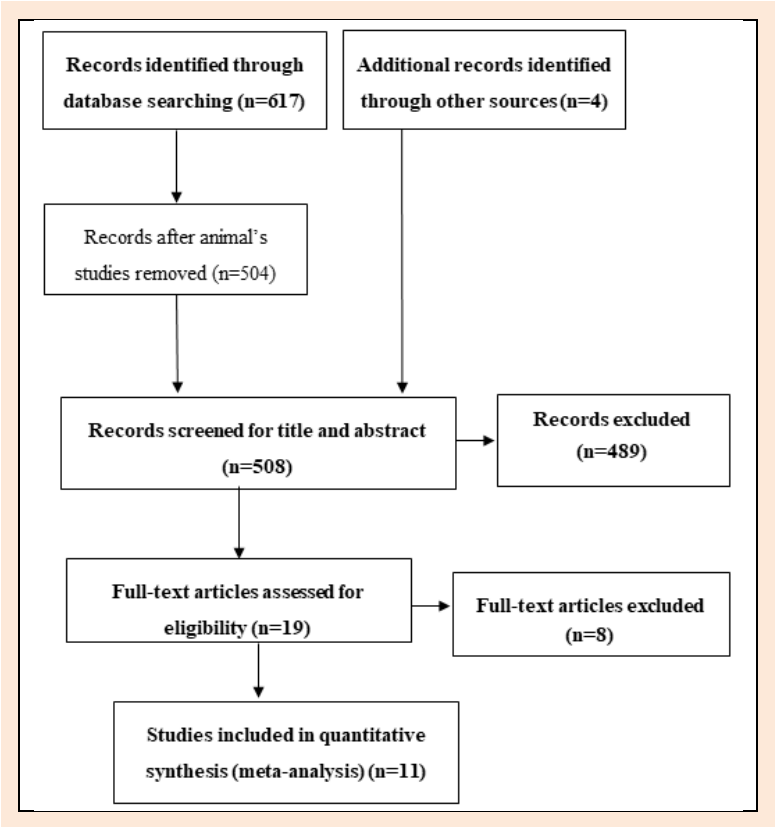

Figure 1. PRISMA flow diagram.

The characteristics of the included articles are shown in Table 2. The eleven included studies had a total of 215 subjects, 195 (91%) males and 20 (9%) females. There were 123 (57%) subjects in heat group and 92 (43%) in the non-heat group. The mean age of all subjects was 26.09 ± 0.09 years. All included articles were RCTs promulgated since 1993. Studies were performed in the United State (1), France (1), Taiwan (1), Denmark (2), England (2), and in Australia (4). The intervention period for studies ranged from 4-14 days and the mean length of each session was 59 min (range 27-90 min). The HOT protocols frequency were 4-14 days (1-2 session per day), 27-90 min in each session at 30% VO_2 to 100% HR_{max}. The reviewed full-text studies were excluded from the analysis with 3 reasons (non-randomized control trial study, used an acute protocol, inadequate participants population).

Table 2. Meta-analysis of heat acclimation included studies.

Study	HA / C group	HA activity	Intervention group: HA frequency and duration	Control group: frequency and duration	Measure (Outcome)	Performance test
Chalmers 2016	Study 1: 9 / 9 Study 2: 12 / 11	Perceptually regulated treadmill exercise training	Study 1: 5 days × 38 min in 35 °C and 30% RH Study 2: 4 days × 58 min in 35 °C and 30% RH	Study 1: 5 days × 38 min in 19 °C and 30% RH Study 2: 4 days × 58 min in 19 °C and 30% RH	HRE, TC, VO2max, PV, Blood Lactate, TComf, RPE	-
Chen 2013	7 / 7	Cycling at 10% below VT to 10% above VT	5 days × 35 min (mean) in 38.4°C ± 0.4°C, 52.0% ± 4.6% RH	5 days × 35 min (mean) in 24.1°C ± 0.3°C, 51.5% ± 4.5% RH	VO_2max, Performance, TS, HRM	Maximal leg cycle exercise test (GXT): time to reach exhaustion
Guy 2016	8 / 8	Cycling at 55 % VO_2max Cycling at 50, 60, and 70 % VO_2 max	7 days × 40 min at 35◦C and 70% RH 3 HST tests × 3 sets × 10 min at 35 ◦C and 70 % RH	7 days × 40 min at 20◦C, 45% RH 3 HST tests × 3 sets × 10 min at 35 ◦C and 70 % RH	TC, Performance, HRTT, RPE, TComf, HRE	5 km TT performance
Karlsen 2015	9 / 9	Cycling at 80–100% HRMAX Cycling at moderate intensity	14 days × 38 min in 35 °C 14 days × 90 min in 35 °C	14 days × 38 min in 5–13 °C 14 days × 90 min in 5–13 °C	VO_2max, PV	-
Kelly 2016	7 / 7	High Intensity Interval Training at 90% and 30% VO_2	5 sessions × 27 min in 38.7 ± 0.5 °C; 34.4 ± 1.3 % RH	5 sessions × 27 min in 22.3 ± 0.2 °C; 35.8 ± 0.6 % RH	HRE, TS, RPE, TComf	-
Lorenzo 2010	12 / 8	Cycling at 50 % VO_2max	10 days × 2 bouts × 45 min with 10 min rest in 40°C and 30% RH	10 days × 2 bouts × 45 min with 10 min rest in 13°C and 30% RH	TC, $\dot{V}O_2max$, TS, HRM, PV, Blood Lactate,	-
Nielsen 1993	8 / 5	Cycling at 60 % VO_2max	9-12 days × 90 min in 40-42°C and 10-15% RH	9-12 days × 90 min in 18-20°C and 10-15% RH	TC, TS, PV	-
Petersen 2010	6 / 6	High intensity cycling	4 days × 38 min (mean) in 30°C, 60% RH	4 days × 38 min (mean) in 20°C, 60% RH	HRE, TC, TS, Blood Lactate, TComf	-
Schmit 2017	19 / 10	Low intensity training or High intensity training	5 days × 60 min in 30°C, 50% RH	Undertook some training sessions in the lab at 21°C, 50% RH	Performance, TC, HRTT, RPE	20-km cycling TT in 35°C, 50% RH
Sunderland 2007	12 / 5	Loughborough Intermittent Shuttle Test	4 sessions × 38 min (mean) in 30°C, 24% RH	4 sessions × 38 min (mean) in 18°C, 41% RH	TC, HRE, PV, Blood lactate, RPE, TComf	-
Willmott 2016	14 / 7	Cycling at 50 % VO_2max	SDHA: 4 days × 45 min in 35.2 ±0.5°C, 60±2% RH TDHA: 2 days × 2 sessions × 45 min in 35.4±0.8, 61±3% RH	4 days × 45 min in 21.7±0.6°C, 39±5 % RH	Performance, HRE, TC, PV, HRTT, RPE	3 km TT performance in 30 °C, 60% RH

HA = Heat Acclimation, HR = Heart Rate, RH = Relative Humidity, PV = Plasma Volume, VT = Ventilator Threshold, HST = Heat Stress Tests, HR_{TT} = Heart Rate Time Trial, T_C = Core Temperature, T_S = Skin Temperature, HR_E = Exercising Heart Rate, RPE = Rate of Perceived Exertion, TComf = Thermal Comfort, HR_M = Maximum Heart Rate, HIIT = High Intensity Interval Training, SDHA = Single Session Per Day Heat Acclimation, TDHA = Twice Daily Heat Acclimation.

Outcome measures

Change in Time Trial (TT) performance: The change in exercise TT performance following HA is depicted in Figure 3. Four studies reported the effects of HA on TT performance, nevertheless, six data sets were investigated owing to subgroups in the studies of Schmit et al. (2018) and Willmott et al. (2016). The SMD in the TT performance significantly changed after HA (SMD, 0.50; 95% CI, 0.03 to 0.97; p = 0.04).

Change in VO_{2max}: The change in VO_{2max} ($ml.kg^{-1}.min^{-1}$) following HA is displayed in Figure 4. Four studies evaluated the VO_{2max}. HA did not have a significant effect on VO_{2max} (MD, 2.51 $ml.kg^{-1}.min^{-1}$; 95% CI, -1.36 to 6.37; p = 0.20).

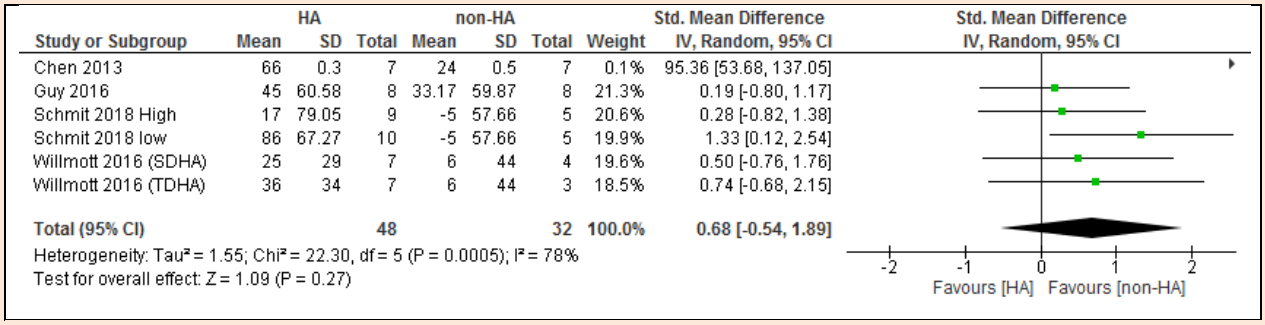

Figure 3. **Forest plot of effect of HA on time trial performance.**

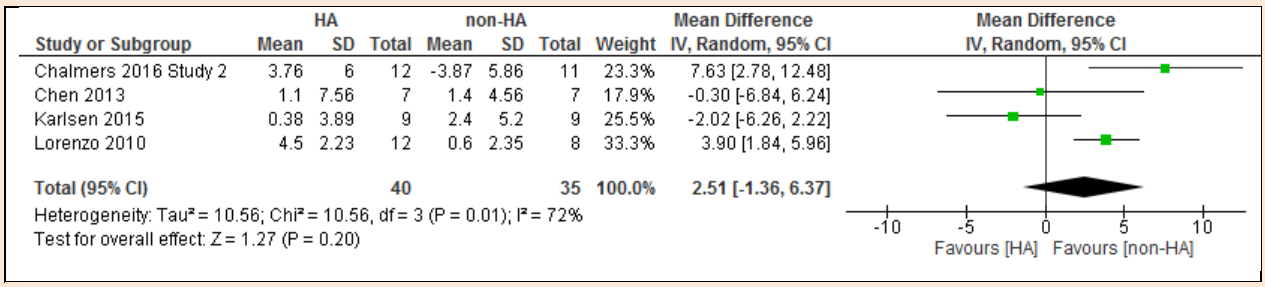

Figure 4. **Forest plot of effect of HA on VO_{2max}.**

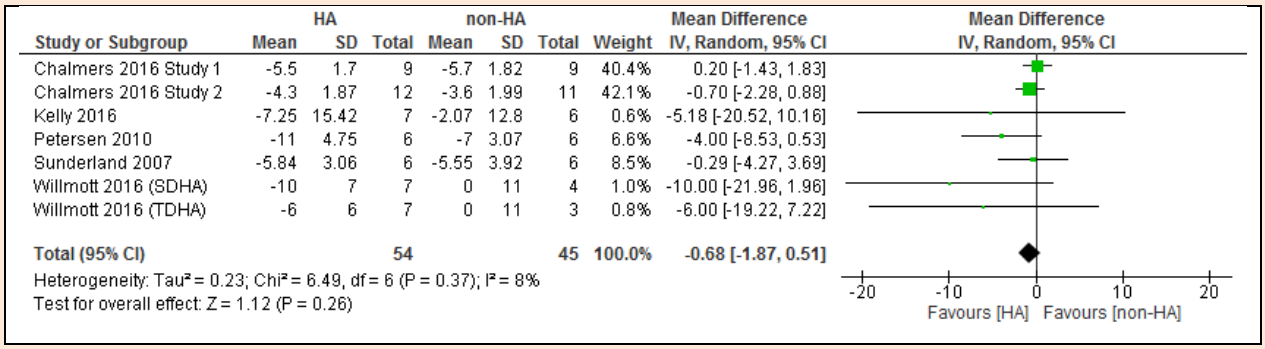

Figure 5. **Forest plot of effect of HA on exercising heart rate.**

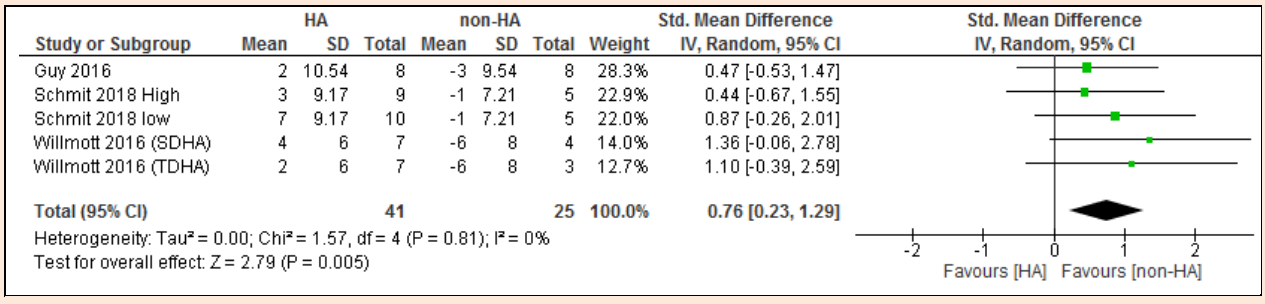

Figure 6. **Forest plot of effect of HA on time trial heart rate.**

Change in Exercise Heart Rate (HR_E): Five studies reported the effects of HA on HR_E, however, seven intervention groups were evaluated owing to subgroups in the studies of Chalmers and Willmott. The MD in the HR_E did not significantly change after HA (MD, -1 beats/min; 95% CI, -2 to 1; p = 0.15) (Figure 5).

Changes in Time Trial Heart Rate (HR_{TT}): The effects of HA on HR_{TT} was reported in three studies, nonetheless, owing to subgroups in the studies of Schmit and Willmott, five intervention groups were analyzed. Figure 6 reveals the SMD change in HR_{TT} with HA. The change in HR_{TT} was significantly higher in the HA groups (SMD, 1 beats/min; 95% CI, 1 to 2; p = 0.007).

Changes in Maximum Heart Rate (HR_M): The effects of HA on HR_M was reported in three studies, nonetheless, owing to subgroups in the studies, four data collections were reported. Figure 7 displays the MD changes in HR_M with HA. The HR_M decreased significantly after HA (MD, -7 beats/min; 95% CI, -13 to -1; p = 0.03).

Changes in Core Temperature (T_C) and mean skin

temperature (T_S): The effects of HA on T_C was reported in eight studies, however, owing to subgroups in the studies, 11 data collections were reported. On the other hand, the mean T_S was reported in five studies. Figure 8 displays the MD changes in T_C (A) and mean T_S (B) with HA, respectively. Neither the changes of T_C nor the changes of mean T_S were significant. (MD, -0.05°C; 95% CI, -0.15 to 0.04; p = 0.28; MD, -0.31°C; 95% CI, -0.68 to 0.06; p = 0.10 for T_C and mean T_S respectively).

Changes in Plasma Volume (PV): Six studies reported the effects of HA on PV, nevertheless, eight data collections were evaluated owing to subgroups in the studies. Figure 9 illustrates the SMD in the PV. PV did not change significantly after HA (SMD, 0.64 percent; 95% CI, -0.18 to 1.45; p = 0.13).

Change in Blood Lactate: Four studies reported the effects of HA on blood lactate, nevertheless, five data sets were evaluated owing to subgroups in one of the studies. Figure 10 illustrates the MD in blood lactate which did not change significantly after HA (MD, 0.37 mmol.L; 95% CI, -0.22 to 0.97; p = 0.22).

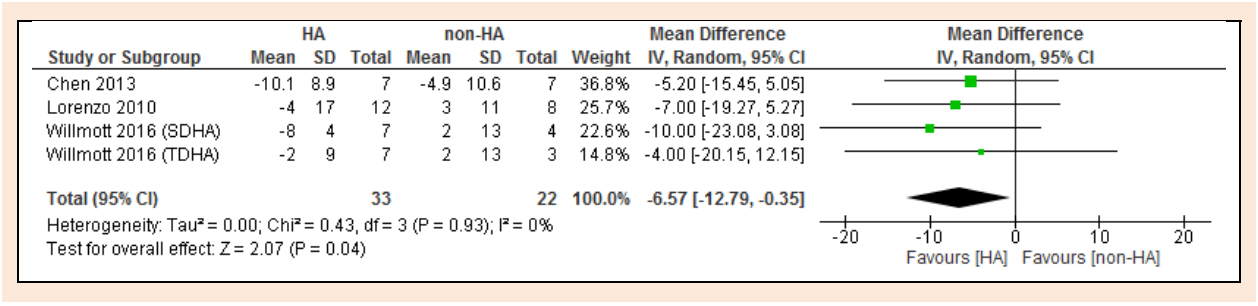

Figure 7. Forest plot of effect of HA on maximum heart rate.

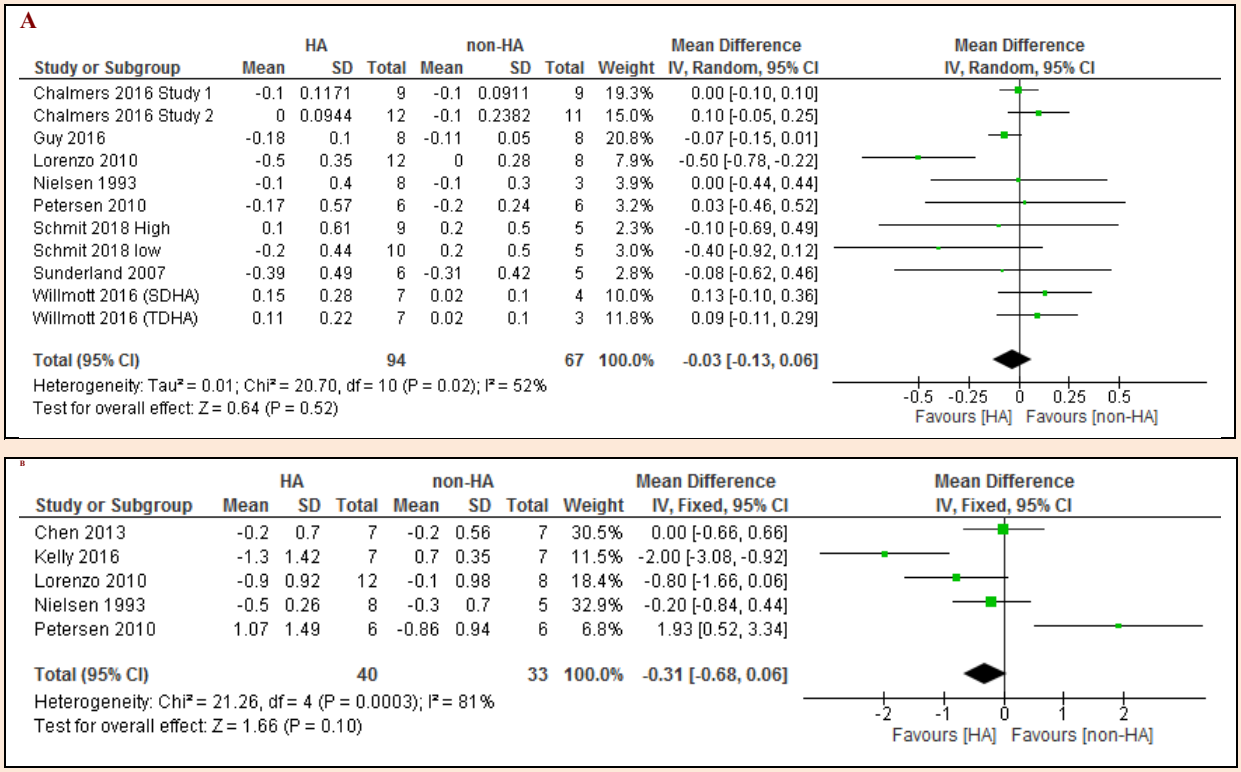

Figure 8. Forest plot of effect of HA on core temperature (A) and skin temperature (B).

Changes in T_{Comf}: The effects of HA on T_{Comf} was reported in five studies, however, owing to subgroups in the studies, six data collections were reported. The change in T_{Comf} was less than 0.2 of a unit and is therefore not reported graphically as it is not physiologically meaningful.

Changes in RPE: The effects of HA on the RPE was reported in six studies, however, owing to subgroups in the studies, nine data collections were reported. The change in RPE was less than 0.5 of a unit and is therefore not presented graphically as it is not physiologically meaningful.

Heterogeneity: For the analyses of TT performance, HR_{TT}, HR_M and T_{Comf} (all 0%) and also for the RPE analysis (6%) heterogeneity was low.

Study Quality: Median TESTEX score was 10 (see Table 1). Allocation concealment and assessor blinding were not performed in any of the included studies. Only two studies performed intention to treat analyses. Only two studies adjusted the relative training intensity.

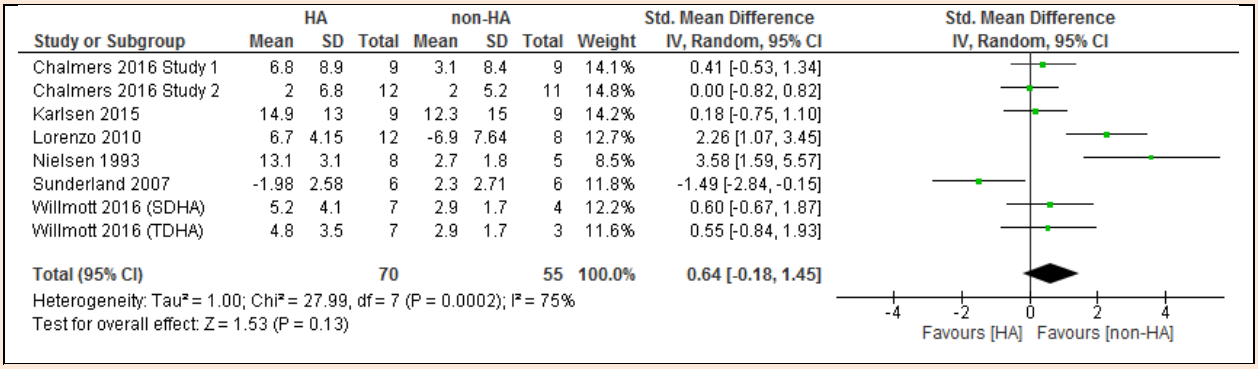

Figure 9. Forest plot of effect of HA on plasma volume.

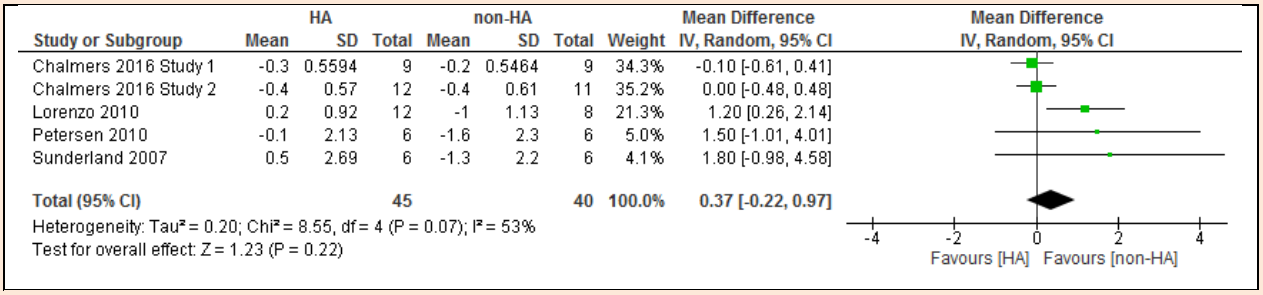

Figure 10. Forest plot of effect of HA on blood lactate.

Discussion

This meta-analysis aimed to update previous pooled analyses, using only level 1 RCT evidence on outcome measures relating to thermoregulatory adaptations attributed to HA during athletic performance. The results reveal that HA significantly improved TT performance, HR_{TT}, HR_M. The change in RPE and T_{Comf} were too small to be meaningful. However, there was no evidence of improvement in VO_{2max}, HR_E, T_C, T_S, PV and blood lactate concentration after HA. The relatively low levels of heterogeneity indicate data pooling was justified in the analyses.

TT Performance

Our result indicates HA had a significant effect on exercise TT performance. This finding is consistent with the results of Tyler et al. 2016, who reported HA had a moderately beneficial impact on exercise performance in the heat; nevertheless, they stated longer regimens (14 days) were more efficient than shorter programs (< 7 days). Another study has also suggested the extent of enhancements are dependent upon the training situation, exercise intensity and duration, environmental conditions and period of the HA protocol utilized (Périard et al., 2015b; Sunderland et al., 2008). Other work has shown that, by diminishing physiological pressure and reducing various other potential fatigue mechanisms, HA mediates improved performance (Nybo et al., 2011). The magnitude of HA advantage depends on the heat exposure frequency, with the highest effect sizes after long-term HA regimens, however both short-term and medium-term HA (8-14 days) shows moderate benefits (Tyler et al., 2016). Our sub-analysis also illustrates that the two studies with 5 days HA produced the highest alteration in TT performance (Chen et al., 2013; Schmit et al., 2018). Whilst there is no information to demonstrate the number of heat exposures required to improve performance, older work suggests full acclimatization may take up to one month (Horvath and Shelley, 1946).

VO_{2max} and PV

Our results revealed no significant change in VO_{2max} and PV following HA. A recent meta-analysis reported that HA had a moderate impact on reducing VO_{2max} during steady-state, fixed-intensity exercise (Tyler et al., 2016). Blood volume adaptations in response to climate manipulation were first published via Barcroft et al. (1922). A full description of the hematologic adjustments correlated with heat exposure have been published in subsequent works thereafter, suggesting that alterations in PV occur quite quickly and induce a transient reduction in hemoglobin and hematocrit, and sometimes the concentration of plasma proteins (Bazett et al., 1940). It has been suggested that an increase in VO_{2max} could be mediated by PV expansion (Périard et al., 2015a), increased myocardial efficiency, and enhanced ventricular compliance (Bhella et al., 2014; Opondo et al., 2015), which would provide larger end-diastolic volume. In our study, neither myocardial efficiency nor ventricular compliance was investigated. Kanstrup and Ekblom (1984) stated that PV expansion was counter-productive in that it enhanced maximal cardiac output 8% but declined hemoglobin concentration by 8%; therefore VO_{2max} remained unaltered. Furthermore, our findings indicate that the size of PV increase is influenced by the number of days of HA, the hydration state when calculated, T_S and whether the person is resting or exercising (Harrison, 1985; Kenefick et al., 2014; Sawka et al., 1983).

HR_E, HR_M and HR_{TT}

The changes in HR_M and HR_{TT} after HA were statistically significant in the HA groups, but HR_E was unchanged. The mechanisms of adaptation in HR_E are various and complicated, however PV changes induced via exercise, may account for most of the exercise-induced hypervolemia up to 2-4 weeks (Convertino, 1991). Willmott et al., 2016 reported no statistically significant changes in resting or HR_E after short-term HA. However, applying their predefined analytical limits, significant decreases of 4% (twice daily for 2 days) and 6% (once daily for 4 days) were seen in exercising HR from sessions 1–4, with no change in the control group (1%). These authors reported that this adjustment is typically concurrent with hypervolemia and is recommended to diminish HR by 1 beat.min^{-1} per 1% ΔPV, consistent with their analytical limits and previous investigations (Garrett et al., 2009; Lorenzo et al., 2010; Nielsen et al., 1993; Patterson et al., 2004).

T_C and mean T_S

Our results failed to show changes in T_C and T_S after HA. Tyler et al. (2016) reported a moderate-to-large positive impact of HA in reducing the T_C prior to and during exercise and they also reported HA had a large impact in decreasing mean T_S during exercise, these findings are different from our results. They stated that for short- (< 7 days) and medium-term (8-14 days) HA protocols, the effect sizes for Ts and T_C were similar and smaller than in long-term HA (14 days) protocols. There is evidence that people living and training over many weeks in the heat might endure higher maximal T_C than those undertaking HA training for just 1 or 2 weeks (Sawka et al., 2001), and trained people can tolerate higher T_C (Mora-Rodriguez et al., 2010; Périard et al., 2012). In addition, it has been reported that trained runners completing an 8-km running TT in warm situations are capable of sustaining running velocity, notwithstanding a T_C exceeding 40 °C (Ely et al., 2009). More recently, it was reported that trained cyclists approach a T_C of 40.1–40.2 °C at the end of a 43.3-km TT in hot situations (Racinais et al., 2015). Consequently, it does appear that raised aerobic fitness presents an enhanced capability to tolerate higher T_C. However, the extent to which HA provides such an advantage remains unclear.

Considerable proof of marked alterations in Tc and Ts exist in many physiological and biochemical functions at a crucial temperature *in vivo* and *in vitro*, and heterogeneity in thermo sensitivity exists among different tissues (Brinnel et al., 1987). The T_C level can rely on several agents such as exercise intensity and duration, fitness, nutrition, dehydration and motivation; and hence would be expected to vary significantly in absolute terms. Moreover, T_C relies on the measurement site and the temperature gradients that exist within the body, particularly throughout exercise heat storage (Nielsen et al., 1993; Nielsen et al., 1990).

Blood Lactate

Our results illustrate that blood lactate did not change significantly after HA and this conflicts with recent meta-analysis findings (Tyler et al., 2016). The decrease in blood lactate concentration through submaximal exercise after HA suggests a decline in glycolytic participation from the contracting muscle, and this is known to happen with more traditional HA programs (Febbraio et al., 1994). Moreover, a prior investigation suggested that the blood lactate alteration was in part due to a reduction in sympathoadrenal activation and levels of circulating catecholamines (Febbraio, 2001). Some investigators propose that metabolic conformities caused by HA during exercise are due to a diminishing aerobic metabolic rate (Aoyagi et al., 1994), or diminishing rate of glycogenolysis (Febbraio et al., 1996). Alternatively, the expanded PV and consequently total blood volume (Bass et al., 1955; Harrison et al., 1981) could affect blood lactate concentration via enhanced blood flow to the splanchnic circulation, improving lactate elimination (Rowell et al., 1968), and therefore delaying the onset of blood lactate accumulation.

RPE and T_{Comf}

The change in RPE and T_{Comf} were too small to be meaningful, in agreement with our findings, Tyler et al. (2016) stated HA had a moderate impact on RPE and small impact on T_{Comf}. T_{Comf} is a crucial stimulus which drives voluntary behavior (such as exercise performance and capability) in a warm situation, as it follows seasonal alterations in air temperature (De Dear and Brager, 2001). This emphasizes that T_{Comf} can be improved transiently in the heat via passive exposure to warmer temperatures. T_{Comf} is due to various psychophysical criteria, and it appears logical to recommend that HA could enhance T_{Comf} via shifting exposure to higher temperatures. Nevertheless, data concerning the effectiveness in doing so are currently inadequate to draw firm conclusions. Further investigation is also needed to examine the variation and specificity of adjustment between natural and artificial heat exposure and the potential for unnatural exposure to improve performance in natural competition. HA may vary with the environmental exercise situations to be faced, including the exercise task, solar radiation, and terrain/geography.

Study Quality

Median TESTEX score was 10. Allocation concealment and assessor blinding were not performed in any of the included studies, however this is unavoidable in HA experiments. Only two studies performed intention to treat analyses, this may be a reflection of the relatively low attrition rates due to small sample sizes of included studies, but ITT may also have been simply overlooked in some case where it was indicated . Only two studies adjusted the relative training intensity and this may explain why VO_{2max} and related performance outcomes were unchanged, although by nature HA studies may be of insufficient duration to elicit changes in these parameters.

Limitations

Our meta-analysis has some limitations that should be considered. First, we only analyzed 11 RCTs, and eight of them have small sample sizes (n<20). This argues that more RCTs with larger sample sizes are needed to provide more definitive results. Second, exercise intensity and

duration, environmental conditions and period of the HA protocol varied substantially in the utilized RCTs, and this may have impacted our results. Finally, about the data collecting, we calculated the mean differences between pre and post-intervention. Nevertheless, in cases where accurate p values within or between groups or 95% CI were unavailable, default p values were employed, and this may also have impacted our results. Egger plots suggest minimal likelihood of publication bias, indicating there may not be negative, unpublished datasets in existence. However, the small number of studies limited the relevance of Egger plots in these analyses.

Conclusion

HA has a beneficial effect on TT performance, HR_{TT}, HR_M, but was not statistically significant in VO_{2max}, HR_E, T_C, mean T_S, PV and blood lactate. The changes in RPE and T_{Comf} were too small to be meaningful. From a high performance coaching perspective, these findings suggest HA improves the athlete's tolerance to discomfort during heat exposure, but may not alter the associated physiological markers of improved performance.

Acknowledgements
The authors report no conflict of interest.

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Key points

- The primary finding of this analysis is that athletic performance is improved with heat acclimatization training
- Our analysis was unable to determine the physiological variable(s) that are associated with improved performance
- After heat acclimatization training athletes may be able to tolerate greater levels of thermal stress but our analysis was unable to determine physiological markers of adaption

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