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COMPREHENSIVE REVIEW



No clear influence of menstrual cycle phase or hormonal contraceptive use on heat acclimation adaptations: A systematic review and meta-analysis

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ABSTRACT

Heat acclimation (HA) involves repeated heat exposures that induce physiological adaptations to improve heat tolerance and performance. However, female-specific physiological factors, including endogenous and exogenous hormonal fluctuations, are rarely considered in HA research. This study examined whether menstrual cycle phase and hormonal contraceptive use influence the magnitude of heat adaptation and evaluated the effectiveness of HA protocols in females. PubMed and SPORTDiscus were searched in March 2025 and April 2026. Pre- and post-HA mean $\pm$ SD values for relevant outcomes were extracted to calculate Hedges' g effect sizes with 95% confidence intervals. Random-effects models were used to estimate pooled effects. Studies were categorized by menstrual cycle phase (follicular and luteal), hormonal status (naturally menstruating and hormonal contraceptive users), reporting type (pooled or separate phases), and HA protocol type (isothermal or fixed work rate). Seven studies were included. Most assessed HA within a single menstrual phase; therefore, findings primarily represent between-subject responses rather than direct comparisons of hormonal effects. No consistent differences were observed between menstrual cycle phases or hormonal contraceptive users. HA protocol type influenced only the exercising heart rate, with fixed-work-rate protocols producing greater reductions than isothermal protocols. Current evidence does not demonstrate a clear influence of menstrual cycle phase or hormonal contraceptive use on physiological adaptations to HA. Adaptations appear to be more strongly influenced by HA protocol characteristics. However, conclusions remain limited by small sample sizes, inconsistent menstrual cycle verification, and the predominance of between-subject study designs, highlighting the need for well-controlled longitudinal research in females.

SUMMARY

- Physiological responses to HA appear to be consistent across protocols as well as menstrual cycle and hormonal contraceptive phases.
- Heat acclimation protocol may influence physiological adaptations more than hormonal status.
- Evidence for menstrual cycle-related effects on HA remains inconclusive, mainly due to methodological limitations, including inaccurate menstrual cycle phase classification, a lack of hormonal verification, and limited use of within-subject designs, which highlight the need for more rigorously controlled studies.

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KEYWORDS

Heat acclimation; menstrual cycle; hormonal contraceptive; females; core temperature; Skin temperature; Heart rate; Plasma volume

Introduction

Exercise in high heat ($>30^{\circ}\text{C}$) imposes a significant thermal challenge on the body, which can impair cardiovascular, neural, and muscular functions relative to thermoneutral environments [1]; [2]; [3]. This is true not just for athletes but also for individuals in physically demanding occupations (e.g. firefighters, miners, and military personnel), who often physically exert themselves in hot environments while using

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thermally restrictive protective clothing [4]. While these fields have historically been male-dominated, increasing female participation means that heat-stress considerations are relevant across sexes.

Heat acclimation (HA) protocols involve repeated exposure to heat and induce a range of physiological adaptations that reduce thermal strain during exercise in the heat [5]. These include lower core (T_{core}) and skin (T_{skin}) temperatures, a reduced exercising heart rate (HR), an earlier onset of sweating, increased volume of sweating, and an expansion of plasma volume (PV) [6]; [7]; [8]; [9]. However, the magnitude and effectiveness of HA depend on factors, such as duration of HA protocol (i.e. number of exposure days), as well as the intensity and duration of exercise performed during the sessions [5]. In general, HA protocols can range from short-term (≤ 7 exposures), medium-term (7–14 exposures) and long-term (≥ 15 exposures). Multiple HA protocols exist, which are generally grouped into passive (e.g. hot water immersion, sauna) or active HA (e.g. self-regulated, fixed work rate, isothermal protocols, clamped heart rate) that can elicit thermophysiological adaptations, although the magnitude of adaptation may differ. Earlier studies implement fixed work rate protocols over a set duration of time for all individuals across multiple sessions with heat stress [10]; [11]; [12]. However, this model presents potential limitations. Specifically, as heat adaptation develops, the relative thermal physiological strain per session decreases; which progressively declines the thermal load per trial and thus the heat adaptation stimulus and may attenuate the magnitude of physiological and performance adaptations [13]. However, more recently, studies have focused on using an “isothermal” approach which focuses on elevating and maintaining a T_{core} of $\sim 38.5^{\circ}\text{C}$ to ensure a similar thermal strain amongst participants within a given time [14].

A notable limitation of exercise and thermal physiology research is the underrepresentation of females and the frequent lack of control for ovarian hormonal status [15]; [16]; [17]; [18]. Only $\leq 23\%$ of investigations exclusively focused on female participants [17]. This limits our understanding of physiological adaptations to heat in females [19]; [20]. Furthermore, hormonal variations throughout the menstrual cycle, menstrual disturbances, and the use of hormonal contraceptives are generally not accounted for in the study designs where participants are typically treated as a homogeneous group rather than being stratified by ovarian hormone or contraceptive status. Endogenous ovarian hormones, including estradiol and progesterone, fluctuate across the menstrual cycle and regulate body temperature [21]. Elevated progesterone levels during the luteal phase have been shown to increase the resting T_{core} set point by approximately $+0.3$ – 0.7°C compared with the follicular phase [22]; [23]; [24]. Progesterone is associated with elevated resting T_{core} , an increased T_{core} threshold for the onset of sweating during exercise in the heat ($\sim +0.22^{\circ}\text{C}$), and reduced skin blood flow, with cutaneous vasodilation happening at higher T_{core} ($\sim +0.27^{\circ}\text{C}$) [25]; [26]. In contrast, the rise in estradiol during the follicular phase promotes greater skin blood flow and initiates sweating at a lower T_{core} , enabling earlier and more effective thermoregulatory responses during heat exposure [27]; [28].

Similar to endogenous ovarian hormones, exogenous estrogen and progestins generally administered through hormonal contraceptives, also influence thermoregulatory control, including resting T_{core} and threshold for cutaneous vasodilation [28]; [29]; [30]; [31]. Exogenous estrogen has been shown to lower T_{core} and promote cutaneous vasodilation [32], while progestins increase the thermoregulatory set-point and promote peripheral vasoconstriction, contributing to elevated T_{core} responses during the active pill phase [28]; [29]; [30]; [31,33]. Notably, exogenous hormone concentrations from oral contraceptives can exceed those produced naturally [22]; [23]; [24], and their effect on thermoregulatory mechanisms may differ from that of endogenous hormonal fluctuations [34]. For instance, oral contraceptive users typically exhibit higher T_{core} at rest and during exercise in the heat compared with naturally menstruating females [30]; [31]. Although T_{core} may decrease during the hormone-withdrawal phase (inactive pill), compared with the active pill phase, evidence suggests that T_{core} can remain elevated relative to females not using hormonal contraceptives, indicating a prolonged effect of exogenous hormones on thermoregulation [35]. Collectively, these mechanisms highlight the importance of considering both endogenous and exogenous hormonal status when interpreting thermoregulatory and performance responses in females.

Understanding how both endogenous hormonal variations across the menstrual cycle and exogenous hormonal modulation through hormonal contraceptive use influence heat adaptations is necessary, as these variations can alter thermal, and consequently, HA responses [3]; [36]. Heat acclimation adaptations are thought to be influenced by both the attainment of a critical T_{core} threshold (38.5°C) and the cumulative heat stress experienced during exercise sessions, often conceptualized as total heat load or area under the

curve [37]; [38]. In this context, utilizing an isothermal HA protocol, individuals with an elevated baseline T_{core} may reach the target threshold more rapidly for a given absolute workload. For example, during the luteal phase of the menstrual cycle or in users of combined oral contraceptives, where resting T_{core} is slightly elevated, less metabolic heat production may be needed to reach a core temperature of 38.5°C [14]. Consequently, this may lower the overall heat load per session (reducing thermal stimulus for adaptation), lower the exercise load per session (decreasing training load and potential detraining), or allow for longer time to be at isothermal target core temperature thereby modifying the stimulus for physiological adaptation [14].

Despite extensive literature on HA, the majority of studies have been conducted in male participants, with limited consideration for female's menstrual cycle phase or status and hormonal contraceptive use. It remains unclear whether ovarian hormone fluctuations or exogenous hormonal modulation meaningfully influence physiological adaptation to repeated heat exposure. This uncertainty is compounded by inconsistent methodological approaches including variability in menstrual cycle classification, limited hormonal verification, and a predominance of between subject designs. Therefore, the present systematic review and meta-analysis aimed to synthesize the available evidence to determine: (1) whether menstrual cycle phase influences the magnitude of heat acclimation adaptations, (2) whether hormonal contraceptive use modifies these adaptations compared with naturally menstruating females, and (3) whether the type of heat acclimation protocol moderates physiological responses in females.

Methods

Databases and key terms

PubMed and SPORTDiscus were used to search for available literature. The key terms for the current study were adapted from a previous relevant study [39] and further refined for the current investigation. The full list of keywords can be found in the Electronic Supplementary Material (Appendix 1). The searches included a combination of keywords and controlled vocabulary terms, which were carefully formulated and truncated as needed to ensure comprehensive results. Additionally, the references of all relevant articles were checked to identify further articles. Searches were conducted in March 2025. A follow-up systematic electronic search was conducted in April 2026 to identify additional articles published later in the year. This review was not registered, and the review protocol was not published. The review protocol is provided in Supplementary Material (Appendix 2).

Inclusion and exclusion criteria

This review follows the PICO approach (Population, Intervention, Comparison, and Outcome), and the most up-to-date version of Preferred Reporting Items for Systematic Review and Meta-analysis statement (PRISMA 2020) to determine the parameters of the review (Figure 1). The search was limited to humans, full text, peer-reviewed (published conference abstracts were not included), English language, and adults over 18 years of age. The inclusion criteria involved studies with female participants aged 18–50 years, who were either naturally menstruating females or hormonal contraceptive users. Studies were included only if the menstrual cycle phase or contraceptive pill phase during testing was clearly defined. Studies were also required to include an exercise HA protocol and to report pre- and post-HA physiological parameters. Studies using either self-reported or hormonally verified menstrual cycle classification were included due to limited availability of objectively verified data in the literature.

Additionally, studies that originally tested follicular and luteal phases separately, but reported pooled results were considered eligible. This approach allowed us to include studies with clearly defined menstrual phases and to assess whether reporting type (i.e. combining follicular and luteal phase data (pooled phase) versus reporting the phases separately) influenced the observed responses as a study-level moderator. Studies without a comparator phase (e.g. only follicular phase or only luteal phase) were also included to support a more exploratory analysis. Although this broader inclusion strategy strengthened the scope of the review, it introduces methodological limitations that should be considered when interpreting the findings. For example, reliance on self-reported menstrual cycle information may not accurately reflect hormonal status, potentially leading to misclassification and confounding the results.

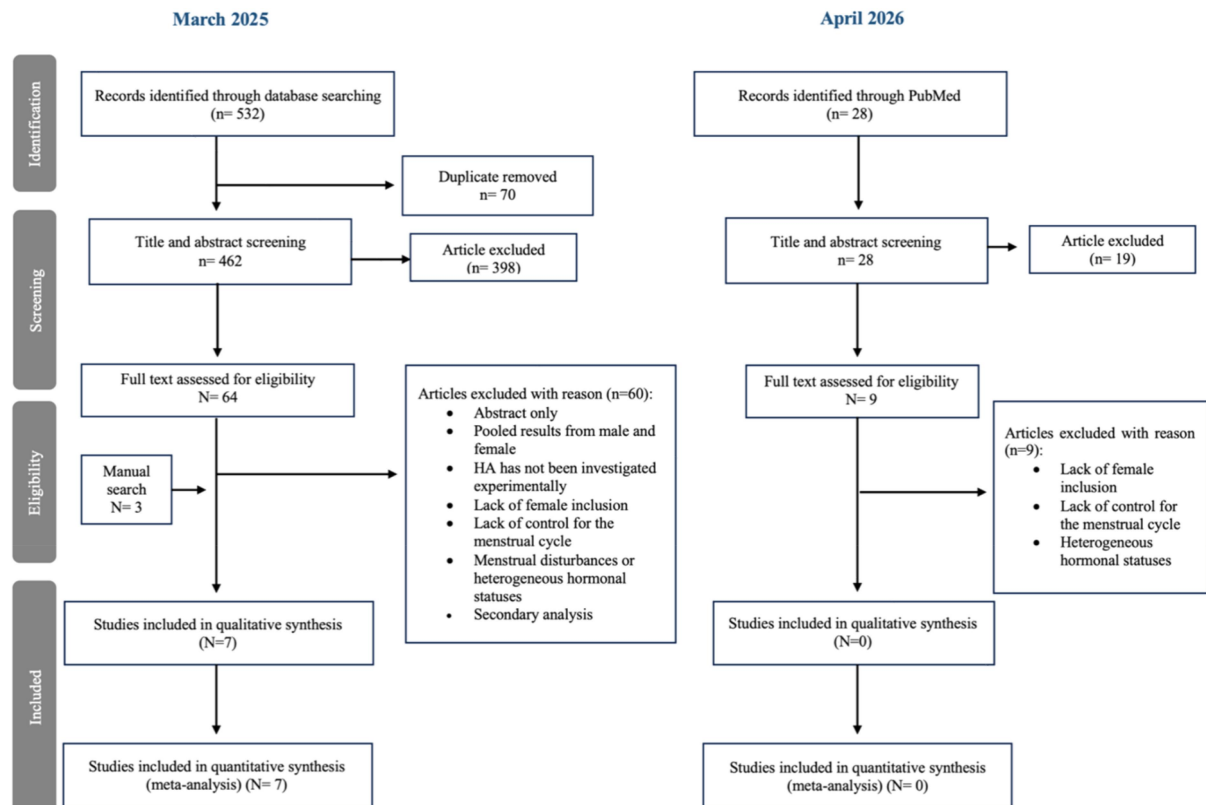


Figure 1. PRISMA flow diagram of studies' screening and selection.

Exclusion Criteria: Acute heat exposure, clinical populations, male-only cohort, passive HA, and menstrual cycle irregularities. Studies were excluded if they included participants with mixed hormonal statuses (i.e. combined menstrual cycle phases, menstrual irregularities, or different hormonal contraceptive statuses/ methods) and reported outcomes as a single combined group, as this prevented analysis of responses specific to a particular menstrual cycle phase or hormonal condition.

For studies that met the inclusion criteria but reported pooled results for males and females, the corresponding authors were contacted to provide separate female data. A follow-up e-mail was sent if no response was received within two weeks of the initial contact. No data were received within five weeks of the initial contact or before the follow-up searches were conducted ($N=7$). Only one study provided the separate data from females outside of this timeframe, however, because the female cohort consisted of only a single participant, we decided to exclude this study to avoid the statistical bias of a single-case analysis. Similarly, for studies that reported combined data for naturally menstruating females and oral contraceptive users ($N=6$), the corresponding authors were contacted to request separate data for naturally menstruating females and hormonal contraceptive users. Following this process, two studies provided subgroup-specific data and were therefore included in the analysis [40]; [41].

Study selection

A two-phase screening strategy was used independently by three authors (SK, SC, and DG) to select relevant articles. Any uncertainty or doubt about the selection process was resolved through discussion. After removing duplicates, titles and abstracts were screened, and ineligible articles were removed based on established inclusion and exclusion criteria. Studies with unclear eligibility were maintained for further assessment in the next phase. The articles remaining from phase underwent a full-text review using the exclusion criteria to determine which ones to include in the final selection.

Data extraction

Data extraction was conducted systematically using a pre-designed template to ensure accuracy and consistency. One independent reviewer (SK) manually extracted data from each included study, with uncertainties resolved through consultation with the research team as needed. Extracted data included publication year, sample size, participant age, training status, intervention characteristics (intensity, duration, frequency of the HA protocol and heat stress test), menstrual cycle phase, menstrual status, and the type of hormonal contraceptive. Quantitative data (e.g. means and SD) for outcome measures (T_{core} , T_{skin} , HR, and PV %) were extracted for statistical analysis. When data were reported at multiple time points (i.e. short-term heat acclimation and medium-term HA), only the data representing the full duration of the protocol (e.g. medium-term HA) were included in the analysis. Further, when only graphical data were available, values were extracted using Web-Plot Digitizer ($n = 2$). Where standard errors (SE) were provided, they were transformed into SD values ($n = 1$). In cases where the SD was not reported, it was estimated from the reported 95% confidence interval using an established statistical equation [42]. A summary of the extracted data is presented in Table 1, detailing key study characteristics and findings.

Grouping strategy

To structure the synthesis, studies were grouped according to menstrual cycle phase (follicular and luteal), menstrual status (naturally menstruating and hormonal contraceptive users), reporting type: pooled phase data (follicular and luteal phase data pooled into a single outcome) versus separate phase-specific data (follicular and luteal phases reported separately), and the type of HA protocol used (isothermal and fixed work rate). A meta-analysis was conducted within these groupings to quantitatively synthesize the available data.

In the subgroup of menstrual cycle phase (follicular and luteal), females using hormonal contraceptives were grouped based on their pill phase. If testing was done during the inactive pill phase, they were placed in the follicular group, and if it was during the active pill phase, they were placed in the luteal group, in line with the recommendations of Elliott-Sale et al [46].

Risk of bias assessment

One reviewer (SK) independently performed the quality assessment of all included articles, which was then independently verified by a second and third reviewers (SC and DG). Any uncertainty was resolved through group discussion and agreement. A modified Downs and Black checklist [47] (Supplementary Material, Appendix 3), adjusted for this review as in earlier studies [48]; [49], was employed to assess the methodological quality of included studies, evaluating reporting (6 items), external validity (2 items), internal validity-bias (6 items), internal validity- confounding – selection bias (2 items), and power (2 items), with a maximum total score of 18. Total scores were used to classify studies as high (≥ 16), moderate (11–15), low (6–10), or very low (≤ 5) quality.

Statistical analyses

The mean $\pm$ SD values before and after the HA from each study were extracted to compute standardized mean differences. Then, Hedges' g effect sizes (ES), standard error, and 95% confidence intervals (CIs) were calculated [50]. A correlation coefficient of 0.7 was used between the pre- and post-values, as this value was previously employed [39] and considered a reasonable approximation of the correlation [50]. A random-effects model meta-analysis using IBM-SPSS Statistics (version 30) to determine the pooled ES with a 95% CIs for T_{core} , HR, T_{skin} , PV%, resting T_{core} , as well as resting HR. Effect size interpretation was based on commonly accepted thresholds, where $ES \leq 0.19$ is considered a trivial/negligible effect, $ES = 0.20$ – 0.49 is classified as a small effect, $ES = 0.50$ – 0.79 is categorized as a moderate effect, and $ES \geq 0.80$ is deemed a large effect [51]. Statistical significance was set to an alpha level of $p < 0.05$. Heterogeneity across studies was assessed using the I^2 statistic test. Therefore, I^2 is considered low when $I^2 < 25\%$, moderate when $I^2 = 25$ – 50% , and high when $I^2 > 50\%$ [50]; [52].

Table 1. Summary of studies included in the systematic review and meta-analysis.

Studies	Sample size	MC phase	intervention	Duration	frequency	Exercise modality	Heat stress test	ΔT_{core} °C	ΔT_{core} °C	ΔT_{skin} °C	ΔHR (bpm)	$\Delta PV\%$	Δ resting HR (b·min ⁻¹)	Note
Mee et al. [41]	EU: 5 HC: 4	Early FP (between 3 rd and 10 th) HC (No pill phase)	Temp: Controlled hyperthermia at 40 °C, 40% RH- T_{core} ~ 38.5 °C Sauna: 20 min sauna intervention, prior to HA	90 minutes daily exposure	5 session HA	Exercise at 65% VO_2 max	30-min running at 9 km/h, 2% gradient in 40 °C and 40% RH	EU-Temp: -0.06 HC-Temp: ± 0.03	EU-Temp: -0.09 HC-Temp: ± 0.06	EU-Temp: -0.28 HC-Temp: ± 0.02	EU-Temp: -3 ± 1 HC-Temp: -1 ± 2	EU-Temp: 2.74 ± 3.18 HC-Temp: -0.53	EU-Temp: -4 ± 5 HC-Temp: -3 ± 4	Included 2 groups: HA sauna and HA temp, with a randomized, cross-over design. Separated by 7 weeks. HC: no pill/placebo phase Sauna: Hormonal status was confirmed using a venous blood sample
								EU-Temp: -0.05 HC-Temp: ± 0.08	EU-Temp: -0.04 HC-Temp: ± 0.16	EU-Temp: 0.41 ± 0.16	EU-Temp: -13 ± 5 HC-Temp: -11 ± 0	EU-Temp: 9.32 ± 8.47 HC-Temp: 9.33 ± 7.56	EU-Temp: -8 ± 0 HC-Temp: -8 ± 1	
								EU-Temp: -0.52 HC-Temp: ± 0.26	EU-Temp: -0.34 HC-Temp: ± 0.03	EU-Temp: -0.52 HC-Temp: ± 0.26	EU-Temp: -13 ± 5 HC-Temp: -11 ± 0	EU-Temp: 9.32 ± 8.47 HC-Temp: 9.33 ± 7.56	EU-Temp: -8 ± 0 HC-Temp: -8 ± 1	
								EU-Temp: -0.51 HC-Temp: ± 0.01	EU-Temp: -0.29 HC-Temp: ± 0.07	EU-Temp: -0.98 HC-Temp: ± 0.29	EU-Temp: -11 ± 1 HC-Temp: -9 ± 3	EU-Temp: -16 ± 5 HC-Temp: -14 ± 4	EU-Temp: -16 ± 5 HC-Temp: -14 ± 4	
Mee et al. [40]	N: 5 HC: 3	Early FP (day 3-5) Day 2 of pill phase	Controlled hyperthermia at 40°C, 40% RH- T_{core} ~ 38.5°C	90 minutes/ daily exposure	10 sessions (two-5day, separated by 48 hrs)	cycling at 65% of VO_2 max	30-min running at 9 km/h, 2% gradient in ~40°C, ~40% RH.	N: -0.51 HC: -0.41	N: -0.29 HC: -0.16	N: -0.98 HC: -1.23	N: -11 ± 1 HC: -9 ± 3	N: -16 ± 5 HC: -14 ± 4	N: -16 ± 5 HC: -14 ± 4	Self-reported MC. HA for FP started 3-5 days after the onset of menstruation, and for HC started on day 2 of the pill phase
								N: -0.01 HC: -0.03	N: -0.07 HC: -0.23	N: -0.29 HC: -1.23	N: -11 ± 1 HC: -9 ± 3	N: -16 ± 5 HC: -14 ± 4	N: -16 ± 5 HC: -14 ± 4	

(Continued)

Table 1. (Continued).

Studies	Sample size	MC phase	intervention	Duration	frequency	Exercise modality	Heat stress test	ΔT_{core} °C	ΔT_{core} °C	ΔT_{skin} °C	ΔHR (bpm)	$\Delta PV\%$	Δ resting HR (b·min ⁻¹)	Note
Armstrong et al. [43]	EU:14 HC:15	EU:FP (days 2–5) HC: days 2–5 of the inactive pill phase	Fixed work rate HA at ~37.0°C and 37% RH	90 minutes/ session, 3 days a week	7–8 week- 6 days/ week. 3 outdoor session and 3 indoor HA session	Bench stepping, stair climbing, cycle ergometry, and walking on a treadmill at ~50–70% VO ₂ max for each mode	walk on a treadmill at 93.6 m/min and 5% grade at 36.5 1.4°C, 37 1%rh, 2.3 m/s air flow	EU: -0.4 ± 0.1 HC: -0.3 ± 0.1	EU: -1.1 ± 0.4 HC: -0.8 ± 0.1	EU: -24 ± 3 HC: -23 ± 3	EU: -0.8 ± 2.1 HC: -1.4 ± 0.9	-	-	Termination criteria: T _{core} ≥ 39.5°C or HR ≥ 180 bpm for 5 min. Participants could rest if fatigued. The protocol did not require T _{core} -driven intensity modulation. HA started during the first week of the follicular phases for EU, and day 1 of the 28-day pill pack for HC. Heat stress test completed on days 2–5 of the menstrual cycle for EU and on days 2–5 of the placebo phase of the pill pack. Hormonal status was confirmed using a venous blood sample

(Continued)

Table 1. (Continued).

Studies	Sample size	MC phase	intervention	Duration	frequency	Exercise modality	Heat stress test	ΔT_{core} °C	ΔT_{core} °C	ΔT_{skin} °C	ΔHR (bpm)	$\Delta PV\%$	Δ resting HR (b·min ⁻¹)	Note
Frye and Kamon [11]	4	FP and LP	Fixed work rate HA at 48/25°C T_{db}/T_{wb} .	daily 2-h bouts of excise	Full HA was achieved within 8–9 days, as indicated by stabilization of rectal temperature and HR during the second hour of exposure on 2 consecutive days	cycle ergometer at 30% of VO_2 max	Walking on a treadmill at ~30% of VO_2 max, for 3 hours. The ambient temperature at the beginning of the test was cool and then was increased gradually by ~1.5°C until it reaches to 48/25°C (T_{db}/T_{wb}).	-0.89 ± 0.12	-	-1.22 ± 0.31	-21.01 ± 0.92	-	-	No washout period between FP and LP. They reported combined results from FP and LP. Self-reported menstrual cycle The exact timing of heat acclimation initiation within the FP and LP was not reported. Ovulation indicated by raise in body temperature

(Continued)

Table 1. (Continued).

Studies	Sample size	MC phase	intervention	Duration	frequency	Exercise modality	Heat stress test	ΔT_{core} °C	ΔT_{core} °C	ΔT_{skin} °C	ΔHR (bpm)	$\Delta PV\%$	Δ resting HR (b·min ⁻¹)	Note
Fortney et al. [10]	9	FP and LP	Fixed work rate HA at 45°C, 30% RH	daily 90-min exposure	2 weeks, then on alternate days for 2 more weeks	Cycle ergometer at 40% VO ₂ max	Maximum oxygen consumption test. Started with 3 min no load, then intensity increased at end of each min by 50-W until volitional exhaustion	-	-0.6 ± 0	-0.9 ± 0.1	-22 ± 3	7.5 ± 2.5	-	Protocol: ~ 3 months of intervention: - baseline testing (in FP and LP) - Training phase- 90 min upright cycling at HR of 140 bpm (daily for 2 weeks, then on alternate days for 2 more week). Phase 3 was HA protocol. No washout period between FP and LP. They reported combined results from FP and LP. Self-reported menstrual cycle The exact timing of heat acclimation initiation within the FP and LP was not reported. The method used to detect ovulation was not reported. No washout period between FP and LP. Heat stress test completed within five days of either menstruation onset for FP or the body temperature rise for LP. Self-reported menstrual cycle
Avellini et al. [44]	4	FP and LP	Fixed work at 36/ 32°C T _{db} / T _{wb} .	Daily 2-h/ session at	10-day HA	Walking at 5.6 km. h up a 2% grade	Walk on a treadmill for 3 h, at 5.6 km. h up a 2% grade	-	FP: -0.19 ± 0.2 LP: -0.36 ± 0.22	FP: -0.4 ± 0.2 LP: -0.4 ± 0.04	-	-	-	Self-reported menstrual cycle

(Continued)

Table 1. (Continued).

Studies	Sample size	MC phase	intervention	Duration	frequency	Exercise modality	Heat stress test	ΔT_{core} °C	Δ Resting T_{core} °C	ΔT_{skin} °C	Δ HR (bpm)	Δ PV%	Δ resting HR (b·min ⁻¹)	Note
Garret et al. [45]	10	HC. Active phase	Controlled hyperthermia at 39.5°C, 60% RH- T_{core} ~ 38.5°C	daily 90-min	5-day HA	Cycling at self-selected resistance at 60 rpm	9 × 5 min blocks of intermittent exercise. Each block consisted of different intensity (% HRmax)	-0.2 ± 0.14	-	-0.5 ± 0.56	-8 ± 14	7 ± 4	-	Phase confirmed by baseline measurement of plasma 17β-estradiol

Tdb: Dry-Bulb Temperature; Twb: Wet-Bulb Temperature; RH: Relative humidity; FP: Follicular phase; LP: Luteal phase; EU: Eumenorrheic; HC: hormonal contraceptive; N: Naturally menstruating.

A sensitivity analysis was performed to assess the influence of the study on the overall ES. Publication bias was assessed by visually inspecting funnel plots and assessing Egger's regression intercept test. A subgroup analysis was conducted to explore whether the effects of HA differed according to the menstrual cycle phase (follicular vs. luteal), menstrual status (naturally menstruating and hormonal contraceptive users), as well as the type of HA protocols (isothermal vs. fixed work rate) on physiological outcomes. A meta-regression was performed to determine whether the moderators (menstrual cycle phase, menstrual status, and type of HA protocol) explained the between-group variability. Additionally, reporting type (pooled vs. separate menstrual phases) was examined as a moderator. This distinguishes between studies that reported follicular and luteal phase outcomes separately and those that pooled the two phases into a single mean value. The analysis examined whether this methodological choice influenced reported thermoregulatory responses.

Results

Search results

A total of 560 articles were identified through an online search. After removing duplicates ($n = 70$), 490 articles remained for title and abstract screening. Of these, 417 were excluded based on relevance. The remaining 73 articles underwent a full-text assessment, resulting in the exclusion of 69 articles for reasons such as lack of full-text availability ($n = 5$), combined results from male and female participants ($n = 9$), absence of experimental HA investigation ($n = 1$), male-only cohorts ($n = 2$), lack of menstrual cycle control ($n = 46$), secondary analysis ($n = 1$) and combined females with different hormonal and menstrual cycle status ($n = 5$; i.e. eumenorrheic, oligomenorrheic, amenorrheic, and various type of hormonal contraceptive users). Ultimately, 7 articles met the inclusion criteria, including those identified through manual search ($n = 3$), all of which were included in both the qualitative and quantitative analyses (Figure 1).

Characteristics of participants

Across seven studies, a total of 73 females participated in HA protocols, with an average age of 22 ± 2 years. The average VO_2max was 46.3 ± 5.6 ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), and the body height and mass were 165.0 ± 7.0 cm and 61.7 ± 8.6 kg, respectively. Overall, participants were naturally menstruating ($n = 22$) [10]; [11]; [40,44], eumenorrheic ($n = 19$) [41]; [43] and combined oral contraceptive users ($n = 32$) [40]; [41,43]; [45]. Across studies, testing occurred in the follicular phase ($n = 41$), luteal phase ($n = 17$), active pill phase ($n = 28$), and placebo phase ($n = 4$). One study directly compared follicular and luteal phases ($n = 4$).

Characteristics of studies

All included studies aimed to standardize or control for menstrual cycle phase; however, not all verified phases objectively through hormonal assessment [10]; [11]; [40,44]. Cycle phase determination was primarily based on self-reported information. Only three studies used blood hormone analyses to verify menstrual cycle phase [41]; [43]; [45]. Ovulation was not rigorously assessed in all studies: only one [43] used venous blood analysis to confirm ovulation, two [11,44] inferred ovulation from an increase in basal body temperature, and one [10] failed to report any verification method. The remaining studies did not report whether ovulation was assessed.

All studies assessed thermoregulatory responses following HA, conducted in a controlled environmental chamber. Commonly measured outcomes across studies included exercising T_{core} , HR, T_{skin} , and PV%, as well as resting T_{core} and resting HR. The publication years of the studies ranged from 1980 to 2019. Due to the nature of HA, none of the studies were blinded.

Studies included physically active and trained female participants [11]; [41,44]; [45] and inactive or untrained females [10]; [40,43]. Additionally, in several included studies, heat stress tests (pre- and post-intervention) were performed under different hormonal environments (e.g. pre-testing in the early follicular phase and post-testing near ovulation or in the early luteal phase). Only one study controlled for this confounding factor by conducting both pre- and post-heat stress tests on the same menstrual cycle day [45].

Grouping characteristics and meta-analytic framework

Group comparisons were conducted to examine if menstrual cycle phase, hormonal status, reporting type, or HA protocols significantly modified the physiological response to HA. Sensitivity analyses were conducted to evaluate whether the grouping of hormonal contraceptive users (as per the inactive/active pill phase classification described in Grouping strategy) influenced the results. The results indicated no difference, suggesting that this classification approach did not substantially affect the findings.

A total of 13 groups from seven studies were included in the meta-analysis. Each group met the inclusion criteria and was treated as an independent data point. One study [41] implemented two pre-exposure conditions: one group sat in a sauna for 20 minutes prior to HA, while the other sat in a temperate room. Each of these groups was further divided into eumenorrheic (EU) (EU.sauna and EU.temp) and hormonal contraceptive users (HC.sauna and HC.temp), resulting in four separate groups. Another study [40] included two independent groups: HC users and naturally menstruating females (N), which were further divided into subgroups, resulting in a total of two groups. In that study, HC users were tested during the active pill phase, while naturally menstruating females were tested during the follicular phase. In another study [44], naturally menstruating females were tested in both the follicular and luteal phases, resulting in a total of two groups. Similarly, one study [43] included both EU females and HC users; the former were tested during the follicular phase, and the latter during the active pill phase. The remaining studies each included a single group tested either during the active pill phase [45] or during what we refer to as the “pooled phase.” In these pooled phase studies, participants were tested separately during the follicular and luteal phases, but the results were reported as a single combined outcome rather than separately by phase [10]; [11]. Except for one study [44], the included studies did not assess both the follicular and luteal phases within the same participants. Therefore, comparisons between menstrual cycle phases and hormonal status were based on independent sample across studies rather than within-subject designs.

Characteristics of heat acclimation protocols

The HA protocols across studies differed in duration and session distribution/frequency. Most studies implemented 5–10-day consecutive HA protocols, whereas two studies employed longer interventions lasting up to two months. Of these, one used a nonconsecutive design combining HA sessions with outdoor training, and the other incorporated two weeks of consecutive-day HA followed by two weeks of alternate-day sessions. Exercise intensity during the HA sessions spanned from 25% to 70% of VO_2max or self-selected resistance, and session duration ranged from 90 to 120 minutes with a median of 90 minutes (interquartile range (IQR) = 90 - 90). Environmental conditions also varied across studies, with ambient temperatures ranging from 36°C to 45°C (median = 40; IQR = 39.5 - 40) and relative humidity ranging from 30% to 60% (median = 40; IQR = 37 - 40). Additionally, two studies reported conditions using dry-bulb/wet-bulb temperatures of 36/32°C and 48/25°C, respectively. Finally, the exercise modalities varied across studies and included running, walking, cycling, and circuit-based aerobic training. Further, the included studies used different methodological approaches, with one employed a preliminary exercise period prior to the HA intervention, and another integrated physical training simultaneously with HA (three days of outdoor training and three days of indoor HA per week), while the remaining studies focused exclusively on the HA protocol without any additional exercise training.

Characteristics of heat stress test

The heat-stress tests used to assess adaptation varied considerably across studies. Some employed standardized treadmill protocols, such as a 30-minute run at $9 \text{ km}\cdot\text{h}^{-1}$ with a 2% gradient in hot conditions, a 90-minute walk on a motorized treadmill at $93.6 \text{ m}\cdot\text{min}^{-1}$ with a 5% gradient, or an incremental VO_2max test increasing by $50 \text{ W}\cdot\text{min}^{-1}$. Other studies employed longer exposures, lasting up to 3 hours of walking in the heat at $6 \text{ km}\cdot\text{h}^{-1}$ with a 2% gradient, or continued the exercise until volitional exhaustion. In some protocols, fluid intake was restricted ($n = 3$). One study began the heat-stress test in a thermoneutral environment and gradually increased the ambient temperature by 1.5°C until reaching 48/25°C (dry-bulb/wet-bulb). Participants walked on a treadmill at 25–30% VO_2max , and the test was terminated when T_{core} or heart

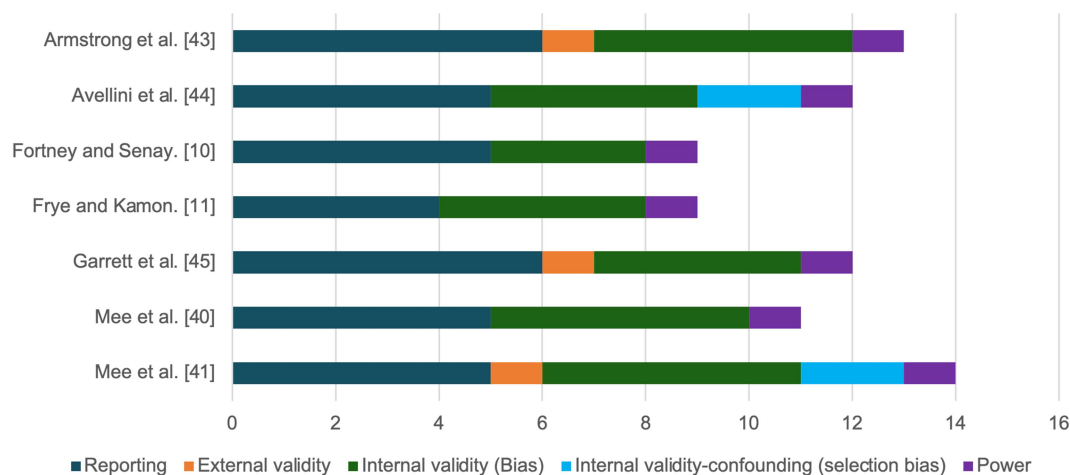


Figure 2. Shows the risk of bias assessment.

rate exceeded 39°C or $160 \text{ b}\cdot\text{min}^{-1}$, respectively. Intermittent exercise protocols were also used, with exercise intensities ranging from 50% to 95% of maximal HR. Environmental conditions also differed across studies. Two studies reported dry-bulb/wet-bulb temperatures of $36/30^{\circ}\text{C}$ and $48/25^{\circ}\text{C}$, respectively. The remaining studies reported ambient temperatures ranging from 31 to 37°C (median = 38.5 ; IQR = $34 - 40$), with relative humidity between 38 and 50% (median = 40 ; IQR = $39 - 45$).

Risk of bias

The methodological quality of the included studies, assessed using a modified Downs and Black checklist [47], ranged from 9 to 14 out of 18. Reporting quality was generally high (scores 4–6, out of 6), whereas external validity was low in most studies (0–1 out of 2 points). A key contributor to the low external validity was that, although most studies identified participants' menstrual cycle or hormonal contraceptive phases (e. g. follicular or luteal, and pill or placebo), few objectively verified hormonal status to confirm phase. Internal validity (bias) scores ranged from 3 to 5 (out of 6 points), adjustment for confounding was limited (0–2, out of 2), and study power was modest (1–2, out of 2). Detailed domain scores are presented in Figure 2.

Meta-analysis results

Across included studies, variability existed in menstrual cycle classification and hormonal verification procedures. Cycle phase assignment varied across studies and may have included self-reported or indirect measures of menstrual status. Overall, subgroup comparisons were conducted to examine whether menstrual status or HA protocol moderated physiological adaptations. Between-study comparisons predominated due to limited within-subject designs across the included literature.

Excluding studies with very large or very small effect sizes in the sensitivity analysis did not change the direction or significance of the results, except where otherwise reported. Egger's regression test showed no significant evidence of funnel plot asymmetry. A random-effects meta-regression (REML) was used to examine whether menstrual cycle phase, menstrual status, type of HA protocol, and reporting types predicted the ES of the outcomes in seven studies. Significant moderating effects are reported in the respective sections for each variable.

Core temperature

HA was associated with reduction in exercising T_{core} of $-0.37 \pm 0.11^{\circ}\text{C}$ and a large overall effect size (Hedges' $g = -0.95$; 95% CIs = -1.29 to -0.60 ; $p < 0.001$), with large heterogeneity ($I^2 = 50\%$; $p = 0.02$) (7 studies, $n = 73$). Although the magnitude of adaptation varied, all studies demonstrate some degree of

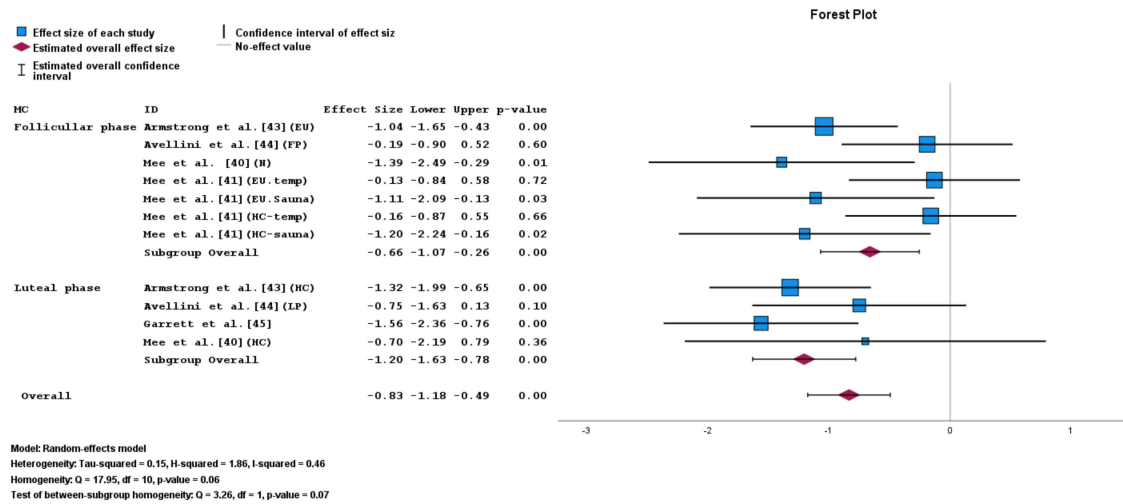


Figure 3. Core temperature forest plot in the follicular and luteal phase.

T_{core} reduction. In two studies, HA also reduced resting T_{core} by an average of $-0.08 \pm 0.08^{\circ}\text{C}$, accompanied by a large effect (Hedges' $g = -0.87$; 95% CIs = -1.55 to -0.20 ; $p = 0.01$) and high heterogeneity ($I^2 = 66\%$; $p = 0.03$).

The menstrual cycle did not appear to influence the magnitude of HA-induced reduction in exercise T_{core} , as no significant differences were observed between the follicular and luteal phases ($p \geq 0.05$) (Figure 3). Both phases exhibited large effect sizes, with a greater pooled reduction in the luteal phase ($-0.33 \pm 0.15^{\circ}\text{C}$) compared with the follicular phase ($-0.29 \pm 0.11^{\circ}\text{C}$). Resting T_{core} showed a similar pattern, with no significant between-phase difference, with luteal phase resulting in $-0.06 \pm 0.15^{\circ}\text{C}$ (Hedges' $g = -0.36$; 95% CIs = -1.07 to 0.35 ; $p = 0.32$) and the follicular phase demonstrated $-0.16 \pm 0.04^{\circ}\text{C}$ (Hedges' $g = -1.06$; 95% CIs = -1.91 to -0.21 ; $p = 0.01$).

Naturally menstruating females and those using oral contraceptives showed no significant differences in T_{core} responses (naturally menstruating: $-0.44 \pm 0.11^{\circ}\text{C}$; hormonal contraceptive users: $-0.25 \pm 0.09^{\circ}\text{C}$) (Figure 4). The change in resting T_{core} also did not differ significantly between groups; where hormonal contraceptive users demonstrated a $0.12 \pm 0.11^{\circ}\text{C}$ reduction (Hedges' $g = -0.49$; 95% CIs = -1.13 to 0.14 ; $p = 0.13$), whereas naturally menstruating females showed a $0.04 \pm 0.05^{\circ}\text{C}$ reduction (Hedges' $g = -1.34$; 95% CIs = -2.60 to -0.07 ; $p = 0.04$).

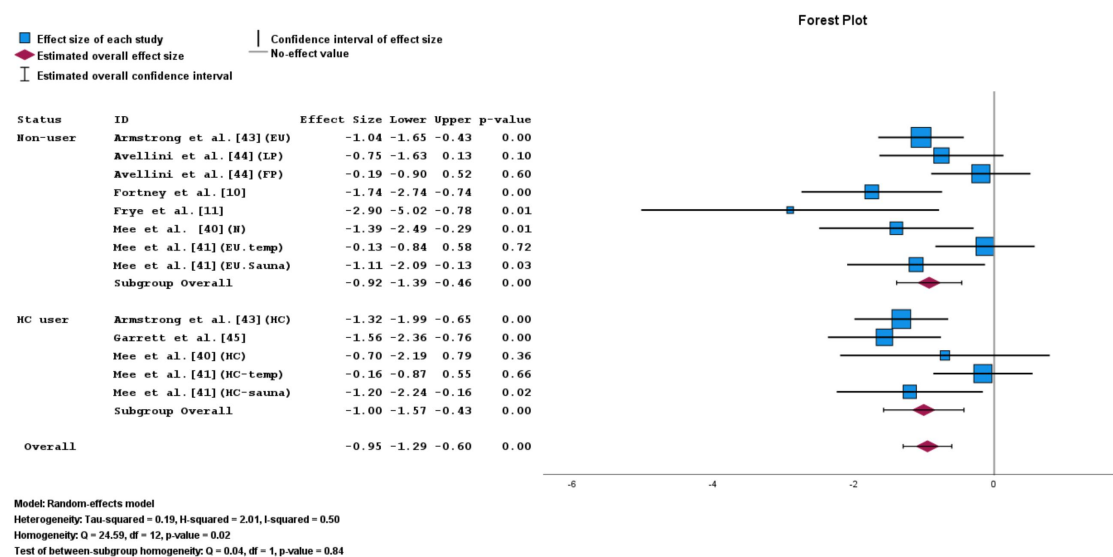


Figure 4. Core temperature forest plot in the hormonal contraceptive users (HC) and non-users.

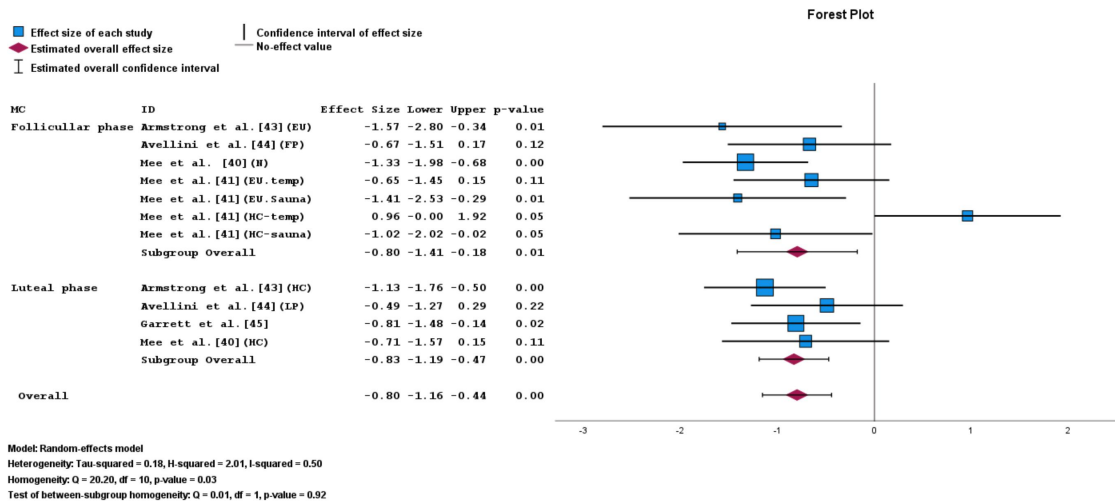


Figure 5. Skin temperature forest plot in the follicular and luteal phase.

The type of heat acclimation protocol did not significantly influence the magnitude of thermoregulatory adaptation. Both fixed work-rate and isothermal models proved effective, yielding robust T_{core} reductions of $-0.45 \pm 0.12^\circ\text{C}$ (Hedges' $g = -1.07$; 95% CIs = -1.50 to -0.56 ; $p < 0.001$) and $-0.29 \pm 0.09^\circ\text{C}$ (Hedges' $g = -0.84$; 95% CIs = -1.34 to -0.34 ; $p < 0.001$) respectively.

Reporting type significantly moderated these outcomes ($Q = 5.13$; $p = 0.02$), with studies pooling menstrual phase showing substantially larger reductions ($-0.74 \pm 0.06^\circ\text{C}$; Hedges' $g = -1.95$; 95% CIs = -2.86 to -1.05 ; $p < 0.001$) than studies reporting phases separately ($-0.30 \pm 0.11^\circ\text{C}$; Hedges' $g = -0.83$; 95% CIs = -1.18 to -0.49 ; $p < 0.001$). Meta-regression confirmed reporting type as a significant moderator ($B = -1.17$; 95% CIs = -2.46 to -0.10 ; $p = 0.04$), explaining 24% of the between-study heterogeneity, with moderate residual variation ($I^2 < 44\%$, $\tau^2 = 0.14$).

Skin temperature

HA elicited a meaningful reduction in T_{skin} of $-0.70 \pm 0.23^\circ\text{C}$, and a large overall effect size (Hedges' $g = -0.90$; 95% CIs = -1.24 to -0.55 ; $p < 0.001$), alongside moderate to large heterogeneity ($I^2 = 50\%$; $p < 0.02$) (7 studies, $n = 73$). While nearly all included studies reported some degree of reduction in T_{skin} , it is worth noting that a single group observed a slight increase [49, HC.temp group]. Despite this, the general trend indicates a robust adaptation toward lower skin temperatures.

Menstrual cycle phases did not appear to influence the magnitude of HA induced reductions in T_{skin} , as no significant differences were observed between the follicular ($-0.58 \pm 0.2^\circ\text{C}$) and luteal ($-0.73 \pm 0.32^\circ\text{C}$) phase, both showing a moderate to large effect (Figure 5).

Naturally menstruating females and hormonal contraceptive users did not differ significantly in T_{skin} responses (Figure 6), where naturally menstruating females resulted in $-0.80 \pm 0.23^\circ\text{C}$, while hormonal contraceptive users demonstrated a $-0.53 \pm 0.25^\circ\text{C}$ response.

Heat acclimation protocol did not appear to influence the magnitude of T_{skin} adaptation ($p > 0.05$) with fixed work-rate leading to a $-1.01 \pm 0.22^\circ\text{C}$ change (Hedges' $g = -1.06$; 95% CIs = -1.44 to -0.69 ; $p < 0.001$), whereas isothermal protocols led to a $-0.56 \pm 0.24^\circ\text{C}$ change (Hedges' $g = -0.72$; 95% CIs = -1.27 to -0.17 ; $p = 0.01$).

Reporting type did not appear to moderate these outcomes ($p \geq 0.05$) between pooled phase ($-1.06 \pm 0.2^\circ\text{C}$; Hedges' $g = -1.62$; 95% CIs = -2.40 to -0.85 ; $p < 0.001$) and separate phases ($-0.63 \pm 0.24^\circ\text{C}$; Hedges' $g = -0.80$; 95% CIs = -1.16 to -0.44 ; $p < 0.001$).

Heart rate

HA elicited a meaningful reduction in exercising HR, with an average decrease of $-13 \pm 4 \text{ b}\cdot\text{min}^{-1}$, and a large overall effect size (Hedges' $g = -1.05$; 95% CIs = -1.52 to -0.59 ; $p < 0.001$) and substantial heterogeneity

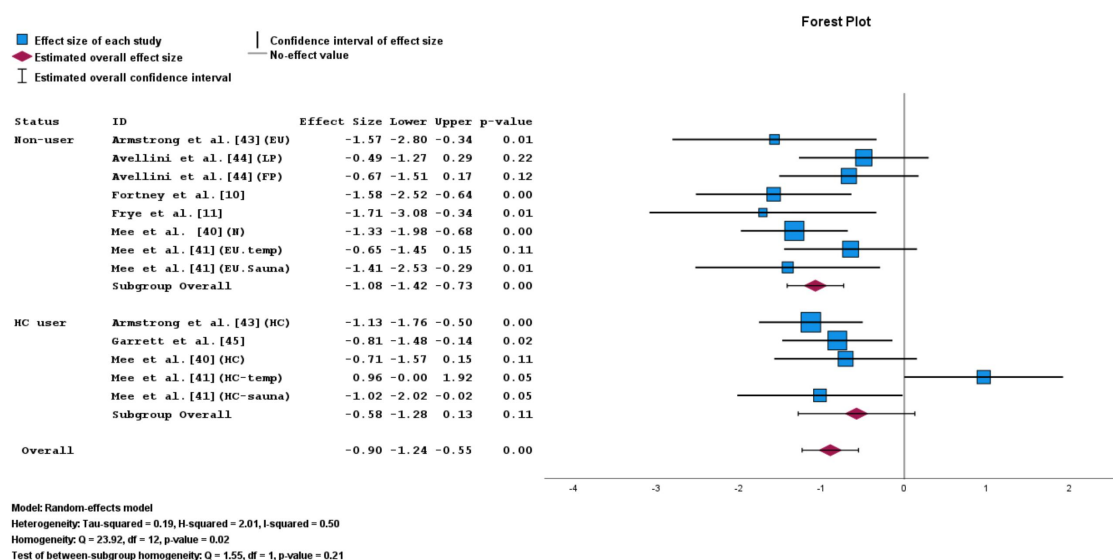


Figure 6. Skin temperature forest plot in the hormonal contraceptive users (HC) and non-users.

($I^2 = 69\%$; $p < 0.001$) (7 studies, $n = 73$). Evidence from two studies involving 17 females demonstrated that HA reduced resting HR by $9 \pm 3 \text{ b} \cdot \text{min}^{-1}$, with a large effect size (Hedges' $g = -0.90$; 95% CIs = -1.36 to -0.44 ; $p < 0.001$) and low heterogeneity ($I^2 = 25\%$; $p = 0.23$).

Menstrual cycle phases were not different between the magnitude of HA-induced reductions in exercising HR ($p > 0.05$), with a reduction of $-10 \pm 3 \text{ b} \cdot \text{min}^{-1}$ in the follicular versus $-14 \pm 6 \text{ b} \cdot \text{min}^{-1}$ in the luteal phase (Figure 7). A similar pattern was observed for resting HR: HA did not differ significantly between phases, where there was a reduction of $-14 \pm 4 \text{ b} \cdot \text{min}^{-1}$ in luteal (Hedges' $g = -1.10$; 95% CIs = -2.20 to -0.00 ; $p = 0.05$) and $-8 \pm 3 \text{ b} \cdot \text{min}^{-1}$ in the follicular phase (Hedges' $g = -0.90$; 95% CIs = -1.45 to -0.35 ; $p < 0.001$).

Heart rate responses did not differ significantly between naturally menstruating females ($-15 \pm 3 \text{ b} \cdot \text{min}^{-1}$) and hormonal contraceptive users ($-10 \pm 4 \text{ b} \cdot \text{min}^{-1}$) (Figure 8). Likewise, reductions in resting HR following HA did not differ significantly between groups, with similar decreases observed for naturally menstruating females ($-9 \pm 3 \text{ b} \cdot \text{min}^{-1}$; Hedges' $g = -1.24$; 95% CIs = -2.20 to -0.27 ; $p = 0.01$) and hormonal contraceptive users ($-8 \pm 3 \text{ b} \cdot \text{min}^{-1}$; Hedges' $g = -0.70$; 95% CIs = -1.22 to -0.18 ; $p = 0.01$).

The heat acclimation protocol significantly influenced the magnitude of HR adaptation ($Q = 19.93$; $p < 0.001$). Fixed work-rate protocol elicited a larger reduction in HR ($-19 \pm 4 \text{ b} \cdot \text{min}^{-1}$; Hedges' $g = -1.93$; 95% CIs = -2.47 to -1.39 ; $p < 0.001$) than isothermal protocols ($-8 \pm 4 \text{ b} \cdot \text{min}^{-1}$; Hedges' $g = -0.54$; 95%

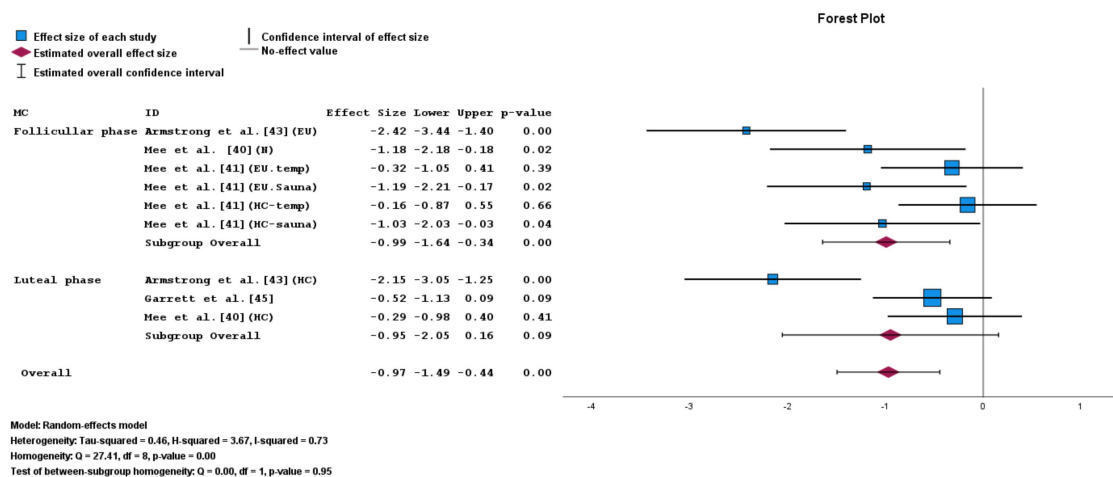


Figure 7. Heart rate forest plot in the follicular and luteal phase.

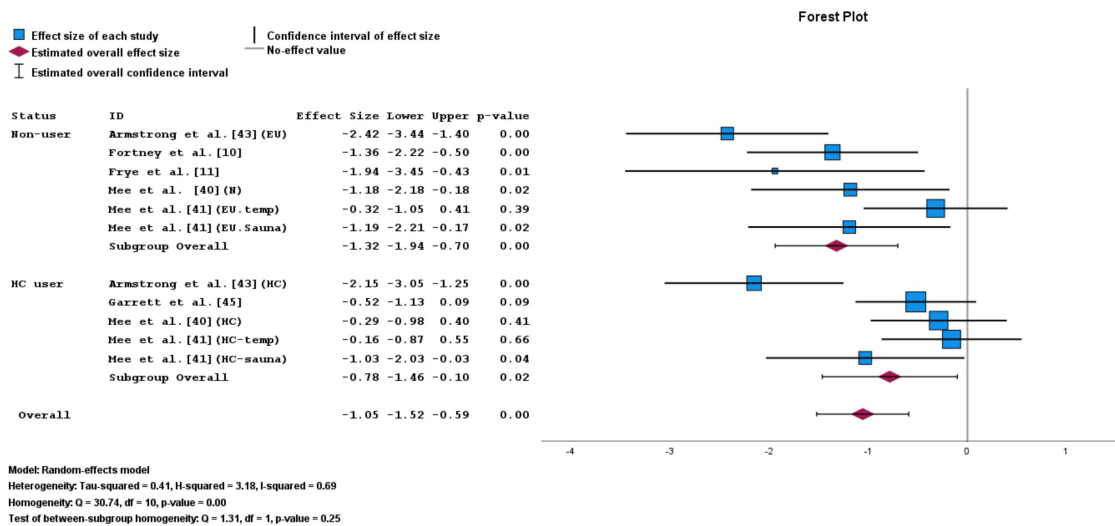


Figure 8. Heart rate forest plot in the hormonal contraceptive users (HC) and non-users.

CI = -0.83 to -0.25 ; $p < 0.001$). Meta-regression further identified HA protocol as a significant moderator ($B = -1.38$; 95% CI = -2.05 to -0.71 ; $p < 0.001$), explaining all the between-study heterogeneity ($R^2 = 100\%$), with no residual heterogeneity remaining. Regardless, the influence of HA protocols on resting HR remains uncertain, as all available resting HR data were derived exclusively from studies using the isothermal HA model.

Reporting type did not appear to moderate the magnitude of HR adaptations ($p > 0.05$) with large effect sizes for studies pooling menstrual (-21 ± 2 b·min $^{-1}$; Hedges' $g = -1.50$; 95% CI = -2.25 to -0.75 ; $p < 0.001$) and studies reporting phases separately (12 ± 4 b·min $^{-1}$; Hedges' $g = -0.97$; 95% CI = -1.49 to -0.44 ; $p < 0.001$).

Plasma volume

HA elicited a meaningful increase in PV% ($4.1 \pm 4.0\%$; Hedges' $g = -0.19$; 95% CI = -0.39 to 0.76 , $p = 0.5$) with large heterogeneity ($I^2 = 80\%$; $p < 0.001$) (4 studies, $n = 57$).

Menstrual cycle phase did not influence the magnitude of plasma volume expansion ($p > 0.05$), with both phases exhibiting small effect sizes and average expansions of $4 \pm 4.6\%$ in the follicular phase and $3 \pm 3\%$ in the luteal phase (Figure 9).

Plasma volume responses did not differ ($p > 0.05$) between naturally menstruating females ($3.8 \pm 3.2\%$; Hedges' $g = 0.39$; 95% CI = -0.25 to 1.03 ; $p = 0.23$) and hormonal contraceptive users ($3.6 \pm 3.4\%$ Hedges' $g = -0.03$; 95% CI = -1.04 to 0.98 ; $p = 0.95$) (Figure 10).

Heat acclimation protocol did not significantly influence PV% responses. However, the isothermal protocol resulted in a significant increase in PV ($5.2 \pm 5.2\%$; Hedges' $g = 0.47$; 95% CI = 0.06 to 0.87 ; $p = 0.02$), whereas the fixed work-rate model did not ($3.1 \pm 2\%$; Hedges' $g = -0.28$; 95% CI = -1.57 to 1.02 ; $p = 0.60$).

Reporting type did not influence these outcomes ($p > 0.05$), however, studies which pooled menstrual phases demonstrated a greater expansion ($7.5 \pm 2.5\%$ Hedges' $g = 0.93$; 95% CI = -0.20 to 1.66 ; $p = 0.01$) compared to studies reporting phases separately ($3.6 \pm 4\%$ Hedges' $g = 0.08$; 95% CI = -0.53 to 0.69 ; $p = 0.80$). The summary of the findings of the current meta-analysis is presented in Tables 2a and 2b, showing the results of subgroup analysis and meta regression analysis.

Discussion

The primary aim of this systematic review and meta-analysis was to determine whether fluctuations in ovarian hormones across the menstrual cycle influence adaptations to HA. Additionally, we examined whether the magnitude of adaptation differs between naturally menstruating females and users of hormonal contraceptives, and whether the effectiveness of HA varies according to protocol. Overall, the findings

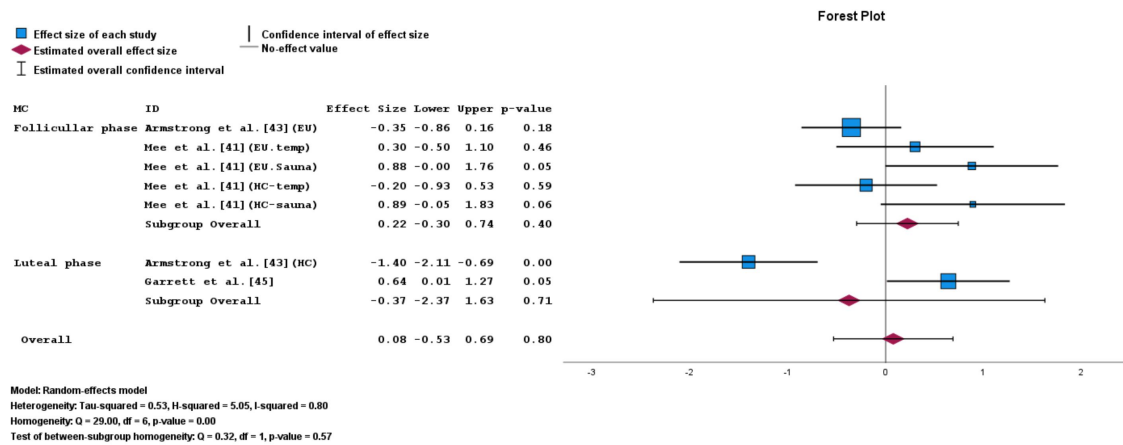


Figure 9. Plasma volume forest plot in the follicular and luteal phase.

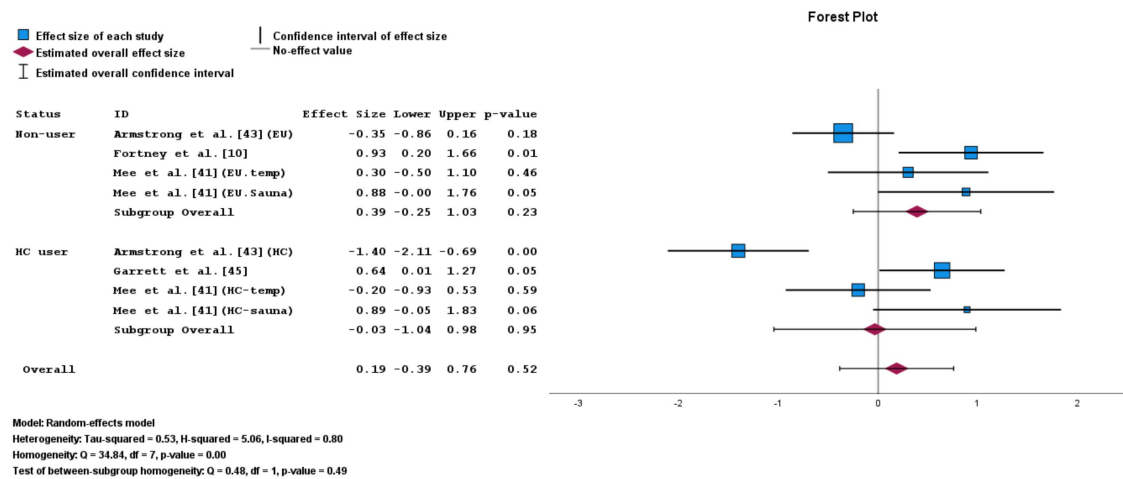


Figure 10. Plasma volume forest plot in the hormonal contraceptive users (HC) and non-users.

Note: Data are presented as Hedges' g (ES), and 95% confidence intervals (CIs). Those to the left of 0 (vertical gray line) indicate a reduction, whereas those to the right of 0 indicate an increase following the HA regimen. One study [41] contributed four separate groups, reflecting its different participant and pre-exposure conditions. In this study, EU.temp and EU.sauna represent eumenorrheic females who completed a 20-min temperate or sauna exposure before HA, while HC.temp and HC.sauna represent hormonal contraceptive users undergoing the same pre-exposure conditions. Other studies also report multiple subgroups for similar methodological reasons, and each group is therefore displayed separately to reflect the distinct characteristics and conditions evaluated. EU = eumenorrheic; N = naturally menstruating; HC = hormonal contraceptive users. FP: Follicular phase. LP: Luteal phase.

Table 2a. Summary of the findings. The values represent the average changes and $\pm$ SD.

Variable	Menstrual cycle		Sub-p	Meta-p	Menstrual status		Sub-p	Meta-p
	FP	LP			Non-users	HC		
T _{core} (°C)	-0.29 $\pm$ 0.11	-0.33 $\pm$ 0.15	0.07	0.10	-0.44 $\pm$ 0.11	-0.25 $\pm$ 0.09	0.84	0.83
T _{skin} (°C)	-0.58 $\pm$ 0.2	-0.73 $\pm$ 0.3	0.92	0.98	-0.80 $\pm$ 0.23	-0.53 $\pm$ 0.25	0.21	0.15
HR (b·min ⁻¹)	-10 $\pm$ 3	-14 $\pm$ 6	0.95	0.91	-15 $\pm$ 3	-10 $\pm$ 4	0.25	0.23
PV%	4 $\pm$ 4.6	3 $\pm$ 3	0.57	0.46	3.8 $\pm$ 3.2	3.6 $\pm$ 3.4	0.49	0.45
Resting T _{core} (°C)	-0.16 $\pm$ 0.04	-0.06 $\pm$ 0.15	0.22	0.47	-0.04 $\pm$ 0.05	-0.12 $\pm$ 0.11	0.24	0.34
Resting HR (b·min ⁻¹)	-8 $\pm$ 3	-14 $\pm$ 4	0.75	0.78	-9 $\pm$ 3	-8 $\pm$ 3	0.34	0.44

Table 2b. Summary of the findings. The values represent the average changes and $\pm$ SD.

Variable	Reporting approach		Sub- <i>p</i>	Meta- <i>p</i>	Heat acclimation type			
	Pooled	Separate			Isothermal	Fixed work	Sub- <i>p</i>	Meta- <i>p</i>
T_{core} ($^{\circ}\text{C}$)	-0.74 ± 0.06	-0.30 ± 0.11	0.02	0.03	-0.29 ± 0.09	-0.45 ± 0.12	0.53	0.52
T_{skin} ($^{\circ}\text{C}$)	-1.06 ± 0.2	-0.63 ± 0.24	0.06	0.11	-0.56 ± 0.24	-1.01 ± 0.22	0.32	0.29
HR ($\text{b}\cdot\text{min}^{-1}$)	-21 ± 2	-12 ± 4	0.25	0.33	-8 ± 4	-19 ± 4	<0.001	<0.001
PV%	7.5 ± 2.5	3.6 ± 4	0.08	0.33	5.2 ± 5.2	3.1 ± 2	0.28	0.17
Resting T_{core} ($^{\circ}\text{C}$)	–	-0.08 ± 0.08	–	–	-0.08 ± 0.08	–	–	–
Resting HR ($\text{b}\cdot\text{min}^{-1}$)	–	-9 ± 3	–	–	-9 ± 3	–	–	–

The significant results are shown inbold. Sub = subgroup analysis. Meta = meta regression analysis. FP = follicular phase. LP = luteal phase. HC = hormonal contraceptive.

indicate that menstrual cycle phase or hormonal contraceptive use do not regulate HA responses. In contrast, HA protocols appeared to moderate some outcomes, with fixed work rate protocols eliciting greater reductions in HR than isothermal protocols.

Influence of menstrual cycle phase on heat acclimation

The elevated resting T_{core} and hormonal profile of the luteal phase [22]; [23,36] have led to the suggestion that females in the luteal phase may exhibit impaired heat adaptation [14]. The potential mechanisms underlying this suggestion may include progesterone-mediated elevations in resting body temperature and shifts in the thermoregulatory set point [22]; [23]; [24,25]; [26]. However, the present meta-analysis found similar HA adaptations in T_{core} , T_{skin} , HR, and PV across menstrual cycle phases, suggesting that the magnitude of HA adaptation is not substantially altered by menstrual phase.

These findings are consistent with previous work by Avellini et al. [44], who reported that although thermophysiological differences existed between menstrual phases prior to HA, these differences were no longer evident following acclimation. Collectively, this supports the concept that HA adaptations are primarily driven by repeated exposure to a sufficient thermal stimulus, characterized by elevations in T_{core} and T_{skin} alongside sustained sweating responses [53]; [54].

The physiological mechanisms underlying these adaptations likely involve repeated activation of central thermoregulatory pathways, resulting in improved autonomic effector responses such as cutaneous vasodilation, sweating, and cardiovascular stability [29]; [55]; [56]. Although elevated basal T_{core} during the luteal phase may initially increase resting thermal strain, it may also enhance the core-to-skin thermal gradient, potentially facilitating heat transfer and dissipation once sweating and skin blood flow are triggered. Additionally, progesterone-related alterations in sweating sensitivity, skin blood flow regulation, sodium handling, and extracellular fluid expansion may further contribute to thermoregulatory responses during HA [57]; [58]. These mechanisms provide a plausible basis for the observed stability of HA adaptations across menstrual phases.

Despite these findings, studies examining the influence of menstrual cycle phase on physiological adaptations to HA remain limited. Future investigations employing standardized hormonal verification, larger cohorts, and directly comparable HA protocols across menstrual phases are required to determine better the extent to which endogenous hormonal fluctuations influence thermoregulatory adaptation to repeated heat exposure.

Naturally menstruating vs hormonal contraceptives

The present data suggests that HA adaptations are robust and broadly similar between naturally menstruating females and hormonal contraceptive users. This suggests that exogenous hormonal modulation does not meaningfully modify the adaptive response to repeated heat exposure. This finding is consistent with previous work by Armstrong et al. [43], and more recent literature from Kirby et al. [59], which similarly reported minimal or no systematic influence of hormonal contraceptive use on thermoregulatory responses during exercise in the heat. Collectively, these findings suggest that females can achieve meaningful HA

adaptations regardless of hormonal profile, although the magnitude and time course of adaptation may vary slightly between individuals.

Several studies reported higher baseline T_{core} in hormonal contraceptive users ($\sim 0.4^{\circ}\text{C}$) compared with naturally menstruating females [29]; [30]; [31,34]. This observation is likely related to progesterone's thermogenic effects and the altered endocrine environment associated with exogenous hormone administration, which elevates the thermoregulatory set point [33]. However, despite these elevated resting temperatures, T_{core} often normalized during exercise in the heat, suggesting effective initiation of cooling mechanisms, such as sweating and cutaneous vasodilation, once a higher internal threshold is reached [34]; [60]. This may indicate that hormonal contraceptive users initiate thermoregulatory responses at a higher core temperature threshold rather than exhibiting an impaired capacity for heat dissipation.

From an applied perspective, these findings support the use of standard HA protocols across female populations regardless of contraceptive status, without the need for hormonal phase-specific modification. This has practical relevance for athletes, occupational workers, and military personnel who undertake exercise or work in hot environments, as it suggests that HA strategies may not need substantial modification based solely on hormonal contraceptive status. Nonetheless, practitioners should stay aware of potential differences in baseline thermal strain, particularly during the early stages of heat exposure, when hormonal contraceptive users and those in luteal phase may begin exercise with higher resting T_{core} . Monitoring individual responses to heat exposure may therefore still be beneficial, especially in high-performance or high-risk settings. Therefore, although the present findings suggest broadly comparable HA adaptations, methodological inconsistencies across studies warrant cautious interpretation.

Heat acclimation protocol

Our meta-analysis indicates that not all HA protocols elicit equivalent physiological adaptations. Specifically, fixed work-rate protocols produced greater reductions in HR compared with isothermal protocols, whereas adaptations in T_{core} , T_{skin} , and PV% were largely similar across protocols. These findings suggest that cardiovascular adaptations may be more sensitive to HA prescription variables than thermoregulatory or plasma volume responses.

The findings are partly in line with those of Gibson et al. [61], who reported no statistically significant differences between HA protocols (isothermal vs. fixed intensity). However, they noted superior responses to isothermal protocols in their dataset, which contrasts with the present meta-analysis, in which greater cardiovascular adaptations, particularly HR reductions, were observed following fixed-work-rate HA. However, it is important to note that their study was conducted exclusively in male participants.

One plausible explanation for the more pronounced HR adaptations observed with fixed-work-rate protocols in the present analysis is the longer total exposure duration in these interventions. Extended HA protocols are generally associated with more substantial and stable physiological adaptations, including improved cardiovascular efficiency, which collectively reduce cardiovascular strain during heat stress [62]; [63]. This would suggest that total heat and metabolic load may be key drivers of cardiovascular adaptation, rather than protocol modality alone.

From an applied perspective, these findings suggest that both fixed work-rate and isothermal HA protocols can elicit meaningful thermoregulatory and hematological adaptations. However, differences in cardiovascular adaptation may be influenced more by the total heat and metabolic load accumulated during the intervention than by protocol modality alone. Practitioners should therefore consider not only protocol type but also total exposure duration, training load, and athlete characteristics when designing HA interventions. Despite these insights, interpretation is limited by considerable heterogeneity across studies, including differences in exercise intensity prescription, environmental conditions, hydration strategies, and total number of HA sessions. In addition, many studies lacked direct comparisons under controlled conditions, making it difficult to attribute observed differences solely to protocol type. Therefore, future studies in larger, more diverse cohorts, including female participants, and standardized protocol comparisons are needed to elucidate mechanistic responses to different HA strategies better.

Limitations

Methodological approaches

A key limitation across the included studies was the widespread reliance on self-reported menstrual cycle information rather than ovulation testing and hormonal verification which introduces potential variability in phase classification. Furthermore, this introduces potential bias, as the population may have included participants with menstrual disturbances, which could confound the findings [46]. Additionally, the use of basal body temperature to “confirm” ovulation in several studies represents a limitation, as this method does not accurately predict ovulation and may lead to menstrual phase misclassification. Environmental and lifestyle factors, including fever, infection, alcohol consumption, emotional or physical stress, and disrupted sleep, may also influence basal body temperature and contribute to false temperature elevations [64]. Consequently, any misclassification in the original studies may have influenced the findings of the present meta-analysis. Furthermore, reporting menstrual cycle data separately by phase, rather than pooling phases, significantly moderated the observed outcomes, suggesting that differences in how menstrual cycle data were analyzed and reported may have contributed to between-study variability. This may highlight the importance of standardized reporting practices in future heat acclimation research.

Another methodological limitation is that the present investigation compared menstrual cycle phases across independent studies rather than within the same participants. Therefore, the findings may partly reflect inter-individual variability rather than true physiological changes across the menstrual cycle. Furthermore, due to the length of HA protocols, studies usually assessed pre- and post-HA responses during different hormonal profiles (e.g. pre-HA testing during the early follicular phase and post-HA testing near ovulation or during the early luteal phase). This introduces a potential confounding effect where changes in T_{core} from HA can coincide with hormonal fluctuations in T_{core} (e.g. from luteal to follicular phase). However, due to the length required for HA protocols, it is difficult to avoid having HA protocols spanning across different menstrual cycle phases. Therefore, from a practical perspective, scheduling an entire HA protocol and all associated testing within a single menstrual cycle phase is often not feasible. However, it is recommended that pre- and post-heat stress testing should be conducted during the same menstrual cycle phase to minimize the influence of hormonal fluctuations.

Differences between included studies

There was a substantial heterogeneity across the HA protocols and heat-stress tests, including differences in duration, frequency, environmental conditions, and exercise intensity. These differences are meaningful, as weight-bearing versus non-weight-bearing exercise and differences in metabolic load directly influence metabolic heat production, thermal strain, and adaptation [65]; [66]. Furthermore, studies reported physiological responses using different outcome measures and time points, including peak values, end-exercise values, and session averages. Such inconsistencies complicate comparisons across studies and may have contributed to variability in the observed findings. Additionally, several studies investigated only a single menstrual phase, most commonly the follicular phase, thereby limiting direct comparisons across the cycle. Variation in participant classification, hormonal verification procedures, and reporting practices further reduced comparability between studies.

Future directions

Future HA research would benefit from adopting established guidelines for menstrual cycle monitoring in sport and exercise science and explicitly report menstrual cycle status (e.g. eumenorrheic or naturally menstruating females) [46] or follow recent methodological recommendations for menstrual cycle classification and scheduling in HA research [20]. Improved characterization of hormonal status would reduce the risk of phase misclassification and strengthen confidence in comparisons across menstrual phases and hormonal contraceptive use. A particular priority is the use of well-controlled within-subject designs in which participants complete pre- and post-HA testing under comparable hormonal conditions. Such approaches would help distinguish true acclimation-induced adaptations from normal hormonal fluctuations occurring across the menstrual cycle. Furthermore, studies are encouraged to include both follicular and luteal phase

assessments to provide a more comprehensive understanding of physiological and performance responses across the menstrual cycle. While these designs are logistically challenging, they would provide stronger evidence regarding the influence of endogenous and exogenous ovarian hormones on HA responses.

Future investigations should aim to standardize key methodological features of HA interventions, including protocol duration, exercise mode, exercise intensity, environmental conditions, and hallmark HA adaptation reporting to reduce methodological heterogeneity. Greater consistency would facilitate comparisons between studies and improve the precision of future evidence synthesis.

Finally, understanding remains limited regarding the influence of hormonal status on several mechanisms that may contribute to HA adaptations, including metabolic heat production, $\text{VO}_{2\text{max}}$, perceived exertion, sweat rate, and core temperature at the onset of sweating. The role of the autonomic nervous system in thermoregulatory adaptation also remains poorly understood. Additional well-controlled studies employing rigorous hormonal verification and directly comparable within-subject designs are therefore needed to clarify how hormonal status influences heat tolerance and exercise performance in females.

Conclusion

This systematic review and meta-analysis provide novel insights into the influence of menstrual cycle phase, hormonal contraceptive use, and HA protocol on thermoregulatory adaptation in females. Overall, these findings suggest that females can effectively achieve HA adaptations irrespective of menstrual cycle phase and hormonal status. The magnitude of adaptation may vary depending on the protocol employed for decreases in HR, but not thermoregulatory changes. This has important practical implications for applied sport, occupational, and military settings, supporting the use of standardized HA protocols across female population without hormonal phase-specific modification. Future investigation should prioritize mechanistic, within-subject designs that accurately classify and account for ovarian hormones in their scheduling and design of HA. However, more rigorous investigation is needed to confirm our findings as the available evidence remains insufficient to determine whether hormonal fluctuations meaningfully influence HA adaptations or potentially obscure adaptive responses.

Abbreviations

HA	Heat acclimation
T_{core}	Core temperature
T_{skin}	Skin temperature
HR	Heart rate
PV	Plasma volume
$\text{VO}_{2\text{max}}$	Maximal oxygen consumption
EU	Eumenorrheic
HC	hormonal contraceptive
N	Naturally menstruating
Tdb	Dry-bulb temperature
Twb	Wet-bulb temperature
RH	Relative humidity
FP	Follicular phase
LP	Luteal phase
SD	Standard deviation
SE	Standard error
CIs	Confidence interval
ES	Effect size
I^2	Heterogeneity
IQR	Interquartile range
REML	Random effects meta-regression

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Author contributions

Sarah Kordrostami: Conceived the study, designed the review protocol, conducted the literature search, screened and selected studies, extracted and analyzed the data, performed the meta-analysis, and drafted the manuscript

Jessica Mee: Idea conception, drafting, commenting, editing, and review of manuscript

Phillip J. Wallace: Idea conception, drafting, and review of manuscript

Stephen S. Cheung: Idea conception, data screening, drafting, and review of manuscript.

Heikki Kyröläinen: Commenting, editing, and approving final manuscript

Ritva S. Mikkonen: Initiation of project (specifics from a female physiology perspective), supervision, editing, commenting, approving final manuscript

Dominique D. Gagnon: Initiation of project, supervision, data screening, editing, commenting, approving final manuscript

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Data availability statement

This study did not generate original data. The extracted datasets used for analysis will be made available upon a reasonable request.

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