Narrative Review Article

Sex Differences in Thermoregulation During Exercise in Hot-Humid Environments: A Narrative Review with Implications for Athletic Populations in Singapore

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ABSTRACT

This narrative review synthesizes current evidence on sex differences in thermoregulatory responses during exercise, with specific application to athletes training in Singapore's hot-humid climate. The review examines physiological mechanisms underlying sex-based differences in sweating, cutaneous vasodilation, and hormonal influences on thermal regulation. Evidence indicates that males generally exhibit higher sweat rates and earlier sweating onset, whereas females demonstrate lower sweat output per gland despite higher gland density, with additional thermoregulatory variability introduced by menstrual cycle phases. In hot-humid environments characteristic of Singapore, reduced evaporative cooling efficiency may attenuate these sex differences, as high ambient humidity limits heat dissipation regardless of sweat production capacity. This review evaluates Singapore's athletic heat stress frameworks, particularly Sport Singapore's Heat Stress Management Plan, identifying gaps in sex-specific provisions. Recommendations include individualized hydration guidelines based on sweat rates, educational initiatives regarding menstrual cycle effects on thermoregulation, and Singapore-specific research to validate laboratory findings in field conditions.

Keywords: thermoregulation; sex differences; athletes; hot-humid environment; Singapore; heat stress policy

INTRODUCTION

Athletic performance in warm-to-hot environments is compromised relative to thermoneutral conditions, with endurance events showing measurable decrements when ambient temperatures exceed 25°C (1). Elite endurance athletes generate metabolic heat at rates of 1000–1300 kcal/hour during competition, necessitating substantial increases in skin blood flow and sweating to maintain thermal homeostasis. When heat dissipation mechanisms are insufficient, core temperatures rise toward dangerous thresholds, impairing both performance and safety.

Singapore's equatorial climate presents challenges for athletic thermoregulation. Daily maximum temperatures of 31–33°C combined with mean relative humidity of 84% create persistent heat stress conditions throughout the year (2). The 2013–2022 decade represented Singapore's warmest on record, with extreme heat events increasing in frequency. For athletes training in Singapore, heat stress represents a chronic challenge requiring systematic management approaches.

The distinction between hot-humid and hot-dry environments fundamentally affects thermoregulatory capacity. In hot-dry conditions, evaporative heat loss

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predominates due to low ambient water vapor pressure. Hot-humid environments constrain this mechanism: elevated ambient humidity reduces the skin-to-environment vapor pressure gradient, limiting evaporative cooling even when sweat production is maximal (3). Singapore's persistent humidity therefore places athletes at a thermoregulatory disadvantage relative to those training in arid climates at similar temperatures.

Despite extensive research on thermoregulation, significant gaps exist in understanding sex-specific responses. A recent scoping review found that 72% of studies investigating sports clothing and thermoregulation exclusively recruited male participants, while only 16% included exclusively female samples (4). This male-dominated evidence base raises questions about the applicability of current guidelines to female athletes. Physiological differences between sexes—including variations in sweat gland function, body composition, and hormonal influences—suggest that thermoregulatory responses may differ in ways relevant to heat injury prevention.

This narrative review addresses three objectives: first, to synthesize current evidence on sex differences in thermoregulatory mechanisms during exercise; second, to examine how Singapore's hot-humid environment affects these sex-specific responses; and third, to evaluate whether Singapore's athletic heat stress policies adequately address documented physiological differences between male and female athletes.

PHYSIOLOGICAL SEX DIFFERENCES IN THERMOREGULATION

Thermoregulatory Mechanisms

Human thermoregulation during exercise depends on two primary effector mechanisms: eccrine sweating and cutaneous vasodilation. Sweating provides evaporative heat loss, representing the dominant cooling pathway during exercise when ambient temperature approaches skin temperature. Vasodilation increases cutaneous blood flow, facilitating convective heat transfer from the body core to the skin surface where both evaporative and dry heat exchange occur. Both mechanisms impose substantial cardiovascular demands, as increased skin blood flow competes with exercising muscle for cardiac output, as shown in Figure 1.

Morphological Factors

Males and females differ in body size and composition, with males typically exhibiting greater height, mass, and absolute maximal oxygen consumption. Females generally possess higher body surface area-to-mass ratios, theoretically favoring heat dissipation through greater relative surface area (9). However, when metabolic heat production is expressed relative to body surface area, apparent sex differences in thermoregulation diminish substantially. This finding suggests that absolute body size, rather than biological sex per se, accounts for a significant portion of observed differences in heat dissipation capacity.

Sudomotor Function

Sex differences in sweating represent the most consistently documented thermoregulatory distinction. Females possess higher eccrine sweat gland density than males but demonstrate lower sweat output per gland, resulting in lower whole-body sweat rates during exercise (10). Research has shown that females initiate sweating at higher mean body temperatures and display reduced sweating sensitivity relative to males (11). Importantly, when males and females are matched for body mass, body surface area, and metabolic heat production, differences in sweating capacity persist, indicating mechanisms independent of body size.

Female sweating responses also show greater suppression when skin is already wet, potentially representing an adaptive mechanism to conserve body water when additional sweating would not enhance evaporative cooling. Physical training modifies

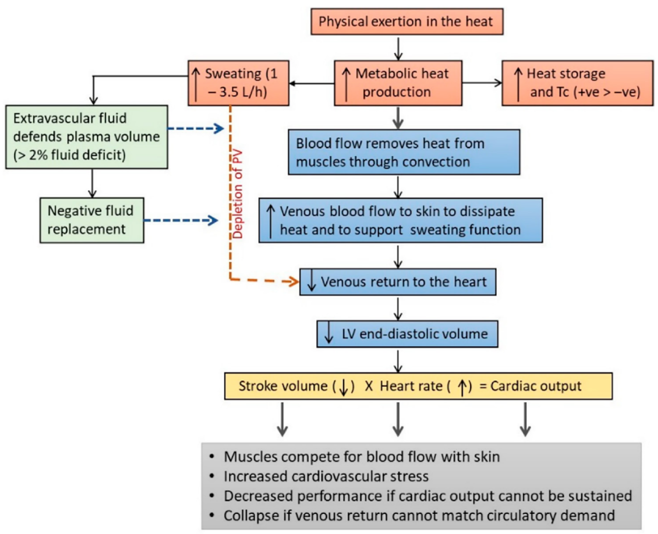

Figure 1. *Schematic overview of human thermoregulatory mechanisms during exercise (8).*

sudomotor function in both sexes, with trained individuals demonstrating earlier sweating onset and greater maximal sweat rates. However, sex differences in sweating capacity persist even after matched training interventions.

Cutaneous Vasodilation

Evidence regarding sex differences in cutaneous vasodilation during exercise-heat stress is less consistent than for sweating. Some studies report greater skin blood flow responses in females, which may partially compensate for lower sweat rates by enhancing dry heat loss through radiation and convection. This pattern—lower sweating coupled with relatively greater vasodilation—may confer advantages in humid conditions where evaporative cooling is constrained. However, increased reliance on vasodilation imposes greater cardiovascular strain through competition for cardiac output between skin and exercising muscles.

Menstrual Cycle Effects

The menstrual cycle introduces additional variability in female thermoregulation. During the luteal phase, elevated progesterone concentrations increase resting core body temperature by approximately 0.3–0.5°C relative to the follicular phase (12). This elevation shifts the thresholds for sweating and vasodilation initiation seen in Figure 2, meaning females in the luteal phase begin active heat dissipation at higher absolute core temperatures.

Whether these threshold shifts translate to increased heat illness risk remains debated. Some evidence suggests

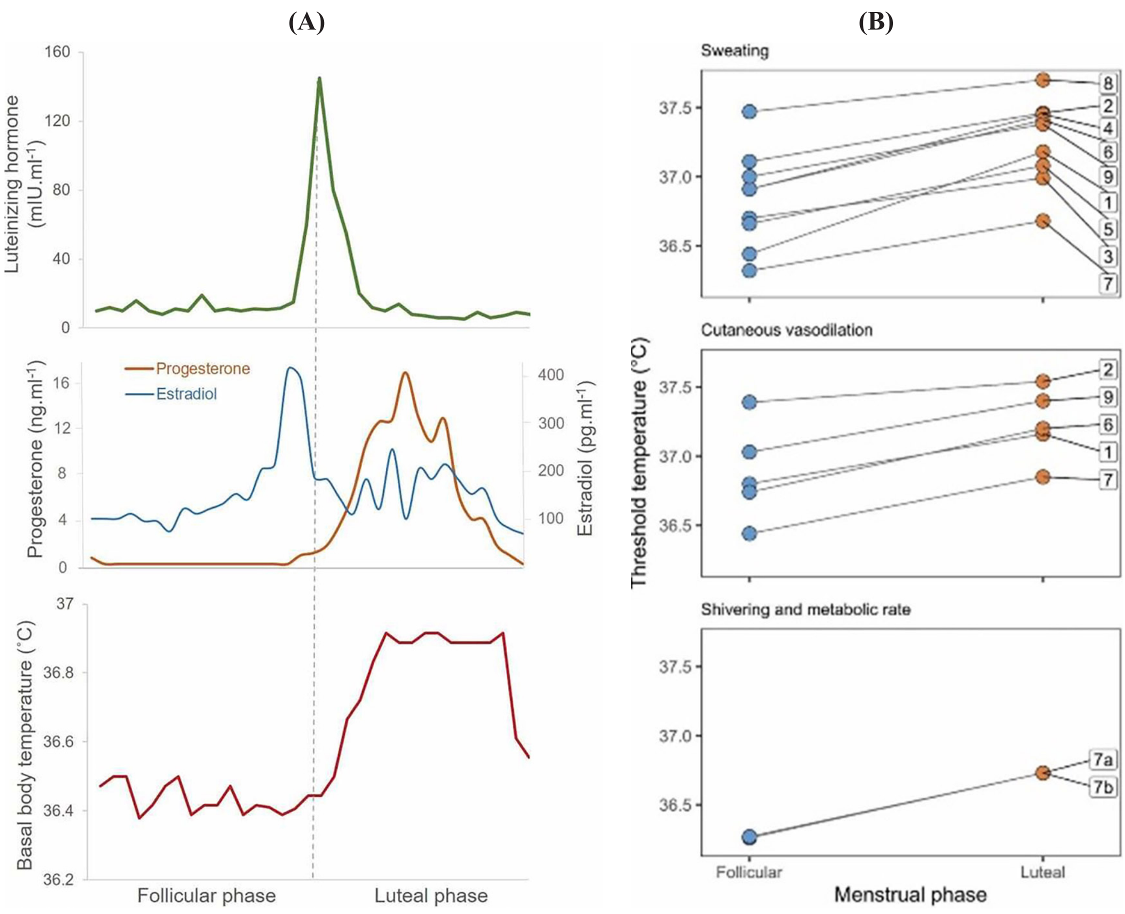

Figure 2. *Menstrual cycle phases and thermoregulatory threshold shifts. (A) Reproductive hormone profiles and core body temperature variation across the menstrual cycle, showing elevated basal temperature (~0.3-0.5°C) during the luteal phase. (B) Threshold core body temperatures for sweating (top), cutaneous vasodilation (middle), and shivering (bottom) in follicular versus luteal phases; upward shifts indicate delayed heat dissipation responses during the luteal phase. Adapted from Baker FC, Siboza F, Fuller A. Temperature regulation in women: Effects of the menstrual cycle. Temperature. 2020;7(3):226-262. doi :10.1080/23328940.2020.1735927. Published under Creative Commons license.*

that thermoregulatory set points adjust proportionally with baseline temperature elevation, maintaining effective heat dissipation. Other studies indicate that exercising with elevated baseline core temperature reduces the margin before reaching hyperthermic thresholds. The prevalence of hormonal contraceptive use, which maintains relatively stable elevated hormone levels, adds further complexity to understanding menstrual cycle effects in athletic populations.

Summary of Sex Differences

Table 1 summarizes documented sex differences in thermoregulatory parameters. When males and females are matched for body size and aerobic fitness, a substantial portion of apparent sex differences is eliminated. Current evidence does not support the conclusion that females possess an inherent thermoregulatory disadvantage; rather, differences appear context-dependent and may favor different sexes under different environmental conditions.

THERMOREGULATION IN HOT-HUMID ENVIRONMENTS

Physics of Evaporative Cooling

Heat loss from the body occurs through four pathways: radiation, convection, conduction, and evaporation. As Figure 3 suggests, when ambient temperature approaches or exceeds skin temperature (approximately 35°C), radiation and convection become ineffective or reverse direction to cause heat gain. Under these conditions, evaporation of sweat becomes the primary mechanism for heat dissipation. Evaporative heat loss depends critically on the water vapor pressure gradient between the skin surface and ambient air. In humid conditions, this gradient is reduced, decreasing evaporative capacity regardless of sweat production.

Sherwood and Huber identified a theoretical wet-bulb temperature threshold of approximately 35°C, beyond which sustained evaporative cooling becomes impossible even at rest (3). Subsequent research has suggested this threshold may be lower during physical exertion, as metabolic heat production outpaces constrained evaporative capacity (13).

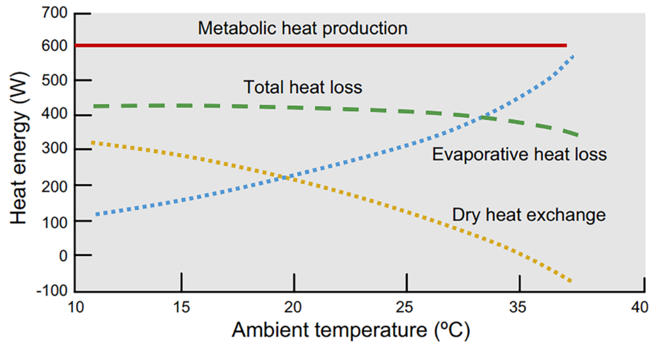

Figure 3. Relative contribution of evaporative and dry (convection and radiation) heat loss during exercise at a constant metabolic heat production rate across different ambient temperatures. As ambient temperature increases toward ~35°C (approaching skin temperature), dry heat exchange diminishes to zero and evaporation becomes the sole avenue for heat dissipation. This illustrates why the Sherwood-Huber 35°C wet-bulb threshold represents a physiological limit — and why this limit is lower during exercise, when metabolic heat production (~600W) must be dissipated entirely through evaporation. Reproduced from Périard et al. (2021) under CC-BY 4.0 license (14).

Table 1. Summary of Sex Differences in Thermoregulatory Parameters.

Parameter	Males	Females	Effect of Body Size Matching	Key References
Whole-body sweat rate	Higher	Lower	Differences persist	Gagnon *et al*., 2013
Sweat gland density	Lower	Higher	N/A (anatomical)	Ichinose-Kuwahara *et al*., 2010
Sweat output per gland	Higher	Lower	Differences persist	Ichinose-Kuwahara *et al*., 2010
Sweating onset threshold	Lower temperature	Higher temperature	Differences persist	Gagnon *et al*., 2013
Cutaneous vasodilation	Variable	Possibly greater	Inconsistent findings	Yanovich *et al*., 2020
Menstrual cycle effect	N/A	+0.3–0.5°C luteal phase	N/A	Baker *et al*., 2020
Wet skin sweating suppression	Moderate	Greater suppression	Differences persist	Gagnon *et al*., 2013

Singapore's Climate Context

Singapore's equatorial location (1°N latitude) produces a hot-humid tropical climate with minimal seasonal variation. Mean daily temperatures range from 26–27°C, with daytime maxima of 31–33°C and relative humidity averaging 84% (2). This combination creates persistent thermoregulatory challenges for athletes throughout the year, unlike temperate climates where heat stress is seasonal.

Climate trends indicate intensifying heat stress. The 2013–2022 decade was Singapore's warmest on record, and extreme heat events are increasing in frequency; Ang Mo Kio recorded 37°C in May 2023 (7). Urban heat island effects compound these conditions in built-up areas where many athletic facilities are located, with reduced airflow and heat-retaining surfaces elevating local temperatures above regional averages.

Sex-Specific Responses to Humid Heat

Direct investigation of sex-specific responses to humid heat remains limited, but theoretical considerations suggest humidity may attenuate sex differences in thermoregulation. When ambient humidity constrains evaporative cooling for both sexes, the male advantage of higher sweat rates diminishes because additional sweat cannot evaporate effectively. Males may experience accelerated dehydration through continued sweating that yields minimal cooling benefit, while females' lower sweat rates and greater sweating suppression on wet skin may conserve body water without substantial thermoregulatory penalty.

Female reliance on cutaneous vasodilation for heat dissipation may prove advantageous in humid conditions, as radiative and convective heat loss remain partially effective when evaporation is constrained. However, these theoretical predictions require validation through controlled studies in Singapore-relevant conditions, as most existing research was conducted in temperate laboratory environments.

Heat Acclimation

Heat acclimation induces beneficial adaptations including expanded plasma volume, reduced resting and exercising core temperatures, earlier sweating onset, decreased sweat sodium concentration, and improved cardiac efficiency (15). Meta-analysis indicates these adaptations improve endurance performance by approximately 23% and time-trial performance by approximately 7% (16). Athletes training continuously in Singapore's hot-humid climate experience chronic heat exposure that induces partial acclimation.

A systematic review and meta-analysis of heat adaptation in females found that acclimation protocols induce beneficial adaptations comparable to those observed in males (17). This finding supports the applicability of standard acclimation protocols across sexes, though optimal protocols for female athletes—particularly considering menstrual cycle timing—remain to be established.

ASSESMENT OF SINGAPORE'S HEAT STRESS POLICIES

Sport Singapore Heat Stress Management Plan

Sport Singapore published the Heat Stress Management Plan in 2023, representing the primary policy framework for athletic populations in Singapore (7). This plan integrates with the whole-of-government Heat Stress Advisory system jointly managed by the National Environment Agency (NEA), Ministry of Manpower (MOM), Ministry of Health (MOH), and Workplace Safety and Health Council (WSHC). The framework provides guidance on activity modification during elevated heat stress periods, hydration practices, and recognition of heat illness symptoms.

The policy utilizes Wet Bulb Globe Temperature (WBGT) monitoring as the primary environmental assessment metric, consistent with international best practices endorsed by the American College of Sports Medicine (5). The framework recommends activity modifications across WBGT categories, though specific thresholds for sport-specific work-rest cycles are less detailed than those developed for occupational or military settings.

Supporting Frameworks

The Workplace Safety and Health Council (WSHC) heat stress guidelines, while primarily targeting outdoor workers, provide supplementary frameworks applicable to athletic contexts (18). These guidelines emphasize four pillars: acclimatization, hydration, rest, and shade. WBGT monitoring at hourly intervals during hot periods is recommended, with tiered interventions based on temperature readings.

The Singapore Armed Forces (SAF) has developed extensive heat injury prevention protocols through decades of managing physical training in Singapore's climate (19). While SAF policies focus on military personnel, their evidence base and operational experience inform broader understanding of heat stress management in Singapore. SAF-MOH Clinical Practice Guidelines for heat injury management provide standardized definitions and treatment protocols applicable across athletic settings (20).

Gap Analysis: Sex-Specific Provisions

Table 2 summarizes key policy elements across Singapore's three principal heat stress frameworks: the Singapore Armed Forces (SAF/MINDEF) protocols, Sport Singapore's Heat Stress Management Plan, and the Workplace Safety and Health Council (WSHC) guidelines. Although the SAF framework targets military rather than athletic populations, its decades of operational experience managing heat stress in Singapore's climate make it the most developed domestic policy precedent and a useful comparator for identifying systemic gaps in sex-specific provisions. Notably, none of the publicly available policy documents specify sex-specific modifications to activity guidelines, acclimatization protocols, or hydration recommendations. This absence reflects the male-dominated evidence base underlying most heat stress research and policy development.

Table 3 shows several specific gaps which have emerged from this analysis. First, hydration guidelines across all three frameworks do not account for sex differences in sweat rates; applying recommendations derived from male athletes or male military populations may lead to overhydration and hyponatremia risk in females with lower sweat outputs. Second, no framework addresses menstrual cycle considerations, despite documented effects on core temperature regulation. Third, acclimatization protocols — though well developed in both the SAF and WSHC systems — are presented uniformly without consideration of potential sex-specific optimization. Finally, elite athletes who may have individualized coaching support, and service personnel monitored by unit medical officers, are better positioned to address these gaps than recreational athletes who rely primarily on public guidelines.

RECOMMENDATIONS

Based on current evidence, sex-differentiated WBGT thresholds do not appear warranted, as thermoregulatory

Table 2. *Comparison of Singapore's three principal heat stress frameworks (SAF/MINDEF, Sport Singapore, WSHC) across key policy dimensions. The SAF framework is included as an operational benchmark reflecting the most developed domestic heat-stress practice, despite its military rather than athletic focus.*

Policy Element	SAF / MINDEF	Sport Singapore Heat Stress Management Plan	WSHC Guidelines (Supplementary)
Environmental monitoring	WBGT monitoring across all training activities; colour-coded flag system	WBGT via Heat Stress Advisory system	WBGT hourly monitoring recommended
Activity modification	Work–rest cycles prescribed by WBGT category; commander discretion for attire and load	Tiered guidance based on heat stress level	Work–rest cycles by WBGT category
Acclimatization	Structured regime from Basic Military Training onward; progressive exposure over the first 10–14 days	General guidance provided	Progressive exposure protocol for new workers
Hydration guidance	Standardised hydration regimes (water parades, ice-slurry pre-cooling); upper intake limits to prevent hyponatremia	General hydration recommendations	Fluid replacement guidance; upper limits to prevent hyponatremia
Heat illness recognition	Standardised definitions and clinical management per SAF–MOH Clinical Practice Guidelines	Symptom identification guidance	Signs and symptoms; emergency response
Sex-specific provisions	None documented	None documented	Pregnancy noted; no other sex-specific guidance
Menstrual cycle considerations	None documented	None documented	None documented
Individualized protocols	Unit medical officer discretion for at-risk personnel	Coach/athlete discretion implied	Supervisor discretion for vulnerable workers

Table 3. *Gap analysis comparing documented sex differences in thermoregulatory responses with current Singapore policy provisions for athletic and active populations across the Singapore Armed Forces (SAF/MINDEF), Sport Singapore, and Workplace Safety and Health Council (WSHC) frameworks. Evidence synthesised from sources cited in text; policy analysis based on the SAF Training Safety Regulations and SAF–MOH Clinical Practice Guidelines on Management of Heat Injury, the Sport Singapore Heat Stress Management Plan, and the WSHC Heat Stress Guidelines.*

Documented Sex Difference	References	SAF / MINDEF	Sport Singapore	WSHC	Assessment
Higher male sweat rates (1.0–1.5 vs 0.4–0.8 L/hr)	(11, 21)	Standardized hydration protocols (e.g., water parades) without sex-specific adjustment	Uniform hydration guidance without individualized targets	General fluid replacement guidance without sex-specific considerations	Gap
Menstrual cycle temperature variation (+0.3–0.5°C luteal phase)	(12, 24)	No menstrual cycle considerations in training or heat injury guidelines	No menstrual cycle guidance in training or competition recommendations	Pregnancy noted as a risk factor; no menstrual cycle considerations	Gap
Sweating suppression on wet skin (hidromeiosis)	(13, 25)	WBGT-based work–rest cycles applied uniformly; no humidity-specific adjustment	WBGT-based activity modification only; no explicit treatment of evaporative constraints	WBGT monitoring with limited recognition of humidity-driven limitations	Gap
Limited research on sex-specific responses in humid heat	(27, 28)	Uniform WBGT thresholds applied across all personnel	Uniform thresholds applied to all athletes	Uniform thresholds applied across workforce	Evidence Gap
Heat acclimatization benefits both sexes	(5)	Structured acclimatization protocols (progressive exposure)	General acclimatization guidance provided	Structured acclimatization programs for workers	Aligned

differences diminish substantially when males and females are matched for fitness level. However, several targeted modifications merit consideration.

First, hydration guidelines should emphasize individualization based on measured or estimated sweat rates rather than uniform volume recommendations. This approach accounts for both sex differences and inter-individual variability. Evidence suggests that female athletes may require approximately 20–30% lower fluid replacement volumes than males of equivalent body mass during similar exercise intensities, although individualized assessment remains preferable to categorical guidance.

Second, acclimatization protocols need not differ by sex, as meta-analytic evidence indicates comparable adaptation responses in females and males. Nevertheless, incorporating initial fitness assessments may allow more appropriate progression rates, particularly given variability in aerobic fitness across populations.

Third, emerging evidence that females may rely more on cutaneous vasodilation for heat dissipation has implications for cooling strategies. Interventions targeting skin blood flow—such as cold-water immersion, fan cooling, and ice towel application—may be particularly effective. These approaches should be further evaluated for sex-specific efficacy in Singapore's hot-humid conditions.

In addition, menstrual cycle considerations should be incorporated primarily through education rather than prescriptive policy. Athletes should be informed about potential thermoregulatory effects during the luteal phase, encouraged to track individual patterns, and given flexibility to adjust high-intensity training during extreme heat when necessary. The potential influence of hormonal contraceptives should also be acknowledged, although current evidence remains limited.

Finally, several research gaps warrant further investigation in Singapore's specific context. Field-based studies are needed to validate sex-specific thermoregulatory responses under local environmental conditions. Prospective monitoring of heat illness incidence by sex would help determine whether physiological differences translate into differential risk. Further research should also examine menstrual cycle effects in real-world settings and evaluate the effectiveness of cooling interventions across sexes to inform optimized heat mitigation strategies.

CONCLUSION

This review synthesized evidence on sex differences in thermoregulation and evaluated implications for athletes in Singapore's hot-humid climate. Physiological differences exist, with females exhibiting lower sweat rates, higher sweating onset thresholds, and menstrual cycle-related temperature variability. However, these differences diminish substantially when body size and fitness are controlled, and current evidence does not establish females as inherently disadvantaged for thermoregulation.

Singapore's high humidity may attenuate sex differences by constraining evaporative cooling for both sexes, potentially favoring female thermoregulatory patterns that rely more heavily on vasodilation and show greater sweating suppression when evaporation is limited. Sport Singapore's Heat Stress Management Plan provides a sound foundation aligned with international best practices, though gaps exist in sex-specific provisions. Recommendations focus on individualized hydration guidelines, educational initiatives regarding menstrual cycle effects, and Singapore-specific research to validate international findings in local conditions. As female athletic participation continues to grow, evidence-based refinement of heat stress policies will be essential for optimizing safety and performance across Singapore's diverse athletic populations.

CONFLICT OF INTEREST

The author declares no conflict of interests.

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