Sex differences in response to exercise heat-stress in the context of the military environment

Invited Review

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Key Messages

Women can now serve in Ground Close Combat (GCC) roles, where they may be required to operate alongside men in hot environments.

The average female soldier may be at a thermoregulatory disadvantage in many hot environments compared to the average male soldier.

Much of the thermoregulatory difference between males and females is due to fitness and anthropometric differences rather than sex, per se.

It is possible that some of these differences may be lessened with appropriate gender free physical employment standards.

Much of the extant literature lacks ecological validity and there are notable gaps in our understanding of a number of key topics in this area.

Abstract

Women can now serve in Ground Close Combat (GCC) roles, where they may be required to operate alongside men in hot environments. However, relative to the average male soldier, female soldiers are less aerobically fit, with a smaller surface area (A_D), lower mass (m) with higher body fat, and a larger A_D/m ratio. This increases cardiovascular strain, reduces heat exchange with the environment, and causes a greater body temperature increase for a given heat storage, although a large A_D/m ratio can be advantageous. Physical employment standards for GCC roles might lessen the magnitude of fitness and anthropometric differences, yet even when studies control for these factors, women sweat less than men at high work rates. Therefore, the average female in a GCC role is likely to be at a degree of disadvantage in many hot environments and particularly during intense physical activity in hot-arid conditions, although heat acclimation may mitigate some of this effect. Any thermoregulatory disadvantage may be exacerbated during the mid-luteal phase of the menstrual cycle, although the data are equivocal. Likewise, sex differences in behavioural thermoregulation and cognition in the heat are not well understood. Interestingly, there is often lower reported heat-illness incidence in women, although the extent to which this is influenced by behavioural factors or historic differences in role allocation is unclear. Indeed, much of the extant literature lacks ecological validity and more work is required to fully understand sex differences to exercise heat-stress in a GCC context.

1. Introduction

Following the publication of the 2016 Interim report on the health risks to women in ground close combat (GCC) roles the exclusion of women from GCC roles was lifted.[1] As a consequence, women can now serve alongside men in these defence positions. At present, women make up around 9% of the British Army.[2] It has been estimated that, in future, approximately 20 women per year will join the Royal Armoured Corps and 10 women per year will join the Infantry;[3] both of these units were previously affected by the exclusion.

It has been acknowledged that GCC roles can require intense physical activity.[3] Moreover, given the variety of theatres in which the British Army operates it is likely that soldiers of both sexes will be exposed to hot conditions during GCC roles. It is, therefore, important to understand the extent to which biological sex impacts upon an individual's ability to operate effectively and safely in these environments. Indeed, the 2014 Women in ground close combat review identified the need for further research to be conducted to better understand the physiological implications of the inclusion of women in GCC roles.[3] Accordingly, this paper presents a brief overview of the current understanding of sex differences in the response to heat exposure, with a particular emphasis on exercise heat-stress in the context of the military environment.

2. Physical Characteristics

Within the general population women are typically shorter and lighter, with a smaller surface area than men and a higher body fat percentage. On average, the maximum rate of oxygen uptake (VO_{2max}) of women is less than men, in absolute terms ($L \cdot min^{-1}$) and also expressed relative to bodyweight ($mL \cdot kg^{-1} \cdot min^{-1}$),[4] which is more relevant during load-bearing exercise. These population-wide anthropometric data are in keeping with data from British Military cohorts.[5] Nevertheless, recent data indicates that only 4.5% of female army recruits met the physical standards required to start Infantry training[3] and it is possible that women who pass current and future gender-free physical employment standards to undertake GCC roles may be fitter, with a lower fat mass than the average women or military recruits.[5] This might result in a reduction in the magnitude of differences in fitness and some anthropometric factors between males and females in GCC roles, although it is likely that they may remain less fit and have a higher fat mass, on average, than the majority of their male counterparts in the same roles. These differences are important because they can influence thermoregulation in the heat.[6 7]

2.1 Anthropometry

Body mass serves as an internal 'heat sink'. Assuming a given body composition, the change in deep-body temperature (T_C) for a given heat storage is inversely related to body mass,[7] and individuals with a greater body mass typically have a smaller increase in deep body temperature (T_C) during a standard heat stress.[6] The 'heat sink' is also influenced by body composition. The heat specific capacity of adipose tissue is less than 'lean' tissue (2.51 *vs*. 3.65 $J \cdot g^{-1} \cdot C^{-1}$) and individuals with higher body fat will have a greater increase in T_C for a given body mass and change in heat content.[7] Although the amount of variance in T_C explained by body-fat may be limited,[8] together these factors likely represent a disadvantage for female soldiers, who are typically lighter with a greater percentage body fat than males. However, body mass also influences metabolic heat production (MHP) during load-bearing exercise at a fixed speed, being lower in lighter individuals than heavier individuals.[9] This may benefit the average female soldier by reducing their heat loss requirements during this type of exercise.

Body surface area (A_D) determines the area available for heat exchange with the environment. When other factors are equal (e.g. skin temperature [T_{sk}] and wettedness, environmental conditions) heat transfer will be greatest in those with a high A_D and the absolute heat-transfer potential is greatest in individuals with the highest A_D.[7] However, in environments where the ambient temperature exceeds T_{sk} a large A_D would enable a higher rate of dry heat-gain from the environment, although high wet heat-loss rates might still be possible if the vapour pressure gradient to the environment is favourable. Thus, whether the lower A_D that is typical in females is a disadvantage, or an advantage, will depend on whether the operational environment favours heat loss, or heat gain.

Body surface area to mass (A_D/m) ratio is also important. For a given increase in body mass, there is a relatively smaller increase in A_D. Consequently, the A_D/m ratio is typically bigger for small body sizes *i.e.* females, than large body sizes, *i.e.* males. Thus, compared to males, females typically have a greater A_D available for heat exchange relative to their 'heat sink'. Moreover, because MHP is typically lower for smaller people during load bearing exercise at a given speed,[9] when compared to the average male soldier, the average female soldier may also have a greater A_D relative to their heat production.[10] However, as discussed subsequently, the extent to which these factors are advantageous, or disadvantageous, may depend on the ambient conditions.[10 11] The A_D/m ratio also influences the thermoeffector pathways for heat-loss, as discussed subsequently (section 3.2).[12]

2.2. Aerobic fitness

The combination of thermal stress and exercise stress presents a significant challenge to the cardiovascular system, where a finite cardiac output must meet the dual demands of delivering blood to the working muscle to supply oxygen and to the skin for heat dissipation. If all other factors are equal, a given absolute external work rate will elicit a relatively greater cardiovascular strain in an individual with a low VO_{2max}, compared to someone with a higher VO_{2max}. Blood volume also tends to be smaller in those with low aerobic fitness.[13] Therefore, in individuals with a low VO_{2max}, the cardiovascular strain associated with thermoregulation is greater because increases in skin blood flow represent a relatively larger shift to the peripheral circulation; this may place the average female soldier at a thermoregulatory disadvantage.[14] Aerobic fitness may also influence sweating and evaporative heat loss, which is lower in those with low aerobic fitness. However, this may only be relevant at high work rates (MHP=500 W) and when VO_{2max} differs to a greater extent (>20 $ml.kg^{-1}min^{-1}$) than is typical between the average male and female soldier.[15]

Designing studies to compare the thermoregulatory responses of groups who typically differ for VO_{2max}, such as male and female soldiers, is challenging. Often the same relative exercise intensity (%VO_{2max}) is studied.[16 17 18] However, MHP and the associated heat-loss requirements will be less in the group with the lower VO_{2max}.[19 20] To avoid this confounding effect, some have compared groups of men and women who are matched for relative VO_{2max}.[21] However, this can still result in a lower MHP and reduced heat-loss requirement in women, if they have a lower body mass.[20] Others have matched groups for *both* relative VO_{2max} and absolute VO_{2max} *i.e.* matched for aerobic fitness and body mass.[12] Although this might be appropriate from a mechanistic perspective, matching independent-groups for characteristics that may naturally differ within the military population in question limits the practical relevance of these findings.

In a GCC context anthropometric and fitness differences might be less than in the wider military population and individuals are likely to be expected to perform certain tasks at a specific minimum rate, irrespective of sex. Thus, study designs comparing thermoregulatory responses of male and female soldiers with fitness (and anthropometric) characteristics representative of the GCC population, performing key physical tasks at a defined rate, may have the best ecological validity. Although these studies have not been conducted, a number of studies examining sex differences in thermoregulation in the heat have employed walking at a given treadmill speed.[10 22] However, because of the influence of body mass on MHP during weight-bearing exercise the heat-loss requirement will likely be lower in (lighter) women. This would necessitate a reduced thermoeffector response, but would not necessarily reflect a 'true' sex difference, *per se*.[20] These important distinctions in study design must be acknowledged when interpreting studies examining sex differences in thermoregulation (see section 3.2).

3 Thermoregulation

3.1 Behavioural

Behavioural thermoregulation is characterised by behaviours which correct deviations from a 'neutral' body temperature to try and maintain 'thermal pleasure'.[23] Behavioural thermoregulation is underpinned by thermo-sensation, mediated by the transient receptor potential family of ion channels. These stimulate small-diameter afferent fibers project to lamina I or to the medullary nucleus of the solitary tract, with the output neurons of these regions conveying afferent information to the hypothalamus and brainstem to generate a conscious change in thermal perception.[24] Perception consists of a discriminative component (*i.e.* sensation), primarily determined by T_{sk}, and an affective (*i.e.* (dis)comfort) component, influenced by T_C and T_{sk}. At rest in the heat thermal (dis)comfort appears to drive behavioral thermoregulation, whereas during exercise the rating of perceived exertion (RPE) may be more relevant. However, when T_C is not noticeably elevated, thermal sensation and comfort influence RPE, whereas sensations related to cardiovascular strain may become more prominent when T_C is elevated.[24]

The literature examining sex differences in behavioural thermoregulation in humans is limited. In thermoneutral environments, women are more sensitive to warm stimuli than men,[25] and perceive a given thermal stimulus to be hotter.[26] It might be anticipated that this would lead female soldiers to initiate behavioural thermoregulatory responses earlier than male soldiers, however, the upper temperature-limit of the thermal comfort zone does not differ between sexes.[27] At present it is clear that further research is required to gain an adequate understanding of any sex differences in behavioral thermoregulation, as well as the relevance, if any, to soldiers operating in GCC roles.

3.2 Autonomic

Cutaneous vasomotion and sudomotion are the autonomically controlled mechanisms for heat-loss. Autonomic thermoeffector activity is mainly determined by afferent information relating to T_C and T_{sk} *i.e.* weighted mean body temperature (T_b).[28] Vasomotion represents the initial autonomic thermoregulatory mechanism, whereby cutaneous vasodilatation increases skin blood-flow, facilitating convective heat transfer to the skin. Sweat evaporation is the predominant heat-loss mechanism during exercise in hot environments and when ambient temperature exceeds T_{sk}. In hot-arid environments the limits of thermal compensability are determined by sweating capacity, but in saturated environments sweating is ineffective due to an insufficient water vapour pressure gradient between the skin and the environment to enable evaporation.

At rest, sweating onset occurs at a higher ambient,[29] or mean T_b,[30 31 32] in women than in men. Sweating sensitivity may also be lower in women.[32] Together this causes a lower sweat rate in women during resting heat exposure.[30] Conversely, women may have a greater skin blood flow during passive heating.[32] Together these data support the assertion that women are more reliant on cutaneous vasodilation and less reliant on sweating than men.[30] However, these passive-heating studies did not control for anthropometric factors· Although this design consideration may be of little practical relevance in a GCC context, the extent to which the differences in these studies are due to sex *per-se* is unclear. Indeed, irrespective of sex, smaller individuals are more suited to passive heat-loss due to their greater A_D/m ratio. This enables them to rely more on vasomotor changes to regulate body temperature, such that it may be efficient for the sudomotor threshold to occur at a higher T_b.[12]

Many studies examining sex differences in thermoregulation during exercise have examined a standardised relative work rate (%VO_{2max}). These typically show women to have a lower sweating rate compared to men. [16 17 18 21 33] Lower sweating has also been reported during treadmill walking at a given speed in the heat.[10 22 34 35] In contrast, the increase in T_{re} was either greater in women than men,[21 33] or similar,[16 17 18] at a given relative work rate, whereas during treadmill walking the increase was either less in women,[22 35] not different between sexes,[34] or higher in women than men in a hot-arid environment, and lower in women than men in a hot–humid environment.[10]

However, as highlighted in Section 2.2, these approaches to standardising work rate can be confound the isolation of sex differences. For example, Schwiening *et al.*[19] demonstrated that the sex differences in sweating reported by Ichinose-Kuwahara *et al.*[18] could simply be explained by differences in MHP, whereas Gagnon and Kenny[36] demonstrated that evaporative heat-loss was strongly associated with MHP (r^2=0.82), irrespective of sex. Similarly, the differential effects of environment on increases in T_{re} reported by Shaprio *et al.*[10] may have been influenced by anthropometry. During load bearing exercise in hot-humid conditions, smaller individuals, with a high A_D/m ratio, produce and store less heat than larger indiviudals:[11] this could favour smaller, *i.e.* female, soldiers. However, the beneficial effect of a high A_D/m ratio is less pronounced under conditions where a greater water vapour pressure gradient exists between the skin and environment and higher sweat rates may be advantageous. Although these are important methodological considerations, they may be of reduced practical relevance in a military context where these anthropometric factors and fitness might differ between the typical male and female soldier. Therefore, some anthropometric characteristics of the average female soldier could be advantageous in hot-humid conditions, although this effect may be lessened within GCC cohorts because of the possibility of less distinct anthropometric and fitness differences between males and females serving in these roles.

Recent studies have controlled for some of these confounding methodological and physiological factors in order to isolate the effects of sex on thermoregulation. Gagnon and Kenny[36] demonstrated that, compared to men, women who were matched for body mass and A_D demonstrated a reduced evaporative heat-loss during exercise in a hot-arid environment (35°C; 12 %rh) at a fixed MHP (500 W). In a subsequent study, Gagnon and Kenny[37] examined MHP rates of 200, 250 and 300 $W \cdot m^{-2}$ of body surface area; a fixed MHP during non-weight-bearing exercise (i.e. cycling) negates the influence of differences in body mass, whilst adjusting MHP per unit A_D negates differences in the A_D available for heat exchange. Only at the highest work rate was the evaporative heat-loss less in women than men, due to a lower sweat output per gland. This reduced sweating sensitivity in women is consistent with studies using pharmacological approaches to stimulate sweating in groups of men and women,[38] and given the controls employed, suggests that, at higher work rates, a 'true' sex difference in sudomotor function exists.

Nevertheless, some of these recent studies have been criticised for investigating a narrow anthropometric range that is not representative of the population[12] and as such the utility of these findings may be limited within a military context. Notley *et al.*[12] examined the thermoeffector responses during light (MHP=135 W·m^{-2}) and moderate (MHP=200 W·m^{-2}) exercise in the heat (28°C; 36 %rh) in a sample of men and women spanning a wide and overlapping anthropometric range. Using hierarchical multiple linear regression, they demonstrated that, after controlling for body fat, VO_{2max} and mean T_b, the A_D/m ratio explained 10-48% of the variance in thermoeffector response; small individuals with a higher A_D/m ratio were more reliant on cutaneous vasomotion whereas larger individuals were more reliant on evaporation of sweat . Furthermore, once the A_D/m ratio had been accounted for, sex explained ≤5% of variance in thermoeffector response. Thus, in a sample that are anthropometrically representative of the wider population range, thermoeffector function appears more dependent on fitness and anthropometry than sex. However, this study only investigated low and moderate work rates and so direct comparison cannot be made with the lower sweating that has been reported in women at higher work rates.[37]

In summary, women who are representative of the wider military population may be more reliant on cutaneous vasomotion to regulate body temperature, and less reliant on sweating, compared to men. However, this may be mainly due to anthropometric and fitness differences rather than a 'true' sex difference, and these effects could be less pronounced among males and female in GCC roles if anthropometric and fitness differences are less distinct. When studies control for relevant anthropometric factors and fitness, thermoregulatory differences between men and women are diminished, although women may still sweat less than men at higher work rates.

4 Hormonal influences

4.1 Effect of menstrual cycle

The influence of sex hormone changes over the menstrual cycle on thermoregulation is summarised in a recent review.[39] Briefly, T_C fluctuates over the course of the menstrual cycle. Oestrogens act on temperature regulating structures within the hypothalamus, increasing the activity of warm sensitive neurons[40] and lowering the temperature thresholds for sweating and cutaneous vasodilatation.[32 41] Thus, in eumenorrhoeic women, T_C is at its lowest during the late-follicular phase, coincident with the peak in oestrogen concentration. In the mid-luteal phase progesterone concentration is at its highest, which increases the thresholds for cutaneous vasodilatation and sweating, elevating T_C by ~0.5°C.[32 41 42] Nevertheless, recent evidence employing a whole body direct calorimetry approach suggests that menstrual cycle phase does not appear to affect the rates of whole body heat loss or heat storage across a range of exercise intensities. However, it is important to note that the changes in body heat content during the mid-luteal phase trial occurred in the context of on an elevated initial resting T_C compared to the trials conducted during the early and late follicular phases.[43] Some studies suggest that there are alterations in thermo-sensation over the menstrual cycle,[44 45] but any influence on behavioural thermoregulation is poorly understood.

Fluctuations in T_C may be attenuated in trained women, possibly due to their smaller changes in sex hormone concentration during the menstrual cycle,[46] and thus it might be hypothesised that the physical training undertaken by women in GCC roles may lessen the degree of fluctuation in T_C typically seen over the menstrual cycle. However, there is limited research comparing the thermoregulatory responses of amenorrheal and eumenorrheal women to exercise heat-stress. On the basis of data obtained from a single pair of monozygotic twins (one eumenorrheal and one amenorrheal) Frye *et al*.[47] concluded that there were no thermoregulatory differences during exercise heat-stress. Clearly more research is needed, particularly given the reported prevalence of amenorrhea and dysmenorrhea among military women[48] and the observation that intense military training may increase the prevalence of menstrual irregularity.[49] Indeed, data from post-menopausal women suggests that their lower oestrogen levels are associated with an elevated T_C, which can be reduced through the effects of exogenous oestrogen therapy lowering the temperature threshold for the heat-loss effector mechanisms.[50]

4.2 Hormonal contraceptives

Hormonal contraceptives commonly consist of combined (oestrogens and progestin), or progestin-only formulations. Studies examining the effects of oral hormonal contraceptives on thermoregulation have often used a within-participant design, comparing the placebo or no-pill phase (quasi-follicular) to the contraceptive phase (quasi-luteal). During the contraceptive phase there is an increase in the temperature thresholds for cutaneous vasodilatation and sweating and an elevated T_C.[51 52 53] However, the wide variations in oral contraceptive formulation and delivery (e.g. mono, biphasic or triphasic) result in variability in the hormones administered, which may influence their thermoregulatory effects.

Using a between-groups design, Armstrong *et al.*[54] examined the effect of different contraceptive hormones (oral contraceptive [estradiol-progestin] *vs*. injection [depot medroxyprogesterone acetate] *vs*. no contraceptive) on thermoregulation, before and after 8-weeks of heat acclimation and physical training. There were no between-groups differences in thermoregulation before the intervention, whereas after the intervention there were some small differences in thermoregulation, but the authors concluded they were small and did nor impart superior physical fitness or heat acclimation in any group. However, thermoregulatory assessments were only conducted during the follicular or quasi-follicular phase and it is unclear whether the same would be evident at other phases of the menstrual cycle.

5 Performance

5.1 Physical

A number of studies show women to have a lower tolerance,[21 28 55 56] or performance level,[57] than men during exercise in the heat, yet others report no sex differences in terms of tolerance,[17] or performance decline,[58] with increasing temperature. Some suggest women have a superior tolerance to heat.[22] However, as described in Section 2, these conclusions can be influenced by environmental conditions as well as the way in which the study controls factors such as MHP, aerobic fitness and anthropometry.

For example, Wyndham *et al.*[28] demonstrated that 8% of unacclimated women and 50% of unacclimated men could complete 4 hrs stepping at 1560 ft lb·min^{-1} in hot-humid (24°C; 89 %rh) conditions. However, it is unclear if groups were matched for fitness and the women were lighter, resulting in a smaller thermal 'sink'. Lower tolerance times were also shown for women than men during treadmill walking at 25-30 %VO_{2max} in a hot-arid environment (48°C; 14 %rh); although groups were matched for relative VO_{2max} and A_D, the women were significantly lighter.[21] Similarly, McLellan[55] demonstrated shorter tolerance times for women than men during intermittent walking in uncompensable conditions, whereas Dill *et al.*[57] demonstrated that men could complete 30-60 minute walks at a faster pace in 'desert heat' than women.

In contrast, Horstman and Christensen[17] demonstrated no sex difference in the tolerance to cycling at 40 %VO_{2max} in hot-arid conditions (45°C; 14 %rh) although estimations of MHP suggest that this may have been lower in the women than men. Likewise, Avellini *et al.*[22] reported that the tolerance of women during the pre-ovulatory stage of the menstrual cycle was superior to that of men during treadmill walking (5.6 $km.h^{-1}$; 2% gradient) at 36°C, 65 %rh. Although the women had a lower VO_{2max} (relative and absolute) and higher body fat percentage, the groups were not statistically different for mass, A_D, or A_D/m ratio. However, the women were, on average, ~7 kg lighter with a larger A_D/m ratio (+14.7 $cm^2 \cdot kg^{-1}$), which could be advantageous in humid conditions.[10] Furthermore, there were no sex differences in tolerance during the post-ovulatory phase. Others have also suggested that heat tolerance changes across the menstrual cycle, being reduced in the mid-luteal phase relative to the follicular phase,[22 42 52] although some studies have shown no differences.[21 59]

Given the varying experimental controls in the aforementioned studies it is unclear to what extent the reported differences were attributable to fitness, anthropometry, or sex. Kazman *et al.*[56] compared 55 men and 20 women during treadmill walking (5 $km \cdot h^{-1}$; 2% grade) for up to 120 minutes at 40°C and 40 %rh. Heat intolerance was defined as attaining a heart rate >150 $beats.minute^{-1}$ or T_C >38.5°C. Using hierarchical regression analysis, it was reported that women were 3.7 times more likely to be classified as heat intolerant than men. However, heat intolerant participants also had lower relative and absolute VO_{2max} and higher body fat percentage. Importantly, when these variables were entered into the regression equation sex became non-significant as a predictor of tolerance, indicating that the 'sex differences' were largely due to fitness and anthropometry rather than sex, *per se*.

Heat acclimation may influence sex differences in physical performance in the heat. Wyndham *et al.*[28] and Avellini *et al.*[22] reported that the thermoregulatory responses of men and women during exercise in humid-heat were more similar post-acclimation, with all participants subsequently able to complete the exercise tasks (4 hrs stepping and 3 hrs treadmill walking, respectively). However, differences in sweating rate, which in each case was lower in women pre-acclimation, remained,[28] or increased.[22] Moreover, in the study of Wyndham *et al.*[28] the pre-acclimation thermoregulatory strain was higher in women, but in Avellini *et al.*[22] the converse was true, whereas completion of the exercise tests does not enable evaluation of the *limits* of tolerance. Frye and Kamon[21] also reported that thermoregulatory function, including sweating, was more similar between sexes during exercise in a hot–arid environment post-acclimation, with all participants now able to complete a 3-hr treadmill walk. Finally, Horstman & Christensen[17] reported that the sweat rate and sensitivity of women increased with heat acclimation whereas men's remained unchanged. Women also demonstrated a greater reduction in T_{re} and heart rate, and although exercise tolerance was no different between men and women pre-acclimation, post-acclimation the women had a significantly longer tolerance time. More recent data also supports the possibility of sex differences in the pattern of heat acclimation, with women demonstrating a more rapid sudomotor adaption than men, but taking longer to achieve thermal and cardiovascular stability.[60]

Overall, the data examining sex differences in physical performance in the heat, before and after acclimation, are somewhat equivocal and it is difficult to draw firm conclusions. Many of these studies are underpowered and the findings heavily influenced by the variations in experimental design. The relevance of some studies within a military, or GCC, context is limited. In keeping with the thermoregulatory research, some more recent data suggests that the average women may be more intolerant to hot-dry environments than the average man, but these 'sex differences' are primarily due to the effects fitness and anthropometry rather than sex, *per se.* As such, they could be diminished in a GCC cohort, but further research is required to verify this hypothesis.

5.2 Cognitive

Numerous studies have shown that heat stress negatively effects cognitive tasks, including those with particular relevance for military roles, such as vigilance,[61] working and visual memory,[62 63] executive tasks,[64] and task planning.[65] However, others (*e.g.* Amos *et al*.[66]) have shown no effect of heat stress on aspects of cognitive performance. The broad consensus from recent reviews appears to be that simple cognitive tasks may be less vulnerable to heat stress than more complex tasks.[67 68]

There is limited research examining sex differences in cognitive performance in the heat. Wyon *et al*.[69] demonstrated that performance of some cognitive tasks (*e.g.* sentence comprehension, recognition memory) declined in both sexes beyond an ambient temperature of ~27°C. However, in a multiplication task, the female participants maintained performance beyond 28°C, whereas the performance of males declined. It was suggested that this was due to a higher thermal discomfort in the men, although this is at odds with research suggesting that there is no sex-effect on thermal comfort.[27] It has also been speculated that the influence of heat stress on cognition might be related to the initial skill level;[67] men may have better visuo-spatial and mathematical abilities than women,[70] whereas women may have superior verbal skills.[71] Gaoua[67] also highlights sex differences in neurotransmitters which could influence arousal, and potentially affect cognitive performance. However, these assertions are largely speculative and further research, utilising cognitive tasks that have relevance within the military context, is needed to understand the influence of sex on cognitive performance in the heat.

6 Heat illness

Heat illness encompasses a spectrum of conditions ranging from light-headedness through to heat stroke and death. Between 2006 and 2010, 25.5 men and 12.7 women per 100,000 population, per year, presented to USA Emergency Departments with heat illness not requiring admission.[72] Similarly, the incidence of heat-related illnesses requiring Emergency Department visitations in Florida is higher in men than women during summer months, with a crude rate ratio of 5.91 per 100,000 worker years and 2.77 per 100,000 person years for work, and non-work heat-related illnesses, respectively.[73] The Centers for Disease Control and Prevention USA[74] reported 2,271 male and 1,135 female deaths from extreme heat exposure between 1999 and 2003, with a death rate of 0.8 per million population in men and 0.3 per million population in women during an extreme heat event in 2012.[75] In Adelaide, South-Australia, 36 male and 18 female deaths were reported during a 2009 heat-wave,[76] whereas between 2006 and 2010, 0.024 men and 0.006 women per 100,000 population, per year, died in Emergency Departments in the USA from heat-related illness.[72] Among military populations, heat stroke rates are higher in men than in women soldiers, although the rates of other heat illness were higher in women than men.[77]

The reasons for the reported sex differences in heat illness rates are not clear, and possibly contrary to that which might be expected based upon the thermoregulatory differences between men and women described in section 3.2. Heat stroke has an inflammatory component occurring in the context of an elevated T_C,[78] but recent research suggests that sex has no effect on intestinal epithelial injury and permeability, and minimal effect on the systemic cytokine response to exertional heat stress.[79] Alternatively, incidence analyses may not take into account differences in the type of activity that have historically been undertaken by men and women, which might demand different rates of MHP, or levels of heat exposure. There may also be relevant behavioural differences; women demonstrate more circumspect attitude towards the health effects of high heat and more precautionary behaviours than men.[80] However, for individuals operating in GCC roles the opportunity to undertake sex-specific physical activities and exercise sex-dependent precautionary behaviours will be limited, and thus the relevance of these data in a GCC context is unclear.

7 Summary

The factors underpinning population level sex differences in males and females in response to exercise heat-stress are summarised in table 1. 'True' sex differences in thermoregulation between men and women are relatively limited, and appear confined to lower sweat rates at higher work rates. Nevertheless, relative to male soldiers, female soldiers are, on average, less aerobically fit, lighter, with a smaller A_D and a higher A_D/m ratio and percentage body fat. These differences may increase the cardiovascular strain of a given task, reduce the rate of heat exchange with the environment, increase reliance on vasomotor changes to regulate body temperature, and lessen the size of the thermal 'heat sink'. Moreover, women may be at a greater thermoregulatory disadvantage during the mid-luteal phase of the menstrual cycle, although some recent data challenges this assertion. However, during load-bearing exercise, lighter individuals have a lower MHP. Overall, these factors mean that, relative to men, women who are representative of the wider military population might be at a thermoregulatory disadvantage in many hot environments, particularly at higher work rates in hot-arid conditions, but this may be lessened in conditions favouring a high A_D/m ratio, where higher sweat rates are of little benefit (hot-humid).

The purported thermoregulatory differences between men and women are consistent with some studies examining sex differences in physical performance in the heat, although there are inconsistencies between studies. Any sex differences may be secondary to the influences of fitness and anthropometric factors and might be lessened with heat acclimation. Heat illness incidence data appear at odds with the apparent thermoregulatory differences between men and women *i.e.* lower heat illness and/or heat stroke incidence in women than men. However, some analyses may not adequately account for sex differences in activity profiles and exposure risk.

Finally, it is important to acknowledge that women who pass current and future gender-free physical employment standards to undertake GCC roles may be fitter, with a lower fat mass than the average female soldier. If they are more similar to their male counterparts then the thermoregulatory and performance differences attributed primarily to fitness and some anthropometric factors may be diminished. Likewise the opportunities for sex differences in activity profiles and exposure risk for those operating GCC roles are likely to be limited, which may limit the relevance of much of the extant heat-illness incidence data. In many areas the literature is of poor quality and does not examine individual's representative of those operating in military roles, undertaking relevant tasks at an appropriate pace, in representative environmental conditions, whilst wearing appropriate operational equipment. In some areas, e.g. behavioural thermoregulation and cognition, further work is urgently required to adequately understand sex differences in the heat that are relevant within a GCC context

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10 Tables

Table 1: Summary of factors underpinning population level sex differences in males and females in response to exercise heat-stress.

Factor	Difference	Significance
Anthropometric		
Mass	Lower in females than males	Low body mass reduces the size of the 'heat sink', resulting in a bigger body temperature increase for a given heat storage. Those with a low body mass have lower metabolic heat production during load bearing exercise.
Body composition	Higher percent body fat in females than males	The heat specific capacity of adipose tissue is less than 'lean' tissue. Individuals with higher body fat percentage will have a greater increase in body temperature for a given change in heat content.
Body surface area	Lower in females than males	Heat-transfer potential with environment is lower with a small body surface area. May be disadvantageous in conditions favouring heat loss or beneficial in conditions favouring heat gain from the environment
Body surface area: mass (A_D/m) ratio	Higher in females than males	High A_D/m ratio affords a large surface are for heat exchange relative to metabolic heat production which may result in lower heat production and less heat storage in some hot environments. May affect heat loss mechanisms (see vasomotion, below).
Fitness		
VO_{2max}	Lower in females than males	At a given absolute work rate competition between muscle and skin for blood flow is greater in those with a low VO_{2max}, this increases the cardiovascular component of thermoregulation. Sweating is lower at high work rates in those with a low VO_{2max}.
Thermoregulatory		
Behavioural thermoregulation	Females may be more sensitive to heat than males	Some limited evidence to support greater female sensitivity to heat, but does not appear to affect upper limit of thermal comfort. Effect on behavioural thermoregulation (if any) is unclear.
Vasomotion	May be more important in females than males	A high A_D/m ratio may increase the reliance on vasomotion for heat loss.
Sudomotion	Possibly lower in females than males at high work rates	Sweating rates may be lower in females than males during exercise at high work rates, even when key anthropometric differences are controlled for.
Hormonal		
Female sex hormones	N/A	Deep body temperature is highest (+0.5°C) in the mid-luteal and lowest in late follicular phase of the menstrual cycle due to changes in concentration of oestrogen and progesterone. Some evidence that this may not adversely affect heat loss or storage during exercise.