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SEX-RELATED DIFFERENCES IN THERMOREGULATORY RESPONSES WHILE WEARING PROTECTIVE CLOTHING

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ORIGINAL ARTICLE

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Sex-related differences in thermoregulatory responses while wearing protective clothing

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Abstract This study examined the thermoregulatory responses of men (group M) and women (group F) to uncompensable heat stress. In total, 13 M [mean (SD) age 31.8 (4.7) years, mass 82.7 (12.5) kg, height 1.79 (0.06) m, surface area to mass ratio 2.46 (0.18) $m^2 \cdot kg^{-1} \cdot 10^{-2}$, Dubois surface area 2.01 (0.16) m^2, %body fatness 14.6 (3.9)%, $\dot{V}O_{2peak}$ 49.0 (4.8) $ml \cdot kg^{-1} \cdot min^{-1}$] and 17 F [23.2 (4.2) years, 62.4 (7.7) kg, 1.65 (0.07) m, 2.71 (0.14) $m^2 \cdot kg^{-1} \cdot 10^{-2}$, 1.68 (0.13) m^2, 20.2 (4.8)%, 43.2 (6.6) $ml \cdot kg^{-1} \cdot min^{-1}$, respectively] performed light intermittent exercise (repeated intervals of 15 min of walking at 4.0 $km \cdot h^{-1}$ followed by 15 min of seated rest) in the heat (40°C, 30% relative humidity) while wearing nuclear, biological, and chemical protective clothing (0.29 $m^2 \cdot °C \cdot W^{-1}$ or 1.88 clo, Woodcock vapour permeability coefficient 0.33 i_m). Group F consisted of eight non-users and nine users of oral contraceptives tested during the early follicular phase of their menstrual cycle. Heart rates were higher for F throughout the session reaching 166.7 (15.9) beats $\cdot$ min^{-1} at 105 min (n = 13) compared with 145.1 (14.4) beats $\cdot$ min^{-1} for M. Sweat rates and evaporation rates from the clothing were lower and average skin temperature ($\bar{T}_{sk}$) was higher for F. The increase in rectal temperature (T_{re}) was significantly faster for the F, increasing 1.52 (0.29)°C after 105 min compared with an increase of 1.37 (0.29)°C for M. Tolerance times were significantly longer for M [142.9 (24.5) min] than for F [119.3 (17.3) min]. Partitional calorimetric estimates of heat storage (S) revealed that although the rate of S was similar between genders [42.1 (6.6) and 46.1 (9.7) $W \cdot m^{-2}$ for F and M, respectively], S expressed per unit of total mass was significantly lower for F [7.76 (1.44) $kJ \cdot kg^{-1}$] compared with M [9.45 (1.26) $kJ \cdot kg^{-1}$]. When subjects were matched for body fatness (n = 8 F and 8 M), tolerance times [124.5 (14.7) and 140.3 (27.4) min for F and M, respectively] and S [8.67 (1.44) and 9.39 (1.05) $kJ \cdot kg^{-1}$ for F and M, respectively] were not different between the genders. It was concluded that females are at a thermoregulatory disadvantage compared with males when wearing protective clothing and exercising in a hot environment. This disadvantage can be attributed to the lower specific heat of adipose versus non-adipose tissue and a higher percentage body fatness.

Key words Rectal temperature · Heat storage · Gender · Body composition · Aerobic fitness

Introduction

In current industrial and military settings, personnel may be required to wear protective clothing to maintain work schedules in a hazardous environment. This requirement does not differentiate between the sexes or any physical characteristic of the individual who must wear the protective ensemble. Typically the protective clothing has a reduced water vapour permeability. Thus the clothing limits the evaporation of sweat, thereby increasing the rate of heat storage for a given rate of heat production. The extent of the heat strain associated with wearing nuclear, biological and chemical (NBC) protective clothing is well documented for males at different ambient temperatures, vapour pressures and metabolic rates (Carter and Cammermyer 1985; Goldman 1963; Henane et al. 1979; McLellan 1993; McLellan et al. 1993; Montain et al. 1994). Some limited information has been reported for females (Kolka et al. 1994; Kolka and Stephenson 1995) but no direct gender comparisons have been documented. Since tolerance to hot environments can be predicted from the rate of heat storage ($\dot{S}$) (Craig et al. 1954; Goldman et al. 1965), it is important to know whether sex-related differences exist for $\dot{S}$ when protective clothing is worn.

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Results from studies reported some 20–30 years ago documented the importance of an increased aerobic fitness (Piwonka et al. 1965) and a decreased body fatness (Buskirk et al. 1965, 1969) for enhancing tolerance to a hot environment. In addition, Shvartz et al. (1973) demonstrated that a larger surface area to mass ratio would be beneficial for thermoregulation during exercise in a warm and dry climate. On average, women typically have a lower aerobic fitness and an increased body fatness compared with males (Dill et al. 1977; Shapiro et al. 1980) Also, the advantage of a larger surface area to mass ratio for radiative and convective heat exchange, as is typically documented for females (Nunneley 1978), disappears in hot climates if the ambient temperature exceeds skin temperature (Shvartz et al. 1973). Thus, based on these characteristics alone, one might expect women to be at a thermoregulatory disadvantage when wearing protective clothing in a hot environment. However, wearing protective clothing in a hot and dry ambient environment creates a hot and wet microenvironment within the clothing layers of the protective ensemble which restricts evaporative heat loss (McLellan et al. 1996). During exposure to hot and humid conditions, Shapiro et al. (1980) reported that women of lower aerobic fitness and higher body fatness were at a thermoregulatory advantage compared with males during light exercise. This advantage was attributed to the larger surface area to mass ratio for the women which allowed a more effective evaporative heat loss to the humid environment.

An increased sweat rate while wearing the protective clothing ensemble will eventually lead to an increased evaporative heat loss if tolerance times are long enough to allow significant quantities of water vapour to move through the clothing layers and be evaporated to a drier ambient environment (Aoyagi et al. 1994, 1995; McLellan and Aoyagi 1996). Therefore, the higher sweat rates of males, despite the lower surface area to mass ratio compared with females (Morimoto et al. 1967; Shapiro et al. 1980), may be an advantage in promoting evaporative heat loss when protective clothing is worn. Conversely, the higher sweat rates may only lead to a faster rate of dehydration (Aoyagi et al. 1994).

Wearing the protective clothing and exercising in a hot environment creates a condition of uncompensable heat stress where the required evaporative cooling necessary to maintain thermal equilibrium at an elevated core temperature exceeds the evaporative capacity of the environment (represented by the clothing and the ambient conditions). As a result, core temperature continues to increase, reflecting the constant gain in body heat. The severity of the uncompensable environment is determined by the interaction of the ambient temperature and vapour pressure, the metabolic rate and the characteristics of the clothing ensemble. The heat stress index, or the ratio of the required evaporative cooling to the evaporative capacity of the environment, was calculated as 2.1 for the conditions of this study (McLellan 1996). This level of heat stress is greater than the conditions imposed by others who have studied thermoregulatory responses of men and women in hot-dry (Bittel and Henane 1975; Shapiro et al. 1980; Shvartz et al. 1973) or hot-wet conditions (Shapiro et al. 1980). As a result, it is not known whether the sex-related differences in thermoregulation reported for less severe heat stress conditions would be applicable for individuals wearing protective clothing and exercising in a hot environment. Thus, the purpose of the present study was to compare the thermoregulatory response of males and females during exposure to uncompensable heat stress. The women were tested during the early follicular phase of their menstrual cycle to eliminate the disadvantage of an elevated resting core temperature during the luteal phase of the cycle on thermoregulation during exercise (Stephenson and Kolka 1993). Despite the higher surface area to mass ratio for women, it was hypothesized that they would be at a disadvantage while wearing the protective clothing in a hot environment because of their lower sweat rates and fitness levels, and higher body fatness compared with their male counterparts.

Methods

Subjects

Following approval from the institute's human ethics committee, 17 females (eight non-users and nine users of oral contraceptives) and 13 males volunteered to participate in the study. No subjects were heat acclimated prior to the beginning of the experiment. The women were evaluated during the early follicular phase (days 2–5) of their menstrual cycle when endogenous progesterone and estrogen levels (verified by radioimmunoassay) were low and when, for the users of oral contraceptives, exogenous synthetic hormone supplementation was zero during the week of menstrual flow. Subjects were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination to ensure that there were no medical contraindications to their participation in the experiment, each subject gave informed consent prior to the first day of data collection.

Determination of peak aerobic power ($\dot{V}O_{2peak}$)

$\dot{V}O_{2peak}$ was determined on a motor-driven treadmill using open-circuit spirometry before the series of experiments in the climatic chamber. Following 2 min of running at a self-selected pace, the treadmill grade was increased at 1% $\cdot$ min^{-1} until subjects were running at a 10% grade. Treadmill speed was then increased 0.22 m $\cdot$ s^{-1} (0.8 km $\cdot$ h^{-1}) each minute until the subject could no longer continue. $\dot{V}O_{2peak}$ was defined as the highest $\dot{V}O_2$ observed during the incremental test. Heart rate (HR) was monitored throughout the incremental test using a telemetry unit (Polar Electro PE3000, Stamford, CT). The HR value recorded at the end of the exercise test was termed HR_{peak}.

Determination of body fatness

Body fatness (BF) was estimated from the sum of five skinfold measurements (biceps, subscapular, suprailiac, abdomen and front thigh) and a population-specific regression equation relating body density determined from underwater weighing and this sum of skinfold thickness (Forsyth et al. 1984).

Experimental design

All subjects first performed a familiarization trial and then an experimental session separated by a minimum of 3 days and a maximum of 7 days. For both sessions subjects wore underwear or jogging shorts, cotton/polyester T-shirt or sports bra, socks, jogging shoes, a cotton and polyester blend combat jacket and trousers, a semipermeable NBC protective overgarment, impermeable overboots and gloves, and a C4 respirator. Women wore small and medium sizes of the NBC overgarment while the men wore medium and large. The total thermal resistance of this ensemble determined using a heated copper manikin was 0.29 $m^2 \cdot {}^{\circ}C \cdot W^{-1}$ (1.88 clo) and the Woodcock vapour permeability coefficient (i_m) determined with a completely wetted manikin was 0.33 (Gonzalez et al. 1993). Variation in thermal and water vapour resistance values for men's and women's sized garments was less than 3% (R.R. Gonzalez, personal communication). All trials were conducted in the late winter and early spring months and were performed at the same time of day for a given subject. Subjects were also asked to avoid alcohol on the day before and caffeine during the morning of each trial. Each session involved alternating 15 min of walking on a level treadmill at 1.11 $m \cdot s^{-1}$ (4.0 $km \cdot h^{-1}$) and 15 min of seated rest in the environmental chamber set at 40°C, 30% relative humidity and a wind speed less than 0.1 $m \cdot s^{-1}$. All trials continued for a maximum of 5 h or until rectal temperature (T_{re}) reached 39.3°C, HR remained at or above 95% of HR_{peak} for 3 min, nausea or dizziness precluded further exercise, the subject asked to be removed from the chamber, or the investigator removed the subject from the chamber.

Dressing and weighing procedures

Subject preparation, insertion of the rectal thermistor and placement of skin thermistors have been detailed previously (Aoyagi et al. 1994; McLellan et al. 1993). Both nude and dressed weights were recorded prior to entry into the chamber. The weight of the clothing ensemble and thermistor harness approximated 8 kg. Upon entering the chamber, the subject's skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer and 2934A printer) and the exercise began. Mean values over 1-min periods for T_{re} and a 12-point weighted mean skin temperature ($\bar{T}_{sk}$) (Vallerand et al. 1989) were calculated, recorded and printed by the data acquisition system. HR was recorded every 5 min from the display on the telemetry receiver. Subjects were allowed the equivalent of one canteen (approximately 1 l) of water during the exposures. After the completion of each trial, dressed weight was recorded within 1 min after exit from the chamber and nude weight was recorded following a 5-min undressing procedure.

Differences in nude and dressed weights before and after each trial were corrected for fluid intake and respiratory and metabolic weight loss (see below). The rate of sweat production was calculated as the difference between the corrected pre-trial and post-trial nude weights, divided by tolerance time, which was defined as the difference in time between removal from and entry into the environmental chamber. Evaporative sweat loss was calculated from the differences in pre- and post-trial corrected dressed weights.

Gas exchange analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation ($\dot{V}_E$) and oxygen consumption ($\dot{V}O_2$) using a 2-min average obtained every 15 min. For all trials, an adaptor was attached to the respirator which allowed expired air to be collected. Respiratory water loss was calculated using the $\dot{V}O_2$ measured during the trial and the equation presented by Mitchell et al. (1972). Metabolic weight loss was calculated from $\dot{V}O_2$ and the respiratory exchange ratio (R) using the equation described by Snellen (1966).

Heat balance calculations

The rate of heat storage ($\dot{S}$ in $W \cdot m^{-2}$) was calculated from the heat balance equation,

$$\dot{S} = \dot{M} - \dot{W} + (\dot{R} + \dot{C}) + \dot{K} - \dot{E}_{resp} + \dot{C}_{resp} - \dot{E}_{sk}.$$

The rate of metabolic heat production, $\dot{M}$, was determined from the measured $\dot{V}O_2$, R and the Dubois surface area, A_D, as (Nishi 1981)

$$\dot{M} = 352(0.23 \cdot R + 0.77)(\dot{V}O_2 \cdot A_D^{-1}).$$

The external rate of work performed ($\dot{W}$) was considered to be zero since the subjects either walked on a level treadmill or sat in a chair.

The rate of radiative and convective heat exchange, $\dot{R}$ and $\dot{C}$, contributed to a positive heat storage since the chamber temperature exceeded skin temperature. For the walking periods of this study, $\dot{R}$ and $\dot{C}$ were estimated using the total insulative value of the NBC clothing ensemble, I_T, of 0.291 $m^2 \cdot {}^{\circ}C \cdot W^{-1}$ (or 1.88 clo) determined at a wind speed of 1.12 $m \cdot s^{-1}$ on a heated and dry articulating copper manikin (Gonzalez et al. 1993), and the difference between the chamber temperature of 40°C and $\bar{T}_{sk}$ averaged over each 5-min interval, as (Gonzalez et al. 1993)

$$\dot{R} + \dot{C} = (40 - \bar{T}_{sk})/0.291.$$

For the periods of seated rest, the higher I_T of 0.364 $m^2 \cdot {}^{\circ}C \cdot W^{-1}$ (2.35 clo) was used for this calculation (Gonzalez et al. 1993).

Conductive heat gain, $\dot{K}$, during the periods of seated rest was estimated from previous work in our laboratory as 3 $W \cdot m^{-2}$ (Aoyagi et al. 1996).

Respiratory evaporative heat loss, $\dot{E}_{resp}$, and convective heat gain, $\dot{C}_{resp}$, were calculated from the chamber vapour pressure, P_A, of 2.21 kPa for 40°C and 30% relative humidity, and the respired vapour pressure, P_{resp}, of 5.32 kPa which assumes 100% saturation of expired air at a mouth temperature, T_{resp}, of 34°C for the chamber conditions (Livingstone et al. 1994), as (Fanger 1970)

$$\dot{E}_{resp} = 0.0173 \cdot \dot{M} \cdot (P_{resp} - P_a)$$

and

$$\dot{C}_{resp} = 0.0014 \cdot \dot{M} \cdot (T_a - T_{resp}).$$

Evaporative heat loss from the skin, $\dot{E}_{sk}$, was determined from the rate of sweat loss from the clothing, SE in $kg \cdot h^{-1}$, and the latent heat of vapourization, $\lambda = 675$ $W \cdot h \cdot kg^{-1}$, as

$$\dot{E}_{sk} = SE \cdot \lambda \cdot A_D^{-1}.$$

Statistical analyses

Data are presented as mean values and the standard deviation of the mean (SD). Comparisons were made for all subjects combined (17 females and 13 males), subjects matched for $\dot{V}O_{2peak}$ (10 females and 10 males), subjects matched for body fatness (8 females and 8 males), subjects matched for surface area to mass ratio (6 females and 6 males) and subjects matched for both $\dot{V}O_{2peak}$ and body fatness (6 females and 6 males). A one-factor (sex) ANOVA was used to evaluate any differences between males and females for sweat production, sweat evaporation, average metabolic rate, rate of heat storage, heat storage per unit of tissue mass, final T_{re} and $\bar{T}_{sk}$ temperatures, tolerance time, and the time for a 1.0° and 1.5°C increase in T_{re}. A two-factor (sex and time) repeated-measures ANOVA was performed for evaluating the changes in $\dot{V}O_2$, HR, T_{re} and $\bar{T}_{sk}$ during the exposure. When a significant F-ratio was obtained, a Newman-Keuls post-hoc analysis was used to isolate differences among treatment means. For all statistical analyses, the 0.05 level of significance was used.

ults

ject characteristics

h the exception of HR_{peak}, there was a significant -related difference for each of the physical charac-stics shown in Table 1. There were no differences ween the non-users and users of oral contraceptives any of these physical descriptors.

ices of heat strain

subjects (n = 17 females and 13 males)

erance to the heat stress test was determined by time, ically imposed endpoints, or subject exhaustion. ne of the trials approached the 5 h time limit. The ial familiarization session served to accustom sub-s to the protocol and any associated discomforts or to the actual test. In addition, the subject popu-on had served or were serving as subjects in other dies focusing on the influence of the menstrual cycle hydration on heat tolerance while wearing the NBC emble. Therefore, the subjects had experience of aring the clothing and appeared highly motivated. Of 30 test trials, 19 were terminated due to exhaustion female and 8 male). Of the remainder, 8 were terminated due to T_{re} reaching 39.3°C (4 female and 4 male) and 3 due to HR reaching 95% of maximum (2 female and 1 male). In all these cases, subjects reported that they were very near the point of exhaustion.

Mean tolerance times, the rate of sweat production and the rate of sweat evaporation from the clothing were significantly greater for the males (Table 2). There was no difference between sexes in the water consumed during the trial [149.9 (69.4) versus 121.6 (52.9) $ml \cdot h^{-1} \cdot m^{-2}$ for males females respectively]. The metabolic rate averaged over an equal number of exercise and rest periods was not different between genders when expressed relative to body mass [7.78 (1.77) versus 7.77 (1.66) $ml \cdot kg^{-1} \cdot min^{-1}$ for the females and males, respectively]. The average R was not different between the sexes. With the exception of the first rest period, HR values were significantly higher for the females throughout the trial, reaching 167 beats $\cdot$ min^{-1} or 85.8 (8.2)% HR_{peak} at 105 min compared with 145 beats $\cdot$ min^{-1} or 76.8 (7.9)% HR_{peak} for the males (Fig. 1). The higher HR for the women during the walking periods could be attributed to the fact that they were exercising at a higher relative intensity [28.0 (4.7) versus 23.0 (3.2)% $\dot{V}O_{2peak}$ for the women and males, respectively]. $\overline{T}_{sk}$ was also significantly higher for the females by 0.1°C to 0.2°C throughout the trial. Final $\overline{T}_{sk}$, however, was not different between sexes [37.63 (0.49) versus 37.79 (0.29)°C for the females and males, respectively]. Figure 2 reveals that the ΔT_{re} re-

le 1 Age, mass, height, body surface area (*BSA*), BSA to mass ratio, body fatness (*%BF*), $\dot{V}O_{2peak}$ and peak heart rate (HR_{peak}) for subjects combined or matched for $\dot{V}O_{2peak}$, %BF, BSA to mass ratio or both $\dot{V}O_{2peak}$ and %BF. Values are means (SD)

jects	Age (years)	Mass (kg)	Height (m)	BSA (m^2)	BSA/Mass ($m^2 \cdot kg^{-1}/10^2$)	%BF	$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	HR_{peak} ($beats \cdot min^{-1}$)
combined								
7 Females	23.2*	62.4*	1.65*	1.68*	2.71*	20.2*	43.2*	193.8
	(4.2)	(7.7)	(0.07)	(0.13)	(0.14)	(4.8)	(6.6)	(7.6)
3 Males	31.8	82.7	1.79	2.01	2.46	14.6	49.0	189.1
	(4.7)	(12.5)	(0.06)	(0.16)	(0.18)	(3.9)	(4.8)	(6.0)
$_{2peak}$								
0 Females	22.3*	60.0*	1.63*	1.64*	2.75*	18.8*	46.9	192.0
	(3.3)	(8.4)	(0.07)	(0.14)	(0.16)	(3.1)	(6.2)	(7.8)
0 Males	30.8	85.4	1.81	2.05	2.43	14.7	48.4	189.8
	(4.1)	(12.8)	(0.03)	(0.15)	(0.18)	(4.2)	(4.9)	(6.2)
BF								
Females	24.6*	60.7*	1.64*	1.65*	2.74*	17.3	45.7	192.0
	(5.4)	(8.4)	(0.08)	(0.14)	(0.15)	(2.3)	(7.9)	(8.4)
Males	32.3	86.9	1.79	2.06	2.38	17.2	47.3	190.0
	(4.2)	(10.5)	(0.08)	(0.16)	(0.12)	(2.2)	(3.3)	(5.8)
A/mass								
Females	24.3*	66.3*	1.68*	1.74*	2.64	19.7*	43.6	191.3
	(5.6)	(5.0)	(0.07)	(0.10)	(0.08)	(3.5)	(4.3)	(5.7)
Males	32.5	73.8	1.79	1.92	2.61	12.2	50.2	187.5
	(6.0)	(6.0)	(0.03)	(0.08)	(0.10)	(3.3)	(6.6)	(5.9)
$_{2peak}$, %BF								
Females	22.8*	59.7*	1.61*	1.62*	2.74*	17.8	46.3	189.3
	(4.1)	(8.7)	(0.08)	(0.15)	(0.16)	(2.6)	(3.7)	(8.8)
Males	32.3	90.1	1.83	2.11	2.35	17.7	46.9	190.2
	(4.5)	(10.2)	(0.04)	(0.14)	(0.11)	(2.1)	(3.8)	(6.6)

ignificant difference between the sexes

Table 2 Tolerance time, the time for rectal temperature (T_{re}) to increase 1.0°C, sweat rate and the rate of sweat evaporation for all subjects combined or matched for $\dot{V}O_{2peak}$, body fatness (*%BF*), body surface area to mass ratio (*BSA/mass*) or both $\dot{V}O_{2peak}$ and body fatness. Values are means (SD)

Subjects	Tolerance time (min)	Time for T_{re} to increase 1.0°C (min)	Sweat rate (kg · h^{-1} · m^{-2})	Evaporation rate (kg · h^{-1} · m^{-2})
All combined				
17 Females	114.4*	76.8	0.330*	0.124*
	(17.4)	(11.4)	(0.098)	(0.012)
13 Males	142.9	86.2	0.454	0.137
	(24.4)	(15.7)	(0.110)	(0.017)
$\dot{V}O_{2peak}$				
10 Females	119.3*	74.9	0.326*	0.126
	(17.6)	(14.1)	(0.119)	(0.012)
10 Males	145.2	88.5	0.464	0.140
	(26.7)	(16.7)	(0.096)	(0.018)
%BF				
8 Females	124.5	71.8*	0.362	0.124
	(14.7)	(10.6)	(0.123)	(0.012)
8 Males	140.3	92.3	0.411	0.135
	(27.5)	(15.8)	(0.106)	(0.021)
BSA/mass				
6 Females	119.0	82.8	0.351	0.128
	(16.1)	(12.6)	(0.095)	(0.010)
6 Males	143.5	80.5	0.469	0.133
	(25.1)	(10.2)	(0.121)	(0.012)
$\dot{V}O_{2peak}$,%BF				
6 Females	122.7	69.0*	0.334	0.125
	(16.8)	(9.5)	(0.121)	(0.014)
6 Males	141.8	95.0	0.438	0.139
	(30.9)	(17.3)	(0.105)	(0.023)

* Significant difference between the sexes

sponse was significantly greater for the females during the exposure to the hot environment. Initial T_{re} was not different between the females [37.13 (0.25)°C] and the males [37.05 (0.22)°C] but final T_{re} was lower for the women [38.75 (0.41)°C] compared with the men [39.02 (0.25)°C]. Figure 3 presents a cumulative heat exhaustion versus T_{re} curve for both genders similar to the curves presented by Montain et al. (1994) for clothed and unclothed individuals. The figure reveals that women end the exposure at a lower T_{re}.

The lower metabolic rates for the females throughout the trial [117.9 (9.5) W · m^{-2} versus 130.1 (11.2) W· m^{-2} for the males] were offset by a lower evaporative heat loss calculated from dressed weight changes [83.7 (8.2)

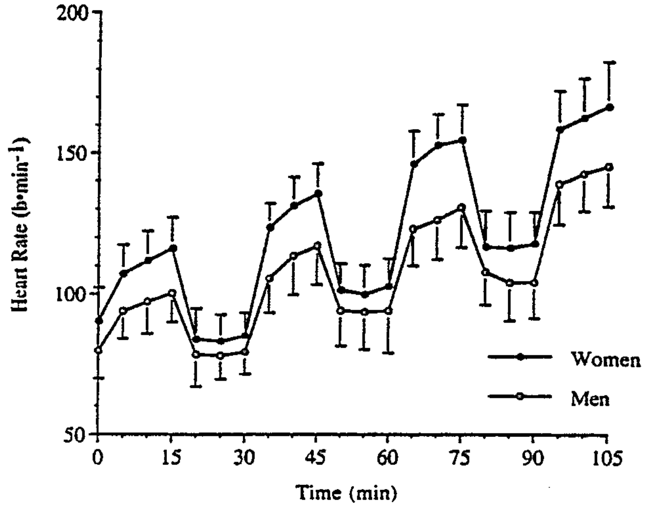


Fig. 1 Changes in heart rate during the alternating 15 min of treadmill walking and seated rest at 40°C and 30% relative humidity. n = 17 women and 13 men to 90 min, thereafter n = 13 for both men and women. Resting heart rates from minutes 20 to 30 were not significantly different. All other values were different between females and males

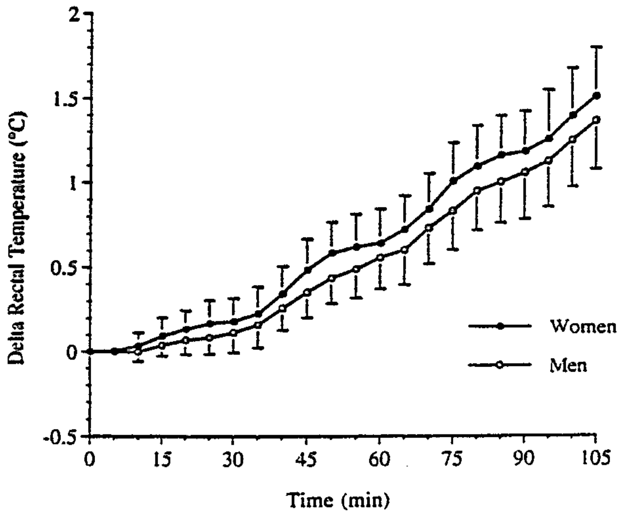
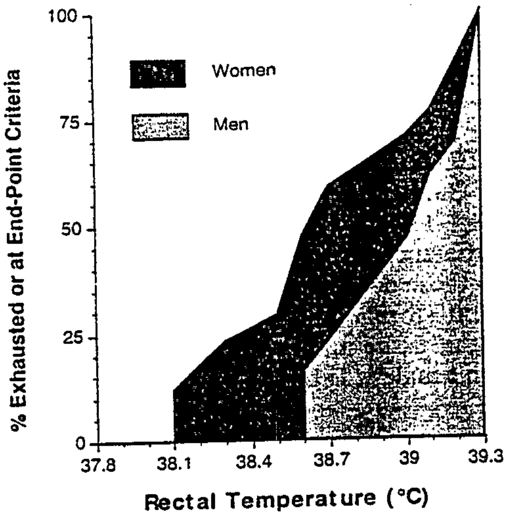


Fig. 2 Delta rectal temperature (ΔT_{re}) during the alternating 15 min of treadmill walking and seated rest at 40°C and 30% relative humidity. n = 17 women and 13 men to 90 min, thereafter n = 13 for both men and women. Women had a significantly higher ΔT_{re} averaged over the exposure



g. 3 A comparison of T_{re} associated with exhaustion or an end-int criteria expressed as a cumulative percentage for 17 women and men

ersus 91.3 (9.4) W · m^{-2} for the females and males, espectively] such that the rate of heat storage (W · m^{-2}) as similar between sexes (Table 3). Since $\dot{E}_{resp}$ and $_{resp}$ were estimated from the metabolic rate (see lethods) there were significant differences between exes for these components of the heat balance equaon. However, these combined differences were less than .6 W · m^{-2}. $\dot{R}+\dot{C}$ [10.2 (1.2) versus 10.1 (0.4) W · m^{-2} or the females and males, respectively] and $\dot{K}$ (estimated as 3 W · m^{-2}) heat gains were not different between sexes. Total heat storage and heat storage per unit of mass were significantly greater for the males (Table 3).

Subjects matched for $\dot{V}O_{2peak}$
(n = 10 females and 10 males)

With the exceptions of $\dot{V}O_{2peak}$ and HR_{peak}, the men and women differed for each of the physical characteristics shown in Table 1. $\dot{V}O_{2peak}$ was 46.9 (6.2) and 48.4 (4.9) ml · kg^{-1} · min^{-1} for the females and males, respectively. Tolerance times and sweat rates were still significantly different between genders (Table 2). The average metabolic rate, HR, $\overline{T}_{sk}$ and ΔT_{re} responses were identical to those described for all subjects combined. For this group of subjects, the ΔT_{re} had increased significantly more after 90 min for the females [1.24 (0.25)°C] compared with the males [1.01 (0.28)°C]. Final $\overline{T}_{sk}$ and T_{re} were not different between sexes. The rate of heat storage and heat storage per unit of lean tissue mass were not different between the males and females (Table 3).

Subjects matched for body fatness
(n = 8 females and 8 males)

Although these subjects were only matched for body fatness [17.3 (2.3)% for the females and 17.2 (2.2)% for

able 3 Calorimetric estimates f heat storage expressed as a ate (W · m^{-2}), as a total value kJ), and as values expressed er kg of total body mass *TBM*) or lean body mass *LBM*) for all subjects combined or matched for $\dot{V}O_{2peak}$, ody fatness (*%BF*), body surace area to mass ratio (*BSA/ nass*) or both $\dot{V}O_{2peak}$ and ody fatness. Values are means SD)

Subjects	Heat storage			
	(W · m^{-2})	(kJ)	(kJ · kg^{-1}TBM)	(kJ · kg^{-1}LBM)
All combined				
17 Females	42.1 (6.6)	483.4* (106.4)	7.76* (1.43)	9.90 (1.71)
13 Males	46.1 (9.9)	776.0 (147.6)	9.45 (1.23)	11.0 (1.57)
$\dot{V}O_2$peak				
10 Females	41.3 (7.1)	483.7* (118.4)	8.04 (1.63)	9.93 (1.93)
10 Males	44.8 (10.9)	779.8 (167.3)	9.19 (1.22)	10.71 (1.62)
%BF				
8 Females	43.0 (7.6)	528.2* (115.5)	8.67 (1.44)	10.51 (1.77)
8 Males	48.1 (8.1)	814.7 (134.2)	9.39 (1.04)	11.34 (1.32)
BSA/mass				
6 Females	40.8 (7.0)	505.1* (104.4)	7.60* (1.21)	9.44 (1.18)
6 Males	43.4 (11.4)	692.6 (109.1)	9.51 (1.59)	10.76 (1.89)
$\dot{V}O_{2peak}$, %BF				
6 Females	45.5 (5.3)	541.0* (108.6)	8.94 (1.45)	11.04 (1.61)
6 Males	47.6 (9.2)	832.1 (148.1)	9.23 (1.11)	11.22 (1.51)

* Significant difference between the sexes

the males]. $\dot{V}O_{2peak}$ also was not different between the sexes [45.7 (7.9) and 47.3 (3.3) ml · kg^{-1} · min^{-1} for the females and males, respectively] (Table 1). However, $\dot{V}O_{2peak}$ differed by more than 10 ml · kg^{-1} · min^{-1} for three of the subjects and by more than 5 ml · kg^{-1} · min^{-1} for an additional two subjects. Thus, although $\dot{V}O_{2peak}$ was not different between the sexes, it cannot be stated that subjects were matched for this measure. All other characteristics were different between the males and females (Table 1). Tolerance time, sweat rate and the rate of sweat evaporation from the clothing were not different between the sexes (Table 2). Similar differences between sexes for metabolic rate, $\bar{T}_{sk}$ and T_{re} were found as described above for all subjects combined. By 90 min of exercise T_{re} had increased 1.29 (0.25)°C for the females compared with 0.94 (0.23)°C for the males. The rate of increase in T_{re} was significantly faster for the females. Final $\bar{T}_{sk}$ and T_{re} were not different between the men and women. HR also were not different, reaching 155.6 (11.9) beats · min^{-1} or 81.1 (8.2)% HR$_{peak}$ at 105 min for the females and 150.1 (15.8) beats · min^{-1} or 79.1 (9.1)% HR$_{peak}$ for the males. The rate of heat storage and heat storage expressed per unit of total mass or lean tissue mass were not different between sexes (Table 3).

Subjects matched for surface area to mass ratio (n = 6 females and 6 males)

Surface area to mass ratio was 2.64 (0.08) m^2 · kg^{-1} · 10^{-2} for the females and 2.61 (0.10) m^2 · kg^{-1} · 10^{-2} for the males. $\dot{V}O_{2peak}$ and HR$_{peak}$ were not different for M and F. All other characteristics were different between the sexes (Table 1). Tolerance time, the rate of sweat production and the rate of sweat evaporation from the clothing were not different between men and women (Table 2). Differences in HR and $\bar{T}_{sk}$ were similar to those described for all subjects combined. The average metabolic rate throughout the trial was not different between the females [119.7 (10.8) W · m^{-2}] and the males [125.6 (9.3) W · m^{-2}]. Furthermore, the T_{re} response and the time for T_{re} to increase 1.0°C were not different. Final T_{re} was similar for the females [38.7 (0.5)°C] and the males [39.0 (0.2)°C]. Heat storage per unit of total mass was significantly lower for the females but these differences were not evident when heat storage was expressed per unit of lean tissue mass (Table 3).

Subjects matched for $\dot{V}O_{2peak}$ and body fatness (n = 6 females and 6 males)

$\dot{V}O_{2peak}$ and body fatness, respectively, were 46.3 (3.7) ml · kg^{-1} · min^{-1} and 17.8 (2.6)% for the females and 46.9 (3.8) ml · kg^{-1} · min^{-1} and 17.7 (2.1)% for the males. The other physical characteristics were different between the sexes (Table 1). Tolerance times, sweat rates and the rate of sweat evaporated from the clothing were not different between the men and women (Table 2). In addition, the average metabolic rate throughout the trial was similar for the females [122.8 (11.0) W · m^{-2}] and the males [131.7 (11.8) W · m^{-2}]. The HR response also was not different with values at 105 min being 155.2 (15.9) beats · min^{-1} or 82.4 (11.3)%HR$_{peak}$ and 151.2 (18.6) beats · min^{-1} or 79.6 (10.8)%HR$_{peak}$ for the females and males, respectively. Differences between sexes for $\bar{T}_{sk}$ and T_{re} were similar to those described for all subjects combined. The rate of heat storage and heat storage per unit of total mass or lean tissue mass were not different between the females and males (Table 3).

Grouping of subjects for final T_{re}

When subjects were separated into two distinct groups defined by a final T_{re} of 39.0°C and above (high T_{re}, $n = 15$, 7 females and 8 males) or 38.7°C and below (low T_{re}, $n = 13$, 10 females and 3 males), groups differed in tolerance time [140.5 (14.7) and 104.5 (11.5) min for high T_{re} and low T_{re}, respectively], $\dot{V}O_{2peak}$ [48.7 (7.0) and 41.9 (4.3) ml · kg^{-1} · min^{-1} for high T_{re} and low T_{re}, respectively] and body fatness [14.8 (3.5) and 21.7 (5.4)% for high T_{re} and low T_{re}, respectively]. Other physical descriptors such as age, height, weight, body surface area and surface area to mass ratio were not different between these groups. Metabolic heat production was not different but sweat rates and the rate of evaporative heat loss from the clothing were significantly greater for high T_{re}. The HR response was significantly higher for low T_{re} after the first and last treadmill walk [118.4 (9.7) beats · min^{-1} and 169.5 (12.6) beats · min^{-1}, respectively] compared with high T_{re} [104.0 (9.3) and 158.0 (11.6) beats · min^{-1}, respectively]. The rate of change in T_{re} and $\bar{T}_{sk}$ was not different between groups. Heat storage per unit of total mass was significantly greater for high T_{re} [9.1 (1.5) kJ · kg^{-1}] compared with low T_{re} [7.5 (0.4) kJ · kg^{-1}] but there was no difference between groups when heat storage was expressed per unit of lean tissue mass [10.6 (1.5) and 9.7 (1.8) kJ · kg^{-1} lean mass for high T_{re} and low T_{re}, respectively].

Power calculations

For the heat strain results with the different subject matchings described above, the reader should be aware that the power of the experimental comparisons would be affected by the changing number of subjects for each analysis. Outlined in Table 4 are the results of power calculations for the dependent measures of tolerance time and heat storage per unit of total mass for the different groups of subjects. Also presented are the number of subjects required to increase the power of the design to 0.8 if the original number of subjects matched for a particular physical characteristic failed to

Table 4 Calculation of the power $(1-\beta)$ of the experimental design and the number of subjects required to increase the power to 0.8 for the dependent measures of tolerance time and heat storage per unit of total mass for all subjects combined or matched for $\dot{V}O_{2\text{peak}}$, body fatness (*%BF*), body surface area to mass ratio (*BSA/mass*) or both $\dot{V}O_{2\text{peak}}$ and body fatness, and for subjects grouped according to their final rectal temperature

Subjects	Tolerance time		Heat storage	
	$(1-\beta)$	Subjects required to increase $1-\beta$ to 0.8	$(1-\beta)$	Subjects required to increase $1-\beta$ to 0.8
All combined	0.96	–	0.92	–
$\dot{V}O_{2\text{peak}}$	0.73	12	0.43	25
%BF	0.3	31	0.21	47
BSA/mass	0.52	12	0.66	9
$\dot{V}O_{2\text{peak}}$, %BF	0.28	26	<0.1	315
High and low T_{re}	0.99	–	0.86	–

achieve this level of power. The reader should also be aware that, in addition to the number of subjects, the difference between the treatment and measurement variances will also affect the power calculation. Thus, if there is little evidence of a treatment effect, the power of the experimental comparison would be quite low and a very large increase in the number of subjects involved in the analysis would be required to increase the power to 0.8. Such was the case for the dependent measures shown in Table 4 when subjects were matched for both body fatness and $\dot{V}O_{2\text{peak}}$, or for body fatness alone. These findings would imply that there is little, if any, difference between the sexes for tolerance time and heat storage per unit of total mass when they are matched for body fatness and aerobic fitness.

Discussion

Heat strain

The present study has revealed that women are at a thermoregulatory disadvantage compared with males when protective clothing is worn and light intermittent exercise is performed in a hot and dry ambient environment. At first glance, these findings appear consistent with results from earlier studies which compared thermoregulatory responses between the sexes during passive heating or exercise in a hot and dry environment when protective clothing was not worn (Bittel and Henane 1975; Fox et al. 1969; Morimoto et al. 1967; Shapiro et al. 1980; Wyndham et al. 1965). A lower $\dot{S}$ for males was attributed to an earlier onset of sweating (Bittel and Henane 1975) and an increased rate of sweating and evaporative heat loss to the dry environmental conditions (Fox et al. 1969; Morimoto et al. 1967; Wyndham et al. 1965). However, in the present study, our calorimetric estimate of $\dot{S}$ revealed no difference between men and women despite significantly higher T_{re}, $\overline{T}_{\text{sk}}$ and HR for the females throughout the trial. The protective clothing essentially eliminated any advantage of an elevated sweat rate for the males. The difference in the calculated evaporative heat loss between the sexes was approximately 10% of the difference in sweat rates (see Table 1). The small differences in evaporative heat loss between males and females were offset by the differences in the average metabolic rate expressed relative to surface area.

Given the hot and wet microenvironment within the protective clothing ensemble (McLellan et al. 1996) and the greater inefficiency of evaporative heat loss from sweating for the males, it might be more meaningful if our findings were compared with previous studies of males' and females' thermoregulatory responses in hot and humid environments. Shapiro et al. (1980) reported lower T_{re} and $\overline{T}_{\text{sk}}$ for females during light exercise and exposure to hot and humid environments. Based on these changes in T_{re} and $\overline{T}_{\text{sk}}$, thermometric estimates of the rate of heat storage were lower for the women (Shapiro et al. 1980). These findings stand in direct contrast to the results of the present study. The description of the subject characteristics for the 9 women and 10 men tested by Shapiro et al. (1980) were similar to those for our 17 women and 13 males and, thus, cannot account for the discrepancies. The subjects involved in this previous study by Shapiro et al. had undergone 6 days of heat acclimation to a hot and dry environment prior to being tested in the humid environments, whereas our subjects were not heat acclimated. Nevertheless, Avellini and co-workers (1980) reported findings similar to those documented by Shapiro et al. (1980) prior to heat acclimation for a small sample of males ($n = 4$) and females ($n = 4$) matched for aerobic fitness and exposed to a humid environment. We must conclude, therefore, that the conditions of uncompensable heat stress used in the present study cannot be compared with the humid test environments imposed by previous investigators (Avellini et al. 1980; Sawka et al. 1983; Shapiro et al. 1980). In the present investigation, the required evaporative cooling ($\dot{E}_{\text{req}}$, estimated as $\dot{M}+\dot{R}+\dot{C}+\dot{K}+\dot{C}_{\text{resp}}-\dot{E}_{\text{resp}}$) exceeded the maximum evaporative capacity of the environment [$\dot{E}_{\max}$, estimated as $16.5\cdot(i_{\text{m}}\cdot I_{T}^{-1})\cdot(P_{\text{sk}}-P_{\text{a}})$, (Gonzalez et al. 1993)] by approximately twofold (McLellan 1996). Although in the previous studies it would appear that $\dot{E}_{\text{req}}$ exceeded $\dot{E}_{\max}$, thus indicating that the heat stress was uncompensable, the ratio of these variables appeared to be less than 1.25. Thus, as the condition of uncompensable heat stress increases in severity the potential advantage of a larger surface area to mass ratio for increasing evaporative heat loss becomes less evident. Indeed, in the present study evaporative heat loss was actually reduced for the females despite their larger surface area to mass ratio.

Influence of body composition and aerobic fitness

Despite differences in T_{re} and $\bar{T}_{sk}$ between the sexes, the partitional calorimetric estimate of $\dot{S}$ was similar for males and females. Notwithstanding the potential overestimation of evaporative heat loss calculated from dressed weight changes (McLellan et al. 1996), the similar $\dot{S}$ but different T_{re} and $\bar{T}_{re}$ implies a different specific heat of the whole body for males and females. This is not too surprising given the lower specific heat of fat versus non-fat tissue (Buskirk et al. 1969) and the greater body fatness of our females compared with the males. Heat storage expressed per unit of total mass was significantly reduced for the women. Thus for a given amount of heat production women could not store as much body heat as the men. It is noteworthy that the difference between genders in terms of total body heat storage was markedly reduced when the value was expressed per unit of lean tissue mass (see Table 2). Previous investigations have revealed little, if any, difference in thermoregulation between the sexes if subjects were matched for fitness, body fatness and/or surface area to mass ratio (Avellini et al. 1980; Frye and Kamon 1981; Sawka et al. 1983). Others have revealed that differences in body fatness, surface area to mass ratio and fitness levels account for over 50% of the variance in heat storage among men and women exposed to dry and humid heat stress (Havenith and van Middendorp 1990; Havenith et al. 1995). In the present study, when subjects were matched for body fatness alone or in combination with $\dot{V}O_{2peak}$, heat storage per unit of total mass and tolerance times were similar between men and women. Matching subjects for $\dot{V}O_{2peak}$ alone did not equate the heat strain as indicated by the change in T_{re}, tolerance time or estimates of heat storage. Havenith et al. (1995) reported that heat storage during exposure to humid heat among 19 men and 8 women was strongly related to $\dot{V}O_{2peak}$ ($r = -0.85$) or the relative intensity represented by cycling at 60 W ($r = 0.88$). However, their estimate of heat storage was determined by thermometry assuming the same average specific heat of the body for all subjects. This assumption may not be appropriate given the variation in body fatness among subjects and the lower specific heat of adipose tissue (Bar-Or et al. 1969; Kakitsuba and Mekjavic 1987).

It should be noted that despite similar estimates of S per unit of total mass for subjects matched for body fatness, T_{re} still increased at a faster rate for the females. Conversely, when subjects were matched for their surface area to mass ratio, T_{re} increased at a similar rate between the sexes but the calorimetric estimate of S per unit of total mass was significantly lower for the females. This means that estimates of body fatness or S were inaccurate or the specific heat of the remaining non-adipose tissue is lower for the females. Body fatness was estimated from skinfold measurements using a gender-specific regression equation developed from hydrostatic measurements of body density (Forsyth et al. 1984). Thus there should have been no bias in the error of estimate of body fatness between genders in this study. The partitional calorimetric estimate of $\dot{S}$ when protective clothing is worn is probably underpredicted since evaporative heat loss is overestimated when it is calculated from changes in dressed weight (McLellan et al. 1996). In the present study, however, this underestimation should be greater for the males since their changes in dressed weight were larger than those for the females. It would appear, therefore, that the specific heat of the non-adipose tissue, which is comprised of muscle, skin, bone, blood and water, must be lower for the females. Since the specific heat of these tissues varies (Gephart and Dubois 1915), the relative proportions of each will determine the overall specific heat of the non-adipose tissue compartment. Since blood and water have a higher specific heat than the other tissues (Gephart and Dubois 1915), the males in our study may have had a higher blood and body water volume expressed per unit of fat-free mass. This explanation is only speculative, however, since we did not measure these fluid volumes. Nevertheless, the assumption that the specific heat of the body is the same among individuals with varied body compositions is not appropriate for estimating heat storage with thermometric procedures.

When subjects were grouped regardless of gender according to their final T_{re}, the group with the lower T_{re} and tolerance times had the lower $\dot{V}O_{2peak}$ and higher body fatness. These findings support the data described above for the comparisons between the sexes (see Fig. 3) and lead to the general conclusion that body composition and aerobic fitness have a significant influence on heat tolerance while wearing the protective clothing and performing light intermittent exercise in a hot environment.

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