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RESEARCH ARTICLE

Don't Deny Your Inner Environmental Physiologist: Investigating Physiology with Environmental Stimuli

Metabolism- and sex-dependent critical WBGT limits at rest and during exercise in the heat

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Abstract

Critical environmental limits are environmental thresholds above which heat gain exceeds heat loss and body core temperature (T_c) cannot be maintained at equilibrium. Those limits can be represented as critical wet-bulb globe temperature ($WBGT_{crit}$), a validated index that represents the overall thermal environment. Little is known about $WBGT_{crit}$ at rest and during low-to-moderate intensity exercise, or sex differences in $WBGT_{crit}$, in unacclimated young adults. The following hypotheses were tested: *1*) $WBGT_{crit}$ progressively decreases as metabolic heat production (M_{net}) increases, *2*) no sex differences in $WBGT_{crit}$ occur at rest, and *3*) $WBGT_{crit}$ is lower during absolute-intensity exercise but higher at relative intensities in women than in men. Thirty-six participants [19 men (M)/17 women (W); 23 ± 4 yr] were tested at rest, during light, absolute-intensity exercise (10 W), or during moderate, relative-intensity exercise [30% maximal oxygen consumption ($\dot{V}O_{2max}$)] in an environmental chamber. Dry-bulb temperature was clamped as relative humidity or ambient water vapor pressure was increased until an upward inflection was observed in T_c (rectal or esophageal temperature). Sex-aggregated $WBGT_{crit}$ was lower during 10 W (32.9°C ± 1.7°C, $P < 0.0001$) and 30% $\dot{V}O_{2max}$ (31.6°C ± 1.1°C, $P < 0.0001$) exercise versus at rest (35.3°C ± 0.8°C), and lower at 30% $\dot{V}O_{2max}$ versus 10 W (P = 0.01). $WBGT_{crit}$ was similar between sexes at rest (35.6°C ± 0.8°C vs. 35.0°C ± 0.8°C, P = 0.83), but lower during 10 W (31.9°C ± 1.7°C vs. 34.1°C ± 0.3°C, $P < 0.01$) and higher during 30% $\dot{V}O_{2max}$ (32.4°C ± 0.8°C vs. 30.8°C ± 0.9°C, P = 0.03) exercise in women versus men. These findings suggest that $WBGT_{crit}$ decreases as M_{net} increases, no sex differences occur in $WBGT_{crit}$ at rest, and sex differences in $WBGT_{crit}$ during exercise depend on absolute versus relative intensities.

environmental limits; exercise; heat balance; heat stress; sex differences

INTRODUCTION

During heat stress, body core temperature (T_c) equilibrates proportionally to metabolic heat production across a wide range of environmental conditions (i.e., compensable heat stress) (1, 2). Hot environments that force T_c out of equilibrium result in a continuous rise in T_c (i.e., uncompensable heat stress) (1, 2). Belding and Kamon (3) developed a time-intensive protocol to determine critical ambient water vapor pressures (P_a), the ambient water vapor pressure above which heat balance cannot be maintained, for a variety of ambient temperatures, exercise intensities, and air velocities. An alternative to presenting the thermal environment as combinations of dry-bulb temperature (T_{db}) and P_a is the wet-bulb globe temperature (WBGT). The WBGT provides a single temperature that represents the overall thermal environment, accounting for ambient temperature, humidity, radiation, and wind speed, the major determinants on thermal interactions between humans and their environment (4, 5). The WBGT is an ecologically valid thermal index, included in ISO7243, and currently used by industry, sport, and the military for the assessment of heat stress because of its simplicity and validity (e.g., 6, 7).

The critical WBGT limit ($WBGT_{crit}$) is the WBGT above which T_c equilibrium (thermal balance) cannot be maintained, and T_c continues to rise for a given exercise intensity. The $WBGT_{crit}$ for acclimatized men and women in different industrial work ensembles during light to moderate metabolic work rates have been well defined (8–10). However, $WBGT_{crit}$ values for unacclimatized men and women at rest and during light-to-moderate intensity exercise have not been established.

Sex differences in body size, aerobic fitness, and thermoregulatory function may lead to differences in $WBGT_{crit}$

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between men and women. Women have a larger surface area-to-mass ratio than men, which leads to a greater heat dissipation while exercising (11). Work intensity determines metabolic heat production, the variable with the greatest impact in the heat balance equations (9, 12). In general, women have a lower maximal aerobic capacity [maximal oxygen consumption ($\dot{V}O_{2max}$)] than men (13, 14). Therefore, women are often at a higher percentage of their $\dot{V}O_{2max}$ when working at an absolute exercise intensity compared with men. Conversely, when working at the same relative exercise intensity, i.e., $\%\dot{V}O_{2max}$, women are typically working at a lower absolute intensity, and therefore, a lower metabolic heat production (15), compared with men. Furthermore, men have a higher whole body sweat rate than women when near maximal sweating is required (11, 16, 17). Because of these differences in metabolic heat production and sweat rate, there may be sex differences in $WBGT_{crit}$. However, to our knowledge, there has yet to be an investigation of sex differences in $WBGT_{crit}$ at rest or during exercise at industry-relevant absolute and relative work intensities.

The purpose of the present investigation was to establish $WBGT_{crit}$ at rest, during light, absolute-intensity exercise (10 W), and during moderate, relative-intensity exercise (30% $\dot{V}O_{2max}$) in unacclimated young men and women. A secondary aim was to examine potential sex differences in $WBGT_{crit}$ at these energy expenditures. We hypothesized that *1*) $WBGT_{crit}$ would be progressively lower as metabolic heat production increased from rest to moderate-intensity exercise, *2*) men and women would have a similar $WBGT_{crit}$ at rest, and *3*) women would have a lower $WBGT_{crit}$ than men during absolute-intensity exercise (10 W), but a higher $WBGT_{crit}$ during relative-intensity exercise (30% $\dot{V}O_{2max}$).

METHODS

Subjects

Data were collected at two locations: the Pennsylvania State University and the Vrije Universiteit Amsterdam in The Netherlands. All experimental procedures received ethics approval from the respective institutions and conformed to the guidelines set forth by the Declaration of Helsinki. After all aspects of the experiment were explained, oral and written informed consent was obtained.

Thirty-six healthy men and women (19 men/17 women) aged 18 to 35 yr were tested in one or two conditions. All subjects were healthy, normotensive (blood pressure was measured using brachial auscultation after 10-min quiet rest), nonsmokers, and not taking any medications that might affect the physiological variables of interest in this study. No attempt was made to control for menstrual status or contraceptive use. To control for acclimation status, participants were excluded if they were physically active in a warm environment for at least 1 wk consecutively within the 2 mo before their experimental visits. For subjects who performed experimental trials at 30% $\dot{V}O_{2max}$, $\dot{V}O_{2max}$ was determined with the use of open-circuit spirometry (Parvo Medics TrueOne 2400, Parvo, UT) during a maximal graded exercise test performed on a motor-driven treadmill. For all other subjects, 16 in total, $\dot{V}O_{2max}$ was estimated using the YMCA submaximal cycle ergometer test (18) (Lode Excalibur, Groningen, The Netherlands). During the experiments, clothing was standardized with subjects wearing thin, short-sleeved cotton tee-shirts, shorts (30% $\dot{V}O_{2max}$ trials) or pants (rest and 10 W trials), socks, and walking/running shoes. For consistency with previous studies that have used similar clothing ensembles and according to the American Conference of Governmental Industrial Hygienists (ACGIH) guidelines for determining the effective WBGT (19, 20), no clothing corrections were made.

Testing Procedures

On arrival at the laboratory, participants provided a urine sample to ensure euhydration, defined as urine-specific gravity ≤1.020 (USG; PAL-S, Atago, Bellevue, WA) (21). All experiments were conducted in an environmental chamber with T_{db} held constant at 38°C. Subjects either *1*) rested in a chair, *2*) cycled on a cycle ergometer (Lode Excalibur, Groningen, The Netherlands) at a work rate of 10 W while maintaining a cadence of 70–90 rpm, or *3*) walked on a motor-drive treadmill at a speed and grade that approximated 30% of their $\dot{V}O_{2max}$. Two subjects walked on a treadmill at a work rate approximating 10 W (established using the formula for external work during treadmill walking, as described in *Measurements*), with metabolic heat production matched to the 10 W cycling trials, and their data were included in the 10 W exercise data set. Because no differences were observed in metabolic heat production or critical environmental limits between subjects who either walked or cycled at 10 W, differences in heat loss between modalities were considered negligible. Subjects completed one or two trials in random order. The distribution for subjects who completed each trial were the following: Rest, n = 16 (8 men, 8 women); 10 W, n = 15 (7 men, 8 women); and 30% $\dot{V}O_{2max}$, n = 18 (9 men, 9 women). Seven men and six women completed both the rest and 10 W exercise trial. For those subjects who completed two trials, the experiments were conducted on separate days, with at least 48 h between visits.

During the first 30 min of each experiment, the environmental chamber was set to either 38°C T_{db} and 40% relative humidity (RH; resting and 10 W exercise trials) or 38°C T_{db} and 9 mmHg P_a (30% $\dot{V}O_{2max}$ trials) to allow participants' T_c to equilibrate. After 30 min, RH or P_a was increased by 10% every 10 min or 1 mmHg every 5 min, respectively, until a clear rise in T_c was observed. With no forced air movement in the environmental chambers, air movement velocity has been measured at 0.2–0.45 m/s (22).

Measurements

In resting and 10 W exercise trials, rectal (T_{re}; 401 YSI Compatible Reusable Temperature Probe, Yellow Spring Instruments, Yellow Springs, OH) and gastrointestinal (T_{gi}; myTemp, Nijmegen, The Netherlands) temperature were measured simultaneously. The rectal probe was inserted 10 cm past the anal sphincter. For T_{gi}, intestinal temperature capsules were swallowed 1 h before the experiment (23). During the 30% $\dot{V}O_{2max}$ trials, esophageal temperature (T_{es}) was measured with a probe made from a thermistor sealed in a pediatric feeding tube. The probe was inserted nasally and lowered in the esophagus to the level of the left atrium, ~0.25 of the subject's standing height. Intraclass correlation

(ICC) for the determination of $WBGT_{crit}$ between T_{re} and T_{gi} was 0.94 (Fig. 1), suggesting excellent reliability for the determination of the T_c inflection point observed at critical environmental limits regardless of the method used to measure T_c. Similarly, extensive pilot data from the Penn State (M.S. Hitscherich, unpublished thesis) and Netherlands laboratories have demonstrated good to excellent reliability for inflection points in T_{es}, T_{re}, and T_{gi} during exercise in the heat, despite poor correlations in absolute temperature.

Metabolic heat production (M; W/m^2), normalized to body surface area, was calculated from oxygen consumption ($\dot{V}O_2$; L/min) and the respiratory exchange ratio (RER; unitless) (24) as:

$$M = \dot{V}O_2 \cdot \frac{\left[\left(\left(\frac{RER-0.7}{0.3}\right)\cdot 21.13\right) + \left(\left(\frac{1.0-RER}{0.3}\right)\cdot 19.62\right)\right]}{60} \times 1{,}000 \cdot A_D{}^{-1}, \quad (1)$$

where A_D is Dubois surface area (m^2). External work (W; W/m^2) was calculated as

$$W = 9.81 \cdot m_b \cdot v_w \cdot F_g \cdot A_D{}^{-1}, \quad (2)$$

where m_b is body mass (kg), v_w is walking velocity (m/min), and F_g is fractional grade of the treadmill (24). M_{net} was then calculated as M – W. For resting trials, $\dot{V}O_2$ and RER were assumed to be 3.5 mL/kg/min (25) and 0.80, respectively. For 10 W exercise trials, RER was assumed to be 0.85 and $\dot{V}O_2$ was estimated using the regression equation for $\dot{V}O_2$ during light cycling established by Reger et al. (26):

$$\dot{V}O_2 = 0.055P + 0.7815, \quad (3)$$

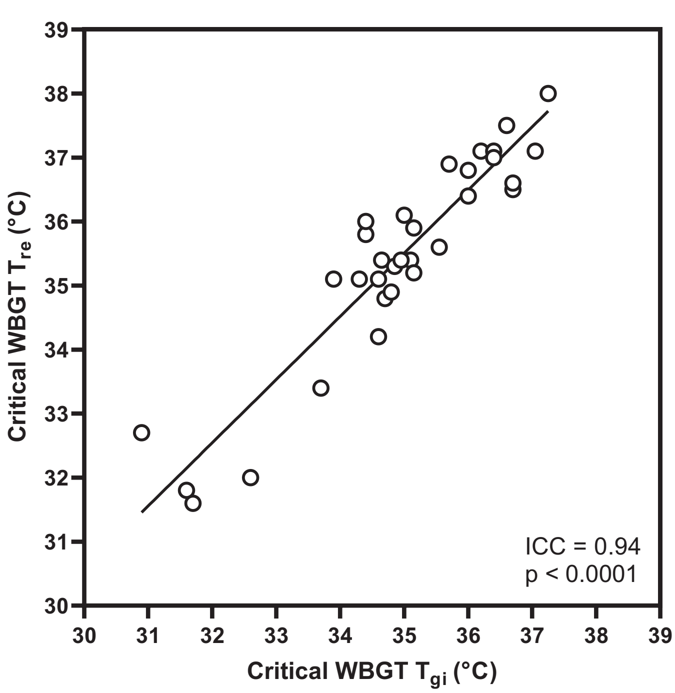

Figure 1. The correlation between critical WBGT limits determined using gastrointestinal temperature (T_{gi}) and rectal temperature (T_{re}). ICC, intraclass correlation; WBGT, wet-bulb globe temperature.

where P is power output in watts. In 30% $\dot{V}O_{2max}$ trials, $\dot{V}O_2$ and RER were measured for each participant using indirect calorimetry.

Sweat rate was determined from the loss of nude body mass on a scale accurate to ±20 g. Fluid intake was prohibited between the initial and final measurements of nude body mass.

Determination of $WBGT_{crit}$

A representative tracing of the time course of T_{es} and the environmental conditions for a typical test with increasing P_a is presented in Fig. 2. An initial rise in T_c was observed that typically began to plateau after 30–40 min and remained at an elevated steady state as RH or P_a was systematically increased. The critical RH or P_a was characterized by the upward inflection of T_c from the elevated steady state, which was selected graphically from the raw data. A line was drawn between the data points, starting at the 30th min. A second line was drawn from the point of departure from the T_c equilibrium phase slope. The RH or P_a 1 min before the point at which the second line departed from the first was defined as the critical RH or P_a, respectively. Inflection points were chosen by two independent investigators naïve to the condition, group, and subject. The inter-rater reliability (ICC) was 0.93 for the T_c inflection point. The value included in the analysis was the average of the values determined by the two investigators. In the case of discrepancies >0.2°C between investigators, the analysis was repeated.

Psychrometric wet-bulb temperature (T_{pwb}) at the T_c inflection point was determined using a standard psychrometric chart for critical P_a and RH experiments. Where necessary, T_{pwb} was converted to natural wet-bulb temperature (T_{nwb}) as (27):

$$T_{nwb} = \frac{0.16(T_g - T_{db}) + 0.8}{200} \times (560 - 2RH - 5T_a) - 0.8 + T_{pwb}, \quad (4)$$

where T_g is globe temperature. The WBGT at the T_c inflection point (i.e., the $WBGT_{crit}$) was calculated with the equation for indoor WBGT provided in ISO7243 (7):

$$WBGT = 0.7T_{wb} + 0.3T_g, \quad (5)$$

where T_{wb} and T_g were substituted for T_{nwb} and T_{db}, respectively.

Statistical Analysis

Student's unpaired *t* tests were used to compare subject characteristics. Paired samples *t* tests (SAS, version 9.4, SAS Institute, Inc., Cary, NC) were used to compare sex-aggregated $WBGT_{crit}$, metabolic heat production, and sweat rate data with metabolic intensity (i.e., rest, 10 W, or 30% $\dot{V}O_2$) as the independent variable. Similarly, within-sex differences in $WBGT_{crit}$, metabolic heat production, and sweat rate were analyzed using paired samples *t* tests. Independent samples *t* tests were used to assess between-sex differences in $WBGT_{crit}$, metabolic heat production, and sweat rate. To account for multiple comparisons (3 comparisons per analysis), significance

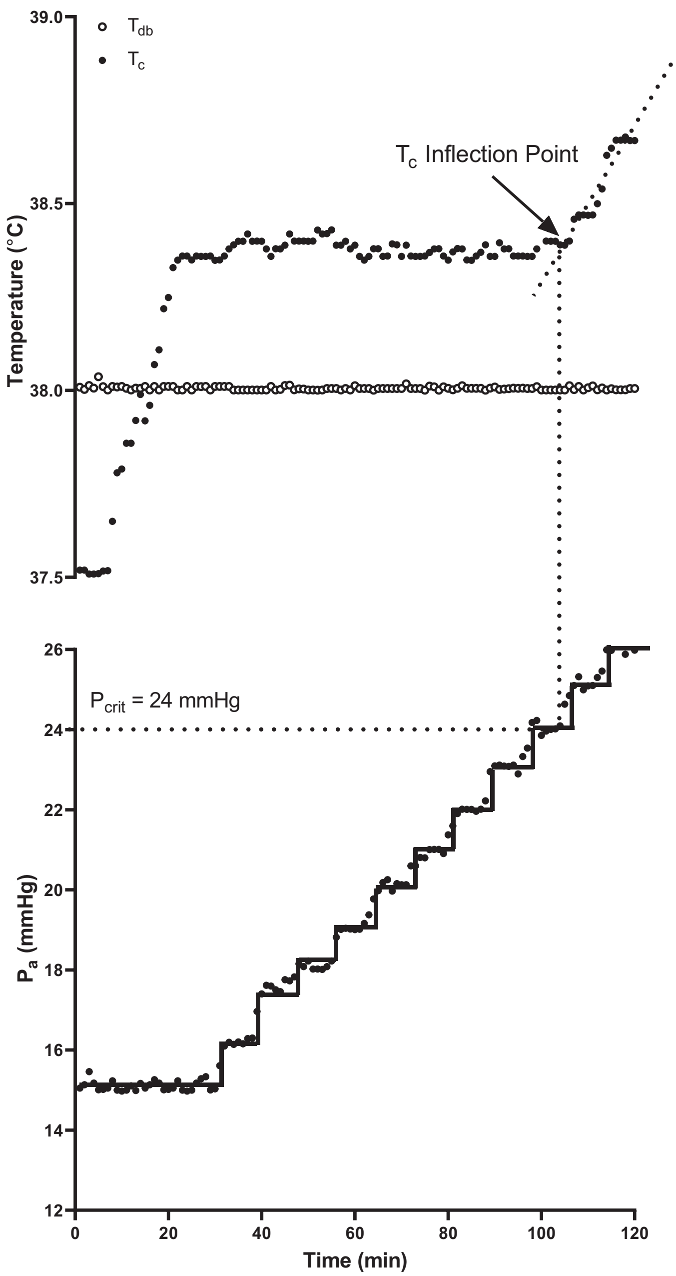

Figure 2. Representative tracing of the time course of esophageal temperature (T_{es}), dry-bulb temperature (T_{db}), and ambient water vapor pressure (P_a) for a 10 W exercise test with increasing P_a. Lines are drawn through data points in the *bottom* panel to demonstrate the stepwise progression of P_a. The T_c inflection point represents the combination of environmental conditions above which heat stress becomes uncompensable and T_c equilibrium can no longer be maintained. In this case, the T_c inflection point (i.e., critical water vapor pressure, P_{crit}) occurs at P_a = 24 mmHg, resulting in a critical wet-bulb globe temperature ($WBGT_{crit}$) of 31.3°C.

was accepted at α = 0.0167. Hedges' *g* effect sizes, a corrected, unbiased measure of effect size for small samples (28), were calculated and reported when comparisons were statistically different (small effect = 0.2, medium effect = 0.5, and large effect = 0.8). No a priori power calculation was performed. However, a post hoc power analysis using the effect size (*g* = 1.73) for the sex differences in $WBGT_{crit}$ during 10 W and 30% $\dot{V}O_{2max}$ exercise

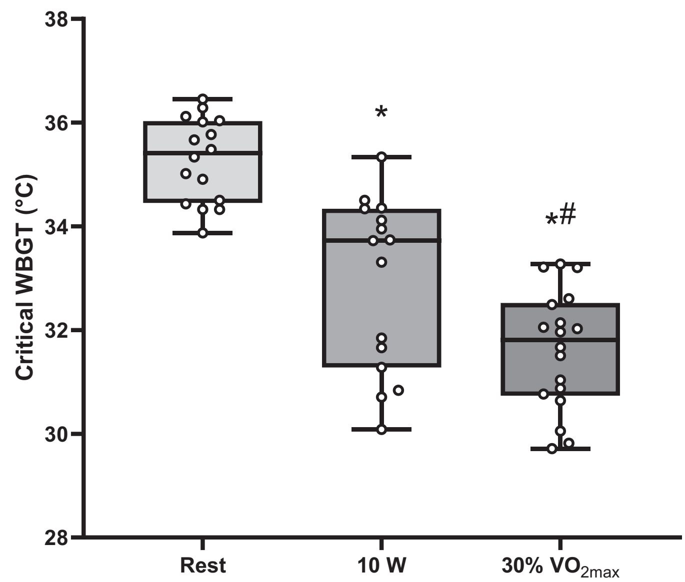

Figure 3. Sex-aggregated critical WBGT limits above which an equilibrium in core temperature can no longer be maintained during rest (*n* = 16), exercise at 10 W (*n* = 15), and exercise at 30% $\dot{V}O_{2max}$ (*n* = 18). Boxes represent first and third quartiles with median values denoted by the horizontal line, and whiskers indicate minimum and maximum observations. Data were analyzed using paired samples *t* tests. To account for multiple comparisons, significance was accepted at α = 0.0167. **P* < 0.0167 compared with rest; #*P* < 0.0167 compared with 10 W exercise. $\dot{V}O_{2max}$, maximal oxygen consumption; WBGT, wet-bulb globe temperature.

suggested that seven subjects per group would provide adequate power (1-β = 0.84). Data are reported as means ± SD except in Figs. 3 and 4, which are presented as box-and-whisker plots with individual data points.

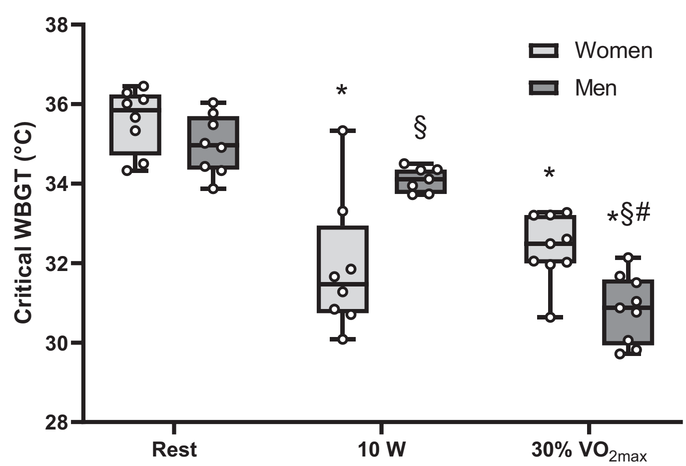

Figure 4. Sex differences in critical WBGT limits above which an equilibrium in core temperature can no longer be maintained during rest (women, *n* = 8; men, *n* = 8), exercise at 10 W (women, *n* = 8; men, *n* = 7), and exercise at 30% $\dot{V}O_{2max}$ (women, *n* = 9; men, *n* = 9). Boxes represent first and third quartiles with median values denoted by the horizontal line, and whiskers indicate minimum and maximum observations. Within-sex and between-sex comparisons were analyzed using paired samples and unpaired samples *t* tests, respectively. To account for multiple comparisons, significance was accepted at α = 0.0167. **P* < 0.0167 compared with rest; §*P* < 0.0167 compared with women; #*P* < 0.0167 compared with 10 W exercise. $\dot{V}O_{2max}$, maximal oxygen consumption; WBGT, wet-bulb globe temperature.

Table 1. *Subject characteristics*

	All	Women	Men
n	36	19	17
Age, yr	23 ± 4	23 ± 4	23 ± 3
Height, m	1.75 ± 0.1	1.66 ± 0.1	1.86 ± 0.1§
BMI, kg·m^{-2}	23 ± 3	22 ± 2	24 ± 3
A_D, m^2	1.86 ± 0.20	1.68 ± 0.16	2.05 ± 0.15§
A_D·kg^{-1}, m^2·kg^{-1}	0.026 ± 0.002	0.026 ± 0.002	0.025 ± 0.002
$\dot{V}O_{2max}$, ml·kg^{-1}·min^{-1}	45 ± 7	42 ± 7	48 ± 6§

Data are presented as means ± SD. Data were analyzed using Student's unpaired *t* tests. A_D, DuBois body surface area; A_D·kg^{-1}, body surface area-to-mass ratio; BMI, body mass index; $\dot{V}O_{2max}$, maximal oxygen consumption. §$P < 0.05$ compared with women.

RESULTS

Subject Characteristics

Sex-aggregated and disaggregated subject characteristics are presented in Table 1. The men and women in this study were representative of the general population with respect to anthropometric characteristics and aerobic fitness (29). Thus, men were taller and had a higher mean $\dot{V}O_{2max}$ and body surface area (all $P < 0.05$), although the two groups were well matched for surface area-to-mass ratio ($P = 0.25$). Importantly, there were no differences in $\dot{V}O_{2max}$, body mass index (BMI), height, A_D, or A_D·kg^{-1} between groups that did each trial, although the group that completed the 30% $\dot{V}O_{2max}$ trials (21 ± 2) was significantly younger than the groups that completed rest (26 ± 3) and 10 W exercise (26 ± 4) trials (both $P < 0.0001$).

Metabolic Heat Production and Sweat Rate

Metabolic heat production and sweat rates at rest, during 10 W exercise, and during 30% $\dot{V}O_{2max}$ exercise, aggregated and disaggregated by sex, are presented in Table 2. M_{net} was higher during 10 W exercise than at rest ($P < 0.0001$; $g = 9.48$) and was higher during exercise at 30% $\dot{V}O_{2max}$ than during 10 W exercise ($P = 0.01$; $g = 1.01$) and at rest ($P < 0.0001$; $g = 9.47$).

In women, M_{net} was higher during exercise at 10 W ($P < 0.0001$; $g = 9.55$) and 30% $\dot{V}O_{2max}$ ($P < 0.0001$; $g = 12.06$) than at rest, but was similar between 10 W and 30% $\dot{V}O_{2max}$ ($P = 0.48$). M_{net} was similarly higher in men during exercise at 10 W ($P < 0.0001$; $g = 13.29$) and 30% $\dot{V}O_{2max}$ ($P < 0.0001$; $g = 9.46$) than at rest; however, in contrast to women, M_{net} was higher during exercise at 30% $\dot{V}O_{2max}$ than at 10 W ($P = 0.001$). M_{net} was higher in men than in women during exercise at 30% $\dot{V}O_{2max}$ ($P < 0.0001$), but was similar between sexes during rest ($P = 0.56$) and 10 W exercise ($P = 0.12$).

Sweat rates were similar between rest, 10 W exercise, and 30% $\dot{V}O_{2max}$ exercise for men ($P \geq 0.07$) and women ($P \geq 0.17$). Sweat rates were higher in men than in women during exercise at 10 W ($P = 0.005$; $g = 1.76$) and 30% $\dot{V}O_{2max}$ ($P < 0.0001$; $g = 1.98$), but not at rest ($P = 0.11$).

Critical WBGT Limits

Figure 3 depicts $WBGT_{crit}$ at rest, 10 W exercise, and 30% $\dot{V}O_{2max}$ exercise. As expected, the $WBGT_{crit}$ was lower during exercise at 10 W (32.9°C ± 1.7°C; $P < 0.0001$; $g = 1.75$) and 30% $\dot{V}O_{2max}$ (31.6°C ± 1.1°C; $P < 0.0001$; $g = 3.59$) than at rest (35.3°C ± 0.8°C). Furthermore, the $WBGT_{crit}$ was lower during exercise at 30% $\dot{V}O_{2max}$ than at 10 W ($P = 0.01$; $g = 0.90$).

Figure 4 illustrates sex-disaggregated $WBGT_{crit}$ at rest and during exercise at 10 W and 30% $\dot{V}O_{2max}$. In men, there was no difference in $WBGT_{crit}$ from rest (35.0°C ± 0.8°C) to 10 W exercise (34.1°C ± 0.3°C; $P = 0.58$), although the $WBGT_{crit}$ was lower during 30% $\dot{V}O_{2max}$ exercise (30.8°C ± 0.9°C) than at rest ($P < 0.0001$; $g = 4.88$) or 10 W exercise ($P < 0.0001$ $g = 4.57$). In contrast, the $WBGT_{crit}$ was lower for women during exercise at 10 W (31.9°C ± 1.7°C; $P < 0.0001$; $g = 2.65$) and 30% $\dot{V}O_{2max}$ (32.4°C ± 0.8°C; $P < 0.0001$; $g = 3.70$) than at rest (35.6°C ± 0.8°C), but there was no difference in $WBGT_{crit}$ between 10 W and 30% $\dot{V}O_{2max}$ exercise ($P = 0.97$).

There were no sex differences in $WBGT_{crit}$ at rest ($P = 0.14$). However, the $WBGT_{crit}$ during 10 W exercise was lower in women than in men ($P = 0.01$; $g = 1.73$). Conversely, the $WBGT_{crit}$ during exercise at 30% $\dot{V}O_{2max}$ was lower in men than in women ($P = 0.001$; $g = 1.73$).

Sex-aggregated and disaggregated environmental conditions (i.e., T_{db} and RH) at the T_c inflection point at rest and during 10 W and 30% $\dot{V}O_{2max}$ exercise are presented in Table 3. Differences in the critical RH for all subjects and when broken down by sex reflect differences in $WBGT_{crit}$ at rest and during 10 W and 30% $\dot{V}O_{2max}$ exercise.

DISCUSSION

To our knowledge, this is the first study to assess the $WBGT_{crit}$ for unacclimated young men and women at varying metabolic intensities ranging from rest to low-to-moderate intensity exercise. As expected, the $WBGT_{crit}$ progressively decreased as metabolic heat production increased. The $WBGT_{crit}$ was similar between men and women at rest, but sex differences were evident during exercise at 10 W and 30% $\dot{V}O_{2max}$. During 10 W exercise, the $WBGT_{crit}$ was higher in men than in women. Conversely, the $WBGT_{crit}$ during exercise at 30% $\dot{V}O_{2max}$ was higher in women than in men.

Table 2. *Metabolic heat production adjusted for body surface area and sweat rates for all subjects and disaggregated by sex at rest and during 10 W and 30% $\dot{V}O_{2max}$ exercise*

	All	Women	Men
M_{net}, W·m^{-2}			
Rest (8 M/8 W)	43.8 ± 2.5	44.2 ± 2.8	43.4 ± 2.4
10 W (7 M/8 W)	138.9 ± 13.6*	144.1 ± 13.7*	133.1 ± 8.7*
30% $\dot{V}O_{2max}$ (9 M/9 W)	163.2 ± 30.2*#	138.7 ± 10.1*	188.8 ± 20.4*§#
Sweat rate, g·m^{-2}·h^{-1}			
Rest (8 M/8 W)	187.0 ± 58.7	163.4 ± 29.1	210.6 ± 72.5
10 W (7 M/8 W)	225.0 ± 64.4	181.1 ± 48.9	269.0 ± 45.7§
30% $\dot{V}O_{2max}$ (9 M/9 W)	207.3 ± 51.1	170.4 ± 33.1	244.2 ± 37.4§

Data are presented as means ± SD. Sex-aggregated and within-sex comparisons were analyzed using paired samples *t* tests. Between-sex comparisons were analyzed using unpaired samples *t* tests. To account for multiple comparisons, significance was accepted at α = 0.0167. Sample sizes for men and women are included in parentheses for each condition. M, men; $\dot{V}O_{2max}$, maximal oxygen consumption; W, women. *$P < 0.0167$ compared with rest; §$P < 0.0167$ compared with women; #$P < 0.0167$ compared with 10 W exercise.

Table 3. *Dry bulb temperature and relative humidity at the core temperature inflection point for all subjects and disaggregated by sex at rest and during 10 W and 30% $\dot{V}O_{2max}$ exercise*

	All	Women	Men
T_{db}, °C			
Rest (8 M/8 W)	37.9 ± 0.2	37.9 ± 0.2	38.0 ± 0.2
10 W (7 M/8 W)	38.2 ± 0.3	38.1 ± 0.2	38.2 ± 0.3
30% $\dot{V}O_{2max}$ (9 M/9 W)	38.1 ± 0.4	38.1 ± 0.4	38.1 ± 0.5
RH, %			
Rest (8 M/8 W)	76.6 ± 7.3	79.4 ± 7.4	73.8 ± 6.5
10 W (7 M/8 W)	57.3 ± 11.4*	50.6 ± 11.9*	65.0 ± 3.2§
30% $\dot{V}O_{2max}$ (9 M/9 W)	48.9 ± 8.2*#	53.8 ± 7.1*	44.1 ± 6.3*§#

Data are presented as means ± SD. Sex-aggregated and within-sex comparisons were analyzed using paired samples t tests. Between-sex comparisons were analyzed using unpaired samples t tests. To account for multiple comparisons, significance was accepted at α = 0.0167. Sample sizes for men and women are included in parentheses for each condition. M, men; RH, relative humidity; T_{db}, dry bulb temperature; $\dot{V}O_{2max}$, maximal oxygen consumption; W, women. $*P < 0.0167$ compared with rest; $§P < 0.0167$ compared with women; $\#P < 0.0167$ compared with 10 W exercise.

Unsurprisingly, the $WBGT_{crit}$ was highest at rest and declined progressively as exercise intensity, and thus M_{net}, increased. The 10 W exercise condition was chosen to approximate the metabolic intensity of activities of daily living, whereas the 30% $\dot{V}O_{2max}$ exercise condition was chosen because it reflects the intensity of many self-paced recreational activities and it is the intensity associated with an 8-h work day in many industrial settings (30). Thus, these data may effectively be used as safe WBGT limits (from a heat balance standpoint) during rest, activities of daily living, and recreational activity or industrial work for unacclimated young men and women.

Differences in $WBGT_{crit}$ at varying metabolic rates in acclimated young men and women have been previously described (9). The $WBGT_{crit}$ during exercise at 10 W and 30% $\dot{V}O_{2max}$ were comparable with previously reported $WBGT_{crit}$ values during moderate and high metabolic rate conditions in acclimated young men and women (9). The similarities in $WBGT_{crit}$ at different metabolic rates between studies (i.e., lower metabolic rates in the current study) are most likely due to the acclimation status of the participants.

The absence of a sex difference in $WBGT_{crit}$ at rest is likely explained by similar whole body sweat rates and M_{net}. Sex differences in sweating are unlikely to manifest at low requirements for heat loss (31). Sex differences in $WBGT_{crit}$ were evident during absolute (10 W) and relative (30% $\dot{V}O_{2max}$) exercise intensity conditions, wherein women demonstrated lower and higher $WBGT_{crit}$ at 10 W and 30% $\dot{V}O_{2max}$ exercise, respectively. Sweat rates were lower in women than in men during exercise at both intensities, similar to previous findings that sex differences in sweat rates mostly occur when the exercise intensity and ambient temperature are high enough that the requirements for sweating are near maximal to maintain thermal balance (11, 32, 33). In contrast, there was no difference in M_{net} between sexes when matched at an absolute work rate of 10 W, but M_{net} was lower in women than in men during 30% $\dot{V}O_{2max}$ exercise. Because men and women differ in $\dot{V}O_{2max}$ on average, this results in lower absolute exercise intensities and M_{net} (15) for women when working at a fixed percentage of $\dot{V}O_{2max}$. Thus, sex differences at 10 W exercise reflect a true sex difference because the two groups were matched for M_{net}, and therefore, the requirement for heat loss was equal. These findings differ from previous data that showed no sex differences in evaporative heat loss when the requirement for heat loss was below 300 $W{\cdot}m^{-2}$ (31). Conversely, the differences during 30% $\dot{V}O_{2max}$ exercise were primarily driven by reduced M_{net} and heat loss requirements for women. Systematic differences in the change in core temperature during exercise in the heat between age-, sex-, and acclimation-matched groups of different body mass and surface area are eliminated when subjects exercise at a fixed heat production per unit body mass (34). However, it is unclear whether this would hold true in the current study when comparing sex differences in $WBGT_{crit}$.

Together, these data suggest that potential sex differences in $WBGT_{crit}$ depend on acclimation status and whether work is being performed at a relative or absolute intensity. Importantly, most self-paced recreational activity and industrial work is likely performed at relative, rather than absolute, intensities (30, 35, 36). Recommendations of the International Organization for Standardization (ISO) are based on absolute metabolic rates; thus, the recommended WBGT limits in ISO7243 may be overestimated for women, particularly those who are unacclimated (7). It is noteworthy that the differences between ISO recommendations and critical WBGT thresholds for women encompass the effect of body size, in addition to the physiological effect of sex, especially at higher metabolic intensities (34, 37, 38). Therefore, separate WBGT standards for unacclimated men and women during continuous work in the heat warrants consideration.

Limitations

Data were collected at two locations with minor differences in protocols. Namely, critical environmental limits were determined at rest and during the 10 W trials with stepwise increases in RH, whereas 30% $\dot{V}O_{2max}$ trials were conducted by increasing water vapor pressure. When converted to WBGT, however, either method results in relatively small increases in the thermal environment (i.e., 0.3°C–1.3°C increments) and are unlikely to influence the overall methodology which relies on the biophysics of heat exchange. These differences are, therefore, unlikely to result in significant systematic disparities in $WBGT_{crit}$. Similarly, subjects wore long pants in the Netherlands trials and shorts during the Penn State trials. This was considered to have a negligible effect on $WBGT_{crit}$ as ACGIH guidelines for determining the effective WBGT for various ensembles (19) does not necessitate the implementation of a clothing correction factor for these conditions.

Metabolic heat production was estimated for rest and 10 W exercise. Resting metabolic heat production was estimated using well-accepted average values for $\dot{V}O_2$ and RER at rest (25), and those estimates closely aligned with empirically derived values previously reported (15). Metabolic heat production during 10 W exercise was estimated assuming an RER of 0.85 and using the regression equation for $\dot{V}O_2$ during light cycling established by Reger et al. (26). The accuracy of the calculated values was confirmed in a subset of subjects for whom $\dot{V}O_2$ and RER were measured via indirect calorimetry, yielding results that fell within the distribution of estimated values.

No attempt was made in this study to control for the menstrual cycle or contraceptive use of the female participants, which may influence core temperature in the women. However, although absolute core temperature varies across the menstrual cycle, the change in core temperature during exercise in the heat is unaffected (39). Likewise, the core temperature profiles during exercise in the heat were similar across menstrual phases. It is, therefore, unlikely that the $WBGT_{crits}$ observed in this study were influenced by not controlling for menstrual cycle.

Finally, the $WBGT_{crit}$ in the rest and 10 W exercise conditions was determined using both T_{re} and T_{gi}, whereas T_{es} was measured during 30% $\dot{V}O_{2max}$ trials. Importantly, as shown in Fig. 1, ICC analysis suggested excellent reliability (ICC = 0.97) between T_{re} and T_{gi}. We, therefore, concluded that, although the absolute value for T_c may vary, the $WBGT_{crit}$ is similar regardless of the method used for measuring T_c.

Perspectives and Significance

The $WBGT_{crit}$ in unacclimated, healthy young men and women progressively decreases as exercise intensity and metabolic heat production increases. Sex differences in $WBGT_{crit}$ were not evident during rest, but were observed depending on whether exercise was performed at an absolute or relative exercise intensity. The $WBGT_{crit}$ was lower in women than in men during absolute-intensity exercise, but higher during relative-intensity exercise. These sex differences are most likely explained by differences in metabolic heat production and sweat rate. Future studies are warranted to investigate the $WBGT_{crit}$ in vulnerable populations with impaired thermoregulatory function, including older adults or those with various disease or disability states such as multiple sclerosis or spinal cord injury.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

S.T.W., H.A.M.D., and W.L.K. conceived and designed research; M.A.F. performed experiments; S.T.W., M.A.F., and R.M.C. analyzed data; S.T.W., M.A.F., H.A.M.D., and W.L.K. interpreted results of experiments; S.T.W. prepared figures; S.T.W., M.A.F., and R.M.C. drafted manuscript; S.T.W., M.A.F., H.A.M.D., and W.L.K. edited and revised manuscript; S.T.W., M.A.F., R.M.C., H.A.M.D., and W.L.K. approved final version of manuscript.

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