Heat Tolerance Testing: Association Between Heat Intolerance and Anthropometric and Fitness Measurements

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ABSTRACT This study investigated associations between heat intolerance, as determined by performance on a heat tolerance test (HTT), and anthropometric measurements (body surface-to-mass ratio, percent body fat, body mass index, and waist circumference) and cardiorespiratory fitness (maximal oxygen uptake [VO_{2max}]). Relationships between predictive variables and specific physiological measurements recorded during the HTT were examined. A total of 34 male and 12 female participants, recruited from the military community, underwent anthropometric measurements, a maximal aerobic exercise test, and a standardized HTT, which consisted of walking on a treadmill at 5 km/h at 2% grade for 120 minutes at 40°C and 40% relative humidity. VO_{2max} negatively correlated with maximum core temperature ($r = -0.30$, $p < 0.05$) and heart rate (HR) ($r = -0.48$, $p < 0.01$) although percent body fat showed a positive correlation with maximum HR ($r = 0.36$, $p < 0.05$). VO_{2max} was the only independent attribute that significantly influenced both the maximum HR and core temperature attained during HTT. Logistic regression analyses indicated that VO_{2max} was the only independent parameter (OR = 0.89, $p = 0.026$) that significantly contributed to overall HTT performance. Low cardiorespiratory fitness was associated with heat intolerance, as defined by HTT performance, and can be addressed as a preventative measure for exertional heat illness. This study provides further evidence that the HTT can be an effective tool for assessment of thermoregulatory patterns.

INTRODUCTION

Exertional heat stroke (EHS) is the most severe type of heat-related illness and continues to pose a significant threat to military operations and training of recruits. During 2012, a total of 365 incident cases of EHS and an additional 2,257 events of heat-related illness other than EHS were reported among all active duty Service Members.[1] EHS is characterized by a pathologic rise in core temperature (Tc), usually >40°C (104°F), coupled with central nervous system dysfunction and potential multisystem organ failure.[2] It remains a common, preventable[3–5] cause of nontraumatic exertional sudden death, and occurs predominantly in young, highly motivated athletes[6,7] and military members[1,8–11] when performing undue strenuous exercise and/or activities in warm or hot environments.[2,12,13] The morbidity associated with EHS can negatively impact the health of warfighters, exhaust valuable medical resources, and compromise unit operational readiness.[4] Given this major medical problem, numerous studies have evaluated risk factors associated with heat-related illnesses and identified several predisposing factors for EHS, including being overweight,[10,13–15] poor aerobic conditioning,[13,14,16] dehydration,[15,17,18] acute illness,[19,20] and lack of acclimatization.[2,21]

Shapiro et al[22] first developed a heat tolerance test (HTT) in 1979 to determine how former heatstroke patients and healthy controls tolerated a standardized exposure to heat.[22] The test comprised stepping for 3 hours on a 30-cm bench in a hot environment. Their results revealed that patients were intolerant to heat (determined by the need to discontinue testing) when core body temperature rose above 39.6°C or subjects complained of exhaustion.[22] Presently, the Israeli Defense Forces (IDF) mandates all warfighters who sustain an episode of EHS to undergo a standardized HTT 6 to 8 week following the event as part of their return to duty (RTD) process.[23] The current HTT test being used by the Israelis consists of walking on a treadmill for 2 hours at 5 km·h^{-1} (3.1 mph) with a 2% incline in an environmental chamber set at 40°C (104°F) and 40% relative humidity (RH). Various physiological responses, such as T_c, HR, and sweat rate (SR) are monitored during the test. Under these standardized settings, an individual's acute thermoregulatory response to mild exertion in the heat can be adequately observed and assessed.[24] Individuals are considered heat intolerant if their T_c exceeds 38.5°C and/or HR exceeds 150 beats/min (bpm).[4,24,25] It is also important that T_c and HR plateau during the HTT because these measures suggest adaptation to a given heat load.[24,26–28] A rise in T_c of less than 0.45°C during the 2nd hour of the HTT has been suggested as an acceptable T_c plateau.[28] The present IDF HTT criteria for heat intolerance combine the two outcomes of the test—HR and T_c–to provide a more comprehensive clinical and practical marker of risk for heat intolerance.[4] However, some researchers

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The views expressed are those of the authors and do not reflect the official policy or position of the Uniformed Services University of the Health Sciences, the Department of the Defense, or the U.S. Government.

doi: 10.7205/MILMED-D-14-00169

remain skeptical of these specific cutoffs, in particular for use in females and elite triathletes.[29,30] An additional way to integrate HTT, HR, and T_c is by using the physiological strain index (PSI): this index was developed as a real-time continuous measure to reflect changes in HR and T_c over the course of the HTT.[31,32] PSI increases as HR and T_c approach the limits deemed safe in most laboratory studies (180 bpm and 39.5°C), with values ranging from 0 to 10.

Currently, military physicians in the United States do not routinely use an HTT as part of the RTD process for victims of EHS. Moreover, the validity of the Israeli HTT remains controversial among sports medicine (military and civilian) clinicians and researchers. Specific issues regarding use of the HTT have been raised, such as its (1) predictive capacity for future EHS events, (2) ability to accurately measure potential deficits within the thermoregulatory system, and (3) utility in guiding the RTD process.[29,30] Nonetheless, the American College of Sports Medicine (ACSM) currently recommends that medical care providers consider a HTT when the decision to return the athlete/warfighter to duty or competition/play (return to play [RTP]) is difficult.[2] The general consensus is that further research is needed to validate the efficacy of a standardized HTT within both athletic and military populations.[30] Additionally, few studies have determined predictors of HTT performance,[23] and no studies have investigated potential associations among U.S. service members. Therefore, the purpose of the present analysis was threefold. First, our primary objective was to examine the associations between performance on a HTT and age, gender, anthropometric measurements, and cardiorespiratory fitness. Second, we examined the relative influence of these parameters on the heat stress response (HR, T_c, and PSI) of participants. Finally, we assessed relationships between these parameters and the specific physiological measurements recorded during the HTT. To address concerns regarding the cutoff for heat intolerance, performance on the HTT was analyzed both categorically (i.e., heat intolerant vs. heat tolerant) and continuously (max HR and max T_c). We hypothesized that heat intolerance defined by HTT would be associated with low cardiorespiratory fitness (VO_{2max}) and high BMI and percent body fat (BF%). We also hypothesized that anthropometric and cardiorespiratory measures would influence T_c and HR during the HTT, with the latter having a larger effect. By relating HTT performance with known EHS risk factors, these findings should help elucidate the relative role of anthropometrics and fitness in thermoregulation, and provide clinical insight into how the HTT might assist with difficult RTD/RTP decision making.

MATERIALS AND METHODS

Subjects

Male (n = 34) and female (n = 12) participants between the ages of 18 and 45 years were recruited from the university population or the military community. Participants were enrolled in the study only if they met the following inclusionary criteria: (1) 18 to 45 years of age; (2) waist circumference (WC) < 39.4 inches (100 cm); (3) systolic and diastolic blood pressure < 140 and < 90 mmHg, respectively; (4) no previous history of malignant hyperthermia; (5) not pregnant or lactating; (6) not anemic; (7) not using glucose-lowering agents, prednisone, or β-blockers; (8) absence of heart disease; and (9) not presently being treated for any mental health disorder. Participants included those with and without a history of EHI. Some participants (n = 18) had a previous, clinically documented EHS; these individuals were tested 6 weeks or more after their EHS. Each participant underwent a thorough telephone health screening and on-site medical examination to ensure that the inclusion/exclusion criteria were met. All participants were informed of the purposes and procedures of the study and provided written consent before participation. This study was approved by the Institutional Review Board at the Uniformed Services University and was part of a larger study.

Baseline Screening and Anthropometric Testing

All measurements for this analysis took place at the Uniformed Services University of the Health Sciences Human Performance Laboratory. Participants visited the laboratory on two occasions. On the first day, participants underwent a medical examination, several anthropometric evaluations (weight, height, WC, and BF%), and a maximal aerobic-graded exercise test to assess cardiorespiratory fitness. After this, they completed a medical history and other questionnaires, and participated in providing measurements of HR, blood pressure (Criticare Systems Inc., Waukesha, Wisconsin), and electrocardiographic activity (Philips StressVue Testing System with Trackmaster Full Vision Inc., Treadmill, Waltham, Massachusetts) at rest. Participant body weight was measured with a calibrated metric scale to the nearest 0.1 kg, and height was measured to the nearest 0.1 cm while the participant was wearing light clothing and no shoes. BMI was calculated from height and weight, and WC was assessed with a tape measure by standard techniques. Skinfold thickness was quantified with a skinfold caliper (Cambridge Scientific Industries Inc., Cambridge, Maryland) at four sites (biceps, triceps, subscapular, and suprailiac) on the right side of the body, and BF% was computed using the Durnin and Womersley calculation.[33] To combine data from a previous study, three skinfold sites were used for 58.7% of participants based on ACSM guidelines,[34] using chest, triceps, and subscapular for men, and triceps, abdomen, and suprailiac for women. Body surface area and surface-to-mass ratio were determined by standard methods.[35] During the second visit, subjects underwent a standardized HTT, which consisted of walking on a treadmill for 2 hours in an environmental chamber as described below.

Determination of VO_2max

VO_{2max} was determined by a maximal aerobic-graded exercise test on a motorized treadmill through indirect calorimetry. Expired respiratory gases were collected continuously and analyzed by open-circuit spirometry (Oxycon Mobile portable system, Viasys Healthcare Inc., Yorba Linda, California). The test used in this study was adapted from a protocol previously described and utilized by our laboratory.[36] In short, the test began with a 5-minutes warm-up at a speed of 5.0 km/h and a 2.0% grade. Following the warm-up, participants ran at a constant speed of 7.7 to 13.7 km/h, depending on the HR achieved during warm-up. The incline started at 0% and was increased 2.5% every 2 minutes until the subject could no longer continue or displayed a plateau in VO_2 with an increase in workload.

Heat Tolerance Testing

Each participant reported to the Uniformed Services University's environmental chamber in the morning and changed into shorts (women additionally wore sports bras) and athletic shoes. The HTT consisted of walking on a treadmill at 5.0 km/h with a 2% grade for 120 minutes at 40°C and 40% RH. To ensure adequate hydration before testing, urine specific gravity (USG) was measured with a handheld refractometer. If USG was ≥1.02 units, the participant was asked to hydrate with water until USG was <1.02. Participants were then instructed to void their bladders, following which nude body weight was measured. From this point, all urine was collected in individual 3,000 mL polypropylene containers. During the HTT, participants were permitted to hydrate with water ad libitum (up to 1 L/h). Body T_c was measured by using a rectal thermistor (MEAS Temperature Probe, Measurement Specialties Inc., Dayton, Ohio) inserted 10 cm beyond the anal sphincter and HR was assessed by a Polar HR monitor (Polar Team 2 Pro, Polar USA Inc., Lake Success, New York). Throughout the test, HR and T_c were continuously monitored and recorded. PSI was calculated, based on change in HR and T_c from baseline, as suggested by Moran et al.[32]

Values on the PSI range from 0 to 10, and are classified as follows: minimal (PSI: 0–2), low (3–4), moderate (5–6), high (7–8), and very high (9–10) strain. Urine was collected and fluid consumption was recorded during the entire HTT to determine values for calculation of SR. SR was computed as the difference in participant nude weight before and after the test corrected for fluid intake and urine output.

The HTT was always discontinued if the participant met any of the following criteria: (1) $T_c > 39.5°C$, (2) HR > 170 bpm, (3) experienced nausea, weakness, or dizziness, or (4) requested early test termination. A person was deemed "heat intolerant" if T_c was >38.5°C, HR was >150 bpm, or when either failed to plateau, as outlined by the Israeli HTT guidelines.[4,24,28]

Data Analysis

Descriptive statistics were calculated for HTT results. Independent-samples *t* tests were used to examine differences in age, anthropometric measurements and maximal aerobic power, and physiological measurements during the HTT between heat tolerant and heat intolerant participants. Zero-order relationships between gender, age, anthropometric measurements and fitness, and physiological measurements during the HTT were assessed by using Pearson correlation coefficients. Multiple regression analyses (stepwise) were then used to determine the relative contributions of demographic, anthropometric, and aerobic fitness measurements on heat tolerance. Heat tolerance was broken down into its components, HR and T_c, which were analyzed both as continuous and as dichotomous dependent variables. Regression analyses were conducted to predict the following continuous HTT outcomes: max HR, max T_c, and max PSI. Logistic regression analyses were conducted to predict the following dichotomous HTT outcomes: HR > 150, $T_c > 38.5$, and heat intolerance (both HR > 150 and $T_c > 38.5$). Data analyses were performed using Statistical Package for the Social Sciences version 16.0 (SPSS, Inc., Chicago, *Illinois*). The results were considered significant at $p \leq 0.05$.

RESULTS

Demographic, anthropometric, and aerobic fitness differences between heat tolerant and heat intolerant subjects are presented in Table I, whereas physiologic differences between these subjects are presented in Table II. Significant

TABLE I. Age, Anthropometric and Aerobic Fitness Measurements (Mean ± SD) of Subjects

Variable	Heat Tolerant (*n* = 32)	Heat Intolerant (*n* = 14)	All (*n* = 46)
Age (yrs)	30.1 ± 5.8	28.7 ± 6.4	29.7 ± 5.9
Height (cm)	174.3 ± 9.0	173.6 ± 10.7	174.1 ± 9.4
Weight (kg)	78.6 ± 14.4	76.5 ± 14.6	78.0 ± 14.3
BMI (kg/m^2)	25.7 ± 3.1	25.3 ± 3.4	25.6 ± 3.2
Body Surface Area (m^2)	1.93 ± 0.22	1.90 ± 0.23	1.92 ± 0.22
Body Surface-to-Mass Ratio ($m^2 \cdot kg^{-1} \cdot 10^2$)	2.49 ± 0.20	2.53 ± 0.23	2.50 ± 0.21
BF%	20.7 ± 6.3	25.4 ± 8.0*	24.1 ± 6.8
Waist Circumference (cm)	82.4 ± 8.9	79.5 ± 8.1	81.5 ± 8.6
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	51.4 ± 7.7	45.2 ± 6.9*	49.5 ± 7.9
Previous EHS (*n*)	13	5	18

*Significant at $p < 0.05$.

TABLE II. Physiological Measurements (Mean ± SD) of Subjects During HTT

Variable	Heat Tolerant (n = 32)	Heat Intolerant (n = 14)
Baseline T_c (°C)	36.9 ± 0.3	37.0 ± 0.3
Max T_c (°C)	37.9 ± 0.3	38.5 ± 0.2**
ΔT_c (°C)	1.0 ± 0.4	1.5 ± 0.3**
Baseline HR (bpm)	63 ± 9.8	73 ± 16.7*
Max HR (bpm)	118 ± 13.1	156 ± 10.5**
ΔHR (bpm)	55 ± 11.4	85 ± 14.5**
SR (l/h)	0.96 ± 0.28	0.85 ± 0.21

*Significant at $p < 0.05$, ** $p < 0.001$.

group differences in BF% and VO_{2max} were noted, such that heat intolerant individuals (n = 14) had higher BF% (Mean: 25.4 ± 8.0) and lower VO_{2max} (45.2 ± 6.9) than those who were heat tolerant (n = 32; BF%: 20.7 ± 6.3; VO_{2max}: 51.4 ± 7.7). Based on how their group assignment was calculated, all physiologic values differed significantly except SR and baseline T_c. Table III presents the Pearson correlation coefficients between continuous physiologic measurements during the HTT and age, gender, anthropometric and aerobic fitness measurements. Figures 1 and 2 depict the relationships between aerobic fitness and BF% and the key HTT outcomes (max T_c and max HR). As shown in Figure 1, VO_{2max} correlated with max T_c and max HR. Figure 2 shows a moderate correlation between BF% and max HR, but not max T_c. Finally, moderate to strong correlations were found for SR with gender (r = 0.40, $p < 0.01$), BMI (r = 0.42, $p < 0.01$), body surface area to mass ratio (r = −0.53, $p < 0.001$), and WC (r = 0.50, $p < 0.001$).

Beta-weights (standardized regression coefficients) and their associated levels of significance for all linear regressions are presented in Table IV. The first regression explored the relative contribution of age, gender, anthropometric and aerobic fitness measurements to the max HR attained during the HTT. VO_{2max} (t = −4.05, $p < 0.001$) was the only variable that significantly contributed to predicting max HR. The second regression explored the relative contribution of the predictor variables to the max T_c recorded during the HTT. Both BMI (t = −2.22, p = 0.032) and VO_{2max} (t = −2.86, p = 0.007) significantly contributed to the prediction of T_c. The third regression explored the relative contribution of the predictor variables to the max PSI calculated during HTT. Similar to T_c, both BMI (t = −2.20, p = 0.034) and VO_{2max} (t = −2.99, p = 0.005) significantly contributed to the prediction of PSI. Importantly, we included history of EHI as a covariate in our preliminary analyses. Our results found that EHI history had a minimal effect on the regression models and therefore was not included in any of our reported linear or logistic regression models.

The odds ratios and the associated levels of significance for all logistic regressions are presented in Table V. The first regression explored the association between age, gender, anthropometric and aerobic fitness measurements, and the heat intolerance classification criteria for HR. As shown, BMI (OR = 0.46, p = 0.01), BF% (OR = 1.24, p = 0.049), gender (OR = 0.02, p = 0.028), and VO_{2max} (OR = 0.74, p = 0.011) were all associated with HR. The second logistic regression explored the association between the predictor variables and the heat intolerance classification criteria for T_c. As shown, gender (OR = 10.67, p = 0.015) was significantly associated with T_c. The final logistic regression explored the association between the independent variables and overall HTT performance (classification of heat intolerance) taking both criteria (HR > 150 bpm and T_c > 38.5°C) into consideration. As shown, VO_{2max} was the only significant inherent characteristic (OR = 0.87, p = 0.024) associated with overall HTT performance.

DISCUSSION

Having quantitative measures that can assist medical care providers help identify individuals at high risk for heat illness and determine when a warrior or athlete should RTD/RTP

TABLE III. Correlations Between Age, Gender, Anthropometric and Aerobic Fitness Measurements, and Physiological Measurements of Subjects During HTT

Measure	Age	Gender†	BMI	BSA_{ratio}	BF%	WC	VO_{2max}	Max T_c	ΔT_c	Max HR	ΔHR	SW
Age	1.000	—	—	—	—	—	—	—	—	—	—	—
Gender[a]		1.000	—	—	—	—	—	—	—	—	—	—
BMI	−0.280	0.319*	1.000	—	—	—	—	—	—	—	—	—
BSA_{ratio}	0.027	−0.5**	−0.953***	1.000	—	—	—	—	—	—	—	—
BF%	−0.08	−0.413**	0.366*	−0.270	1.000	—	—	—	—	—	—	—
WC	0.021	0.572***	0.815***	−0.889***	0.154	1.000	—	—	—	—	—	—
VO_{2max}	0.031	0.398**	−0.428**	0.308*	−0.596***	−0.180	1.000	—	—	—	—	—
Max T_c	0.053	−0.193	−0.141	0.130	0.241	−0.161	−0.303*	1.000	—	—	—	—
ΔT_c	0.037	−0.042	−0.190	0.102	0.008	−0.197	0.038	0.704***	1.000	—	—	—
Max HR	−0.182	−0.171	−0.007	0.037	0.362*	−0.091	−0.477**	0.742***	0.469**	1.000	—	—
ΔHR	−0.127	−0.104	−0.160	0.143	0.103	−0.198	−0.235	0.718***	0.653***	0.810***	1.000	—
SR	0.007	0.398**	0.418**	−0.526***	0.074	0.503***	0.000	−0.071	−0.113	−0.108	−0.152	1.000

Note: †Male coded 1, female 0; *Significant at $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ BMI, body mass index; BSA_{ratio}, body surface area to mass ratio;; BF%, body fat percent; WC, waist circumference; VO_{2max}, maximal oxygen uptake; Max T_c, maximum core temperature; ΔT_c, change core temperature; HRmax, maximum heart rate; ΔHR, change heart rate; SR, sweat rate. [a]Male coded 1, female 0. *Significant at $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

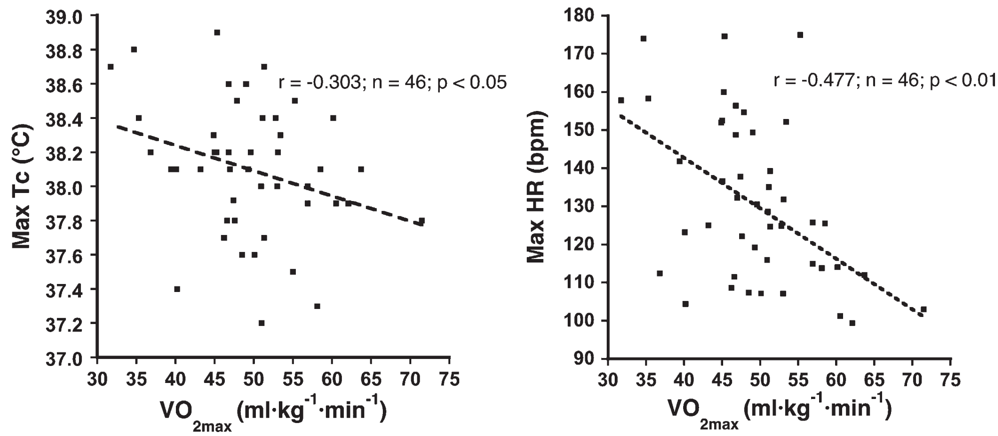

FIGURE 1. Relationship between cardiorespiratory fitness (VO_{2max}) ($mL \cdot kg^{-1} \cdot min^{-1}$) and Max T_c (°C) and max HR (bpm) during HTT.

following EHS would be useful in both military and civilian populations. Given the suggested association between heat intolerance and previous EHS, premature RTD/RTP may predispose a warfighter/athlete to subsequent EHI. The IDF has developed a standardized HTT that medical and military leadership currently use to guide RTD decisions for all victims of EHS. However, their diagnostic tool is not routinely used by military and civilian physicians in the United States, as experts have suggested that further research is needed to validate its utility, validity, and practice. This study examined the associations between HTT performance and age, gender, anthropometric measurements, and cardiorespiratory fitness, to add to the evidence-base for the use of HTT. Correlation analyses revealed moderate inverse relationships between maximal aerobic power and both max T_c and max HR and a moderate positive relationship between BF% and max HR. Linear regression analyses indicated that VO_{2max} was the only independent attribute significantly influencing both max HR and T_c attained during HTT. Furthermore, logistic regression analyses indicated that VO_{2max} was the only independent parameter contributing significantly to overall HTT performance. Collectively, these analyses indicate a genuine and moderate relationship between low cardiorespiratory fitness and heat intolerance (as measured by HTT performance), regardless of gender or participant physical attributes.

Low aerobic fitness has consistently been related to incidence of EHS in military populations,[12,13] and a reduced ability to thermoregulate during exercise in heat stress environments.[37–40] For instance, male Marine Corps recruits with slower 1.5 and 3-mile run times were three to four times more likely to suffer an EHS than those with faster times[12]; similar findings have been reported for female recruits.[13] Additional studies have shown that VO_{2max} is a significant influence with regard to physiological responses (T_c, skin temperature [T_{sk}], and SR) to exercise under conditions of uncompensable heat stress.[37,38,41] For instance, authors reported that subjects with higher levels of aerobic fitness (>55 $mL \cdot min^{-1} \cdot kg^{-1}$) presented lower levels of physiological strain (T_c and T_{sk}) at each timepoint during exercise at a fixed intensity in comparison to their less fit (<50 $mL \cdot min^{-1} \cdot kg^{-1}$) counterparts.[38] Others have demonstrated a linear relationship between aerobic fitness and duration of exercise under similar test conditions.[41] Similar to the present study, Havenith et al[39,40] used linear regression to analyze the relative influence of aerobic

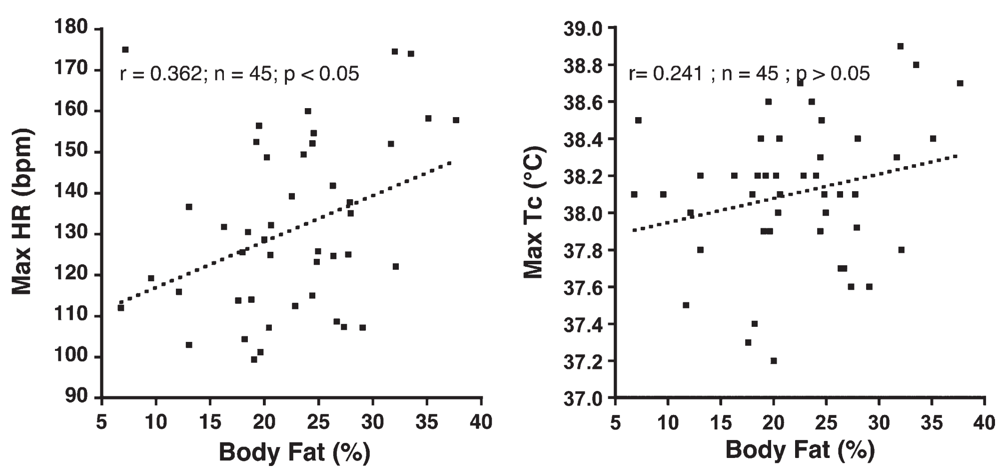

FIGURE 2. Relationship between BF% and Max T_c (°C) and max HR (bpm) during HTT.

TABLE IV. Beta Weights From Regression Analyses Examining the Influence of Age, Gender, Anthropometric and Aerobic Fitness Measurements on HR and T_c During HTT

Independent Variable	Physiological Measurements During HTT		
	Max HR	Max T_c	Max PSI
BMI (kg/m^2)	—	−0.34*	−0.34*
VO_{2max} (mL·min^{-1}·kg^{-1})	−0.58***	−0.44**	−0.47**

Stepwise linear regressions were conducted separately for max HR, max T_c, and max PSI. *Significant at $p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

power, gender and anthropometric measurements on the physiological responses to exercise at fixed and relative intensities in warm/humid (35°C, 80% RH) and hot/dry (45°C, 80% RH) conditions. Overall, they found that VO_{2max} contributed significantly at both intensities and under all environmental conditions. Specifically, aerobic fitness was the most influential contributor to the total variance explained in T_c during exercise at a fixed intensity,[40] whereas BF% and surface-to-mass ratio were more influential at low relative workloads (25%–40% VO_{2max}) than aerobic fitness.[39] As might be expected, VO_{2max} had the largest influence on HR[39,40] relative to anthropometric factors. Of note, these studies utilized a relative exercise intensity substantially lower than those reporting no significant differences in T_c between groups of high and low aerobic fitness during exercise in neutral environments.[42] However, the Israeli HTT involves an absolute workload performed in a thermally challenging environment, which may make it more suitable for large numbers of military members who are required to perform group tasks in hot conditions, regardless of their aerobic capacity.[4,25] The relative intensity of the HTT ranged from 23.4% to 52.2% of the participants' VO_{2max} in this study—as might be the case under field conditions when all military members are performing the same work in the same conditions. Thus, a constant workload in a thermally challenging environment allows for test standardization and represents the majority of high-risk EHS conditions.[16]

BF% and BMI were the only anthropometric measurements contributing to the prediction of selected heat intolerance criteria (HR > 150 bpm), although neither was associated with overall performance on the HTT. However, the current study's finding that for every one standard deviation increase in BMI, participants were 0.5 times less likely to have a HR in excess of 150 bpm, one of the two physiological criterion needed for classification of heat intolerance, should be viewed with caution. Moreover, results showed that heat intolerant participants had lower BMIs (25.3 vs. 25.7) than those categorized as heat tolerant. Although surprising, it is reasonable to suggest that this demonstrates the inability of BMI to serve as an appropriate surrogate for BF%. Importantly, a BMI between 25 and 30 may reflect increased amounts of lean muscle mass in athletic and military populations. BF%. also significantly influenced the HR criterion for heat intolerance. This finding is similar to work by Havenith et al,[39,40] which demonstrated the influential contribution of body surface-to-mass ratio and BF% to HR and T_c responses. In addition, a recent epidemiological study found that Army recruits with excess body fat were 3.6 times more likely to suffer an EHI during basic training vs. those meeting normal standards.[10] Our finding that for every one standard deviation increase in BF% increased the likelihood of surpassing the HR criterion (HR > 150 bpm) for HTT by 1.2 times, would be expected, given the thermoregulatory differences between adipose and lean tissue. Adipose tissue has a lower heat capacity and reduced ability to offload heat compared with leaner tissue, such as skeletal muscle, bone, and connective tissue.[37] Consequently, subjects with high BF % should have greater increases in HR in response to exercise under heat stress and be more likely to exceed the HR criteria for the HTT than those with low body fat.

Road marches over long distances with heavy external loads are common tasks performed by military personnel. Load carriage has been shown to increase the metabolic demands of walking at slow and moderate paces, and negatively impact lower body strength and endurance.[43] Physiological factors affecting load carriage capacity include absolute aerobic power,[44,45] BF%,[43] and fat free mass (kg).[44,46] Additional analyses of our data demonstrate that absolute VO_{2max}, but not fat-free mass, correlates with both HTT max T_c ($r = -0.296$, $p < 0.05$) and max HR ($r = -0.383$, $p < 0.01$). Although the HTT involves walking at a set speed for 2 hours with no external load, it is likely that individuals with low aerobic power would present with augmented physiological responses (T_c and HR), if an external load were carried. Furthermore, previous work has demonstrated that the majority of EHS cases in the IDF occurred during the

TABLE V. Odds Ratios From Regression Analyses of the Associations Between Age, Gender, Anthropometric and Aerobic Fitness Measurements and HTT Performance

Independent Variable	Physiological Measurements During HTT		
	HR > 150 bpm	T_c > 38.5°C	Heat Intolerant
BMI (kg/m^2)	0.46 (0.26–0.83)*	—	—
Body Fat (%)	1.24 (1.00–1.54)*	—	—
Gender	0.02 (0.00–0.64)*	10.67 (1.58–71.90)*	—
VO_{2max} (mL·min^{-1}·kg^{-1})	0.74 (0.59–0.93)*	—	0.89 (−0.80–0.99)*

Stepwise logistic regressions were conducted separately for HR > 150 bpm, T_c > 38.5°C, and heat intolerance. *Significant at $p < 0.05$.

first 2 hours of exercise, a finding that adds to the overall applicability of the HTT.[15]

Although the present study found gender was not associated with overall HTT performance (classification of heat intolerance), it was a significant predictor of individual heat intolerance criteria for both HR and T_c. Results showed that females were 10.7 times more likely to surpass a T_c of 38.5°C during the HTT than males but were significantly less likely to exceed a HR > 150 bpm. This finding is consistent with our previous results,[47] demonstrating the impact of anthropometric and fitness measurements on the association between gender and HTT performance. Alarmingly, approximately 42% (5 of 12) of females were classified as heat intolerant in comparison to only 27% (9 of 34) of males. This finding is similar to Druyan et al[23] who recently reported that 27% and 67% of male and female subjects, respectively, were diagnosed as heat intolerant by a HTT. However, all participants in their study had a past episode of EHS, an attribute that may have accounted for the larger percentage of females found to be heat intolerant. Further studies found that RH influenced the response to heat between genders; men were more tolerant (lower HR and T_c) to hot-dry environments, but less tolerant (higher T_c and SR) in hot-wet environments.[48] Similar to our work, differences in thermoregulation between genders are negligible once cardiorespiratory fitness is considered.[49] Nevertheless, women, as compared to men, generally have lower cardiorespiratory fitness, higher BF% and surface area-to-mass ratio, and a lower SR, all of which influence thermoregulation.[50] Importantly, the difference in thermoregulatory patterns between genders as measured in laboratory studies has coincided with epidemiological reports on the incidence on EHS and EHI in active duty U.S. Service Members. However, the incidence rate has been shown to be dependent on the severity of heat injury. In 2012, women had a higher incidence rate than men for all EHI cases other than EHS (2.35 vs. 1.44 per 1,000 person-years), whereas men had a higher rate for EHS (0.27 vs. 0.15). Although the total number of EHI (1,765 vs. 492) and EHS (334 vs. 31) incident cases was far greater in men than women, these numbers raise concern given the continuing increased operational involvement of women in austere field environments. Our results, when combined with those of Druyan et al,[23] demonstrate that women are more likely to be diagnosed as heat intolerant, as defined by performance on the HTT, than males. Given the small sample of female participants tested in both studies (9 and 12), further research is warranted to better understand the factors contributing to the higher intolerance rate and whether or not creating new criteria for women is necessary.

Limitations of this study must be noted. First, our sample population had a very homogenous and high level of cardiorespiratory fitness. Over two-thirds (71.7%) of participants had a VO_{2max} that was ≥ 70th percentile ranking for their respected age group, as determined by ACSM standards.[34] Moreover, 41.3% (19 of 46) had a VO_{2max} that placed them above the 90th percentile ranking. Since all active duty Service Members are required to take a physical fitness test (PFT), it is reasonable to suggest they would have higher levels of aerobic fitness relative to the general civilian population. Secondly, this sample size was small (n = 46) and included a relatively limited number (n = 12) of female participants. Thus, further work on military populations with a larger sample size and wider range of cardiorespiratory fitness values is warranted. Finally, results from the multivariate analyses indicate that cardiorespiratory fitness predicted only a moderate proportion of the variance in the HTT T_c and HR. Future work examining other parameters or combinations of factors that influence the heat stress response during HTT is warranted.

CONCLUSIONS

EHI and EHS remain significant threats to military operations and all training involving physical activity. Premature RTD/RTP following EHS may predispose a warfighter/athlete to a subsequent EHI. Quantitative measures that help clinicians identify individuals at high risk for EHI and determine when a warrior or athlete should RTD/RTP following EHS are needed. Our results demonstrate that maximal aerobic power is one of the main factors predictive of and associated with heat intolerance as defined by HTT performance. By demonstrating the association between heat intolerance, as determined by HTT performance, and a known risk factor of EHI, we provide further evidence that the HTT can be an effective tool for assessing thermoregulatory patterns. Alternatively, if we know the aerobic power of personnel, then they could be risk stratified for likelihood of heat intolerance, in association with other known contributors, such asBF%.

ACKNOWLEDGMENTS

The project was funded by the office of Naval Research, grant no. N0001411MP20023.

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