Effects of physical characteristics on predicted heat casualty rate

Miyo Yokota and Xiaojiang Xu
U.S. Army Research Institute of Environmental Medicine (USARIEM), Natick, MA, USA
Contact person: Miyo.Yokota@us.army.mil

INTRODUCTION

Human thermal regulatory models have been increasingly utilized to examining and anticipating physiological responses of deployed Soldiers and workers under various stressful situations. The benefits of using these computer models include assessment of thermal strains without the risk and cost, and time of related human experiments. Traditional thermal modeling represents the average physiological responses for all individuals in a given population (Gagge et al., 1986;Stolwijk, 1970). However, most populations consist of workers with diverse body sizes and composition (Bathalon et al., 2004) and consequently the physiological responses of some individuals within the population may differ from the average responses. The purpose of this study is to demonstrate how anthropometric variability affects physiological responses of individuals and ultimately, heat casualty rates using Monte Carlo (MC) method and a thermoregulatory model. We used a variable dependent (VD) MC approach, which simulates individual variability with realistic human dimensions (Yokota et al., 2009), and a six-cylinder thermoregulatory model (SCTM) that provides individual tolerance times in thermal stressful conditions using a core temperature (Tc) as an indicator of heat strain level (Xu and Werner, 1997).

METHODS

A simulated sample of one hundred subjects was generated based on the VD-MC method (Yokota et al., 2009). VD-MC was developed from the correlation matrix shown in Table 1 and mean $\bar{x}$ and standard deviation (SD) of height (177 ± 7 cm), weight (81 ± 12 kg) and body fat (BF) (17 ± 6 %) from a U.S. Army male anthropometric database (Bathalon et al., 2004).

Table 1. Correlation coefficient between height (cm), weight (kg) and body fat (%) from 2004 U.S. Army male database

	Height	Weight	Body fat
Height	1		
Weight	0.5*	1	
Body fat	-0.03	0.7*	1

*statistical difference at $p < 0.05$

The principal component (PC) analysis was used to classify samples into primary somatic forms. The analysis provides the best representations of multivariate data in simple dimensions by transforming linear orthogonal axes (eigenvectors) and maximizing variation (eigenvalues) of the data (Tatsuoka, 1988). The ellipse that represents data within 25% from the centroid (0,0 coordinate) was classified as the "medium" somatic form. Individuals outside of the ellipse on PC dimensions are identified with "extreme individuals" and further classified into somatic forms based on eigenvectors (or multivariate anthropometric patterns).

The anthropometric values (i.e., height, weight, %BF) identified with somatic forms were applied to the SCTM model. The SCTM models combine the application of the first principles of biophysical heat exchange with a realistic approximation of human physiology. It is applicable to cold, warm/heat, and water immersion conditions (Xu and Werner, 1997). SCTM takes into account physiological mechanisms, including metabolic heat production, sweating heat loss, respiratory heat loss, and blood circulation. It is able to predict both core and regional temperatures, and evaporative water loss through the skin and lungs, which can then be used to estimate dehydration. SCTM inputs include individual characteristics (i.e., height, weight, %BF) and metabolic cost, as well as environmental (i.e., air temperature (Ta), relative humidity (RH), and wind velocity) and clothing (i.e., clothing insulation, moisture permeability index) properties for each of the six cylinders (Xu and Werner, 1997).

The simulated heat stress conditions were for subjects, wearing battle dress uniform, walking at 1.34 ms^{-1} for 400 min while carrying different loads (0, 30kg) in three different environment (Ta: 25ºC, 30ºC, 35ºC, all at 50%RH). Heat tolerance time (i.e., the time to reach Tc of 39.5ºC) for different heat stress conditions was estimated. Heat tolerance times were compared by operational conditions and somatic groups using Analysis of Variance (ANOVA) ($p = 0.05$).

RESULTS

Principal component analysis (PCA): Figure 1 displays the PCA result of individuals simulated by VD-MC. The first PC (X axis) represents 59% of total variability and corresponds to all positive loadings of variables indicating overall body size. The second PC represents 34% of the total variation and corresponds with dichotomous loadings between high loadings on height and % BF and a low loading on weight. Overall, five somatic forms including "tall-fat (TF)," "tall-lean (TL)," "short-fat (SF)," "short-lean (SL)," and "medium" (MED) were identified in PCA. Some overlap between extreme and MED groups can be explained with two reasons: 1) the anthropometric values are similar between extreme and MED groups; or 2) 7% of total variability, which was not included in this two-dimensional PC graph (Figure 1), may distort the locations of some individuals.

Thermal modeling and heat tolerance time: The descriptive summary of anthropometric variables in each somatic group identified in PCA is displayed in Table 2. Simulations of 400 min exposures to heat stress were run and the predicted heat tolerance times (Tc <39.5ºC) were compared by environmental, operational conditions and somatic forms. Figure 2 indicates the distribution of heat tolerance times by different Ta (25, 30, 35ºC) and load carriage (0, 30kg). Heat tolerance times of individuals in 25 ºC without load carriage were 400 min for all somatic forms. Overall, $\bar{x}$ and SD of tolerance time were reduced when heat stress (i.e., Ta, load carriage) was increased ($p < 0.05$). For instance, $\bar{x}$ (± SD) tolerance times in 30 and 35 ºC without load carriage were 270 (± 89) min and 108 (± 12) min, respectively. $\bar{x}$ (± SD) tolerance times in 30 and 35 ºC with 30kg load carriage reduced to 81 (± 5) min and 62 (± 3) min, respectively.

Figure 3 displays an example of differences in heat tolerance time between somatic forms in different load carriage when Ta is controlled (i.e., 30ºC/0 kg, 30ºC/30 kg) ($p < 0.05$). Lean groups (i.e., SL, TL) could be active longer than fat individuals (SF, TF) without load carriage. Conversely, individuals with heavy body weight (i.e., TF, TL, SF) could work longer than SL individuals when they were carrying heavy loads and working in the heat ($p < 0.05$).

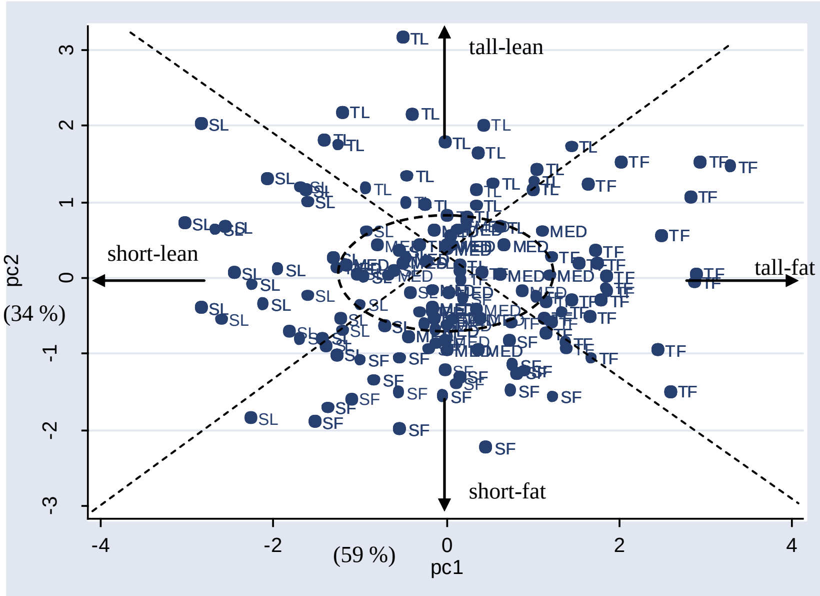

Figure 1. Principal component analysis of individuals simulated by variable independent Monte Carlo simulation. It represents 93% of total variability. TF: tall-fat; TL: tall-lean; SF: short-fat: SL: short-lean; MED: medium. The dotted ellipse represents 25% of the sample (n=100) from the centroid (0,0). The dotted axes separate extreme somatic forms.

Table 2. Descriptive summary of anthropometric variables by extreme somatic forms

Somatic group	Height (cm)	Weight (kg)	Body Fat (%)	BMI (kg/m^2)	BSA (m^2)
short-fat	168.6 ± 2.7	79.2 ± 8.2	22 ± 3	28 ± 2	1.89 ± 0.10
short-lean	171.9 ± 3.6	64.8 ± 8.3	11 ± 4	22 ± 3	1.77 ± 0.09
tall-fat	180.9 ± 5.2	94.8 ± 6.1	22 ± 3	29 ± 2	2.13 ± 0.09
tall-lean	182.7 ± 3.9	79.5 ± 7.6	13 ± 4	23 ± 3	2.00 ± 0.08
medium	175.4 ± 3.3	79.0 ± 4.2	17 ± 2	26 ± 2	1.94 ± 0.06

BMI: body mass index; BSA: body surface area; Mean ± Standard deviation

DISCUSSION

Our simulation results showed that the risk of becoming heat casualty was dependent on not only operational and environmental heat stress but also individual body size and composition. The model simulations indicated that $\bar{x}$ and individual variability of heat tolerance time were reduced when Ta and load carriage were increased. Individuals simulated using VD-MC and PCA were classified into five somatic forms (i.e., TF, TL, SF, SL, MED). Predicted results showed that fat groups, whose Tc were higher than lean groups, were more vulnerable to heat stress when Ta is a primarily heat stress factor. This appears to be consistent with observation that body mass index (BMI) is related to an increase rate of exertional heat illness during military basic training (Gardner et al., 1996;Wallace et al., 2006), as BMI of fat individuals were higher than lean individuals. Lean individuals, having low %BF and higher body surface area (BSA) per mass, can dissipate heat more readily than fat individuals because of lower passive thermal resistance between the core and skin.

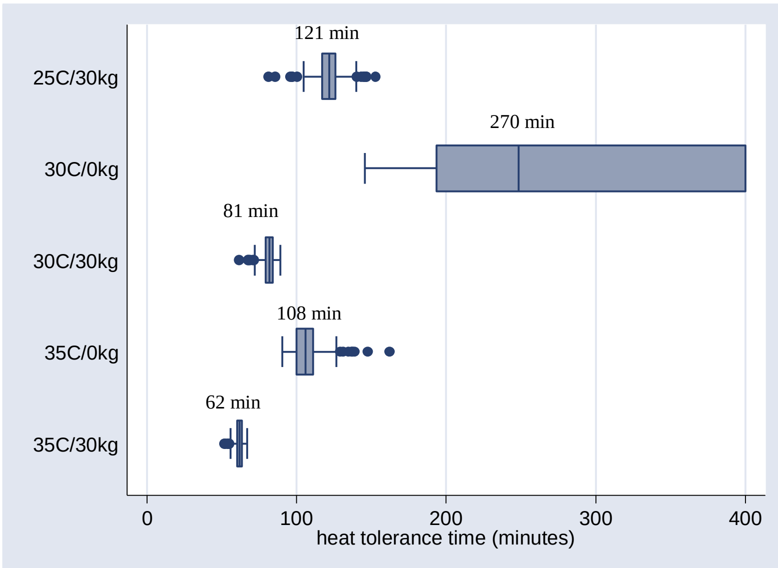

Figure 2. The box plot summary of predicted heat tolerance time by different air temperature (25, 30, 35ºC) and load carriage (0, 30 kg).

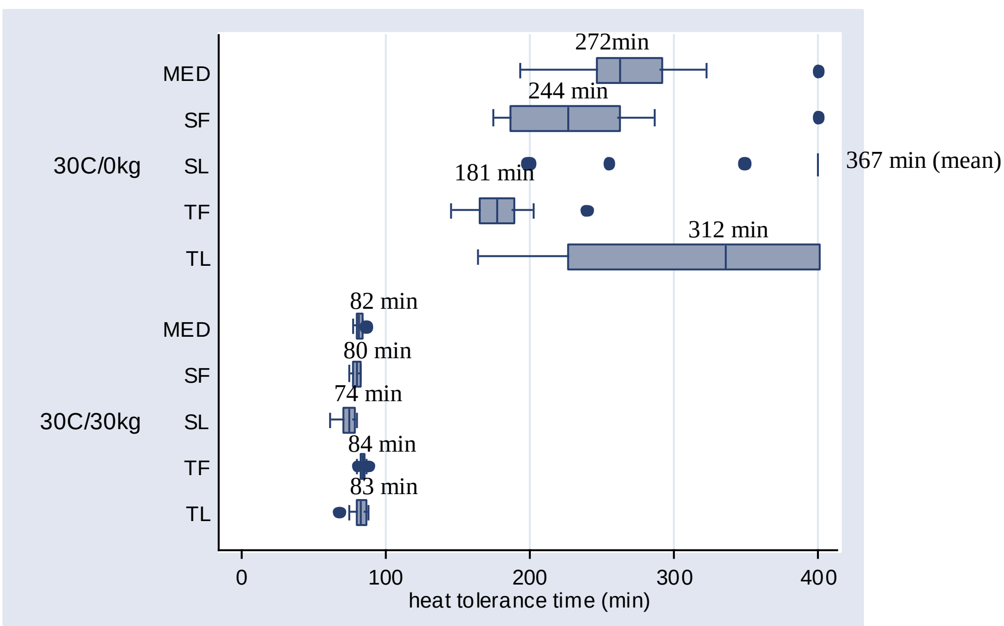

Figure 3. The comparison of predicted heat tolerance time between different somatic forms (SF: short-fat; SL: short-lean, TF: tall-fat, TL: tall-lean, MED: Medium) by two conditions (30ºC/0 kg, 30ºC/30 kg). The number adjacent to each box plot indicates the mean tolerance time.

In addition, the model Tc predictions are partially associated with metabolic heat production per BSA (w/m^2). For a given environmental and exercise condition without any load carriage, lean individuals, producing less w/m^2, could lower their Tc than fat individuals.

In contrast, when heat strain is triggered by higher Ta and heavier loads, individual with heavy body weight could be active longer than individuals with light body weight. Carrying heavy loads during exercise increased the physiological strain on individuals with light body weight by producing more w/m^2 than those with heavy body weight. For instance, w/m^2 of subjects, carrying 40kg load and walking at 1.34 ms^{-1} are 191 w/m^2 for a short-lean individual (height: 171 cm; weight: 64 kg; BSA: 1.75 m^2) and 178 w/m^2 for tall-fat individual (height: 190 cm; weight: 104 kg, BSA: 2.32 m^2), respectively.

As the current version of SCTM does not identify individual differences in physiological responses to heat stress (e.g., vasodilation and sweating), the predicted differences were mainly due to differences in somatic form. The approach used in this study allows us to identify, based on somatic form, who is or is not susceptible to thermal stress in certain environmental and activity conditions, ultimately assisting the reduction and prevention of thermal related injuries, illness and performance decrement. It is also useful for developing survival guideline and strategic planning for search and rescue operations in extreme environment (e.g., sea, mountain). Finally, the method is applicable to both military and civilian occupational populations (e.g., firefighters, coal miners) at the risk of exposure to environmental extremes.

ACKNOWLEDGEMENT
The authors thank Dr. L. Berglund, Dr. W. Santee, and Dr. R. Hoyt, USARIEM for critical comments on this paper during manuscript preparation.

DISCLAIMER
The investigators adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in accordance with the provisions of 32 CFR Part 219. The opinions and assertions contained herein are the private views of the author(s) and are not to be construed as official or as reflecting the views of the Army or the Department of Defense (USARIEM-E02-20).

REFERENCES
Bathalon GP, McGraw SM, Friedl KE, Sharp MA, Williamson DA, and Young AJ. 2004. Rationale and evidence supporting changes to the army weight control program. In: Natick, MA: US Army Research Institute of Environmental Medicine (USARIEM). p 1-45.

Gagge AP, Foblets AP, and Berglund LG. 1986. A standard predictive index of human response to the thermal environment. In: ASHARAE transactions. Portland, Oregon: p 709-731.

Gardner JW, Kark JA, Karnei K, Sanborn J, Gastaldo E, Burr P, and Wenger CB. 1996. Risk factors predicting exertional heat illness in male Marine Corps recruit. Medicine and Science in Sports and Exercise 28:939-944.

Stolwijk JA. 1970. Mathematical model of thermoregulation. In: Gagge AP, Stolwijk JA, editors. Physiological and behavioral temperature regulation. Illinois: Charles Thomas. p 703-721.

Tatsuoka M. 1988. Multivariate analysis: Techniques for educational and psychological research. New York: Macmillan publishing company.

Wallace RF, Kriebel D, Punnett L, Wegman DH, Wenger CB, Gardner JW, and Kark JA. 2006. Risk factors for recruit exertional heat illness by gender and training period. Aviat Space Environ Med 77:415-421.

Xu X, and Werner J. 1997. A dynamic model of the human/clothing/environment-system. Appl Human Sci 16:61-75.

Yokota M, Berglund LG, and Bathalon GP. 2009. Individual variability for thermal regulatory models using Monte Carlo simulations. [abstract]. 3rd International Symposium on Physiology and Pharmacology of Temperature Regulation