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Thermoregulatory modeling use and application in the military workforce

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A B S T R A C T

Thermoregulatory models have been used in the military to quantify probabilities of individuals' thermal-related illness/injury. The uses of the models have diversified over the past decade. This paper revisits an overall view of selected thermoregulatory models used in the U.S. military and provides examples of actual practical military applications: 1) the latest military vehicle designed with armor and blast/bulletproof windows was assessed to predict crews' thermal strains levels inside vehicles under hot environment (air temperature [T_a]: 29–43 °C, dew point: 13 °C); 2) a military working dog (MWD) model was developed by modifying existing human thermoregulatory models with canine physical appearance and physiological mechanisms; 3) thermal tolerance range of individuals from a large military group ($n = 100$) exposed to 35 °C/40% relative humidity were examined using thermoregulatory modeling and multivariate statistical analyses. Model simulation results assist in the decisions for the strategic planning and preventions of heat stress.

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1. Introduction

Military operations are widely dispersed across the globe to areas such as Africa, the Middle East, Europe, Asia, Pacific regions, and throughout domestic and extended territories (Department of Defense, 2004; Nevola et al., 2010). One of the major challenges the military faces is sustainment of missions in diverse environment and operational situations. For instance, soldiers working in a battlefield often wear body armor and use vehicles (e.g., High Mobility Multipurpose Wheeled Vehicle [HMMWV], etc) in hot-dry weather (e.g., Iraq air temperature: ~50 °C/dew point 13 °C). Under these extreme conditions, soldiers experience heat stress and are at inherently higher risk of thermal-related illnesses/injuries. Various strategies/guidelines have been developed to reduce the risk of heat illness for military personnel including early morning/late night patrols, the usage of personnel cooling systems, appropriate hydration, and heat acclimation prior to deployment (Department of the Army and Air Force, 2003; Epstein et al., 2012). However, methods are needed to quantify the effectiveness of these strategies in improving military personnel's ability to sustain their operations. An actual experimental method to replicate military working conditions can be ideal to verify if the strategies/guidelines are up-to-date (Nevola et al., 2004, 2010; Amos et al., 2000). However, this verification method can be costly and time-consuming and it is difficult to replicate or consider all possible military operational and environmental situations.

Considering the above problem, human thermoregulatory models are being developed in the military. They variously predict physiological responses of military personnel and the probabilities of thermal-related illnesses/injuries, estimate safe thermal work times, and predict the time available for successful rescue (Berglund et al., 2006; Kraning and Gonzalez, 1997; Pandolf et al., 1986; Xu and Werner, 1997; Yokota et al., 2008). Thermoregulatory models, consisting of series of biophysical processes and physiological control equations rationally integrated to represent the human thermal physiological mechanisms, can provide simulations of human thermo-physiological responses to various combinations of environmental and operational conditions. These simulations can be conducted repeatedly and efficiently at low cost and without risk to human test volunteers. The various models enable and facilitate equipment, clothing and their design and mission planning to reduce heat illness related risks.

Thermoregulatory models developed over the years include pioneering work (Gagge et al., 1986; Stolwijk and Hardy, 1966; Stolwijk, 1970; Werner and Buse, 1988; Wissler, 1964) and more modern successors including sophisticated models to represent detailed human body parts and models adaptable for different

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individuals exposed to various environments (Berglund et al., 2009; Fiala et al., 1999; Haslam and Parsons, 1987; Havenith, 2001; Li et al., 2008; Shitzer et al., 1997; Tanabe et al., 2002; Tikuisis et al., 1988; Xu et al., 2011; Yokoyama et al., 2007; Zhang et al., 2001). However, utilization of these models to solve practical problems in working environments is infrequently reported. The purpose of this paper is to describe basic overviews of thermoregulatory models used by the US military together with examples of their usage and applications. The ultimate goal of the US military for utilizing thermoregulatory models is to prevent thermal-related illness/injury, promote occupational safety, sustain operations, and maximize the physical performance of military personnel.

2. Methods

2.1. Thermoregulatory models

Thermoregulatory models are mathematical representations of the human, rationally constructed from physiology, heat transfer and thermodynamic principles. Generally, the models' inputs such as environmental conditions (e.g., air temperature [T_a], thermal radiation, relative humidity [RH], wind speed [WS]), clothing characteristics (e.g., insulations [clo], water vapor impermeability), anthropometrics (e.g., height, weight, age, %body fat), and activities (e.g., metabolic costs) of subjects are combined to derive physiological outputs (e.g., core temperature [T_c], skin temperature [T_{sk}], sweat rates, heart rates [HR]) from appropriate heat, energy and moisture balances on lumped parameter parts of the modeled anatomy.

The overall heat balance for the total person can be expressed as:

$$S = \dot{M} - \dot{M}_w - R - C - K - E - \text{Res} \quad \left[\text{W m}^{-2}\right], \tag{1}$$

where S is the rate of heat storage; $\dot{M}$ is the rate of metabolic heat production; $\dot{M}_w$ is the rate of the mechanical work; R is the rate of radiative heat loss; C is the rate of convective heat loss; K is the rate of conductive heat loss; E is the rate of evaporative heat loss; and Res is respiratory heat loss. The driving forces for dry or sensible heat transfer values (R, C, K) are the temperature differences between skin and the environment. The driving force for evaporative respiratory, sweating and vapor diffusion through skin processes are the vapor pressure differences between the environment and the surfaces. These heat transfer values depend on the physical properties and heat transfer process relationships for the situation and surface. When the environmental temperature approaches or is higher than T_{sk}, dry heat transfer becomes zero or negative and evaporative heat transfer becomes the only avenue for the human body to dissipate heat. Heat production reflects the activity/exercise level and can be quantified or estimated by various methods. For instance, ASHRAE (2009) provides the list of typical metabolic rates for various activities. Givoni and Goldman (1971), Pandolf et al. (1977) and Santee et al. (2003) established equations to estimate the metabolic cost of soldiers involved in load carriage, different topography, and mechanical work in the field. These quantitative relationships/equations are commonly utilized in the US military for metabolic estimates to this day. Berglund (1977) developed a metabolic rate equation for metabolic cost estimates using ambient/operative temperature, working and resting HR and body surface area of subjects. The equation can be useful to more easily capture transient changes in energy expenditure influenced by activities, clothing, environment, and load carriage.

The human body is often simplified for modeling to a cylindrical shape to more easily obtain numerical solutions to Eq. (1). Some simpler models represent the human body as a cylinder consisting of only skin and core compartments (Gagge et al., 1986; Yokota et al., 2008). Other more complicated models represent the human body with one cylinder or multi-cylinders (e.g., head, torso, arms, legs, etc) consisting of core, muscle, fat, and skin layers (Kraning and Gonzalez, 1997; Stolwijk, 1970; Wissler, 1964; Xu and Werner, 1997). Thermoregulatory control actions such as vasoconstriction, vasodilation, sweat, and shivering metabolic heat production are generally proportional control types responding to differences between tissue temperatures and their thermally neutral thresholds, or set-points.

One of the US Army thermoregulatory models developed by Kraning and Gonzalez (1997) was constructed mainly for simulating heat stress conditions and responses. The human body is represented by a system of concentric cylinders consisting of six compartments or layers (i.e., core, muscle, fat, vascular skin, avascular skin, and blood). $\dot{M}$ in each compartment is related to work metabolism and allocated with fixed percentages related to an individual's anthropometry (i.e., weight = 70 kg and body surface area (A_D) = 1.8 m). Heat flow between compartments is passively conducted through tissue and actively transported by blood flows. Active regulatory systems (e.g., sweating, skin blood flow) are modeled as proportionally controlled by combinations of mean skin temperature ($\overline{T}_{sk}$), skin blood flow, $\dot{M}$ and central blood temperature (T_{bl}). For instance, sweating rate ($\dot{M}_{sw}$) is determined by the following equation (Kraning and Gonzalez, 1997):

$$\begin{aligned}\dot{M}_{sw} &= A_D \cdot \lambda_{SR}\left(\alpha_{SR}\left[T_{bl} - \text{Th}_{bl\text{-}SR}\right] + \beta_{SR}\left[\overline{T}_{sk} - \text{Th}_{sk\text{-}SR}\right]\right) \\ &\quad \cdot \exp\left(\overline{T}_{sk} - \text{Th}_{sk\text{-}SR}/\delta_{SR}\right) \quad \left[\text{g min}^{-1}\right],\end{aligned} \tag{2}$$

where A_D: body surface area (m^2), α_{SR}: 4.83 g min^{-1} °C^{-1}, β_{SR}: 0.56 g min^{-1} °C^{-1}, δ_{SR}: 10, $\text{Th}_{bl\text{-}SR}$ as a central blood threshold temperature: 36.96 °C, $\text{Th}_{sk\text{-}SR}$ as a skin threshold temperature: 33.0 °C, and λ_{SR}: (160 (VO_2max in l min^{-1})/(bodyweight in kg) − 3.2)/3.84. The α_{SR} and $\text{Th}_{bl\text{-}SR}$ values are adjusted when progressive dehydration occurs. Temperature set points are adjusted for thermal acclimation.

This model predicts T_c, T_{sk}, sweat rates, skin wettedness, and HR, as well as cardiac output, stroke volumes (SV), and radial arterial temperatures. For instance, SV, which is associated with cardiac output and HR, is determined from a level of work ($\dot{M}$), physical fitness (VO_2max), $\overline{T}_{sk}$, and the level of dehydration. The model sets the minimum (SV_{min}) and maximum (SV_{max}) values of SV using linear equations of VO_2max. Then normal SV is determined by SV_{min}, SV_{max}, and $\dot{M}$ (Kraning and Gonzalez, 1997). Physiological Strain Index (PSI), a scale to express physiological strain levels of the individuals using their deviations of HR and T_c at a time from initial resting HR and T_c (Moran et al., 1998), was also implemented in this model. This index, representing the categorical scales between 0 (no/little PSI) and 10 (very high PSI), has been widely utilized in military physiological research (Hadid et al., 2008; Kenefick et al., 2011).

Another rational model used by the US Army is the six cylinder thermoregulatory model (SCTM) (Xu and Werner, 1997; Xu et al., 2005, 2011). The cylinders represent different parts of the human body (i.e., head, trunk, arms, hands, legs, and feet) with each cylinder consisting of concentric layers for core, muscle, fat, and skin. The integrated thermal signals to control physiological mechanism (e.g., blood flow, sweat) are composed of the weighted thermal inputs from thermal receptors at various sites distributed throughout the body. In order to maintain thermal homeostasis, thermoregulatory actions (i.e., vasomotor changes, $\dot{M}$, and sweat production) are activated in response to differences between its set point and the integrated thermal signal received by the