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Thermoregulatory model to predict physiological status from ambient environment and heart rate

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Abstract

A real-time thermoregulatory model was developed for predicting real-time physiological responses of workers engaged in various tasks for prolonged time. The unique feature of the present model is primarily on metabolic activity inputs derived from minimum non-invasive measures (i.e., heart rate and ambient temperature). In addition, it utilizes individual anthropological characteristics (height, weight, and clothing) as an input to estimate core temperatures (T_c). The model was validated using data from five laboratory studies ($n = 63$) with varied environments, clothing, and heat acclimation status. Overall, T_c predictions using this simplified model, corresponded well with measured values (root mean square deviation: 0.05–0.31 °C).

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Keywords: Real-time modeling; Heat stress; Heart rate; Core temperature; Air temperature

1. Introduction

Thermoregulatory mathematical models have been increasingly utilized to assess thermal strains of workers without risk, cost, and time related human experiments. Although statistical models limit simulation conditions based on model assumptions, mathematical models consisting of series of thermal physiological equations can provide simulations by generating various combinations of environmental and operational heat stress situations. Previous thermal regulatory models require body core temperature (T_c) as an input [1–3], which is an important physiological parameter for the assessment of thermo physiological strain as it reliably indicates impending injury [4,5]. However, T_c is an invasive measurement and often impractical and undesirable measurement for monitoring during varied activities over prolonged periods in industrial and military situations. In addition, utilizing previous models to predict

physiological responses can be inconvenient and inaccurate for workers, especially soldiers, engaged in various strenuous field activities for prolonged time. For instance, some models can predict physiological responses based on only consistent environmental and operational conditions during work controlled duties [2,3]. Furthermore, many inputs, some of which may be invasive, are required for previous models and tend to provide more inappropriate or missing data in field working environment because strenuous activities in a field are likely to cause sensor malfunctions [1,6]. Therefore, this new suggested model based on a minimum number of non-invasive inputs was needed for predicting real-time physiological responses of soldiers during various prolonged and heat stress related operations. The purpose of this paper is to develop the new model and test the accuracy of the model predictions with a focus on T_c using available data. Although the model in this study was primarily designed for military personnel who are usually heat acclimatized during training with normal or low levels of body fat relative to the general population, the concept of the model can be applicable to industrial and emergency operations.

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Comparisons of physiological data with model predictions provide the analytical basis necessary to characterize model performance and, may if necessary, identify areas of further improvements.

2. Methods

The new model represents the human as two active physiological compartments (core and skin) surrounded by a passive clothing compartment. The initial temperature in each compartment was set lower (40.3°C) for heat acclimated individuals [6]. Within a compartment the thermophysiological properties are assumed to be uniform; that is for example, T_c has the same value at time t throughout the core compartment and likewise for skin temperature. All metabolic heat production (M) occurs in the core. Some of the core heat is lost directly to the environment by respiration with the remaining flowing to the skin by conduction and skin blood flow. Overall, the regulation of T_c in the model is achieved primarily by controlling blood flow to the skin and sweating rate of the skin. These are reasonable representations and simplifications because of increased blood circulation in warm and hot conditions [6]. The basic thermal regulatory functions including heat production, transfer, balance, and thermal strain index utilized in the model were described below.

2.1. Metabolic rate (M)

A unique feature of this model is the use of real-time estimates of M (Watts) derived from the measured heart rate (HR) and environment temperature [7]. This equation was utilized because the parameters are minimum non-invasive measures and overall good correlation between O_2 uptakes and HR were demonstrated [7,8]. The M equation using HR and environmental temperature was described as follows:

$$M = [0.68 + 4.69(\text{HRratio} - 1) - 0.052(\text{HRratio} - 1)(T_a - 20)]58.1A_D \quad (1)$$

where HRratio—observed HR given at the time/resting HR of the individual, and T_a —ambient temperature in $^{\circ}\text{C}$. A_D is the body surface area (m^2). Cardiac output, indicated by HR, supplies blood and oxygen for metabolism and also blood flow to the skin for thermoregulation. For a given metabolic activity, the HR will increase with increasing environmental temperature because of the thermoregulatory need for increased skin blood flow. The prediction of M shown in Eq. (1) was derived from HR and oxygen consumption measured over a range of metabolic activity and environmental temperature [7]. The equation is tested for the conditions including $20^{\circ}\text{C} \leq T_a \leq 40^{\circ}\text{C}$, $1.2 \leq \text{HRratio} \leq 2.1$, wind speed $\approx 1.25 \text{ m s}^{-1}$, dew point temperature $\leq 20^{\circ}\text{C}$.

2.2. Heat transfer

Heat exchange from the skin to the environment by radiation and convection is classified as dry heat exchange. The rate of

dry heat loss (Q_{dry} , W m^{-2}) was determined by

$$Q_{\text{dry}} = (T_{\text{sk}} - T_o) / (R_{\text{clt}}) \quad (2)$$

where R_{clt} is the total dry thermal resistance between skin and the environment and T_o is the operative temperature of the environment [6]. T_{sk} is the skin temperature.

R_{clt} values for military clothing used in validation process for the present model are from thermal manikin measurements. T_o is the average of ambient air (T_a) and mean radiant temperatures weighted by their respective heat transfer coefficients as described by Kraning and Gonzalez [6].

The evaporative heat loss from the skin (Q_{evap} , W m^{-2}) is from water diffusion through the dry skin and from evaporation of areas covered with sweat. It is quantified as [9]:

$$Q_{\text{evap}} = (1 - w)0.06E_{\text{max}} + wE_{\text{max}} \quad (3)$$

where the maximum rate of evaporative heat loss from the skin surface (E_{max}) completely covered by sweat is calculated from saturated vapor pressure (Torr) of water at the skin temperature, the ambient water vapor pressure (Torr) and the vapor resistance of the clothing system from skin to the surrounding environment. Skin wettedness (w) or the fraction of the skin surface covered by sweat was determined from the rate of sweat secretion to the rate of maximum evaporation from completely wet skin [2].

The heat exchanged via respiration (Q_{res} , W m^{-2}) was estimated [9] as

$$Q_{\text{res}} = M / A_D (0.0014(34 - T_a) + 0.0023(44 - P_a)) \quad (4)$$

where P_a is the ambient water vapor pressure (Torr) and T_a is the ambient temperature ($^{\circ}\text{C}$).

2.3. Heat balance

A heat balance analysis of the core compartment yields,

$$M / A_D = Q_{\text{res}} + Q_k + Q_{\text{skbf}} + (W_c / A_D) c_{\text{bt}} (dT_c / dt) \quad (5)$$

where M / A_D is in W m^{-2} , Q_{res} is respiratory heat loss, Q_k is passive heat conduction from core to the skin, and Q_{skbf} represents heat transported by the blood from core to skin compartments. The last term (dT_c / dt) on the right in Eq. (5) represents the rate of heat storage of the core compartment where W_c is the mass (kg) of the core (≈ 0.95 of total body mass in this case) and specific heat of body tissue (c_{bt}) is $0.97 \text{ Wh kg}^{-1} ^{\circ}\text{C}^{-1}$ [2]. The passive heat conduction from core to skin (Q_k) was estimated based on the temperature differences between skin and core and the constant conductance (k) value of the tissue between two compartments ($5.28 \text{ W m}^{-2} ^{\circ}\text{C}^{-1}$) [9]. Similarly, the heat transported by blood flow (Q_{skbf}) to the skin is determined based on skin blood flow, which is modeled proportional to changes in core and skin temperatures from their set point temperatures ($T_{\text{cset}} = 36.8^{\circ}\text{C}$; $T_{\text{skset}} = 33.7^{\circ}\text{C}$) and specific heat of blood as a constant value of $1.163 \text{ Wh L}^{-1} ^{\circ}\text{C}^{-1}$ [2]. The rate of T_c ($^{\circ}\text{C}$) change (dT_c / dt) can be rearranged by Eq. (5) to find the next T_c . The energy balance of the skin compartment (W m^{-2}) is

Table 1

The summary of three heat study conditions used in this study.

Study#	HS1	HS2	HS3	HS4	HS5
Ta (°C)	27	49	30	35	40
RH (%)	75	18	50	45	40
Acclimation status	No	Yes	Yes	Yes	Yes
Clothing	HWBDU	T-shirt & shorts	HWBDU	CPG	T-shirt & shorts
Activity (W)	277–350	420–620	510–840	~450	~410
Duration (min)	~170	< 100	110	< 40	125
N	9	5	11	8	30
Reference (#)	[11]	[12]	[12]	[13]	[14]

HWBDU—hot weather battle dress uniform and CPG—chemical protective garment.

modeled similarly to T_c substituting the mass (kg) of the skin compartment and T_{sk} , instead [2].

2.4. Physiological strain index (PSI)

The thermal strain index called PSI was utilized based on measured HR and predicted T_c by the model for evaluating on-line heat strain levels of individuals calculated as follows [10]:

$$PSI = 5(T_{ct} - T_{c0})(39.5 - T_c)^{-1} + 5(HR_t - HR_0)(180 - HR_0)^{-1} \quad (6)$$

where T_{c0} and HR_0 are the initial T_c and HR, respectively. T_{ct} and HR_t are taken at a given time t during the heat exposure [10]. Unlike other thermal indices, PSI is simple, easier to use, and feasible for different operational and environmental conditions [10]. The PSI consists of 0–10 scale, classifying them into five thermal categorical states (no to little, low, moderate, high, very high) [10].

2.5. Validation data

The validation of the model was conducted using data from five different laboratory studies. In all cases, participants provided their informed consent prior to participation and were free to withdraw from the study at any time.

Heat Study 1 (HS1): Nine unacclimated volunteers (8 males, 1 female; age: 23 ± 4 [SD] yr; height 174.2 ± 5.2 cm; weight: 73.4 ± 6.5 kg), wearing the US Army hot weather battle dress uniform (HWBDU) did intermittent exercise in a warm-humid environment (air temperature (T_a): 27°C , relative humidity (RH): 75%RH) for 170 min [11]. The exercise routine consisted of walking on a level treadmill at 1.34 ms^{-1} for 30 min followed by 10 min of rest. Grand mean of subjects' HR ranged between 74 and 106 bpm and that of T_c ranged between 37.0 and 37.5°C during the experiment. Rectal temperature was measured each minute [11].

Heat Study 2 (HS2): Five heat acclimated male soldiers (age: 22 ± 5 yr, height 176 ± 4 cm; weight: 71.1 ± 9.3 kg) wearing t-shirt and shorts continuously walked at 420–620 W in a hot dry (49°C , 18%RH) environment [12]. The maximum exercise duration was 100 min and subjects continued a test session until they voluntary withdrew. Grand mean of subjects' HR

increased from 83 to 157 bpm and that of T_c increased from 36.8 to 38.6°C during the experiment. T_c was measured with an ingestible telemetry temperature pill [12].

Heat Study 3 (HS3): Eleven volunteers (10 males, 1 female; age: 21 ± 8 yr; height: 175 ± 7 cm; weight: 78.0 ± 11.4 kg), wearing HWBDU, did intermittent exercise in a warm-humid environment (30°C , 50%RH) for 110 min [12]. Subjects are partially heat acclimated by natural summer acclimation but no official acclimation. The exercise routine consisted of walking on a treadmill (1.56 ms^{-1} , 7% grade) for 50 min, followed by 10 min rest. Grand mean of subjects' HR ranged between 82 and 152 bpm and that of T_c ranged between 36.8 and 38.2°C during the experiment. Rectal temperature, measured with an ingestible telemetry temperature pill was recorded every 10 min [12].

Heat Study 4 (HS4): Eight heat acclimated men (age: 23 ± 6 yr; height: 176 ± 6 cm; weight: 76.0 ± 15.4 kg), wearing chemical protective garments, walked on a treadmill with a 4–9% grade at 1.56 – 1.65 ms^{-1} that resulted in metabolic effort about 450 W and oxygen uptake around 55% of $\text{VO}_{2\text{max}}$ until they voluntary withdrew from the study or $T_c > 39.5^\circ\text{C}$ [13]. Subjects were able to continue exercising for < 40 min under environmental conditions of $35^\circ\text{C}/45\text{RH}$. T_c was measured by a rectal probe [13].

Heat Study 5 (HS5): Thirty heat acclimated male volunteers (age: 19 ± 1 yr; height: 180 ± 1 cm; weight: 76.3 ± 2.8 kg) wearing t-shirt and shorts walked on a treadmill at ~ 410 W in the environmental chamber (40°C , 40%RH) for 125 min [14]. Grand mean of subjects' HR increased from 77 to 121 bpm and that of T_c increased from 37.2 and 37.9°C during the experiment. Rectal temperature was measured every minute utilizing a thermistor [14].

Table 1 is the summary of heat study conditions described above. Depending upon the individual study, HR and T_c were collected at different time intervals. Previous studies have shown the reliability of swallowed telemetry sensing to measured T_c [15,16].

2.6. Statistical analysis

The predicted and observed T_c for each individual participant were compared using root mean square deviation (RMSD)

method as described in Haslam and Parsons [17]. The RMSD was used to quantify the average difference between predicted and observed measurements across time [17].

3. Results

3.1. Model structure

The concept of the model described above was integrated and the basic operational structure of the new model was summarized in Fig. 1. The model can use individual values, group means or default population values as the input for anthropological characteristics (height, weight, or clothing). Then, real-time input of measured HR and local weather (T_a , wind speed, RH, and radiant load) are used to make predictions and estimates of physiological parameters including T_c , sweat rate, accumulated water loss, T_{sk} , metabolism, and thermoregulatory strain [18]. The shaded area indicates an input variable. A box with dotted lines displays multiple functions of the model for predicting outputs (a box with solid lines).

3.2. Validation

Figs. 2–6 summarize the comparisons of the mean measured T_c to the corresponding mean model predicted T_c using each HS data. Overall, the predictions of T_c agreed well with measured values and the RMSD ranged between 0.05 and 0.31 °C.

HS1: In a moderate environment, subjects' T_c were < 37.5 °C and the model predictions were within one SD of the mean measured values (Fig. 2). The mean of one standard deviation (SD) between subjects across the time was 0.19 °C and the prediction errors for HS1 were small (RMSD = 0.10 °C) (Fig. 2).

HS2: Under hot dry environment, mean T_c of volunteers raised ~38.5 °C with more variability between subjects across

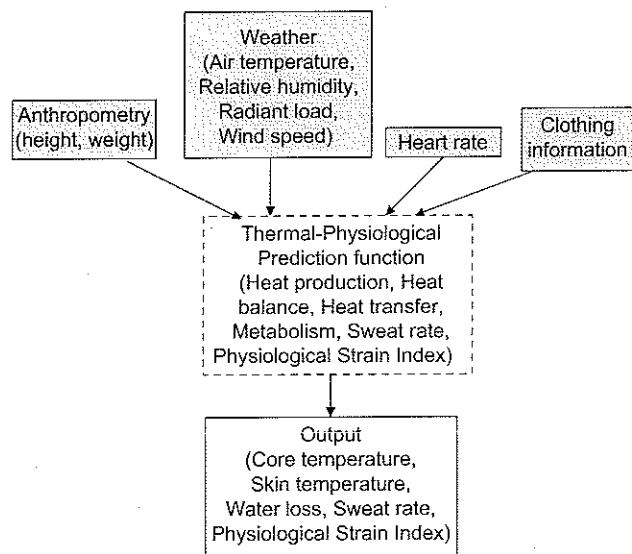


Fig. 1. Basic operational structure of the new model.

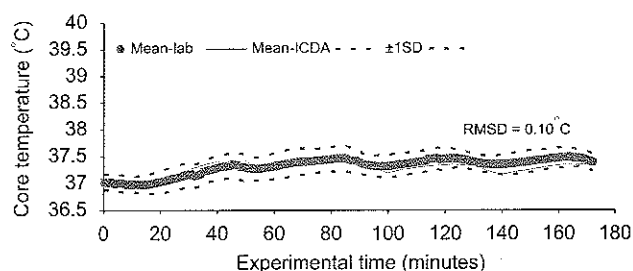


Fig. 2. The summary comparisons between mean measured and predicted core temperature (T_c) from Heat Study 1 (27 °C, 75%; hot weather battle dress uniform; $n = 9$).

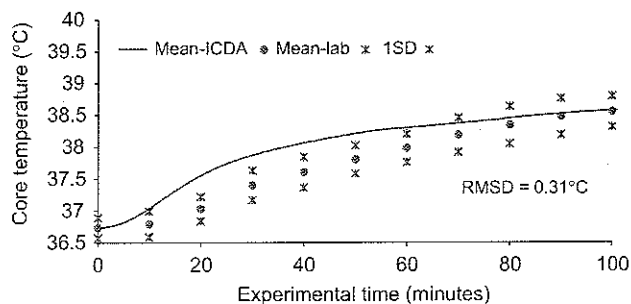


Fig. 3. The summary comparisons between mean measured and predicted core temperature (T_c) from Heat Study 2 (49 °C, 18%; t-shirt and shorts; $n = 5$).

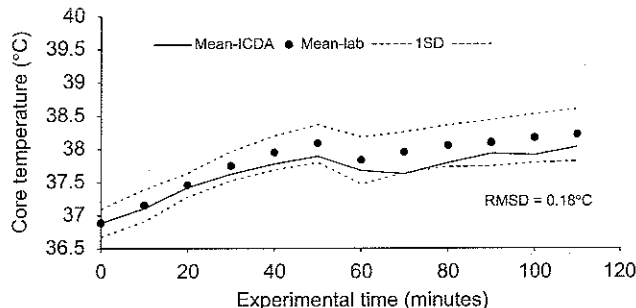


Fig. 4. The summary comparisons between mean measured and predicted core temperature (T_c) from Heat Study 3 (30 °C, 50%; hot weather battle dress uniform; $n = 11$).

the time (0.23 °C) than HS1 (Fig. 3). The RMSD for the model prediction errors was 0.31 °C. Initially, the model predicted a faster rate of increase in T_c than measured T_c for these heat acclimated participants exercising 49 °C/18%RH. However, the predictions improved after 50 min and were very good deriving the second hour of moderate exercise (Fig. 3).

HS3: During the intermittent exercise in a warm-humid condition, subjects' mean T_c increased to 38.2 °C. The variability (SD) was also increased from 0.26 to 0.38 °C, toward the end of the exercise (Fig. 4). The model prediction followed the patterns of T_c responses to intermittent exercise, within 1SD. RMSD was 0.18 °C (Fig. 4).

HS4: During the intermittent exercise, subjects' measured mean T_c raised ~38.4 °C (Fig. 5). More variability in measured T_c between subjects was observed toward the end of the

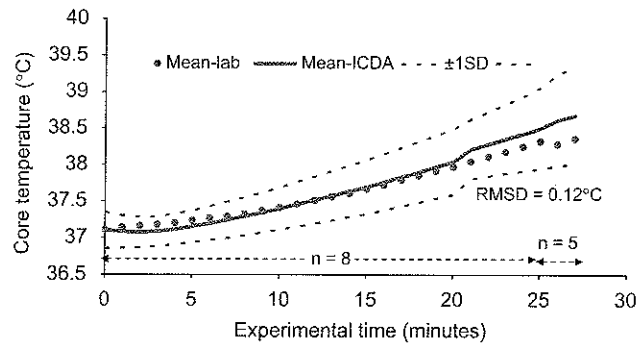


Fig. 5. The summary comparisons between mean measured and predicted core temperature (T_c) from Heat Study 4 (35°C, 45%; protective garment; $n \leq 8$).

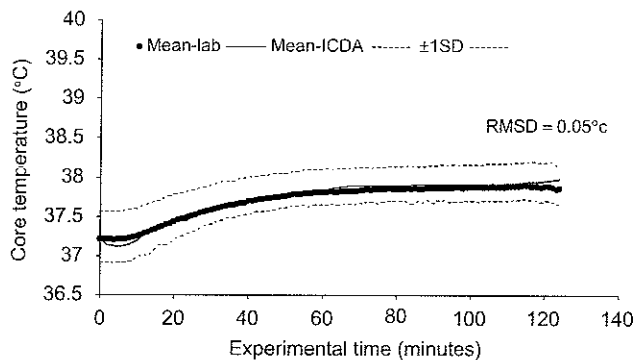


Fig. 6. The summary comparisons between mean measured and predicted core temperature (T_c) from Heat Study 5 (40°C, 40%; t-shirt and shorts; $n = 30$).

exercise, indicating different physiological responses to heat (Fig. 5). The prediction of T_c in this study agreed with measured values within 1SD, and RMSD for the model prediction errors was relatively small (0.12°C) (Fig. 5).

HS5: Under the operational heat stress (40°C, 40%RH), subjects' mean T_c increased to 37.8°C during the exercise (Fig. 6). The mean of SD between subjects across the time was 0.35°C. T_c predicted by the model agreed well with the measured values and the model prediction errors were very small (RMSD = 0.05°C) (Fig. 6).

4. Discussion

The new model was developed to assist with real-time physiological monitoring of individuals engaged in prolonged work during training or military operations. The initial analysis of the model described in this paper yielded encouraging results for predicting the thermal status of individuals or groups exposed to various heat stress. The model predictions corresponded to the patterns of T_c responses to different exercises including intermittent or constant exercise. Predictions for T_c were within an acceptable range ($\pm 1SD$) among five laboratory studies varying different environmental and operational heat stress, acclimation status, and clothing except for a certain exercise period in HS2. Initially, in HS2, the prediction of T_c was

conservative in hot dry environment, that is, it tended to increase faster than measured T_c ; however, after approximately sixty minutes, T_c predictions were in good agreement with measured values. This is because of higher HR ratio, resulting into higher M estimates than actual rates, in the beginning. Despite comparing non-compensable heat stress, that occurring with protective clothing (HS4), predictions represented measured T_c fairly well (RMSD = 0.12°C). Normally, soldiers deploying to regions known for extreme heat will be acclimatized during training for maximizing their performance and prevention from heat-related injuries. As the model based on a minimum number of non-invasive measures was primarily developed for heat acclimated individuals, an acclimatization will provide more accurate predictions of soldiers' physiological status than unacclimated individuals, particularly under strenuous environmental conditions.

The model introduced in this study has an advantage over other heat prediction models in that estimates of M from HR and environmental temperature are obtained using non-invasive methods. Because HR and oxygen consumptions tend to be linearly associated [7,8], HR is useful to estimate metabolic rates. Other methods such as oxygen consumptions and doubly labeled water are alternative to measure metabolic rates; however, they can be destructive, impractical or costly, in prolonged hours of free-range working operations [8]. In addition, invasive measures (e.g., T_c) may interfere with performance and real-time monitoring of soldiers or workers engaged in long hours of training in a wide range of hot environment. The model predicts good agreement with measured T_c , which is useful for screening physiological and health status of workers who may be required to perform different tasks over many hours or even days. This model can provide additional assistance for military operations. For instance, recent reports from Iraq and Afghanistan indicate that faster access to medical care and rapid identification of probable evacuations would save more soldiers' lives [19,20]. One current strategy to shorten the time between injury and treatment is to position a small surgical care unit near the battlefield [19]. The model can contribute to this effort by forecasting both near real-time and the future probability of individual soldier's physiological status and by directing medical attention to the individual soldier, unit medical personnel, or command elements.

There are several programs underway in the Department of Defense to establish methodologies and systems for the accurate "real-time" measurement of physiological status. Although obtaining "true" values of environmental, physiological and operational conditions are desirable for optimum assessment of soldier status, the reality of military operations or other strenuous effort under extreme conditions requires consideration of alternative methods. For instance, the loss of sensor signal, calibration errors, and interference between sensors, are common occurrences resulting in the loss of physiological measurements and accurate health assessments. If model predictions are complicated by the requirements of many physiological, operational, and environmental parameters, the accurate predictions are limited. Strenuous activity may cause sensor malfunction, or make it difficult to repair the device during training or

operational activities. The present model provides a “rugged” alternative to more elaborate sensor suites by utilizing minimum inputs of non-invasive measurements, and can easily be adjusted after sensor loss or to recover data.

This paper has described the promising performance of a new prediction model using laboratory data. However, to further assess model performance, to build user confidence in model predictions, and to identify possible improvements in application and hardware, it is important to test the model during field training involving operational and environmental conditions that are close to operational conditions. Although the present version of our model was created for a specific application using a highly trained, heat acclimated population, the model is readily adaptable to population with variations in fitness, heat acclimation status, body mass, age, or other physical characteristics to extend the model’s application to more diverse groups of populations and environments.

5. Summary

A thermal regulatory model was developed for predicting real-time physiological responses of workers engaged in various tasks for prolonged time. The model can use individual values, group means or default population values as the input for anthropological characteristics, real-time input of measured HR and local weather to predict real-time physiological parameters including T_{re} , T_{sk} , M , water loss, and thermoregulatory strain. The model was validated with various operational (e.g., clothing, activities, acclimation status) and environmental (e.g., 27–49°C) conditions from five laboratory heat studies ($n = 63$). The T_{re} predictions were overall in good agreement (RMSD: 0.05–0.31°C) with measured core temperatures.

Conflict of interest statement

None.

Disclaimer

The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70–25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. The opinions or 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.

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