Comparison of two mathematical models for predicted human thermal responses to hot and humid environments

Adam W. Potter a,*, Irena I. Yermakova b, Andrew P. Hunt c, d, Jason W. Hancock d, A. Virgilio M. Oliveira e, f, David P. Looney d, Leslie D. Montgomery g

Keywords: Physiology, Biophysics, Thermoregulation, Heat stress

A R T I C L E   I N F O

Keywords:
Physiology
Biophysics
Thermoregulation
Heat stress

A B S T R A C T

Purpose: We compared the accuracy and design of two thermoregulatory models, the US Army’s empirically designed Heat Strain Decision Aid (HSDA) and the rationally based Health Risk Prediction (HRP) for predicting human thermal responses during exercise in hot and humid conditions and wearing chemical protective clothing.

Methods: Accuracy of the HSDA and HRP model predictions of core body and skin temperature (Tc, Ts) were compared to each other and relative to measured outcomes from eight male volunteers (age 24 ± 6 years; height 178 ± 5 cm; body mass 76.6 ± 8.4 kg) during intermittent treadmill marching in an environmental chamber (air temperature 29.3 ± 0.1 °C; relative humidity 56 ± 1%; wind speed 0.4 ± 0.1 m·s⁻¹) wearing three separate chemical protective ensembles. Model accuracies and precisions were evaluated by the bias, mean absolute error (MAE), and root mean square error (RMSE) compared to observed data mean ± SD and the calculated limits of agreement (LoA).

Results: Average predictions of Tc were comparable and acceptable for each method, HSDA (Bias 0.02 °C; MAE 0.18 °C; RMSE 0.21 °C) and HRP (Bias 0.10 °C; MAE 0.25 °C; RMSE 0.34 °C). The HRP averaged predictions for Ts were within an acceptable agreement to observed values (Bias 1.01 °C; MAE 1.01 °C; RMSE 1.11 °C).

Conclusion: Both HSDA and HRP acceptably predict Tc and HRP acceptably predicts Ts when wearing chemical protective clothing during exercise in hot and humid conditions.

1. Introduction

Mathematical human thermoregulatory models are useful tools for informing heat strain and heat injury risks associated with physical activities (Friedl, 2012; Kraning and Gonzalez, 1997; Gonzalez, 2000; Potter et al., 2019). Typically these models make predictions of core and body skin temperatures (Tc and Ts) as well as some indication of sweat loss or hydration status. As the ultimate goal of these models is to be useful to a wide audience, they are often wrapped into user friendly decision aids that make forecasted predictions of thermoregulatory responses based on exposure to various protective clothing, physical activities, and environmental conditions (Kraning and Gonzalez, 1997; Yermakova and Candas, 2007; Potter et al., 2017a; Fiala et al., 2001; Malchaire et al., 2001).

The basis of these models can be divided into three categories: empirical (i.e., statistical, data-driven), rational (mechanistic), or hybrid (both rational and empirical). Given the complexity of obtaining relevant data most of the useable models are, by design, hybrid models, as they include both rationally and empirically derived equations. However, often the main components of each can be seen as more balanced to one-side-or-the-other in this spectrum. Legacy models (Kraning and Gonzalez, 1997; Kraning, 1991) have been based on a ‘lumped human’...
design where the human is essentially represented as a single cylinder with layers. While other models have divided the human into multiple cylinders and layers to provide higher resolution to both the human form (head, torso, arms, hands, legs, and feet) as well as human responses (i.e., different methods for calculating heat exchange and physiological responses for skin blood flow and sweating) (Xu and Werner, 1997; Werner et al., 1989; Montgomery, 1974a, 1974b; Montgomery and Williams, 1976; Yermakova, 2001; Yermakova et al., 2013a).

The US Army’s Heat Strain Decision Aid (HSDA), is primarily empirically based, as the main equation for predicting the equilibrium state of $T_c$ was developed based on experimentally derived data (Potter et al., 2017a, 2019). Alternatively, the Health Risk Prediction (HRP) model from Yermakova et al. (Yermakova, 2001; Yermakova et al., 2013a), is derived mainly from mechanistic methods as the main predictions (e.g., $T_c$, $T_s$, and sweat rate) are calculated based on a series of equations built on a rational construct. The model from Yermakova divides the human into 14 segments (13 cylinders and one sphere) and 39 compartments (38 layers and a blood compartment) (Fig. 1).

These models each make predictions based on inputs of the human individual (or group mean), clothing biophysics of heat transfer, environmental conditions, and metabolic rate. Human inputs include height, weight, hydration status, and initial $T_c$ and $T_s$. Clothing biophysical properties are also required for each method to include thermal and evaporative resistances. Each method uses a different approach for calculating additional values from these measurements. Environmental condition inputs for each method include ambient temperature ($T_a$; °C), relative humidity ($RH$; %), wind velocity ($V_w$; m·s$^{-1}$), and mean radiant temperature ($T_{mr}$; °C). Activity inputs (metabolic rate) for each of these models is expressed in watts (W), as it is directly related to heat production.

The main outputs of HSDA include and $T_c$ and sweat rate (SR); while from these interpreted calculations can be made for suggested work-rest times (Potter et al., 2017a). In contrast, the rational calculations of the HRP model are fairly extensive and are designed to output regional total body temperature responses, to include local (14 locations) and mean skin ($T_s$), brain, blood, internal organs, muscles, fat temperatures (°C). Cardiovascular outputs from the HRP model include stroke volume (SV, mL), cardiac output (CO, l/h), and heart rate (HR, bpm) (Yermakova et al., 2013a; Troynikov et al., 2013).

There have been many models over the past several decades that have each been originally developed for use in specific environmental conditions. Given the constraints of early computational systems, these models have typically been hosted as singular programs. However, with

![Graphical representation of the 14 segment Health Risk Prediction (HRP) model.](image-url)
significant improvements in computational ability and form factors (e.g., hand-held computers) it has become of increased interest to extend the use of these types of models to wider ranges of conditions or to seek to combine models. One important step in this process is to begin to make comparisons of models in different conditions to assess and compare the predicted outputs to real-world data. This study compared the simulated outputs of the HSDA, and the rational HRP model compared to human experimental data collected during physical activity in hot and humid conditions and wearing chemical protective clothing. Additionally, predictions of $T_s$ from the HRP model were compared to those observed.

2. Methods

2.1. Design

Utilize human experimental data collected under a range of heat production rates and three chemical protective ensembles with differing biophysical properties and assess the bias, mean absolute error (MAE), and root mean square error (RMSE) of HSDA and HRP predictions compared to observed data (mean ± SD) and calculated limits of agreement (LoA).

2.2. Human laboratory experiment

Data was obtained from a previously collected study of eight healthy males (age 24 ± 6 years; height 178 ± 5 cm; body mass 76.6 ± 8.4 kg; body surface area $A_p$ 1.94 ± 0.1 m$^2$). Volunteers wore three different chemical clothing ensembles during three tests within controlled environmental conditions ($T_a$, 29.3 ± 0.3 °C; RH, 56 ± 7%; $V_w$, 0.4 ± 0.1 m s$^{-1}$). For each of the three trials, volunteers walked for 60 min on a treadmill at 0.84 m s$^{-1}$ on a 0% grade, rested for 10 min, then walked for an additional 30 min at 1.68 m s$^{-1}$ on a 3% grade. Core body temperature was recorded minute-by-minute using a rectal thermometer (Edale Instruments Ltd, U.K.). Mean skin temperature was obtained based on thermistor (Type EU, Yellow Springs Instruments Co. 170 Ltd., Yellow Springs, OH, U.S.A.) measurements from eight locations (scapula, chest, upper arm, forearm, dorsal hand, anterior thigh, posterior calf) (ISO 9886, 2004). Additional publications from this data has been reported based on the original intent, to include additional physiological data and analyses (Potter et al., 2018a; van den Heuvel et al., 2009; Taylor and Patterson, 2014).

The metabolic costs for each of the walking and rest conditions was calculated for each individual (Looney et al., 2018a, 2019a, 2019b). The mean value of the group metabolic demands was used as inputs for the modeling predictions; where the modeled conditions included 211 W (181 kcal/h) for 60 min, 114 W (98 kcal/h) for 10 min, and 490 W (421 kcal/h) for 30 min.

2.3. Biophysical testing of clothing

Biophysical assessments were conducted using a 20-zone sweating thermal manikin (Thermetrics, Seattle, WA http://www.thermetrics.com/) located in a climatically controlled environmental chamber. Standard biophysical tests for the thermal and evaporative resistances ($R_t$, m$^2$ C/W and $R_e$, mPa/W) were conducted (ASTM F1291-16 & ASTM F2370-16) (Standard Test Metho, 2016a, 2016b) for three chemical protective ensembles on the thermal manikin while in a static upright standing posture (Fig. 2). Each ensemble included different chemical protective over-garments; while each included the same base layers: a cotton t-shirt, cycling shorts, standard cotton socks, running shoes, over-boots, over-gloves, self-contained breathing apparatus (SCBA), and military body armor vest (Fig. 2). Values ($R_t$ and $R_e$) were converted to total insulation (clo), a permeability index ($i_m$), and a ratio of clo and $i_m$ (clo/clo) was used as a measure of the ensembles evaporative potential (Woodcock, 1961, 1962; Gonzalez et al., 1988). Testing was conducted at three wind velocities ($V$) to enable the calculation of exponent (gamma) values ($\gamma$) to describe the change in insulation and evaporative potential with increasing wind speeds (Potter et al., 2014, 2015a; Potter, 2016). The parallel method of calculation was used to obtain values of total insulation ($I_t$), accounting for the total resistance of the clothing and air layers of the ensemble (Oliveira et al., 2008, 2011). Measured biophysical properties and associated calculations of the total clothing ensemble used for both models are shown in Table 1. The HSDA model uses the lumped (total ensemble values) calculated at 1 m s$^{-1}$ wind velocity.

Table 1

| Thermal insulation ($R_t$) | Insulation wind effect ($i_m$) | Evaporative Resistance ($R_{ew}$) | Vapor permeability ($i_m$) | Evaporative Potential ($I_m$) | Evaporative Potential wind effect ($i_m$) |
|---------------------------|------------------------------|---------------------------------|---------------------------|-----------------------------|----------------------------------|
| 0.276                     | 0.060                        | 0.28                            | 0.16                      | 0.362                       | 0.225                            |
| 0.523                     | -0.225                       | 0.079                           | 0.25                      | 0.314                       | 0.377                            |
| 0.377                     | -0.178                       | 0.12                             | 0.19                      | 0.141                       | 0.243                            |

Fig. 2. Three chemical protective ensembles tested on thermal sweating manikin.
conditions; while the HRP model uses these standard values at 0.4 m·s⁻¹ wind and distributed into 14 body regions (Table 2).

2.4. Models and inputs

Each of the modeling methods require similar inputs for the human/group, activity rates, environmental conditions and clothing. For practical assessment, both of the models were initialized using the mean body size inputs and with assumed normal starting Tc and Ts temperatures (~37, and ~33 °C, respectively) and healthy states (e.g., hydrated, not injured).

Both methods require similar inputs of human dimensions (e.g., body surface area (BSA) dimensions (Du Bois and Du Bois, 1916; Looney et al., 2020), environmental conditions (air temperature (Tᵃdb, °C), relative humidity (RH, %), and wind velocity (V, m·s⁻¹)), activity rate (watts or kcal/h), and an element of elapsed time. A main difference between the two required inputs are those related to clothing, as HSDA requires a lumped total value of the clothing properties and the HRP model requires distributed values to account for the multiple sections of the human-model-representation (Fig. 1).

The HSDA method relies on an empirical equation for estimating an equilibrium point of Tc (Tᵣ) developed by Givoni and Goldman (1972), where:

\[
Tᵣ = Tᵢ + 0.004M + 0.0025 + 0.0011 \left( \frac{BSA}{K_p} - Tᵢ \right) + 0.8 \cdot 10^{-0.0047(Emax-Eᵢn)}
\]

where Tᵣ is the point where Tc reaches a final equilibrium within the environment, Tᵢ is initial Tc, M is total metabolic rate (W), BSA (m²), Tᵢn is average skin temperature (°C) at the surface, Tᵢdb is dry bulb temperature (°C), Eᵢn is required evaporation for balancing heat, and Eᵢmax is the maximal evaporative capacity.

The HRP model relies on a rational system of dynamic heat balance equations to account for exchange between cylinders, layers and environment; where the general equation is:

\[
cᵢj \frac{dTᵢj}{dt} = Mᵢj - aᵢj-₁λᵢj-₁(ΔTᵢj - ΔTᵢj₋₁) - aᵢj-₁λᵢj₋₁(ΔTᵢj₋₁ - ΔTᵢj₋₂) - hᵢjλᵢj(ΔTᵢj - ΔTₑᵢ) - hᵢjQₑᵢ(ΔTᵢj - ΔTₑᵢ) - hᵢjλᵢj(ΔTᵢj - ΔTₑᵢ)
\]

where i,j represent each cylinder and layer of interest, c is specific heat, m is tissue mass, T is temperature, t is time, M is metabolism, a is tissue thickness, λ is tissue conductivity, ρ is tissue density, b is blood, A is body surface, E is sweat evaporation, P is partial vapor pressure, C is convection, and R is radiation. This modeling approach accounts for specific to metabolic heat production, conductive heat transfer and convective heat transfer by blood flows within the body, heat exchange with environment by radiation, convection and sweat evaporation.

Equation for blood temperature is specific to heat flows transported by blood flows of ij-compartments, cardiac output and respiratory heat loss:

\[
Vᵢj\rhoᵢjcᵢj\frac{ΔTᵢj}{Δt} = \sum_{i=1}^{N} \sum_{j=1}^{K} Wᵢj\rhoᵢjcᵢjTᵢj - Wᵢj\rhoᵢjcᵢjTᵢj - Vᵢj\rhoᵢcᵢj(\rhoᵢcᵢj - \rhoᵢcᵢj)
\]

where Vᵢj is volume of blood, N is the number of cylinders, K is the number of layers, W is blood flow of ij-compartment, Wᵢj is cardiac output, Vᵢj is pulmonary ventilation, “ex” and “in” are expired and inspired air, and “e” is environment. The HRP model accounts thermoregulatory responses that take place during exposure in hot humid environment with an increase of skin blood flow and sweating.

2.5. Statistical analysis

Statistical analyses were performed using MATLAB (The MathWorks, Inc., Natick, MA). Descriptive statistics are presented as means ± SD. Bias, mean absolute error (MAE), and root mean square error (RMSE) were used to compare predictions to observations. Acceptable accuracy of Tc was assessed based on three criterion, 1) a comparison of observed and modeled mean ± SD, 2) a bias of ±0.27 °C (Casa et al., 2007) based on the mean difference between predicted and measured data, and 3) by comparing MAE and RMSE to the standard deviation (SD) of the observed data (Cadarette et al., 1999; Castellani et al., 2007). Based on the population mean observed data and predictions, levels were acceptable if RMSE values were within ±SD, within ±1.5°SD, or within ±2.5°SD of the observed values (Cadarette et al., 1999) collected at 5 min intervals for each individual.

For the HRP model, predictions of Ts were considered acceptable based on their comparison of model bias, MAE, and RMSE to the SD of observed data; while an additional range for model performance was for these values to be ±3 °C based on inter-individual variability reported in the literature (Chen et al., 1996; Prim et al., 1990).

3. Results

The HSDA predicted values to observed mean ± SD Tc for each ensemble trial are presented in Fig. 3. Predicted Tc from HSDA for each clothing ensemble (A, B, and C) for each exercise trial were in close agreement to those observed. The mean predictions of HSDA stayed within the mean ± SD of the observed data for each trial with the exception of being slightly low during the early stage wearing uniform C. The HRP predicted internal organ temperatures to observed data are presented in Fig. 4, and modeled to observed Ts are presented in Fig. 5. The HRP internal organ temperature predictions were in close agreement to the mean ± SD of the observed data Tc for the majority of each

---

**Table 2**

Biophysical properties 14 body regions of chemical protective clothing ensemble.

| Region    | Rt m² C/W | Ret m²Pa/W | IP | Density kg/m³ | Thickness mm |
|-----------|-----------|------------|----|---------------|--------------|
| Head      | 0.036     | 0.004      | 0.541 | 500           | 1.27         |
| Torso     | Values for A, B, and C in Table 1 | 440 | 1.3 | 100          |
| Right Arm | 440       | 1.3        | 100          |
| Left Arm  | 440       | 1.3        | 100          |
| Right Forearm | 440       | 1.3        | 100          |
| Left Forearm | 440       | 1.3        | 100          |
| Right Hand | 0.036 | 0.004      | 0.541 | 500           | 1.27         |
| Left Hand  | 0.036     | 0.004      | 0.541 | 500           | 1.27         |
| Right Thigh | Values for A, B, and C in Table 1 | 440 | 1.3 | 100          |
| Left Thigh | 440       | 1.3        | 100          |
| Right Calf | 440       | 1.3        | 100          |
| Left Calf  | 440       | 1.3        | 100          |
| Right Foot | 0.083 | 0.047      | 0.1 | 860           | 3.2          |
| Left Foot  | 0.083     | 0.047      | 0.1 | 860           | 3.2          |
trial but slightly over-predicted during the last 30 min of each trial. Skin temperature comparisons for each clothing ensemble (A, B, and C) exercise all held patterns consistent with the observed mean ± SD data but slightly over-predicted for each trial. 

Table 3 presents the observed and modeled mean ± SD, model bias, calculated limits of agreement (LoA) for each trial, mean absolute error (MAE), and root mean square error (RMSE) over time for each exercise trial. Additionally, predictions from the HSDA do well initializing and staying within close agreement with the observed $T_c$ (Fig. 3). Fig. 4 shows that predictions from the HRP model does well both at the initialization point and midpoint of the exercise trials. However, for each uniform the HRP model begins to over-predict $T_c$ at the higher intensity exercise phase. The HSDA model explicitly outputs predictions of $T_c$ so the comparisons are predicted to observed $T_c$ whereas HRP model outputs used were internal organs temperature values. Both the HSDA and HRP $T_c$ predictions had acceptable LoA and met the criterion for bias ($±0.27 ^\circ C$), MAE and RMSE (within SD) acceptability. The HRP $T_s$ predictions were also within the acceptable criterion, with low LoA and acceptable bias, MAE, and RMSE compared to the observed values.

4. Discussion

Both the HSDA and HRP met the a priori criteria for acceptability for predictions of body core temperature. However, the data suggest that the HSDA core body temperature estimates of rectal temperature responses may be more accurate than HRP. That said, since HRP does not
directly estimate rectal body temperature but internal organ temperature, part of the variance between predicted and observed might be attributable to regional differences between the predicted and measured locations (Mündel et al., 2016). The simple linear design of the HSDA model make it an easy tool for estimating expected thermal strain during steady-state activities or when activities can be used to lump average estimates. The comprehensive design of the HRP model make the predictions more valuable in complex simulation scenarios. Figs. 6–8 share the array of variables that can be predicted with HRP; in these examples the predictions shown are from the data collected during intermittent exercise (60 min low intensity, rest 10 min, 30 min moderate intensity) in ensemble A. Fig. 6 presents predicted brain, internal organs, blood, body, muscles, fat, and skin temperatures, Fig. 7 shows predicted heart rate and cardiac output, and Fig. 8 shows predicted blood flows (to skin and muscles). Both HSDA and HRP make predictions of sweat rate. However, HRP predictions are more comprehensive providing details regarding these changes in sweat and evaporation states (Fig. 9); while HSDA predicts an average rate to be applied based on the input conditions (Gonzalez et al., 2009, 2012).

There are several challenges to successfully modeling the thermoregulatory and physiological responses to exercise particularly in warmer environments. One challenge is the need for having an accurate estimate of initial values. This is important as the starting point in the model (e.g., initial $T_c$, $T_s$) will influence the rate of change or the trajectory of the predictions. A second challenge is accurate estimates of the metabolic rate or heat production; which is particularly challenging during intermittent work or work of varying intensities. Finally, accurate representation of the biophysical properties of the clothing being worn, not only when dry, but as the clothing accumulates moisture. Inaccurate assumptions of the clothing properties will impose systemic issues within the model and be more noticeable in extreme conditions (high or low heat, high wind velocities, and in high humidity cases). The HRP model has a specific advantage compared to HSDA, as the HRP model uses rational calculations of physiology and therefore is more likely to mathematically correct any imbalances in predictions over time; while the HSDA model does have any ‘balancing’ equations that could offset incorrect physiological responses.

Thermoregulatory models like these provide quantitative means of making predictions and simulations that can be used in planning to help provide guidance and potentially mitigate thermal injuries. These models are also used extensively to assess clothing and individual equipment based on predictions of thermal strain (Potter et al., 2013, 2015b, 2017b, 2018b). Wide-scale use of these models also allow for continued collection of data to conduct validation and modeling improvements. This information can be used for public safety (Potter et al., 2015c), for competitive sporting events (Yermakova et al., 2020), or for use in providing guidance to mitigating heat or cold related risks globally on land (Potter et al., 2018c; Berglund and Yokota, 2005) and in immersed environments (Montgomery, 1974a; Yermakova and Montgomery, 2018; Xu et al., 2007; Looney et al., 2019c; Berglund et al., 2019).

### Table 3
Comparison of observed to modeled predictions of core body and skin temperature.

| Model | Uniform | Output | Observed | Bias | LoA | MAE | RMSE |
|-------|---------|--------|----------|------|-----|-----|------|
| HSDA A | $T_c$ (°C) | 37.6 ± 0.38 | 0.08 | -0.31 to 0.48 | 0.20 | 0.22 |
| B     | 37.7 ± 0.48 | 0.01 | -0.37 to 0.39 | 0.16 | 0.19 |
| C     | 37.9 ± 0.60 | -0.16 | -0.45 to 0.12 | 0.18 | 0.22 |
| Average | 37.6 ± 0.50 | 0.02 | - | 0.18 | 0.21 |
| HRP A | Internal Organs (°C) | 37.6 ± 0.38 | 0.11 | -0.49 to 0.71 | 0.23 | 0.32 |
| B     | 37.7 ± 0.48 | 0.11 | -0.51 to 0.73 | 0.25 | 0.33 |
| C     | 37.9 ± 0.60 | 0.09 | -0.64 to 0.83 | 0.26 | 0.38 |
| Average | 37.7 ± 0.50 | 0.10 | - | 0.25 | 0.34 |
| A     | $T_s$ (°C) | 35.4 ± 0.70 | 1.04 | 0.08 to 2.01 | 1.04 | 1.15 |
| B     | 35.6 ± 0.76 | 1.13 | 0.29 to 1.97 | 1.13 | 1.20 |
| C     | 36.3 ± 0.95 | 0.87 | 0.03 to 1.71 | 0.87 | 0.97 |
| Average | 35.8 ± 0.80 | 1.01 | - | 1.01 | 1.11 |

Note: Solid lines are observed mean±SD $T_s$, dashed lines are predicted $T_s$. Fig. 5. HRP predictions compared to observations of $T_s$ in hot and humid conditions (29.3 °C, 56% RH, 0.4 m·s$^{-1}$).
Additionally, methods like these have larger future implications specific to climate change and increased risks of thermal injuries (Sherwood and Huber, 2010; Vyrostek et al., 2004; Basu and Samet, 2002; Anderson and Bell, 2009; Ebi and Meehl, 2007). The results from this analysis are in agreement with prior comparisons of the HSDA model (Potter et al., 2019; Cadarette et al., 1999; Gonzalez et al., 1997; Blanchard et al., 2007; Glisson, 2017) and for the HRP model (Yermakova et al., 2013a, 2013b; Troynikov et al., 2013) in hot environments. However, another key limitation to this analysis is that it has only been compared to a single environmental condition (e.g., hot and humid), has a limited sample of volunteers (n = 8, all male), and has a relatively simple work-rest design. Data from multiple environmental conditions would allow for more robust assessment of the human and environment heat transfer calculation methods (Welles et al., 2018; Santee et al., 2020). Assessment of these models with more diverse human characteristics are needed to evaluate the models’ accuracy specific to some areas where there are known differences in thermal responses e.g., females, age groups, and fitness levels (Larose et al., 2013, 2014; Kenny and Jay, 2007; Gagnon et al., 2008; Notley et al., 2002).
2018; Cramer and Jay, 2015). Assessing the accuracy of these models during more dynamic activity conditions will also allow for an assessment of the issues related to shifts in metabolic demands and enable comparisons of more realistic conditions (Looney et al., 2018b, 2018c; Potter et al., 2018d). Future work should be conducted to specifically and systematically address these limitations.

5. Conclusion

The present analysis shows both HSDA and HRP can be used to acceptably predict core body temperature (Tc) and HRP can acceptably predict mean body skin temperature (Ts) in health individuals wearing chemical protective clothing during exercise in hot and humid conditions. This work provides evidence to support the use of these models as risk mitigation tools for planning military and civilian activities that require work in these conditions.

The present study highlights the importance of simulation programs to carry out detailed evaluations of the human body thermophysiological responses. Mathematical models like the ones used in this study are particularly relevant in extreme environments, by allowing the anticipation of actions to attenuate heat stress, avoid heat-related disorders, and protect lives.

Ethics approval and consent to participate

The associated human research study received approval by University of Wollongong Human Research Ethics Committee. Each participant willingly gave their written informed consent to participate in this study.

Availability of data and supporting materials

Data from this analysis has been obtained through sharing agreements and therefore must be coordinated for use by the originators.

Funding

This study and analysis was funded by the U.S. Army Military Operational Medicine Research Program (MOMRP), and U.S. Army Research Institute of Environmental Medicine, and National Academy of Sciences of Ukraine.

Disclaimer

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. 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. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

Author statement

AWP and IY analyzed and interpreted data used for validation in this study; AHP collected and shared the human research data; AWP, IY, APH, JWH, AVMO, DPL, and LDM contributed to analyses and manuscript preparation.

Acknowledgements

The authors acknowledge the invaluable contributions of the volunteers and researchers at the University of Wollongong and the Defence Science and Technology Group who collected the human data, and the talented scientists whose work has made these models possible. The authors would also like to thank Dr. Scott Montain for his review and critique of this manuscript.

References

Anderson, B.G., Bell, M.L., 2009. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. Epidemiology 20 (2), 205.
Basu, R., Samet, J.M., 2002. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. Epidemiol. Rev. 24 (2), 190–202.
Berglund, L.G., Yokota, M., 2005. Comparison of Human Responses to Prototype and Standard Uniforms Using Three Different Human Simulation Models: HSDA, Scenario_J and Simulink2NM, 8/2005. Report No.: T05-08.
Berglund, L.G., Gonzalez, R.R., Heled, Y., Moran, D.S., 2002. Simulated Human Responses to Transient Cold Wet Sea Exposure Sequences. Natick, MA, 9/2002.
Cramer, M.N., Jay, O., 2015. Explained variance in the thermoregulatory responses to exercise: the independent roles of biophysical and fitness/fatness-related factors. J. Appl. Physiol. 119 (9), 982–989.
Du Bois, D., Du Bois, E.F., 1916. Clinical calorimetry: tenth paper a formula to estimate the approximate surface area if height and weight be known. Arch. Intern. Med. XVII (6), 853–871.
Ebi, K.L., Meehl, G.A., 2007. The Heat Is on: Climate Change and Heatwaves in the Midwest. Regional Impacts of Climate Change: Four Case Studies in the United States, pp. 8–21.
Fiaa, D., Lomas, K.J., Stohrer, M., 2001. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. Int. J. Biometeorol. 45 (3), 143–159.
Friedl, K.E., 2012. Predicting Human Limits—The Special Relationship between Physiology Research and the Army Mission. Military Quantitative Physiology: Problems and Concepts in Military Operational Medicine: Problems and Concepts in Military Operational Medicine, pp. 1–38.
Frim, J., Livingstone, S., Reed, L., Nolan, R., Limmer, R., 1990. Body composition and skin temperature variation. J. Appl. Physiol. 68 (2), 540–543.
Gagnon, D., Jay, O., Lemire, B., Kenny, G.P., 2008. Sex-related differences in evaporative heat loss: the importance of metabolic heat production. Eur. J. Appl. Physiol. 104 (5), 821–829.
Givoni, B., Goldman, R.F., 1972. Predicting rectal temperature response to work, environment and clothing. J. Appl. Physiol. 32 (6), 812–822.
Glisson, K.E., 2017. The Ability of the US Army Heat Strain Decision Aid (HSDA) to Predict a Limiting Heat Stress Exposure.
Gonzalez, R.R., 2000. Models useful for predicting human responses to the environment: application to hazard material operations. J. Hum. Environ. Syst. 14 (1), 1–10.
Gonzalez, R.R., 1988. Biophysics of heat transfer and clothing considerations. In: Goldblatt, K.B., Sawka, M.N., Gonzalez, R.R. (Eds.), Human Performance Physiology and Environmental Medicine at Terrestrial Extremes. Indianapolis. Benchmark Press, Inc., pp. 45–95.
Gonzalez, R.R., McLellan, T., Withey, W., Chang, S.K., Pandolf, K., 1997. Heat strain models applicable for protective clothing systems: comparison of core temperature response. J. Appl. Physiol. 83 (3), 1017–1032.
Gonzalez, R.R., Cheuvront, S.N., Montain, S.J., Goodman, D.A., Blanchard, L.A., Berglund, L.G., et al., 2009. Expanded prediction equations of human sweat loss and heat strain responses to various clothing conditions. J. Appl. Physiol. 107, 379–388.
Gonzalez, R.R., Cheuvront, S.N., Ely, B.R., Moran, D.S., Hadid, A., Endrusick, T.L., et al., 2012. Sweat rate prediction equations for outdoor exercise with transient solar radiation. J. Appl. Physiol. 112 (8), 1300–1316.
Kenny, G.P., Jay, O., 2007. Sex differences in postrace heat strain and exercise muscle temperature responses. Am. J. Physiol. Regul. Integr. Comp. Physiol. 292 (4), R1632–R1640.
Kraning, K.K., 1991. A Computer Simulation for Predicting the Time Course of Thermal and Cardiovascular Responses to Various Combinations of Heat Stress, Clothing and Exercise. Natick, MA, 1991 June. Report No.: T13-91.
Kraning, K.K., Gonzalez, R.R., 1997. A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration. J. Therm. Biol. 22, 331–342.
Larose, J., Boulay, P., Sigal, R.J., Wright, H.E., Kenny, G.P., 2013. Age-related decrements in heat dissipation during physical activity occur as early as the age of 50. PLoS One 8 (12), e8148.
Larose, J., Boulay, P., Wright-Beatty, H.E., Sigal, R.J., Hardcastle, S., Kenny, G.P., 2014. Age-related differences in heat loss capacity occur under both dry and humid heat stress conditions. J. Appl. Physiol. 117 (1), 69–79.
Potter, A.W., Coca, A., Quinn, T., Wu, T., Isherwood, K., Perkins, A., 2017b. Tradespace Configurations Based on Different Environmental Conditions. US Army Research Institute of Environmental Medicine, Natick, MA, 01760, USA. Technical Report.

Looney, D.P., Santee, W.R., Hansen, E.O., Bonventre, P.J., Chalmers, C.R., Potter, A.W., 2019c. Heat Strain Decision Aid (HSDA) accurately predicts individual-based core body temperature rise while wearing chemical protective clothing. PloS One 10 (11), e0143461.

Potter, A.W., Hunt, A.P., Cadarette, B.S., Fogarty, A., Sririvanas, S., et al., 2019. Heat Strain Decision Aid (HSDA) accurately predicts individual-based core body temperature rise while wearing chemical protective clothing. PloS One 10 (11), e357.

Werner, J., Buse, M., Foegen, A., 1989. Lumped versus distributed thermoregulatory models of the human forearm, hand, and fingers. Ann. Biomed. Eng. 4 (3), 209–219.

Yermakova, I., 2001. Development and validation of the predicted heat strain model. Ann. Occup. Hyg. 45 (2), 123–135.

Yermakova, I., Nikolaienko, A., Regan, M. (Eds.), 2013b. International Conference on Electronics and Nanotechnology (ELNANO). IEEE, Kiev, Ukraine.

Yermakova, I., 2001. Mathematical modeling of thermal processes in man for development of protective clothing. J. Kor. Soc. Living Environ. 8 (2), 127–133.