Heat Strain Decision Aid (HSDA) accurately predicts individual-based core body temperature rise while wearing chemical protective clothing

Adam W. Potter[a,b,*], Andrew P. Hunt[c,d], Bruce S. Cadarette[e], Alison Fogarty[c], Shankar Srinivasan[b], William R. Santee[a,f], Laurie A. Blanchard[a], David P. Looney[a]

[a] *Biophysics and Biomedical Modeling Division, U.S. Army Research Institute of Environmental Medicine, 10 General Greene Avenue, Bldg 42, Natick, MA 01760, USA*
[b] *Rutgers University, School of Biomedical and Health Sciences, Newark, NJ, 07102, USA*
[c] *Land Division, Defence Science and Technology Group, Department of Defence, Melbourne, VIC, Australia*
[d] *School of Exercise and Nutrition Sciences & Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, QLD, Australia*
[e] *Thermal and Mountain Medicine Division, U.S. Army Research Institute of Environmental Medicine, 10 General Greene Avenue, Bldg 42, Natick, MA 01760, USA*
[f] *Oak Ridge Institute for Science and Education (ORISE), 1299 Bethel Valley Rd, Oak Ridge, TN, 37830, USA*

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ABSTRACT

Purpose: We examined the accuracy of the Heat Strain Decision Aid (HSDA) as a predictor of core body temperature in healthy individuals wearing chemical protective clothing during laboratory and field exercises in hot and humid conditions.
Methods: The laboratory experiment examined three chemical protective clothing ensembles in 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 $56 \pm 1\%$; wind speed 0.4 ± 0.1 m s^{-1}). The field experiment examined four different chemical protective clothing ensembles in twenty activity military volunteers (26 ± 5 years; 175 ± 8 cm; 80.2 ± 12.1 kg) during a prolonged road march (26.0 ± 0.5 °C; $55 \pm 3\%$; 4.3 ± 0.7 m s^{-1}). Predictive accuracy and precision were evaluated by the bias, mean absolute error (MAE), and root mean square error (RMSE). Additionally, accuracy was evaluated using a prediction bias of ± 0.27 °C as an acceptable limit and by comparing predictions to observations within the standard deviation (SD) of the observed data.
Results: Core body temperature predictions were accurate for each chemical protective clothing ensemble in laboratory (Bias -0.10 ± 0.36 °C; MAE 0.28 ± 0.24 °C; RMSE 0.37 ± 0.24 °C) and field experiments (Bias 0.23 ± 0.32 °C; MAE 0.30 ± 0.25 °C; RMSE 0.40 ± 0.25 °C). From all modeled data, 72% of all predictions were within one standard deviation of the observed data including 92% of predictions for the laboratory experiment (SD ± 0.64 °C) and 67% for the field experiment (SD ± 0.38 °C). Individual-based predictions showed modest errors outside the SD range with 98% of predictions falling < 1 °C; while, 81% of all errors were within 0.5 °C of observed data.
Conclusion: The HSDA acceptably predicts core body temperature when wearing chemical protective clothing during laboratory and field exercises in hot and humid conditions.

1. Introduction

Soldiers often work in extremely hot and humid environments to complete mission critical orders. Thermal-work strain causes over 2,500 U.S. military hospitalizations per year [1]. Soldiers are at greater risk for heat injury when enclosed in chemical protective clothing ensembles [2]. Optimizing the workloads of individual soldiers in order to avoid excessive heat strain is challenging due to the unique physical demands of each mission.

Thermoregulatory models can aid workload decision-making and reduce heat casualties. Due to these broad implications, the development of models, indices, and algorithms related to the human thermal stress has been a fruitful field of research for more than 70 years. During this time more than 100 different methods have been developed

specifically related to heat stress [3]. These methods range from climate driven indices and simple heat balance equations to rational models of thermoregulation and elaborate models combining physics, physiology, and weather.

The U.S. Army's Heat Strain Decision Aid (HSDA) is a thermoregulatory model that predicts core body temperature (T_c) from individual, clothing, environment, and activity-related factors [4]. The HSDA has assisted military training guidance doctrine [5], public fluid intake guidance [6,7], emergency response efforts [8], and U.S. military clothing evaluation [9,10]. The biophysical properties of clothing worn can have a significant effect on how well an individual is able to dissipate heat within a given environment [3,4,8–10]. The two main properties measured for a given clothing's biophysical characterization, thermal insulation and vapor permeability, directly relate to the amount of dry or wet heat that can pass from the human's skin out to the environment and therefore directly impact thermophysiological responses.

The HSDA has been shown to be a reliable predictor of time limited exposures of heat stress in healthy civilians [11]; but has not been validated in soldiers. Evaluating the predictive accuracy of the HSDA when working in new chemical protective clothing ensembles is essential to Soldier workload optimization. The HSDA must accurately predict T_c in different individuals, activities, and environmental conditions. We examined HSDA's predictive accuracy in healthy individuals and active soldiers wearing various chemical protective clothing ensembles during separate laboratory and field exercises in hot and humid conditions. A mean bias of ± 0.27 °C was used as a measure of acceptable accuracy, as this limit has been previously used to validate direct measurement accuracy from devices used in field conditions [12].

2. Methods

2.1. Design

This study evaluated the accuracy of the HSDA for predicting T_c during a laboratory experiment and a field experiment. The laboratory experiment examined healthy male personnel in three chemical protective clothing ensembles during intermittent treadmill marching in a hot and humid environmental chamber. The field experiment involved four different chemical protective clothing ensembles during a prolonged road march in hot and humid conditions. We scheduled chemical protective clothing ensembles in a randomized and counterbalanced order in both experiments.

2.2. Heat Strain Decision Aid (HSDA)

The HSDA is a hybrid model that uses both empirically derived equations as well as physics-based methods to describe the rise in core body temperature (T_c) over time [4]. It requires 16 inputs of individual or population characteristics and health status, environmental conditions, clothing properties, and activity rate (Fig. 1). Collectively these inputs are used to perform subroutines and ultimately to make predictions of T_c. Potter et al. [4], provide a comprehensive overview of the history and composition of HSDA, a modeling schematic, and a linked pseudo-code variant.

2.3. Chemical protective clothing

The biophysical properties of the seven different chemical protective clothing ensembles were assessed using standard test methods for obtaining measures of thermal insulation (R_t [m²K/W]) and evaporative resistance (R_{et} [m²P$_a$/W]) (American Society for Testing and Materials (ASTM)) [13,14]. These values of R_t and R_{et} were converted to units of clo (1 clo = 0.155 m²K/W), a vapor permeability index (i_m), and combined for characterizing evaporative potential (i_m/clo) [15,16].

The HSDA model requires four inputs related to clothing properties, direct or estimated measures of clo and i_m/clo at 1 m s^{-1}, as well as wind exponents to reflect wind effects on the clothing, clo^g and i_m/clo^g. In order to obtain the wind effects, ensembles were tested using ASTM standard chamber conditions for multiple tests at wind velocities (V) of approximately 0.4, 1.2, and 2.2 m s^{-1} [17].

Table 1 summarizes the biophysical properties of the three chemical protective clothing ensembles worn in the laboratory trials (L1, L2, L3) and the four ensembles worn in the field trials (F1, F2, F3, F4). In all trials, the subjects wore respirator, gloves, and over-boots. For the laboratory tests the subjects also wore body armor and webbing over the chemical protective garments. The thermal and evaporative resistance properties for the seven chemical protective clothing ensembles were similar across all trials.

2.4. Laboratory experiment

Eight males (age 24 ± 6 years; height 178 ± 5 cm; body mass 76.6 ± 8.4 kg; body surface area A_D 1.94 ± 0.1 m²) volunteered for the laboratory experiment. Researchers briefed volunteers on the purpose, risks, and potential benefits of the study and obtained written informed consent prior to study participation.

Volunteers wore different chemical clothing ensembles for the three tests in a controlled environmental chamber (air temperature (T_a) 29.3 ± 0.3 °C; relative humidity (RH) 56 ± 7%; wind speed 0.4 ± 0.1 m s^{-1}). In each trial, they walked for 60 min on a treadmill at 0.84 m s^{-1} on a 0% grade, rested for 10 min, and then walked for 30 min at 1.68 m s^{-1} on a 3% grade. A rectal thermometer (Edale Instruments Ltd, U.K.; UKAS test certificate accuracy within ± 0.02 °C; observed mean bias 0.04 °C. [18]) measured minute-by-minute Tc. Full reporting specific to the original intent of this data has been previously published [19,20].

2.5. Field experiment

Twenty soldiers experienced in military chemical response operational training (19 male and 1 female; age 26 ± 5 years; height 175 ± 8 cm; body mass 80.2 ± 12.1 kg; body surface area A_D 2.0 ± 0.2 m²) volunteered for the field experiment. Researchers briefed volunteers on the purpose, risks, and potential benefits of the study and obtained written informed consent prior to study participation. A field medical evaluator cleared each volunteer for participating in the study following a medical history review.

Volunteers wore a different chemical protective clothing ensemble during four field tests scheduled every other day. For each test, the volunteers marched for 120 min at a set pace of 1.10 m s^{-1} on a 0% grade paved road. The combined weight of clothing and external loading was 15.6 ± 1.1 kg. Environmental conditions were similarly hot and humid on each test day (T_a 26.0 ± 0.5 °C; RH 55 ± 3%; wind speed 4.3 ± 0.7 m s^{-1}). A rectal thermometer (Respironics Mini Mitter, Inc., Bend, OR; bias < 0.1 °C [21]) measured minute-by-minute Tc.

2.6. Statistical analysis

Statistical analyses were performed using MATLAB (The MathWorks, Inc., Natick, MA). Descriptive statistics are presented as means ± SD. The bias, mean absolute error (MAE), and root mean square error (RMSE) were used to compare HSDA predictions to the observed T_c. The bias indicates whether the model over- or underpredicted T_c and is calculated as the mean difference between predictions and measurements. A predetermined criterion for the acceptable range of accuracy was a bias of ± 0.27 °C [12]. The MAE is the average of the absolute prediction errors and is calculated with the formula:
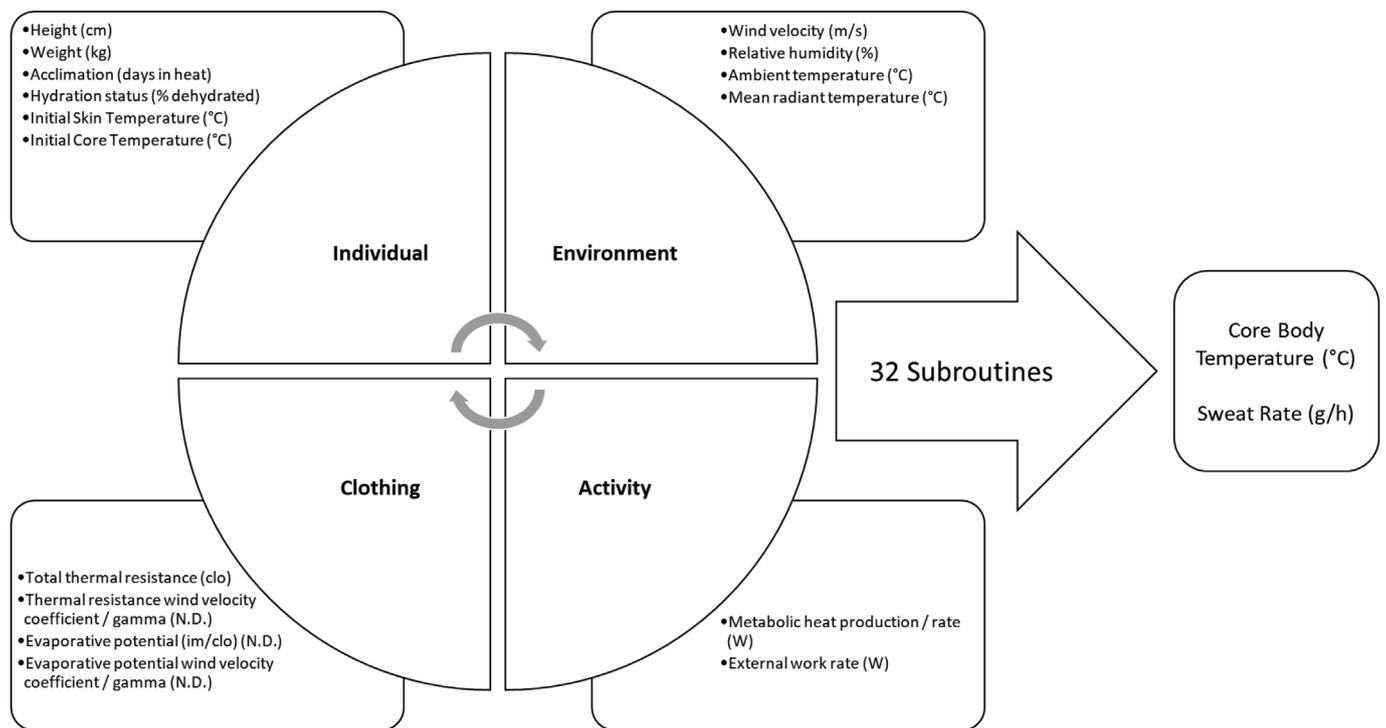
Fig. 1. High level schematic of the Heat Strain Decision Aid (HSDA) process.

Table 1
Biophysical properties of chemical protective clothing ensembles worn during laboratory (L1-L3) and field (F1-F4) exercises.

Environment	Clothing	Thermal insulation (clo) at 1 m/s	Insulation wind effect (clo^g)	Evaporative Potential (i_m/clo) at 1 m/s	Evaporative Potential wind effect (i_m/clo^g)
Laboratory	L1	1.46	−0.23	0.21	0.36
	L2	1.79	−0.18	0.16	0.31
	L3	2.13	−0.15	0.09	0.14
Field	F1	1.83	−0.22	0.15	0.28
	F2	1.98	−0.19	0.16	0.29
	F3	2.00	−0.18	0.15	0.23
	F4	1.93	−0.16	0.15	0.21

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |f_i - y_i| = \frac{1}{n} \sum_{i=1}^{n} |e_i|$$

where f_i is the predicted value, y_i is the actual value, and e_i is the absolute error.

The RMSE applies a greater penalty to larger errors and is calculated with the formula:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_i^2}$$

where d_i is the difference between observed and predicted T_c and n is the number of data points, in this case being the number of measurements for each minute.

3. Results

3.1. Laboratory and field validation

Table 2 shows the SD of observed data, model bias, mean absolute error (MAE), and root mean square error (RMSE) for each trial within the laboratory and field. Core body temperature predictions during the laboratory trials for each chemical protective clothing ensemble were on average within acceptable limits for bias, MAE, and RMSE (Bias −0.10 ± 0.36 °C; MAE 0.28 ± 0.24 °C; RMSE 0.37 ± 0.24 °C). The

same held true for the field experiments (Bias 0.23 ± 0.32 °C; MAE 0.30 ± 0.25 °C; RMSE 0.40 ± 0.25 °C). Collectively, the data from the laboratory and field conditions showed relatively low positive weighted bias (0.16 ± 0.36 °C) and 72% of all predictions were within one standard deviation of the observed data including 92% of predictions for the laboratory experiment (SD ± 0.64 °C) and 67% for the field experiment (SD ± 0.38 °C).

Fig. 2 shows the mean and standard deviation prediction errors by observed T_c by elapsed time point. Errors in Fig. 2 are calculated at 5 min intervals for each of the study volunteers for both the laboratory and field trials. Fig. 2 clearly shows that the model tended to over predict T_c over time compared to the observed data; while the laboratory data under predicted initially and then rose after the onset of the second exercise to slightly over predict. Fig. 3 shows the comparison of observed measured to modeled predictions by core temperature at 5 min intervals. Fig. 4 shows the percentage of the modeled data that fell within ranges of the observations; where individual-based predictions showed modest errors outside the SD range with 98% of predictions falling < 1 °C of the observed data.

4. Discussion

The HSDA consistently and acceptably predicted T_c when individuals were wearing the three chemical protective clothing

Table 2
Accuracy of HSDA model when predicting T_c (°C) in soldiers wearing different chemical protective clothing ensembles during exercise in hot and humid conditions.

Environment	Clothing	T_c	Bias	MAE	RMSE
Laboratory	L1	37.64 ± 0.55	− 0.15 ± 0.26	0.23 ± 0.20	0.30 ± 0.13
	L2	37.75 ± 0.64	− 0.14 ± 0.34	0.29 ± 0.24	0.38 ± 0.20
	L3	37.88 ± 0.70	0.03 ± 0.42	0.31 ± 0.28	0.42 ± 0.33
	Total	37.76 ± 0.64	− 0.10 ± 0.36	0.28 ± 0.24	0.37 ± 0.24
Field	F1	37.69 ± 0.35	0.22 ± 0.30	0.29 ± 0.24	0.37 ± 0.21
	F2	37.67 ± 0.36	0.21 ± 0.32	0.30 ± 0.24	0.39 ± 0.21
	F3	37.55 ± 0.35	0.36 ± 0.30	0.37 ± 0.28	0.47 ± 0.27
	F4	37.79 ± 0.43	0.13 ± 0.32	0.27 ± 0.23	0.35 ± 0.20
	Total	37.68 ± 0.38	0.23 ± 0.32	0.30 ± 0.25	0.40 ± 0.25
Collective Total	**L1-L3 F1-F4**	37.69 ± 0.45	0.16 ± 0.36	0.30 ± 0.25	0.39 ± 0.23

Note: HSDA, Heat Strain Decision Aid; MAE, mean absolute error; RMSE, root mean square error; T_c, core body temperature.

ensembles in the laboratory exercise as well as when they were wearing the four remaining ensembles in the separate field exercise. The model showed remarkable consistency in the predictions across each of the trials both in the laboratory and field setting. These results support that the HSDA is an accurate predictor of core body temperature when individuals wear chemical protective clothing during laboratory and field exercises in hot and humid conditions.

When using a direct measurement criteria of a bias of ± 0.27 °C, the predicted values of T_c were acceptably accurate. This was true for both the laboratory data bias (−0.10 ± 0.36 °C), field data (0.23 ± 0.32 °C), and collective total data (0.16 ± 0.36 °C) (Table 2). While the majority of the individual clothing trials also predicted within this bias criteria, it is important to note that one of the field trials was outside this range (F3; 0.36 ± 0.30 °C). While there was no observed or measurable differences in the biophysical properties of this ensemble (Table 1); there is a possibility of additional design features that were not captured from the thermal manikin assessments (e.g., fit differences).

A limitation to this model, specifically from the data reported, is the model's inability to maintain accuracy during activity transition periods. The HSDA was initially designed using data from steady-state continued exercise conditions and therefore there is a current accuracy drift that occurs when exercise is interrupted with rest periods. This limitation can be seen in Fig. 3, where the majority of the data up to 38.5 °C is fairly symmetrical around the zero line, but were the
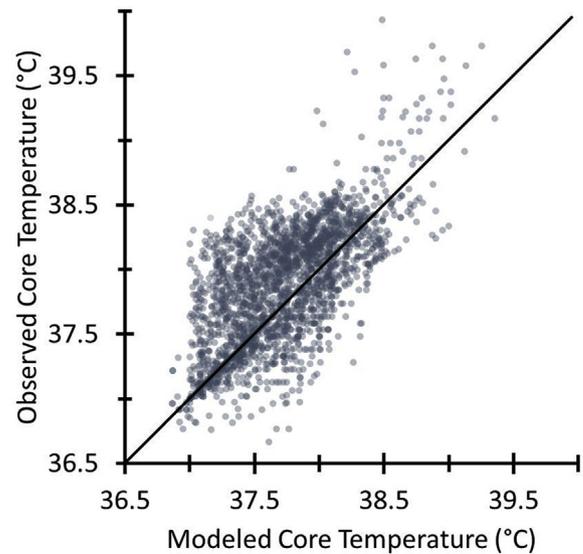
Fig. 3. Observed to modeled core temperature. **Note:** circles are all the same color; increased density shows overlapping of values.
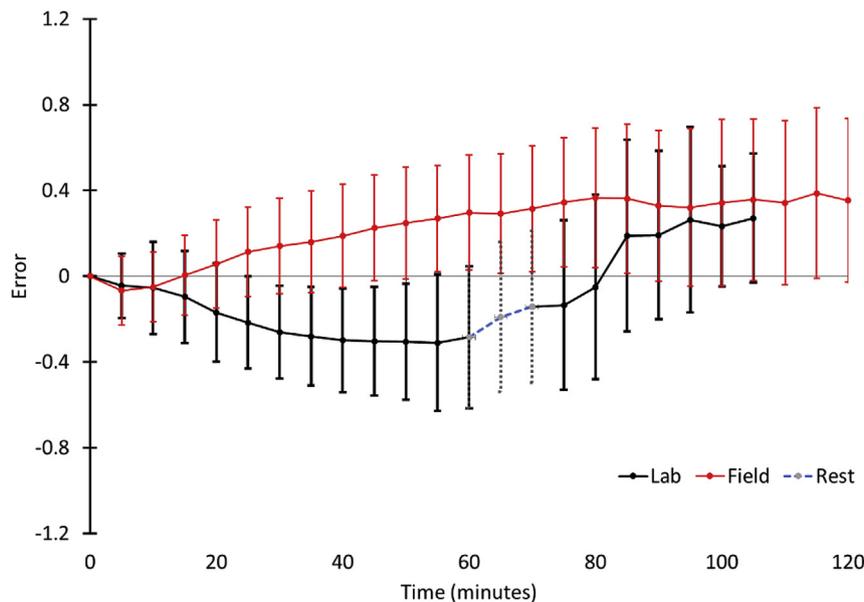
Fig. 2. Mean error by elapsed time points (minutes). **Note:** error bars represent SD of observed to modeled core body temperature at 5 min intervals.
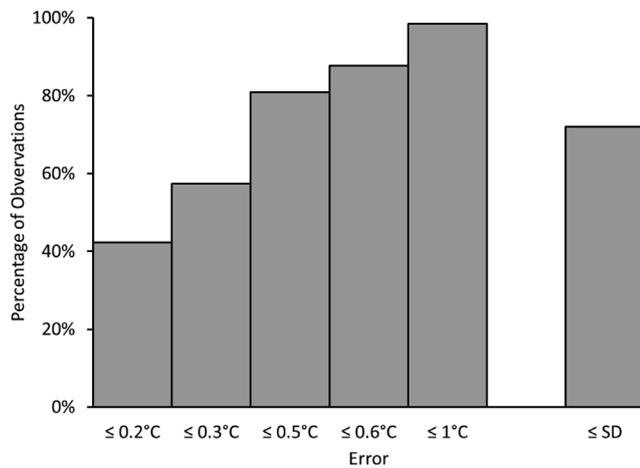
Fig. 4. Modeled accuracy compared to observed data.

observed data is higher than the modeled predictions when T_c exceeded 38.5 °C. Future improvements to account for dynamic activities is needed to improve the modeling robustness.

There are a number of limitations to the model that currently reduce the applicability to the broader general public. Some important limitations to note in the current version of this model is the lack of resolution to account for age-, gender-, and fitness-related differences in heat loss responses. However, recent work has been conducted specifically outlining the heat loss profile differences related to age [22,23], gender [24,25], as well as a combination of both [26,27]. Additionally research has shown a path for developing modeling improvements related to body composition [28] and fitness differences [29–31] specifically with respect to changes in blood flow and sweating responses.

An interesting observation after reviewing the results of the measured biophysical clothing properties (Table 1) and the prediction accuracy findings (Table 2), is a relationship between the clothing's thermal insulation (clo) and accuracy of the HSDA predicted T_c. For example, T_c predicted accuracy for L1-L3 trials progressively became less accurate (via MAE and RMSE) as the thermal insulation increased. This same trend, albeit less obviously, occurred in the field trials data. The inverse trend could be seen in the laboratory data with respect to evaporative potential (i_m/clo); where, as i_m/clo reduced so did the predicted accuracy. While the thermal insulation should be considered important, the primary focus is typically paid to the i_m/clo values, as these relate more to the clothing effect on the human's ability to effectively dissipate heat through evaporative heat loss via sweat.

Implementation of a computer- or application-based approach like HSDA can lead to improved health-state awareness as well as provide guidance to help injury prevention. Broad use of models and decision aids also enables a feedback loop of quantitative data to be used for improved methods and understanding of individualized factors that increase susceptibility of hot or cold related injuries (e.g., fitness, body composition). While this information has been collected specifically from a military population, the predictions can be generalized for public safety of young healthy individuals [11]; as quantitative and interactive guidance for mitigating heat related injuries has global relevance. This global influence also has larger future implications specific to climate changes and the increased likelihood of hot or cold related injuries [32–34] or specific to semi-isolated incidences such as heat waves [35].

There are several other modeling methods [36–38], indices [39,40] and other openly accessible decision aids [41–44] that seek to protect individuals or populations from thermal strain. While there is obvious utility in many of these methods, there are shortcomings as well. Indices by their nature are non-individualized methods that protect populations but lack specificity of scenarios or individual elements

needed. Other decision aids, such as the predicted heat strain (PHS) model [45,46], have been widely used to predict scenario-based heat strain but have been shown to lack accuracy in certain clothing scenarios such as during use of personal protective clothing [47,48]. While limitations exist, the findings from the present study show that HSDA is acceptably accurate for the prediction of T_c when working in chemical protective clothing.

5. Conclusion

The HSDA acceptably predicts core body temperature in individuals wearing chemical protective clothing during exercise in hot and humid conditions. Therefore, the HSDA is recommended for use by military and civilian planners to predict core body temperature rise and resulting thermal strain over time for young healthy individuals needing to perform work in these clothing and environmental conditions.

Declarations conflicts of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Ethics approval and consent to participate

This study received approval by both the Scientific and Human Use Review Committees (SRC and HURC) at the U.S. Army Research Institute of Environmental Medicine (USARIEM) (Natick, MA), University of Wollongong, and the Australian Defence Human Research Ethics Committee. Each participant willingly gave their written informed consent to participate in these studies.

Availability of data

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

Author contributions

AWP DPL conceived, developed, and wrote this manuscript; WRS SS LAB contributed to the development and writing; AF APH BSC collected data used for validation in this study; AWP DPL analyzed and interpreted the results of this study.

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. Human subjects participated in these studies after giving their free and informed voluntary consent. 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.

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