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HEAT STRAIN DECISION AID (HSDA): REVIEW OF INPUT RANGES, DEFAULT VALUES, AND EXAMPLE INPUTS AND OUTPUTS FOR VERIFICATION OF EXTERNAL IMPLEMENTATION

United States Army
Medical Research & Development Command

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HEAT STRAIN DECISION AID (HSDA): REVIEW OF INPUT RANGES, DEFAULT VALUES, AND EXAMPLE INPUTS AND OUTPUTS FOR VERIFICATION OF EXTERNAL IMPLEMENTATION

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14. ABSTRACT

This report provides a brief review of the Heat Strain Decision Aid (HSDA) and serves as a guide for users, programmers, and scientists intending to use it. The report also includes: 1) a brief summary of validation conditions and results for chemical protective clothing and combat clothing in both warm and hot/humid conditions, as well as cold weather clothing in cold conditions. 2) Example inputs and associated outputs for verification of correct implementation. 3) A table of the generally used equations for HSDA. 4) A table of clothing values for use in HSDA. HSDA consistently and acceptably predicts core body temperature (Tc) when individuals are wearing chemical protective clothing, combat uniforms, and cold weather clothing. The model has been shown to be acceptably accurate across a range metabolic demands (activity rates) and in a wide range of environmental conditions. The HSDA has been shown to be acceptable using a direct measurement criteria of a bias of ± 0.27°C, and modeled errors (mean absolute and root mean square error (MAE, RMSE)) within observed SD criteria.

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EXECUTIVE SUMMARY

This report provides a brief review of the Heat Strain Decision Aid (HSDA) and serves as a guide for users, programmers, and scientists intending to use it. The report also includes: 1) a brief summary of validation conditions and results for chemical protective clothing and combat clothing in both warm and hot/humid conditions, as well as cold weather clothing in cold conditions. 2) Example inputs and associated outputs for verification of correct implementation. 3) A table of the generally used equations for HSDA. 4) A table of clothing values for use in HSDA.

HSDA consistently and acceptably predicts core body temperature (T_c) when individuals are wearing chemical protective clothing, combat uniforms, and cold weather clothing. The model has been shown to be acceptably accurate across a range metabolic demands (activity rates) and in a wide range of environmental conditions. The HSDA has been shown to be acceptable using a direct measurement criteria of a bias of ± 0.27°C, and modeled errors (mean absolute and root mean square error (MAE, RMSE)) within observed SD criteria.

INTRODUCTION

The U.S. Army's Heat Strain Decision Aid (HSDA) is an empirically based thermoregulatory model that predicts core body temperature (T_c) from inputs related to an individual (or group average), clothing values, environmental conditions, and activity-related factors (1). HSDA has been developed and refined based on three main equations developed by Givoni and Goldman that were created to predict T_c at rest, rise in T_c during exercise, and the decrease in T_c following exercise (2, 3). From these equations, a final equilibrium model was generated that predicts T_c trajectory or rate of rise based on inputs of the biophysical conditions (e.g., human, environment). The model in its current embodiment is designed with several modular components to allow for incremental improvements to component subroutine equations.

The HSDA method relies on the heat balance equation (Eq. 1), where in order to predict heat rise or fall in humans, heat storage (S) is calculated from the sum of heat produced, heat gained, and via heat dissipation to the four pathways of heat exchange:

$$S = M \pm W \pm R \pm C \pm K - E \; [\mathrm{W/m^2}] \qquad \text{Eq. 1}$$

where M and W represent metabolism and work rate; R is radiation transferred via electromagnetic waves (e.g., solar or infrared); C is convective heat transfer with fluid contact (e.g., air or water); K is conductive heat transfer from direct contact with a solid objects (e.g., touching a cold surface); E is evaporative heat loss to the environment of water from liquid to vapor (e.g., sweat and respiratory evaporative water loss). HSDA requires ~16 inputs (Tables 1–3) that are passed into a series of approximately 32 subroutine equations (Appendix A.) that are collectively used to make predictions of T_c and sweating rates (S_{wt}), which can then be used to produce maximal safe (uninterrupted one-time) work times, optimal work rest cycles for prolonged work, estimation of water requirements, and establish cooling requirements (Figure 1).

Figure 1. Heat exchange and the Heat Strain Decision Aid (HSDA)

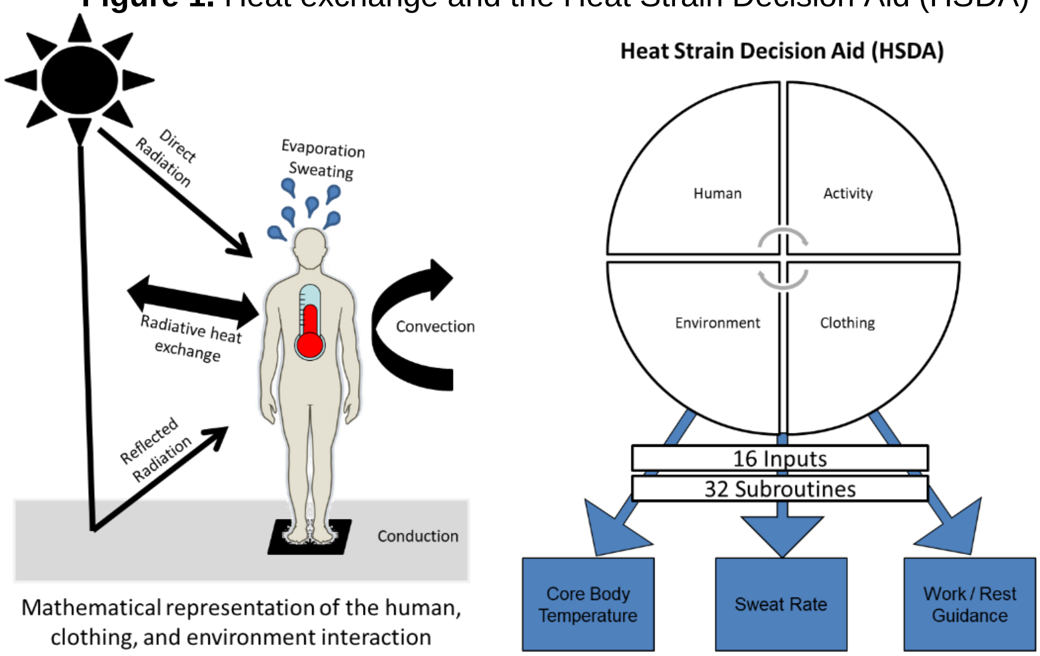


Table 1. HSDA Human and Activity Input Variables, Ranges, Defaults and Comments

HUMAN INPUTS				
Category	**Variable**	**Range**	**Default value**	**Comments**
Dehydration	dhyd	0 – 6%	1.24%	0% euhydrated, 1.24% mildly dehydrated, 2.5% slightly dehydrated, 4.0% moderately dehydrated, 6.0% severely dehydrated.
Acclimatization	DIH	0 – 12 days	12 days	Represented as number of 'days in heat'. Fully acclimatized is 12 days. Beyond that has negligible effects on the model but less than will have a weighted decrements in performance.
Height	Ht	Human ranges (cm)	170cm	Ht and Wt are currently mainly used as an input calculation to determine body surface area (BSA). BSA is directly linked to the amount of metabolic heat production for that size person.
Weight	Wt	Human ranges (kg)	70kg	
Initial Skin Temperature	iTsk	33 – 40°C	33°C	Skin temperature affects the main outcomes of this model as it shifts the rate of heat gain. In previous software versions it was used for casualty (injury) predictions.
Initial Core Body Temperature	iTc	36 – 39°C	36.5-37°C	The modeling method outlined (Potter et al., 2017) (1) initializes human thermoregulation at the beginning of the modeling run (this is the dip seen initially). So as it is written the model can be edited to cut out that initialization period but it is not recommended. While you can initialize at a higher iTc; we recommend not starting higher than 37.5°C unless a value is known. Beyond this is in the range of risk area for heat exhaustion (~38°C)
(HUMAN) ACTIVITY INPUTS				
Work Intensity	M	100 – 1000 Watts	N/A	Work intensity is regulated by individual size (BSA) and their level of activity. Resting metabolic rate for an individual is typically calculated as BSA * 58.2 or 58.2 W/m^2. An average individual of $1.8m^2$ will have a resting (minimum value of M) of 1.8 * 58.2 = ~105
External Work	Wex	0 – 200 Watts	N/A	This is used as an offset to account for energy that goes directly (more efficiently) to work and less for heat production. However, an easy method would be to always use an 80/20 ratio of W and Wex. This assumption is based on a best-case efficiency of energy to heat. For example, working at a work intensity with a 500 W total intensity could be entered as 400M and 100Wex (still a total of 500 but offset for optimal efficiency). This efficiency is still based on some thermal assumptions.

Table 2. HSDA Environmental Input Variables, Ranges, Defaults and Comments

ENVIRONMENTAL INPUTS				
Category	**Variable**	**Range**	**Default value**	**Comments**
Air Temperature	Ta	10 – 50°C (50 –122°F)	N/A	Warm – Hot conditions
Relative Humidity	RH	1 – 100%	N/A	Full range of conditions.
Mean Radiant Temperature	Tmr	Additive to Ta, 0-40 increase. Example, if Ta = 30°C; T_{mr} = 30-70°C	N/A	This can be accurately calculated based on location and time.
Wind Velocity	V	0.45 - 9 m/s (1 -20 mph)	1 m/s	0.45 m/s is generally considered still air. Most simulations we use 1 m/s. As wind has a direct effect on the thermal environment and can directly impact clothing properties, higher or more dynamic wind conditions are difficult to model effectively.

Table 3. HSDA Clothing Input Variables, Ranges, Defaults and Comments

CLOTHING INPUTS				
Category	**Variable**	**Range**	**Default value**	**Comments**
Clothing Insulation	I_T / clo	0.6 – 4.0 clo	N/A	See clothing table in Appendix B. From table mean±SD; 1.48 ± 0.44
Insulation Wind Exponent	$I_T$vg / cloVg	-0.37 to -0.152	N/A	See clothing table in Appendix B. This is always a negative value. From table mean±SD; -0.23 ± 0.05
Evaporative Potential	i_m/clo	0.1 to 0.75	N/A	See clothing table in Appendix B. From table mean±SD; 0.31 ± 0.14
Insulation Wind Exponent	i_m/cloVg	0.18 to 0.44	N/A	See clothing table in Appendix B. This is always a positive value. From table mean±SD; 0.28 ± 0.05

Improvements to underlying equations and methods have been made over the past several years. These improvements include exercise coefficients (4), improved sweat rate predictions (5, 6), calculation methods for clothing wind assessments (7, 8), body surface area calculations (9), accurate predictions of metabolic costs of military activities (10-12), and for added costs of locomotion over various terrains (13, 14).

HSDA has been used to generate guidance for military doctrine (15), public fluid intake (16), and emergency response efforts (17). The model has also been used extensively for evaluation of military clothing, to include general uniforms (18-21), body armor systems (22-24), chemical protective ensembles (25, 26), physical fitness clothing (27), and cold weather clothing (28, 29). Additionally, HSDA modeling has provided simulated guidance related to effectiveness of personal cooling systems (30, 31).

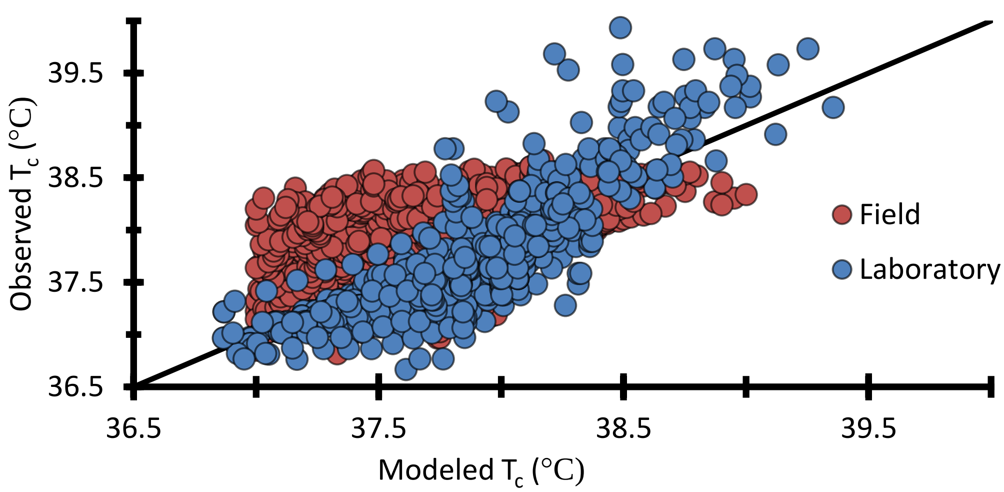
VALIDATION

HSDA has been validated for heat stress guidance in healthy civilians [11] and in Soldiers (32, 33). HSDA's predictive accuracy of T_c has been shown to be acceptable in based on group mean (32) and individual (33) inputs for healthy and active Soldiers wearing various chemical protective clothing ensembles during separate laboratory and field exercises in hot and humid conditions. Criterion for acceptable accuracies were based on bias, mean absolute error (MAE), and root mean square error (RMSE). A direct measurement accuracy criterion of mean bias ± 0.27°C was used, as well as MAE and RMSE within observed SD values (4, 34, 35).

Chemical Protective Ensembles

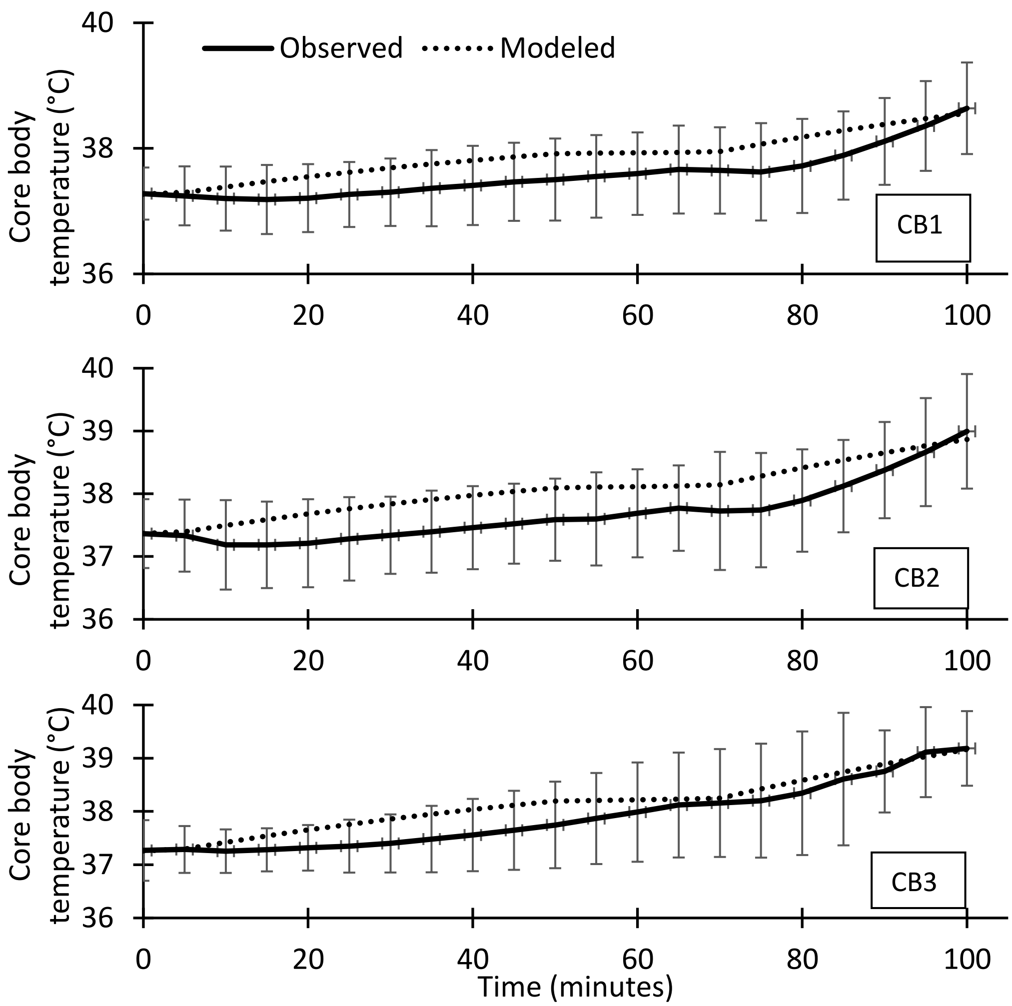
A validation study by Potter et al. (33) found HSDA to acceptably predict T_c for individuals when wearing chemical protective clothing during laboratory and field exercises in hot and humid conditions. The laboratory study included eight male volunteers (age 24 ± 6 years; height 178 ± 5 cm; body mass 76.6 ± 8.4 kg) wearing three different chemical protective ensembles 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). The field experiment included twenty activity military volunteers (26 ± 5 years; 175 ± 8 cm; 80.2 ± 12.1 kg) wearing four different chemical protective ensembles during a prolonged road march (26.0 ± 0.5°C; 55 ± 3%; 4.3 ± 0.7 m/s). HSDA predictions of T_c met the acceptable criteria for each chemical protective ensemble in both the laboratory (Bias -0.10; MAE 0.28; RMSE 0.37°C) and field experiments (Bias 0.23; MAE 0.30; RMSE 0.40°C). Additionally, 72% of all predictions were within one SD 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 (Figure 2).

Figure 2. Modeled to observed T_c in CBRN clothing in hot-humid conditions



Eight human research volunteers (age 23.9 ± 5.5 years; 178 ± 5 cm; 76.6 ± 8.4 kg; BMI 24.2 ± 2.7) participated in a controlled laboratory study. Volunteers conducted a 60 minute stage of exercise walking on a treadmill at 0.84 m/s on level gradient (0 %), followed by a 10 minute rest period, and concluded with a second walking exercise period of 30 minutes at 1.68 m/s at a 3% inclined grade. Each volunteer conducted this three stage testing protocol wearing three different chemical protective ensembles (CB1, CB2, and CB3) for a total of 3 tests each and 72 time series periods (24 at level walking, 24 resting, and 24 increased speed at an incline). Volunteers were assessed within a controlled laboratory environment (air temperature: 29.3°C; relative humidity 56%; near still air ~0.4 m/s (indoors)). Core body (rectal) temperature was collected throughout the duration of each study stage (CB1, 37.6 ± 0.38; CB2, 37.7 ± 0.49; CB3, 37.9 ± 0.60°C). HSDA predictions were made based on the mean values of the group and compared to the mean outputs of the group (32). While this method is generally less accurate as compared to an individual, the results showed that the RMSE was within the acceptable criterion of being within 2*SD of observed values (CB1, 0.70; CB2, 0.37; CB3, 0.25°C) (Figure 3).

Figure 3. Modeled and observed T_c data for three chemical protective ensembles.



Note: Error bars represent observed 2*SD

Combat Clothing Ensembles

Core body temperature and metabolic cost was collected from nine healthy Soldiers (age, 22 ± 4 years; height, 175 ± 10 cm; body mass 76.4 ± 10.7 kg; body fat, 23.4 ± 5.8%; $VO2_{max}$, 49.2 ± 3.3 ml•kg^{-1}•min^{-1}), walked on a treadmill in an environmental chamber at two work intensities, moderate (350 ± 25 W) and higher intensity (535 ± 31 W), in a warm humid environment (air temperature 25°C, relative humidity 50%) (36). HSDA predictions were made for T_c based on individual inputs and metabolic rates. Predictions met the acceptable criteria for both the moderate (Bias -0.03; MAE 0.06; RMSE 0.08°C) and higher-intensity walks (Bias 0.00; MAE 0.07; RMSE 0.10°C) (Figure 4 and 5).

Figure 4. Individual subject predictions of T_c during moderate intensity walking trials

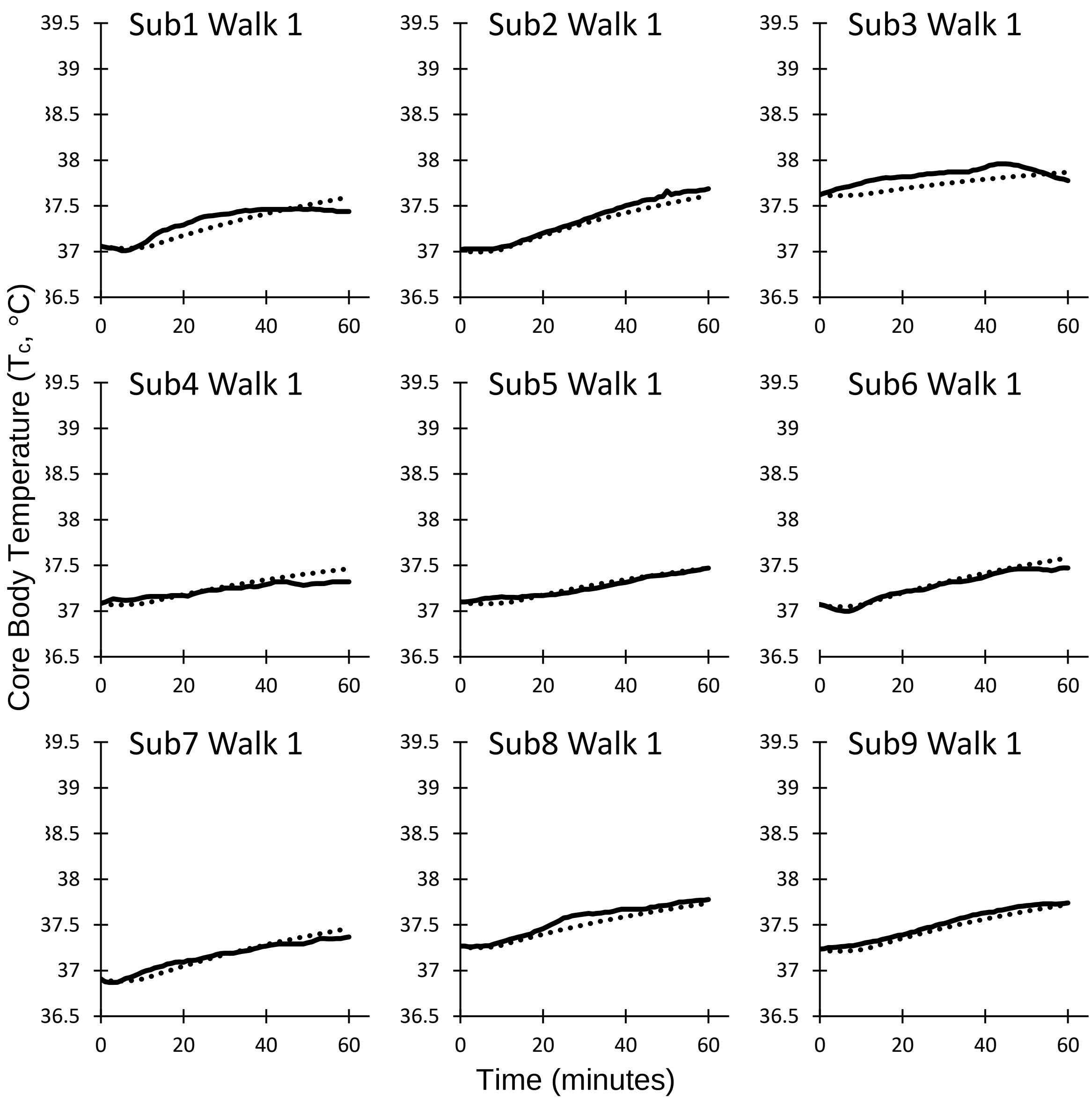
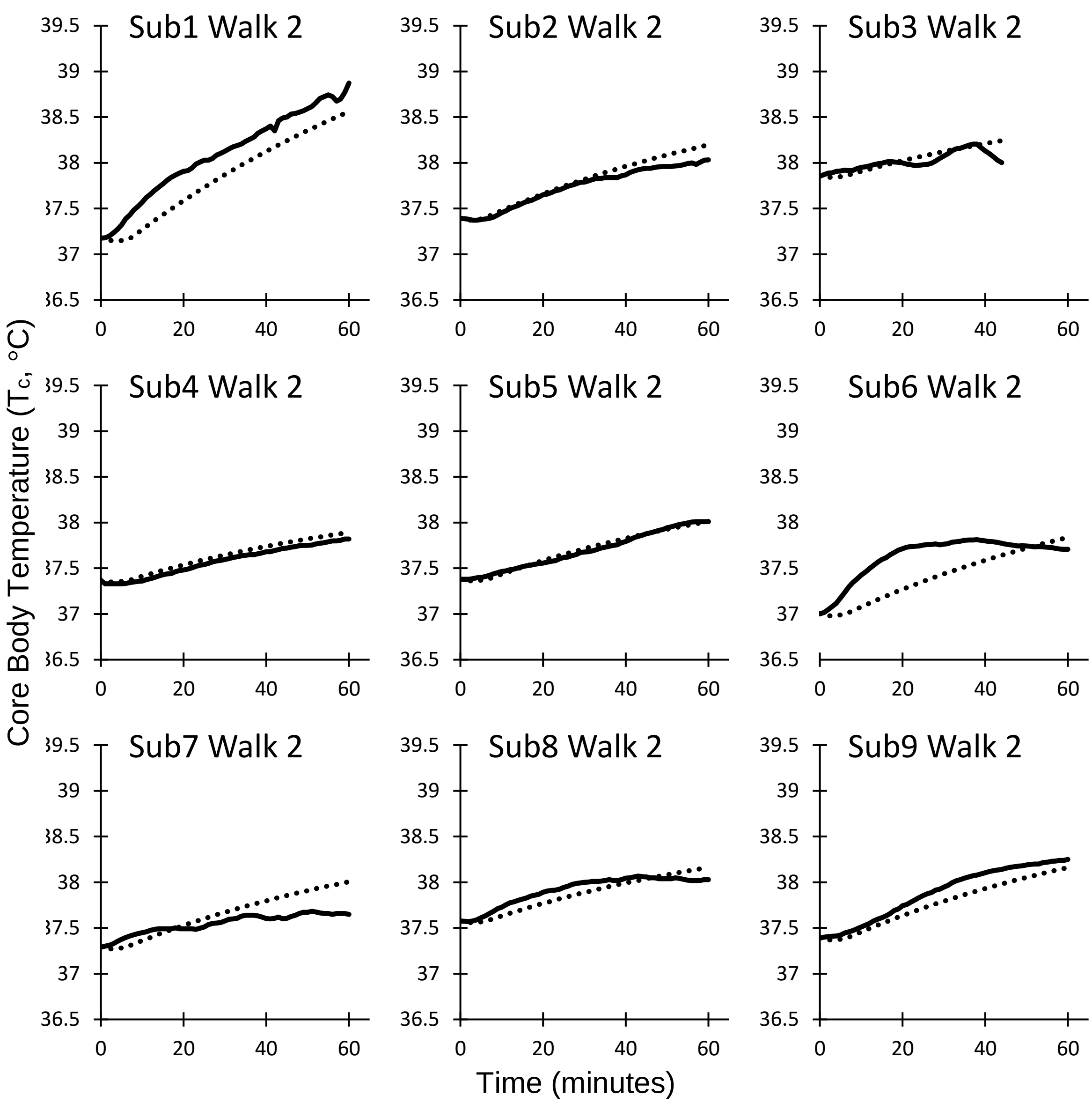


Figure 5. Individual subject predictions of T_c during higher intensity walking trials



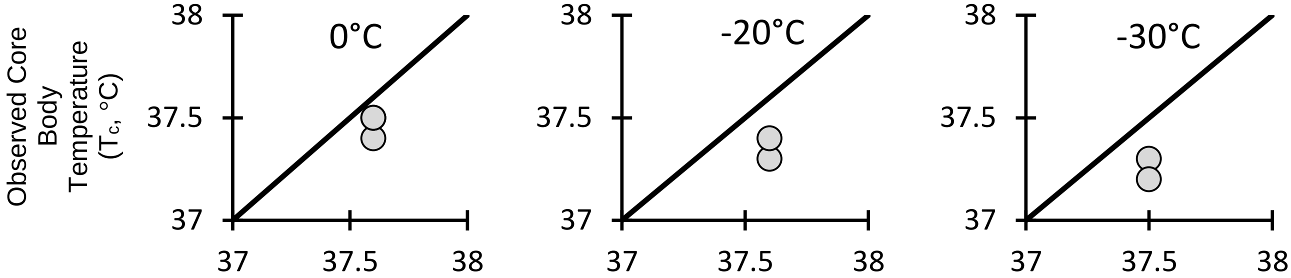
Civilian Work Clothing

Glisson (38) conducted an assessment of HSDA predictions compared to data collected during 120 minute heat stress exposure trials with twelve healthy civilian males (n=8) and females (n=4) in hot dry conditions (50°C, RH: 20%). Volunteers conducted moderate work (190 W/m^2) in these environmental conditions while wearing three different ensembles representing civilian work clothes (1.20 clo; 0.3 i_m/clo; 1.19 clo, 0.26 i_m/clo; and 1.21 clo, 0.19 i_m/clo). This work found that HSDA provided acceptable predictions T_c and could be useful for planning and prevention of heat stress exposure. This work from Glisson (38) showed it is possible to use HSDA along with ACGIH Threshold Limit Value (TLV) (16) to provide guidance for the general population for protecting workers.

Cold Weather Clothing

Data from a published report were compared to HSDA predictions of T_c. Volunteers from the laboratory study by Gonzalez et al., (37) walked on a treadmill for a maximum of 120 minutes per test in three cold chamber conditions (0, -20, and -30°C, RH: 20%, 1.34 m/s) with three cold weather clothing variants. Measures of core body temperature were compared to HSDA predictions and were in close agreement for each trial (0.2 ± 0.08°C) (Figure 6).

Figure 6. Modeled to observed T_c during light intensity walking trials in cold conditions



Example Inputs and Outputs for External Implementation

Ideally comparisons will be continuously made against human data. However, as HSDA has been constructed and implemented into several programming languages, or has been embedded into larger programs, it is important to have a platform to compare expected outputs from a set of inputs. Table 4 includes a series of inputs and Table 5 and Figure 7 provide their associated outputs. Each of the inputs from Table 4 assume an individual height (*Ht*) 176.5 cm, weight (*Wt*) 81.3 kg, with an initial T_c of 37°C, 12 days acclimatized (DIH), and 0% dehydrated.

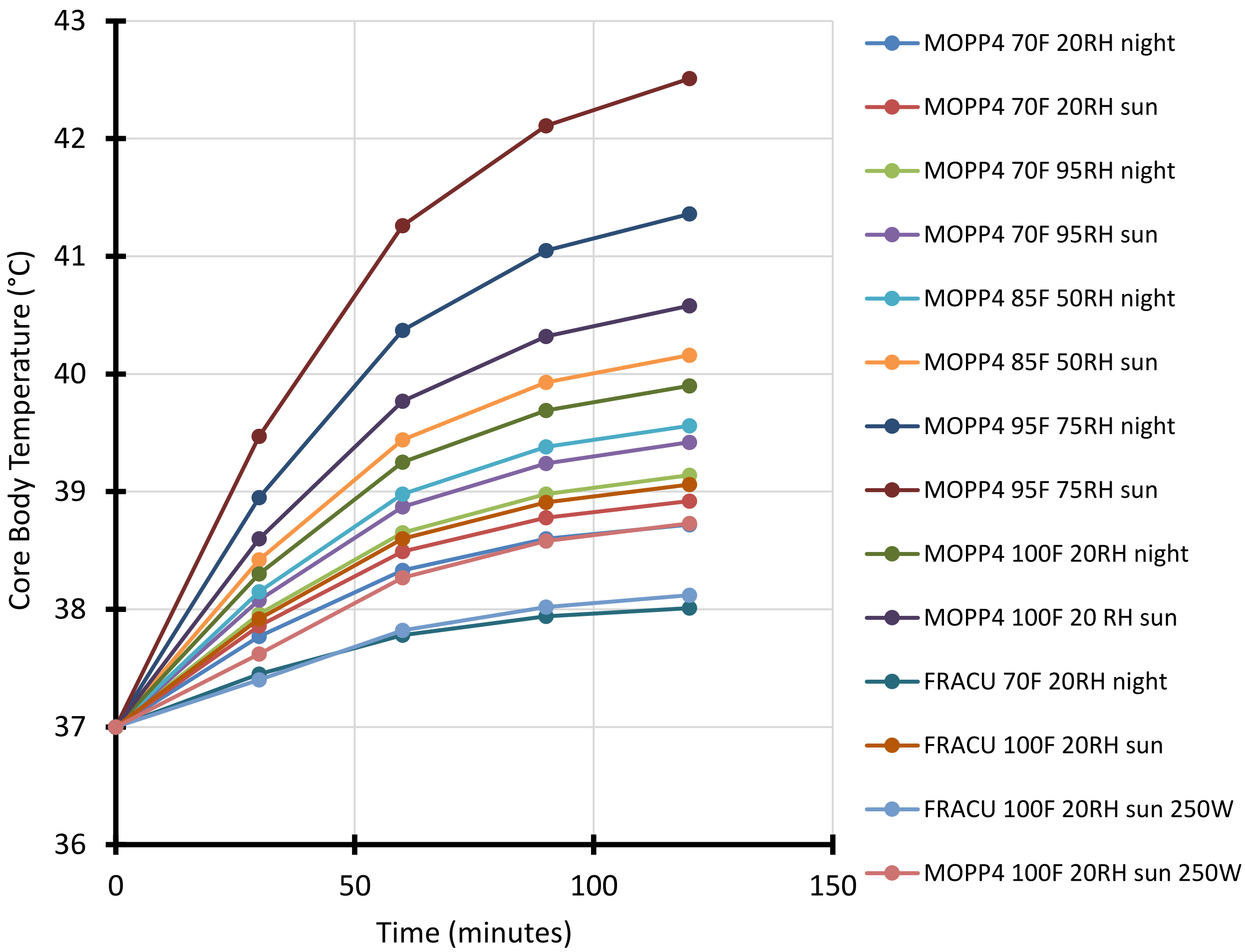
Table 4. Example Inputs to HSDA

Trial	Ta	RH%	V	Tmr	M	Wex	clo	im/clo	clo g	im/clo g
MOPP4 night	21.11	20	2	21.11	425	0	1.730	0.202	-0.175	0.210
MOPP4 sun	21.11	20	2	41.11	425	0	1.730	0.202	-0.175	0.210
MOPP4 night	21.11	95	2	21.11	425	0	1.730	0.202	-0.175	0.210
MOPP4 sun	21.11	95	2	41.11	425	0	1.730	0.202	-0.175	0.210
MOPP4 night	29.44	50	2	29.44	425	0	1.730	0.202	-0.175	0.210
MOPP4 sun	29.44	50	2	69.44	425	0	1.730	0.202	-0.175	0.210
MOPP4 night	35	75	2	35	425	0	1.730	0.202	-0.175	0.210
MOPP4 sun	35	75	2	75	425	0	1.730	0.202	-0.175	0.210
MOPP4 night	37.78	20	2	37.78	425	0	1.730	0.202	-0.175	0.210
MOPP4 sun	37.78	20	2	77.78	425	0	1.730	0.202	-0.175	0.210
FRACU night	21.11	20	2	21.11	425	0	1.110	0.404	-0.253	0.304
FRACU sun	37.78	20	2	77.78	425	0	1.110	0.404	-0.253	0.304
FRACU sun 250W	37.78	20	2	77.78	250	0	1.110	0.404	-0.253	0.304
MOPP4sun 250W	37.78	20	2	77.78	250	0	1.730	0.202	-0.175	0.210

Table 5. Example Outputs of HSDA (associated to Table 4 inputs)

Time (min)	0	30	60	90	120
MOPP4 70F 20RH night	37	37.77	38.33	38.60	38.72
MOPP4 70F 20RH sun	37	37.86	38.49	38.78	38.92
MOPP4 70F 95RH night	37	37.96	38.65	38.98	39.14
MOPP4 70F 95RH sun	37	38.08	38.87	39.24	39.42
MOPP4 85F 50RH night	37	38.15	38.98	39.38	39.56
MOPP4 85F 50RH sun	37	38.42	39.44	39.93	40.16
MOPP4 95F 75RH night	37	38.95	40.37	41.05	41.36
MOPP4 95F 75RH sun	37	39.47	41.26	42.11	42.51
MOPP4 100F 20RH night	37	38.30	39.25	39.69	39.90
MOPP4 100F 20 RH sun	37	38.60	39.77	40.32	40.58
FRACU 70F 20RH night	37	37.45	37.78	37.94	38.01
FRACU 100F 20RH sun	37	37.92	38.60	38.91	39.06
FRACU 100F 20RH sun 250W	37	37.40	37.82	38.02	38.12
MOPP4 100F 20RH sun 250W	37	37.62	38.27	38.58	38.73

Figure 7. Example Outputs of HSDA (plot of Table 5)



Transitions

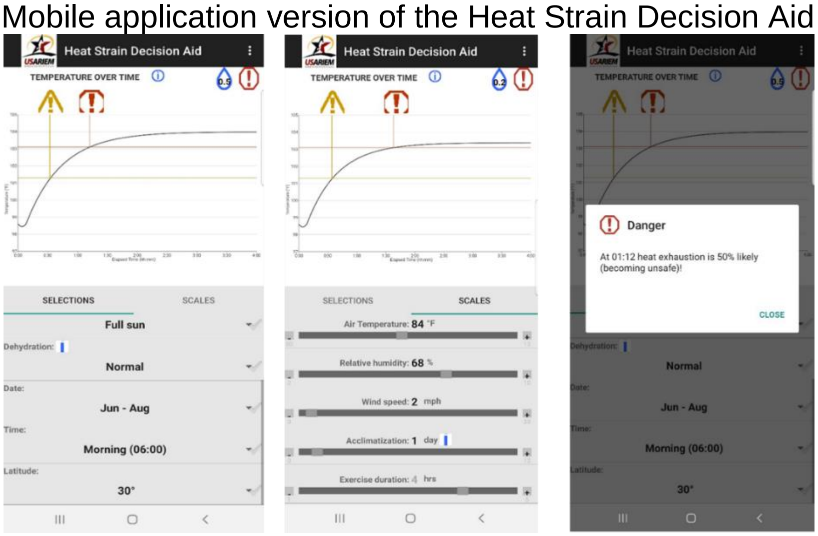
A publically available version of HSDA has been transitioned, associated with an open literature publication (1) https://ars.els-cdn.com/content/image/1-s2.0-S0306456516302741-mmc1.xlsx); while several equation-based and software variants have been transitioned across to multiple Department of Defense (DoD) organizations as well as internationally.

In 2007, a software variant of HSDA was transitioned to the Joint Warning and Reporting Network (JWARN) Acquisition Program. The JWARN is a computer-based application that networks nuclear, biological and chemical sensors directly with joint and service command and control (C2) systems. HSDA was used to meet a JWARN requirement for a certified heat strain model and functionality within their larger application (https://asc.army.mil/web/portfolio-item/jpeo-cbd-joint-warning-and-reporting-network-jwarn-increments-2/, accessed 9 February 2021).

In 2011, a software variant of HSDA was transitioned along with a verification and validation report outlining the acceptable use for “Thermal Burden Assessment of Chemical/Biological (CB) Ensembles” to a Joint Chemical, Biological, Radiological and Nuclear (CBRN) Defense group. The group consisted of Joint Program Executive Office for Chemical Biological Defense (JPEO-CBD), Joint Requirements Office (JRO) for Chemical, Biological, Radiological, and Nuclear Defense, Joint Science and Technology Office (JSTO), Marine Corps Operational Test & Evaluation Activity (MCOTEA), Expeditionary Warfare Commander Operational Test and Evaluation Force (COMOPTEVFOR), and US Army Test and Evaluation Command (ATEC).

In 2018, a mobile application version of HSDA (HSDApp) was transitioned to the US Army Medical Materiel Development Activity (USAMMDA) (Figure 8). This version uses simplified inputs of the environment and activity and provides predicted times for safe duration of activities, water requirements, suggests clothing, and provides estimates of the number of heat casualties and when they are likely to occur.

Figure 8. Mobile application version of the Heat Strain Decision Aid (HSDApp)



In 2019, a software version of HSDA (Figure 9) was transitioned to the US Special Operations Command & US Air Force 352nd Battlefield Airmen Training Squadron. Similar to the mobile application (HSDApp), this version was designed with simplified inputs for clothing (i.e., shorts and t-shirt, Army Combat Uniform with and without body armor), and selectable activities based on user community interests (i.e., 5 mile run or 12 mile ruck march).

Figure 9. Software version of the Heat Strain Decision Aid (HSDA) tailored to user community needs.

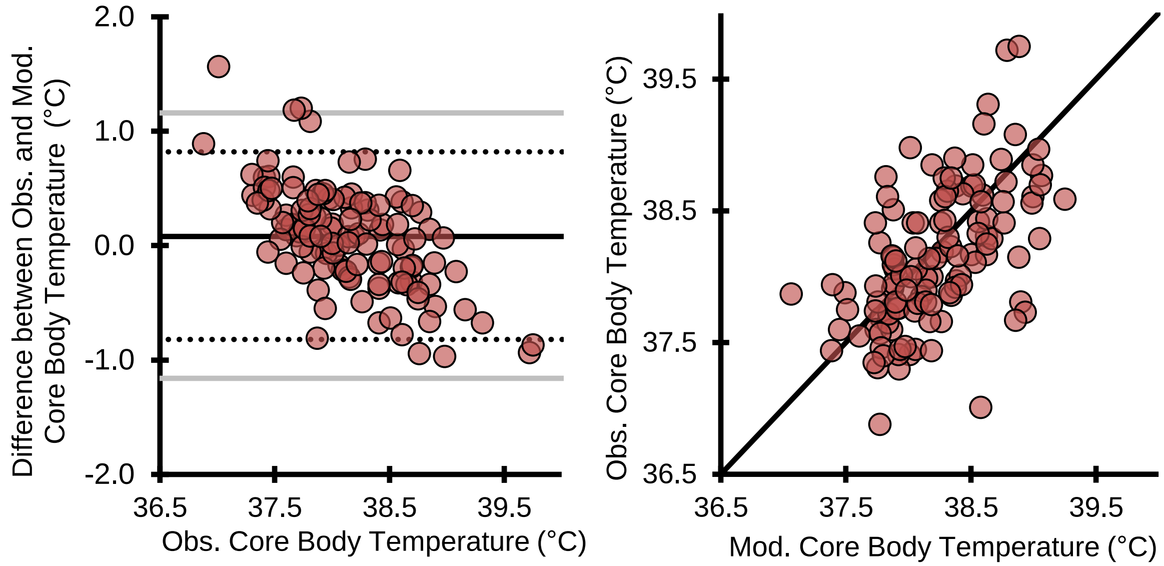
From March to August 2020, HSDA was transitioned and implemented into the One Semi-Automated Forces (OneSAF) model. The OneSAF model is considered the DoD's "gold standard" for conducting force-on-force modeling and simulation. The OnSAF model as a whole is being packaged as part of a Foreign Military Sales program. Partners in this transition included of Joint Program Executive Office – Chemical, Biological, Radiological, Nuclear Defense (JPEO-CBRND) Analytical Framework group, Program Executive Office Simulation, Training, and Instrumentation (PEO-STRI), and Combat Capabilities Development Command Data & Analysis Center (CCDC DAC) (https://www.peostri.army.mil/onesaf, accessed 9 February 2021).

April to December 2020, HSDA was used in collaboration with the United Kingdom (UK) Institute of Naval Medicine (INM) to provide updates to the UK Heat Illness Guidance as well as to generate new UK work/rest guidance tables.

From May to October 2020, HSDA was provided to the UK Department of Army Health and Physical Performance Research (DAHPR) to help assess heat injuries during training and work towards improved guidance materials. HSDA was specifically used by DAHPR scientists with their own human study assessing the potential use of HSDA as a heat stress tool for their newly developed Role Fitness Test (RFT) with

Ground Close Combat (GCC) personnel. The HSDA predictions were compared to T_c measurements of British soldiers conducting a load carriage exercise and were found to provide acceptable predictions of the observed values. HSDA predictions were in close agreement with the observed data (Bias, 0.08; MAE 0.37; RMSE 0.46°C) (Figure 10).

Figure 10. Modeled accuracy to observed T_c values for self-paced load carriage



May 2020, HSDA was transitioned along USARIEM's Load Carriage Decision Aid (LCDA) to the Combat Capabilities Development Command Data & Analysis Center (CCDC DAC) group for integration into the Soldier and Squad Trade Space Analysis Framework (SSTAF) and as part of the Integrated Visual Augmentation System (IVAS) modeling and simulation effort (https://www.army.mil/article/231403/ccdcs_road_map_to_modernizing_the_army_soldier_lethality, accessed 9 February 2021).

February 2021, HSDA and LCDA were transitioned to the Combat Capabilities Development Command Soldier Center (CCDC SC) Simulation and Training Technology Center (STTC) for integration into the Augmented Reality Sandtable (AReS) route planning tool being developed by STTC (https://simulation.arl.army.mil/ares, accessed 9 February 2021). This integration of HSDA and LCDA enable metabolic costs and physiological response predictions, and expand the capabilities of AReS model.

DISCUSSION

HSDA consistently and acceptably predicts T_c when individuals are wearing chemical protective clothing, combat uniforms, and cold weather clothing. The model has been shown to be acceptably accurate across a range metabolic demands (activity rates) and in a wide range of environmental conditions. The HSDA has been shown to be acceptable using a direct measurement criteria of a bias of ± 0.27°C, and modeled errors (MAE, RMSE) within observed SD criteria.

"All models are wrong but some are useful" (39)

As an empirically designed method, there are several limitations to HSDA. However, the modular design has allowed for continued updating and improvements to specific equations (e.g., body surface area, metabolic rate). Additional limitations include the need for continued validation and potential improvements related to the ability to account for higher resolution in individual differences. Recent work has found differences in heat stress responses based on age (40-43), sex (44, 45), body morphology (46, 47), and fitness-related factors (48-50).

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 (19, 22, 23, 28). Wide-scale use of these models also allows for continued collection of data to conduct validation and modeling improvements. This information can be used for public safety (17), for competitive sporting events (51), or for use in providing guidance to mitigating heat or cold related risks globally on land (52, 53) and in immersed environments (54-58). Additionally, methods like these have larger future implications specific to climate change and increased risks of thermal injuries (59-63).

Data from multiple environmental conditions would allow for more robust assessment of the human and environment heat transfer calculation methods (64, 65). 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 (40, 41, 43-45, 48). 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 (10, 66, 67). Future work should be conducted to specifically and systematically address these limitations.

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Appendix A. General Set of Equations for the Heat Strain Decision Aid (HSDA)

Parameter	Equation	units	Ref.
Body Surface Area (A_D) Height (Ht, cm) Weight (Wt, kg) Sex (Male 1; Female 0) Armspan (AS, cm)	Only height is known $A_D = 0.000338 * Ht^{1.6798}$	m^2	(9)
	Only weight is known $A_D = 0.181465 * Wt^{0.5392}$		
	Only sex and height are known Male $A_D = 0.000872 * Ht^{1.4971}$ Female $A_D = 0.190837 * Ht^{0.5242}$		
	Only sex and weight are known Male $A_D = 0.211577 * Wt^{0.5058}$ Female $A_D = 0.190837 * Wt^{0.5242}$		
	Only height and weight are known $A_D = 0.013143 * Ht^{0.5985} * Wt^{0.4352}$		
	Only sex, height, and weight are known Male $A_D = 0.211577 * Wt^{0.5058}$ Female $A_D = 0.190837 * Wt^{0.5242}$		
	Armspan (cm), sex, height, and weight are known Male $A_D = 0.010245 * Ht^{0.3548} * Wt^{0.4284} * AS^{0.2956}$ Female $A_D = 0.013546 * Ht^{0.3291} * Wt^{0.4414} * AS^{0.2578}$		
Effective wind velocity (Veff)	$V_{eff} = V + 0.004 \cdot (M - 105)$	m/s	(1, 2)
Air Vapor Pressure (P_a)	$P_a = 10^{(8.1076-(\frac{1750.286}{Ta+235}))} \cdot (\frac{RH}{100})$	Torr	(1, 68)
Effective total thermal resistance (I_{Teff})	$I_{Teff} = I_T \cdot Veff^{I_T V^g}$	clo	(1, 69)
Effective clothing evaporation (C_{evap})	$C_{evap} = \frac{i_m}{clo} \cdot Veff^{im/clo V^g}$	i_m/clo	
Radiative and Convective heat transfer (H_{rc})	$H_{rc} = 6.45 \cdot A_D \cdot \frac{T_a - T_{sk}}{I_{Teff}}$	W	(1, 2)
Insulation efficiency (U)	$U = \left(\frac{0.41}{I_T}\right) \cdot Veff^{(-(0.43+clo V^g))}$	N.D.	(1, 69)
Solar load (R_{load})	$R_{load} = (-0.071 \cdot (T_{mr} - T_a)^2 + 10.432 \cdot (T_{mr} - T_a)) \cdot (A_D/1.8)$	W	(1, 70)
Evaporation required (E_{req})	$E_{req} = H_{rc} + M - W_{ex} + U \cdot R_{load}$	W	(1, 2, 69)
Saturated Vapor Pressure at skin ($SVPT_{sk}$)	$SVPT_{sk} = 10^{(8.1076-(\frac{1750.286}{Tsk+235}))}$	Torr	(1, 68)

Parameter	Equation	units	Ref.
Maximum evaporative capacity (E_{max})	$E_{max} = 14.21 \cdot A_D \cdot C_{evap} \cdot (SVPT_{sk} - P_a)$	W	(1, 2, 69)
Maximum evaporative capacity at altitude (E_{maxA})	$P_{atm} = (1 - 2.5577 \cdot 10^{-5} \cdot Z)^{5.2559}$ $I_{TA} = I_T \cdot (P_{atm} \cdot V_{eff})^{I_T V^g}$ $E_{maxA} = P_{atm^{-0.45}} \cdot LR \cdot 6.45 \cdot A_D \cdot C_{evap} \cdot (SVPt_{sk} - P_a)$	W	(1, 71)
Final equilibrium core temperature (T_{cf})	$T_{cf} = (36.75 + 0.004 \cdot M + 0.0025 \cdot U \cdot R_{load} + 0.0011 \cdot H_{rc} + 0.8 \cdot \exp(0.0047 \cdot (E_{req} - E_{max)})$	°C	(1, 2)
Heat acclimation effect on T_c (A_{eff})	$A_{eff} = (0.5 + 1.2 \cdot (1 - EXP\left(\frac{37.15 - T_{cf}}{2}\right))) \cdot (1 - EXP(-0.005 \cdot E_{max})) \cdot (EXP(-0.3 \cdot DIH))$	N.D.	
Adjusted T_{cf} from acclimatization (T_{cf_a})	$T_{cf\_a} = T_{cf} + A_{eff}$	°C	(1, 72)
Adjusted T_c based on work (D_{tc_W})	$D_{tc\_W} = T_{cf\_a} - T_{c\_i}$	°C	
Improved piecewise (PW) Swt	$PW = 147 + (1.527 \cdot E_{req}) - (0.87 \cdot E_{max})$	g/hr	(6, 73)
Time delay for work (TDWK)	$TDWK = \frac{3480}{M}$	°C/min	(1, 71)
Time constant for work (KWK)	$KWK = \frac{[1 + 3 \cdot EXP(0.3 \cdot (T_{c_i} - T_{cf_a})]}{225}$	N.D.	(1, 69)
Work adjusted by hydration (KWKd)	$KWKd = KWK \cdot (1 + 0.1 \cdot dhyd)$	N.D.	(1, 71)
Cooling power (CP)	$CP = 0.015 \cdot (E_{max} - E_{req})$	W	
Time delay for rest and recovery (TDRY)	$If\ CP < 0, then\ TDRY = 15$ $Else\ (TDRY = 15 \cdot EXP(-0.5 \cdot CP))$	Min	(1, 2)
Time constant for rest and recovery (KRY)	$KRY = \frac{1 - EXP(-1.5 \cdot abs(CP))}{40}$	N.D.	
Hydration adjusted for rest and recovery (KRYd)	$KRY_d = KRY \cdot (EXP(-0.07 \cdot dhyd)$	N.D.	(1, 69)
Core temperature by time point (T_{c_t})	$IF(M \leq (58.2 * A_D), then = 0,$ $Else\ T_{c_i} + D_{tc} \cdot (1 - EXP(-KWkd \cdot IF((E_t - TDWK) < 0,$ $0.5 \cdot (E_t - TDWK) \cdot (\frac{E_t}{TDWK}), E_t - TDWK))))$	°C	(1, 2, 69)

Appendix B. Table of Clothing Types and HSDA Inputs.

Tested clothing biophysical values

Type 1: Physical fitness clothing (PT#) (shorts, t-shirt, sneakers)

Type 2: Regular clothing (RC#) (Long-sleeve shirt, undershirt, underwear, pants, boots/sneakers)

Type 3: Combat clothing with body armor (CC#) (Type 2 plus equipment and body armor)

Type 4: Chemical protective clothing (CB#; with body armor (BA) (e.g., hazmat suits, face masks, respirators)

Type 5: Explosive ordnance disposal suits (EOD#) (full armor protection suits with equipment)

Type 6: Cold weather clothing (CWC#) (full body clothing coverage)

Ensemble	0.4 ms^{-1} Standard test values			1ms^{-1} (values used in HSDA)				Type
	clo	i_m	i_m/clo	clo	cloV^g	i_m/clo	i_m/cloV^g	
PT-1	0.877	0.467	0.536	0.646	-0.334	0.742	0.354	1
PT-2	0.910	0.462	0.507	0.652	-0.364	0.730	0.397	1
PT-3	0.909	0.473	0.528	0.652	-0.363	0.738	0.366	1
PT-4	0.919	0.464	0.522	0.655	-0.370	0.727	0.362	1
PT-5	0.891	0.461	0.518	0.653	-0.340	0.728	0.371	1
RC-1	1.368	0.410	0.276	1.092	-0.246	0.377	0.340	2
RC-2	1.405	0.422	0.300	1.118	-0.249	0.439	0.438	2
RC-3	1.354	0.451	0.333	1.085	-0.242	0.470	0.348	2
RC-4	1.323	0.475	0.359	1.052	-0.250	0.513	0.345	2
RC-5	1.302	0.468	0.360	1.040	-0.245	0.510	0.344	2
RC-6	1.373	0.483	0.352	1.086	-0.255	0.481	0.316	2
RC-7	1.290	0.421	0.327	1.035	-0.240	0.468	0.245	2
CC-1	1.566	0.401	0.246	1.230	-0.264	0.327	0.307	3
CC-2	1.586	0.391	0.246	1.247	-0.263	0.316	0.274	3
CC-3	1.619	0.396	0.245	1.290	-0.248	0.308	0.251	3
CC-4	1.578	0.385	0.238	1.243	-0.260	0.311	0.292	3
CC-5	1.574	0.382	0.237	1.248	-0.253	0.306	0.280	3
CC-6	1.577	0.383	0.236	1.251	-0.253	0.306	0.283	3
CC-7	1.583	0.363	0.217	1.261	-0.248	0.283	0.288	3
CC-8	1.603	0.358	0.223	1.290	-0.237	0.278	0.244	3
CC-9	1.632	0.350	0.217	1.283	-0.263	0.270	0.238	3
CC-10	1.529	0.374	0.223	1.202	-0.263	0.311	0.362	3
CC-11	1.466	0.437	0.298	1.184	-0.234	0.413	0.327	3
CC-12	1.675	0.440	0.262	1.344	-0.240	0.356	0.308	3
CC-13	1.423	0.537	0.377	1.116	-0.265	0.457	0.296	3
CC-14	0.882	0.350	0.396	1.652	-0.177	0.238	0.185	3
CC-15	1.524	0.400	0.263	1.240	-0.225	0.364	0.262	3
CC-16	1.648	0.422	0.256	1.338	-0.228	0.330	0.251	3
CC-17	1.603	0.433	0.270	1.286	-0.241	0.360	0.279	3
CC-18	1.641	0.453	0.276	1.307	-0.249	0.365	0.281	3
CC-19	1.614	0.416	0.258	1.298	-0.238	0.332	0.255	3
CC-20	1.510	0.373	0.250	1.251	-0.206	0.304	0.227	3
CC-21	1.510	0.418	0.280	1.258	-0.198	0.340	0.221	3
CC-22	1.900	0.448	0.240	1.533	-0.232	0.337	0.385	3
CB-BA-1	1.832	0.280	0.152	1.504	-0.215	0.196	0.276	4

CB-BA-2	1.976	0.310	0.157	1.657	-0.192	0.205	0.292	4
CB-BA-3	2.002	0.304	0.152	1.697	-0.180	0.188	0.233	4
CB-BA-4	1.894	0.148	0.079	1.577	-0.200	0.105	0.314	4
CB-BA-5	2.016	0.301	0.149	1.722	-0.172	0.185	0.240	4
CB-BA-6	2.033	0.294	0.145	1.733	-0.174	0.182	0.252	4
CB-BA-7	1.740	0.264	0.151	1.436	-0.210	0.192	0.263	4
CB-BA-8	2.231	0.284	0.128	1.925	-0.161	0.154	0.207	4
CB-1	1.729	0.293	0.172	1.416	-0.218	0.223	0.281	4
CB-2	1.864	0.330	0.178	1.577	-0.182	0.226	0.261	4
CB-3	1.868	0.320	0.171	1.616	-0.158	0.210	0.225	4
CB-4	1.773	0.157	0.088	1.467	-0.207	0.119	0.324	4
CB-5	1.934	0.301	0.156	1.609	-0.201	0.204	0.294	4
CB-6	1.945	0.301	0.155	1.632	-0.192	0.199	0.270	4
CB-7	1.716	0.261	0.152	1.447	-0.186	0.190	0.242	4
CB-8	1.685	0.250	0.149	1.449	-0.165	0.176	0.178	4
CB-9	1.777	0.262	0.148	1.507	-0.180	0.188	0.259	4
CB-10	1.782	0.251	0.140	1.531	-0.166	0.166	0.186	4
CB-11	1.849	0.266	0.149	1.558	-0.187	0.188	0.258	4
CB-12	1.796	0.255	0.142	1.545	-0.164	0.168	0.184	4
CB-13	1.393	0.430	0.309	1.097	-0.260	0.440	0.286	4
CB-14	1.651	0.429	0.260	1.351	-0.219	0.326	0.279	4
CB-15	1.926	0.411	0.213	1.517	-0.261	0.298	0.332	4
CB-16	2.079	0.402	0.193	1.712	-0.212	0.253	0.282	4
CB-17	2.530	0.394	0.156	2.203	-0.151	0.183	0.240	4
CB-18	2.392	0.360	0.151	1.939	-0.229	0.218	0.289	4
CB-19	2.582	0.349	0.135	2.248	-0.151	0.172	0.265	4
EOD-1	3.031	0.000	0.000	2.360	N/A	2.118	N/A	5
EOD-2	3.209	0.000	0.000	2.766	N/A	1.808	N/A	5
EOD-3	3.039	0.000	0.000	2.502	N/A	1.998	N/A	5
EOD-4	3.501	0.000	0.000	3.063	N/A	1.633	N/A	5
CWC-1	1.296	0.518	0.400	0.918	-0.347	0.552	0.370	6
CWC-2	1.548	0.548	0.354	1.090	-0.343	0.485	0.366	6
CWC-3	1.729	0.361	0.209	1.386	-0.232	0.269	0.267	6
CWC-4	2.806	0.390	0.139	2.205	-0.161	0.165	0.207	6
CWC-5	1.490	0.325	0.218	1.230	-0.232	0.282	0.266	6
CWC-6	1.825	0.367	0.201	1.457	-0.227	0.258	0.263	6
CWC-7	1.342	0.313	0.233	1.124	-0.237	0.305	0.270	6
CWC-8	1.316	0.368	0.280	1.058	-0.268	0.374	0.298	6
CWC-9	1.554	0.382	0.246	1.233	-0.256	0.324	0.288	6
CWC-10	1.812	0.399	0.220	1.420	-0.245	0.286	0.279	6
CWC-11	2.103	0.449	0.214	1.606	-0.248	0.276	0.282	6
CWC-12	2.445	0.415	0.170	1.901	-0.203	0.211	0.243	6
CWC-13	2.328	0.458	0.197	1.775	-0.234	0.251	0.271	6
CWC-14	2.657	0.434	0.163	2.052	-0.196	0.202	0.238	6
CWC-15	3.109	0.460	0.148	2.384	-0.174	0.179	0.219	6

CWC-16	2.638	0.494	0.187	1.988	-0.228	0.237	0.267	6
CWC-17	2.509	0.438	0.175	1.933	-0.210	0.218	0.250	6
CWC-18	1.812	0.361	0.199	1.452	-0.225	0.255	0.261	6
CWC-19	1.638	0.358	0.218	1.318	-0.237	0.283	0.271	6
CWC-20	1.671	0.408	0.244	1.302	-0.260	0.321	0.292	6
CWC-21	2.199	0.360	0.163	1.756	-0.194	0.202	0.234	6
CWC-22	2.406	0.354	0.147	1.922	-0.175	0.178	0.217	6
CWC-23	1.484	0.361	0.244	1.195	-0.251	0.321	0.283	6
CWC-24	1.742	0.386	0.222	1.376	-0.244	0.289	0.277	6
CWC-25	1.806	0.394	0.218	1.420	-0.243	0.283	0.277	6
CWC-26	2.516	0.416	0.165	1.957	-0.198	0.204	0.239	6
CWC-27	2.516	0.454	0.180	1.925	-0.218	0.226	0.257	6
CWC-28	2.000	0.419	0.209	1.551	-0.240	0.269	0.275	6