



U.S. Army Research Institute of Environmental Medicine

Natick, Massachusetts

TECHNICAL REPORT NO. T21-06
DATE April 2021

**ACCURACY OF THE HEAT STRAIN DECISION AID (HSDA) DURING
RANGER TRAINING BRIGADE'S ROAD MARCH EXERCISE**

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**United States Army
Medical Research & Development Command**

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USARIEM TECHNICAL REPORT T21-06

**ACCURACY OF THE HEAT STRAIN DECISION AID (HSDA) DURING
RANGER TRAINING BRIGADE'S ROAD MARCH EXERCISE**

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April 2021

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REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 06-04-2021		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To) 2007-2021		
4. TITLE AND SUBTITLE Accuracy of the Heat Strain Decision Aid (HSDA) During Ranger Training Brigade's Road March Exercise				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) William J. Tharion, Miyo Yokota, Anthony J. Karis, and Adam W. Potter				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER H		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Biophysics and Biomedical Modeling Division U.S. Army Research Institute of Environmental Medicine Building 42 - 10 General Greene Ave Natick, MA 01760				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Development Command, Fort Detrick, MD 21702				10. SPONSOR/MONITOR'S ACRONYM(S)		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) T21-06		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT This research assessed the accuracy of a USARIEM mission planning software, the Heat Strain Decision Aid (HSDA), for predicting thermal strain associated with US Army Ranger Training Brigade (RTB) road marches during Spring, Summer, and Winter classes. Data was collected from 65 Ranger students (Spring: n = 15, Summer: n = 20, Winter: n = 30) and compared to HSDA predictions. Five methods were used to assess the validity of HSDA to predict core body temperature (Tcore); Bias, mean absolute error (MAE), root mean square deviation (RMSD), limits of agreement (LoA) and a non-parametric comparison similar to a Bland-Altman analysis. Calculated Bias, MAE, and RMSD between predicted and actual Tcore showed a calculated Bias of -0.02, MAE of 0.40, and RMSD of 0.45 °C for the three classes combined. These analyses showed HSDA predictions was able to meet many of the accuracy criteria used to determine acceptability.						
15. SUBJECT TERMS thermal strain; biophysics; predictive modeling; thermoregulation; model validation; ranger training brigade						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Unclassified	18. NUMBER OF PAGES 40	19a. NAME OF RESPONSIBLE PERSON Adam W. Potter	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 508-206-2357	

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ACKNOWLEDGMENTS

We would like to thank Dr. Mark Buller, Dr. William Santee, Steve Mullen, Laurie Blanchard, SGT Andrew Coggins, Dr. Kenneth Pitts, and SGT Scott Harris for their assistance during data collection, Mitesh Amin and Dr. Mark Buller for graphical user interface enhancements to the Heat Strain Decision Aid computer application, and Tejash Patel and Nancy Hebert for her assistance with data reduction. We thank Dr. Scott Montain for his helpful edits and review of this report. We are indebted to Fred Dupont for his invaluable assistance with this study. Great appreciation is extended to the Ranger Training Brigade (RTB) leadership for inviting us to Ft. Benning, GA to collect this valuable information during the actual RTB training course. Specifically, we would like to thank COL Gregory Hager, COL Douglas Flohr, MAJ Robert Proctor, MAJ Robert Boone, LTC Sean Mullen, MAJ Dwight Griffith, CPT John Walsh, CPT Paul Cluverius, SGM Erik Wilson, MAJ Thomas Sager, CPT Dustin Martin, and SGT Chris Duncan. Finally, we thank all the students who volunteered for this study, while they were undergoing the physically and mentally challenging events of the U.S. Army Ranger Training Course.

EXECUTIVE SUMMARY

The U.S. Army's Ranger School oversees a physically and mentally challenging 62-day course of training that teaches small unit dismounted combat skills. During the first week of training, students must successfully perform a number of tasks to remain in the course. One event is the timed road march; usually 12 miles in length. The Ranger Training Brigade (RTB) wants to ensure that this event and all training are stressful and challenging but at the same time are conducted safely. The purpose of the present study was to determine if the current USARIEM Heat Strain Decision Aid (HSDA) is valid for use by the RTB during this course. Test volunteers were students taking part in the road march conducted during the first week of Ranger School.

Volunteers wore the Hidalgo EQ-01 Equivital™ (Equivital, Swavesey, Cambridge, UK) physiological monitoring system that recorded core temperature [T_{core}] (using an ingestible thermometer pill) and heart rate to assess thermal strain during the march. Data from global positioning systems (GPS) were used to calculate location on the course, pace, and arrival time at various mile marks. The HSDA was used to predict T_{core} during the march for volunteers with usable data sets in Spring ($n = 15$), Summer ($n = 20$), and Winter ($n = 30$) classes. Comparisons between predicted T_{core} and observed T_{core} values were made using calculated Bias, Mean Absolute Error (MAE), and Root Mean Square Deviation (RMSD) and Limits of Agreement (LoA). Variability of measurements was also assessed by a Non-Parametric Comparison method. Predicted T_{core} values were compared to a selected acceptable level of error, (0.50 °C).

Air temperature (°C) and relative humidity (%) measurements during the marches were: Spring: 15.5°C, 92.6%; Summer: 23.6°C, 99.9%, and Winter: 11.1°C, 83.7%. Spring and Winter air temperatures were outside the valid range of the HSDA (20°C to 50°C) but were used anyways because of its potential as a useful tool for the RTB. The HSDA was developed as a tool for preventing heat injuries during training in warm and hot environments. Estimated Wet Bulb Globe Temperature (WBGT) index was less than the lowest heat category for each of these marches, but students generated a large amount of metabolic heat. Mean observed T_{core} for Spring, Summer, and Winter marches were $37.94 \pm 0.41^{\circ}\text{C}$, $38.43 \pm 0.63^{\circ}\text{C}$, and $37.96 \pm 0.36^{\circ}\text{C}$.

Results showed that HSDA was within the statistical criterion for all classes with some variations observed with individual predictions. Use of the HSDA allows for safe planning of training since most of the errors over-predict what T_{core} would be for a given set of conditions. Modifications to HSDA, and other thermoregulatory models that incorporate individual Soldier characteristics are being evaluated, and may provide more accurate predictions.

INTRODUCTION

The U.S. Army's Ranger School, headquartered at the Ranger Training Brigade (RTB), Ft. Benning, Georgia, oversee a physically and mentally challenging 62-day course of training that teaches small unit dismounted combat skills (<https://www.benning.army.mil/Infantry/ARTB/Student-Information/>: accessed 11 December 2020). Training starts with the physically demanding Rapid Assessment Phase (RAP) (Table 1). The RAP is designed to identify individuals who are capable of completing Ranger School training. Physical demands during RAP are high (i.e., in excess of 5000 kcal/day), and are similar to the most strenuous phase of Ranger School training, the Mountain Phase (1).

Table 1. Typical schedule of activities on Days 1 to 4 during Ft. Benning Rapid Assessment Phase (RAP)

Mon	Tues	Wed	Thur
Day 1	Day 2	Day 3	Day 4
1) In-Process Medical Screen 2) 5 Mile Run 3) Orientation Briefs 5) Combat Water Survival Assessment 6) Dead Reckoning Training 7) Battalion Layout Brief 8) Brigade In-Process	1) Land Navigation 2) Weapons Skills 3) Common Soldiers Tasks 4) Confidence Course	1) Land Navigation (Re-Take) 2) Common Soldier Skills 3) Weapons Skills 4) 12 Mile Foot March Preparation	1) 12 Mile Foot March 2) Hand to Hand Combat 3) Ranger Task Call for Fire Training

Students need to successfully complete all elements of the RAP to remain in Ranger School. For example, the 5-mile run, held on Day 1 of RAP week, must be performed at an eight minute/mile pace. The road march, held on Day 4 of RAP, is performed in standard uniform while carrying a rifle and a 15.8 kg rucksack (~35 lbs: note: load carried increased from time of this study to 47 lbs as of June 2018), and completed under a set time limit. For most classes, a 12-mile road march must be completed in less than 3 hours and 15 minutes. Unlike the 5-mile run event, which is run in formation at a specified pace, students pace themselves during the road march. From a practical standpoint, Ranger students need to complete the road march without rest breaks.

Hot weather can adversely impact the physical performance and well-being of Ranger students (2-4). Furthermore, the RTB Command recognizes that heat stress during summer months can add significant physiological strain. However, the RTB currently lacks a systematic and scientifically-valid method of making weather based adjustments to physical performance standards for the various RAP week events. To help address this need, the RTB requested that a computerized mission planning tool be developed and validated that would provide the RTB a more systematic way of adjusting training parameters.

The RTB initially wanted USARIEM to provide an application (App) enabling systematic adjustments to the road march (e.g., change pace, load, length of march, time of day, and clothing worn) to achieve a consistent thermal strain from winter to summer. The use of an App to allow for adjustments in the required pace or other parameters to manage thermal strain could provide for the stressful but safe training of Ranger students.

The specific focus of this research was to assess the accuracy of a USARIEM mission planning software product to predict the thermal strain associated with the RTB road march. The current Heat Strain Decision Aid (HSDA), a USARIEM thermoregulatory model (5-7) with a user-friendly computer interface was chosen for this RTB application. This report documents the thermal strain between RTB training classes and the validity of this model's predictions during the RTB's road march. Data from this study was previously published comparing the physiological and performance differences between classes (8).

SCIENTIFIC BACKGROUND

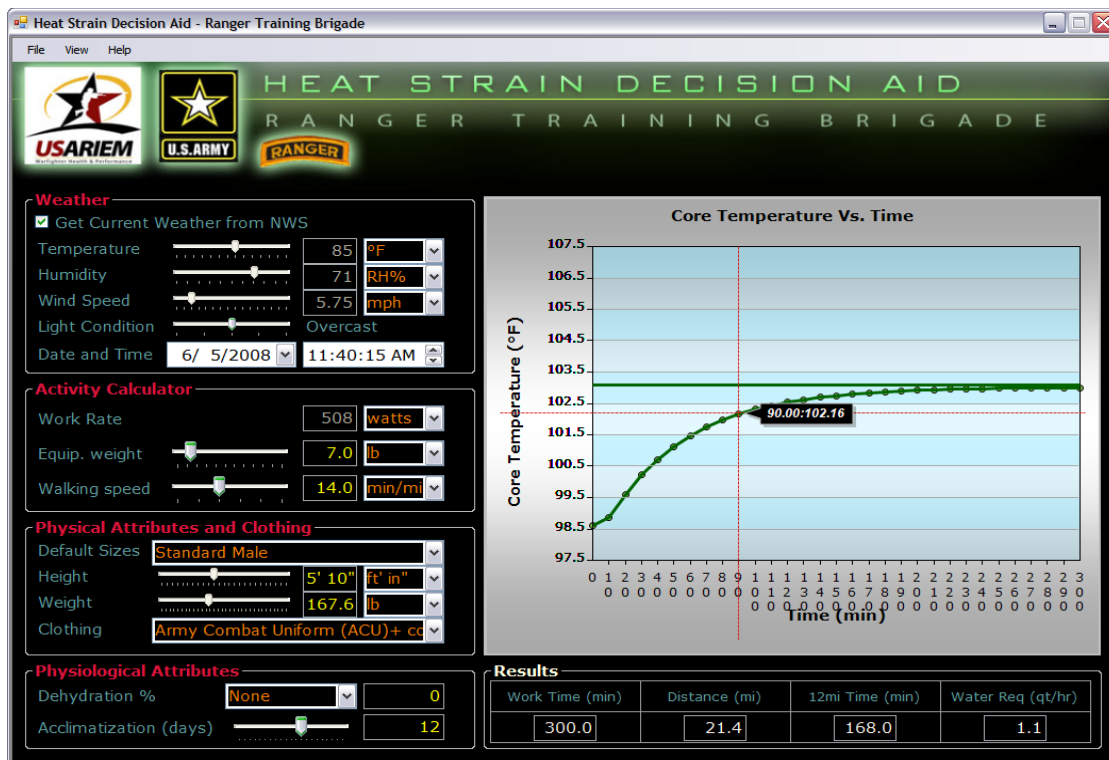
The main Department of Defense reference for heat injury prevention is Army Technical Bulletin (TB) 507 (TB-MED 507) / Heat Stress Control and Heat Casualty Management (2). This document provides guidance on physical exercise in various heat exposure conditions. The HSDA (5, 7, 9), was used to expand the utility of the Wet Bulb Globe Temperature (WBGT) based guidance in TB-MED 507 including Tables 3-1 and 3-3 that provide fluid replacement recommendations, work/rest guidelines, continuous work duration recommendations, and adjustments for a chemical, biological, radiological, nuclear, and explosive (CBRNE) environment and body armor (2). A specific guide for RTB students is the Ranger and Airborne School Students' Heat Acclimation Guide (10). Historically, USARIEM has played a major role in providing safety guidance to the RTB (3, 11, 12).

Documents such as TB-MED 507 (2) are frequently used by Soldiers to reduce the risk of heat illness or injury during basic training, while conducting field exercises, and in theatre. Because of the high variability in the human response to heat stress, guidelines based on the WBGT index found in TB-MED 507 are conservative in nature to protect the majority of the population. The Warfighting community has increasingly called for computerized biomedical models to predict thermal strain associated with various missions. For example, a variant of the HSDA was transitioned to the Joint Warning and Reporting Network (JWARN) program for prediction of the thermal strain and water requirements associated with chemical-biological missions.

The current version of HSDA was selected and evaluated to ensure it had a high probability of meeting the needs of the RTB. The HSDA-RTB (Figure 1) uses inputs of weather, physical activity levels, clothing, acclimatization, and hydration status to generate outputs that include core temperature (T_{core}), recommended water intake, work/rest cycles, and the predicted maximum endurance times for a single sustained bout of exercise. The use of HSDA can show how heat strain varies as weather

changes. It can also show how reductions in walking speed, load carried, and length of the march can reduce thermal strain. The HSDA incorporates physiological and biophysical elements, but it is primarily an empirical model designed to be used for populations, not individuals. The details of the HSDA model have been described elsewhere (7, 12).

Figure 1. Graphical user interface (GUI) for Heat Strain Decision Aid (HSDA)



The left side of the HSDA-RTB graphical user interface (GUI) screen has a number of slider bars or drop-down menus where information can be entered. Once information is entered, a graphical representation of T_{core} over time is displayed on the right side of the screen. If the curved line is green as shown in this figure, the risk of heat illness is low. The line will turn red if the risk is high. The critical limit of 103.1 °F or 39.5 °C, when most individuals will experience significant thermal strain (in compensable conditions) (13, 14), is represented by the green horizontal line. This limit can be adjusted based on different levels of risk assumed. Although the majority of individuals will feel the effects of heat at T_{core} of 39.5°C, human physiology varies and this is not an absolute limit. Many individuals will experience the effects of thermal strain, including some signs and symptoms of heat injury, at lower T_{core} values, while other individuals may still be able to function satisfactorily at 39.5°C and above. The “Results” block below the T_{core} over time on the graph above shows recommended continuous work times, distance covered in miles, road march time for 12 miles based on the walking speed entered, and water intake requirements.

The purpose of this study was to determine if HSDA-RTB, depicted in Figure 1, is valid for use in field environments by the RTB using one RTB-RAP week event, the 12-mile road march. Three classes, Spring, Summer, and Winter were assessed to see if the use of the model could be applied over different classes.

METHODS

This report describes model performance using a standard set of methods for evaluating HSDA. Use of these standard set of analytical tools allows a comparison between models for a specific intended use. Because various models make various assumptions some analytical methods may not be entirely appropriate. For example, HSDA was originally developed with the intended use of predicting a steady-state work rate while walking or running. That did not occur within this study nor would it be the case if adopted by the RTB, as Soldiers self-paced themselves and therefore pace was varied throughout the course. However, it was a model that was considered for use by the RTB for training events with varying work rates, and as such it was evaluated for this purpose even though some assumptions may not have been met. Furthermore, if it was deemed valid it would be a model that would be simple to use with a minimum number of input variables. Multiple methods for evaluation were chosen to ensure a model didn't just perform well with a single specific evaluation method. This evaluation approach ensured a more complete understanding of model performance by using multiple methods to confirm or deny the model's accuracy in predicting T_{core} .

VOLUNTEERS

Eighty-three RTB students (Spring Class: $n = 28$, Summer Class: $n = 25$, Winter Class: $n = 30$) were studied. For measures, like road march times or weight carried the complete data set was used. However, due to incomplete data sets, data analysis for model analysis was performed on a smaller subset of 65 students (Spring: $n = 15$, Summer: $n = 20$, Winter: $n = 30$). Incomplete data was most often due to one or more sensors not recording for the entire measurement period.

Volunteers were briefed on the purpose, risks, and benefits of the study and gave their written informed consent prior to study participation. This study was approved by the Scientific and Human Use Review Committees at the U.S. Army Research Institute of Environmental Medicine and the U.S. Army Medical Research and Development Command.

PROCEDURES

Volunteers were fitted with the Hidalgo EQ-01 Equivital™ system (Equivital, Swavesey, Cambridge, UK, www.equivital.co.uk) the day prior to the march. The EQ-01 Equivital™ system measures heart rate, respiration rate, body motion, body position, and skin temperature (T_{skin}).

Volunteers were surveyed about demographic information and had body weight, height, and skin circumference measured. Percent body fat was estimated from skin circumferences measured according to procedures outlined in AR 600-9 (15). Each measurement was repeated three times by the same trained individual.

Ingestible thermometer pills (MiniMitter, Inc., Bend, OR) were used to assess T_{core} . Thermometer pills were administered at the same time as volunteers were fitted with the EQ-01 Equivital™ units, approximately 18 hours before the road march. Ingesting the pills at this time allowed the pill to pass into the intestinal tract, thereby minimizing the effect of ingested water on T_{core} (16, 17). Thermometer pill information was transmitted to a sensor electronics module (SEM) receiver located in the EQ-01 Equivital™ harness system.

Core temperature was checked just prior to the march to ensure that the thermometer pill was functioning. While not ideal, four volunteers (three from the summer class and one from the spring class) had to be administered a new pill approximately one to two hours before the march. However, only one volunteer from the summer class that was administered a new pill was included in the analyses. Core temperatures in these individuals were omitted if rapid decreases in T_{core} were observed, as the ingestion of cool water can affect T_{core} readings (16, 17). At this time, one to two hours before the road march, the EQ-01 Equivital™ system, was donned and participants were given global positioning system (GPS) monitors (Fortrex 101; Garmin, Olathe, KS) to wear on their wrists. The GPS devices were used to track the time and distance covered on the course and to determine the pace of the march. Total weight of the RTB participant (i.e., body weight plus all clothing and equipment weight carried during the march) was obtained just prior to the road march. All canteen-hydration systems (filled) were weighed separately to obtain a measure of the amount of fluid participants would carry and potentially consume. Water was also available on the route to refill canteens. Participants proceeded with the road march under the direction of the RTB cadre. The Spring and Winter marches began at 0400, while the Summer march began at 0300 due to warmer temperatures and high humidity. The Summer march was shortened from 12 miles to 8 miles by the RTB leadership to reduce the risk of heat illness.

METEOROLOGICAL CONDITIONS

Air temperature (T_a), percent of relative humidity (RH), solar radiation (T_{mr}), and wind speed (V_{ws}) were measured along the road-march course using a combination of three different data collection instruments; the Campbell Scientific, Inc. (Logan, UT) CR-10x weather station, the ADA Weather Pod (ADA Technologies Inc.; Littleton Colorado), and the HOBO® Pro v2 T_a /RH logger (Onset Computer Corporation; Pocasset MA).

DATA ANALYSIS

Heat Strain Decision Aid (HSDA)

The HSDA was used to predict T_{core} values from the beginning to the end of the road march for each participant, even though it is better suited for use with populations than individuals. The HSDA predicts up to a maximum of 300 minutes, a period of time that was well-suited to cover the duration of the road march. The slowest participant in the study took 3:30:00 (200 minutes) to complete the march.

The following participant information was entered into the model: initial T_{core} ($^{\circ}\text{C}$) i.e., the average T_{core} for the 15 minutes just prior to the start of the march, days of heat acclimatization, dehydration (%), body mass, height, time averaged velocity and grade, load carried, and clothing coefficient values ($clo = 1.08$, $i_m/clo = 0.47$, $clo_y = -0.24$, and $i_m/clo_y = 0.35$) for the Advanced Combat Uniform (ACU). The clo is the thermal insulation of the clothing ($1\ clo = 0.155\ \text{m}^2\text{K/W}$); i_m is a non-dimensional measure of water vapor resistance of the clothing, and i_m/clo is a characterization term to describe the ensemble's evaporative potential (18-21). The clo_y and i_m/clo_y are correction factors for the effect of wind on clothing properties (22, 23). See these references (18-23) for a more complete understanding of clo and i_m since this is beyond the scope of this report. Since days of heat acclimatization were not known, a value of 20 days was used. Students were advised by their instructors to be fully hydrated and to have full canteens for the road march, and they were assumed to be fully hydrated. The work rate was obtained using the Pandolf Equation (24) shown below as:

$$M = 1.5BM + 2.0(BM + L) \left(\frac{L}{BM} \right)^2 + \eta(BM + L)(1.5V^2 + 0.35VG)$$

where M = metabolic rate (in Watts (W)); BM = participant body mass (kg); L = weight of load carried (kg); V = speed of walking (ms^{-1}); G = grade (%); and η = terrain factor.

Individual inputs were used for all of the predictions. Therefore, energy costs were associated to the individual body size (i.e., body surface area * 58.2W for rest/homeostatic state). Metabolic rate during activity was based on individual pace and calculated via the Pandolf equation (24).

The grade of the course was mostly flat although there were some uphill and downhill sections of approximately 6% grade or less. Due to the limited capability of the HSDA to accommodate multiple inputs for M , a single value for grade, $G = 0\%$ was used. For the terrain factor, walking on a treadmill or paved roads has an $\eta = 1$. For hard packed dirt the terrain factor is $\eta = 1.1$. The course was approximately 1/3 dirt road and 2/3 paved. However, we used $\eta = 1.1$ for the terrain factor to account for the dirt and the uneven surface of the road (25).

Statistical Analyses

Data are reported as means $\pm$ standard deviations except for the variance comparing Bias, mean absolute error (*MAE*), and root mean standard deviation (*RMSD*) and limits of agreement (*LoA*) comparisons which use standard error of the mean to make direct comparison between what was predicted versus what was observed. Ranges are also presented to describe the variability of the data.

Model Validation

Reliability and validity measurements “cannot be interpreted as an all-or-none condition” (26). Five methods were used to assess the validity of HSDA to predict T_{core} ; Bias, *MAE*, *RMSD*, *LoA* and a non-parametric comparison similar to a Bland-Altman (27) analysis. The Bland-Altman analysis assumes that data are independent, and this data is time series data. However, this Non-Parametric Comparison method was used primarily for an illustration purpose to show graphically the presentation of data within acceptable limits of disagreement. Moreover, using multiple, but similar, statistical methods, although potentially redundant, reduces the risk any one method may distort the evaluation.

The Bias is used to indicate whether the model over- or under-predicted T_{core} and is calculated as the mean difference between predictions and measurements. A direct measurement criterion for the acceptable range of accuracy was a Bias of $\pm 0.27^{\circ}\text{C}$ (28). The *MAE* is the average of the absolute prediction errors and is calculated with the formula:

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

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

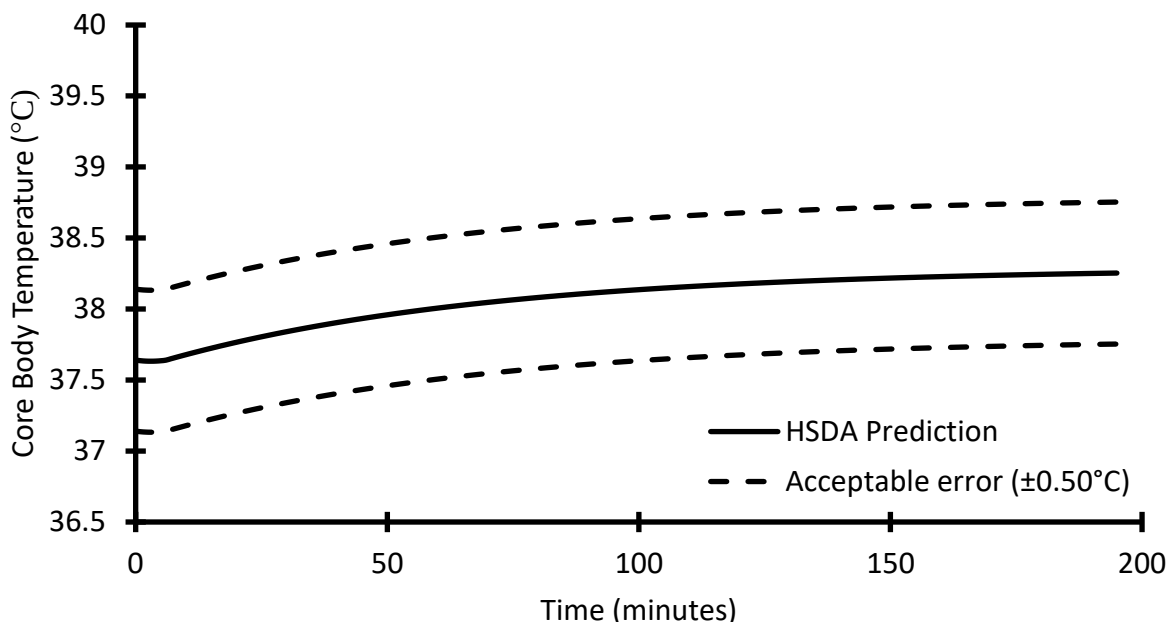
Using the *RMSD* applies a greater penalty to larger errors and is calculated with the formula:

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

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. Use of *RMSD*, also known as root mean square error (*RMSE*) represents the mean absolute difference between predicted values and measured values (29). One advantage of *RMSD* is that the value calculated is in the same units as the original data, i.e., degrees Celsius. Overall *RMSD* was compared to a variation of 0.50°C , the criteria used by Gunga et al. (30).

The area between the HSDA prediction line and the band (0.50°C) lines shown in Figure 2 would be acceptable model performance. If the model's prediction falls above or below these band lines (the dashed lines) then the model would be determined to be inaccurate. Obviously, at the higher temperatures accurate model prediction is more critical.

Figure 2. Example of 0.50°C acceptable error bands surrounding Heat Strain Decision Aid (HSDA) prediction curve



Model accuracy was also assessed by the Non-Parametric Comparison technique. This technique plots the differences between predicted and measured T_{core} against the measured T_{core} . The Non-Parametric Comparison analysis also shows the percentage of predicted values that fall within or outside the criterion level. Reference values $\pm 0.50^{\circ}\text{C}$ were used on the plots to show deviations in measures. The proportion of differences that fell outside the reference values of $\pm 0.50^{\circ}\text{C}$ were tabulated.

RESULTS

Table 2 shows the mean environmental conditions by class. These conditions were consistent during the road march for each class. Table 3 shows the mean, fastest, and slowest times for the road march by class for those participating in this study. The amount of weight carried differed between classes is shown in Table 4. There were significant differences ($p < 0.001$) between classes in total weight, water weight, and non-water weight carried. Participants in the Spring class carried significantly more total weight and more non-water weight than the Summer or Winter classes ($p < 0.001$). The Spring and Summer classes carried more water weight than the Winter class.

Table 2. Mean environmental conditions by class

Class	Air Temperature (°C)	Relative Humidity (%)	Wind Speed (m/s)	Solar Radiation (W/m ²)
Spring	15.5	92.6	0.21	0
Summer	23.6	99.9	0.48	0
Winter	-11.1	83.7	0.08	0

Table 3. Road march times by class

Class/Distance		<i>n</i>	Mean Time	Fastest	Slowest
Spring	12-Mile	26	3:07:45 ± 6:06	2:54:16	3:19:49
Summer	8-Mile	24	2:00:18 ± 7:43	1:38:09	2:10:15
Winter	12-Mile	29	3:03:07 ± 12:06	2:29:30	3:20:00

Table 4. Load weight (kg) carried by class

Class		<i>n</i>	Total Weight Carried (kg)	Water Weight Carried (kg)	Non-Water Weight Carried (kg)
Spring	12-Mile	28	34.1 ± 1.9 ^b	8.0 ± 0.8 ^b	26.0 ± 1.6 ^b
Summer	8-Mile	20	31.6 ± 1.2 ^a	7.8 ± 0.8 ^b	23.8 ± 1.1 ^a
Winter	12-Mile	30	30.8 ± 1.6 ^a	6.5 ± 2.1 ^a	24.3 ± 1.7 ^a

Within a column, values with different letters are significantly different from one another using Least Significant Differences post hoc test at $p < 0.05$.

Metabolic heat production (M) is a function of pace and load. Table 5 shows the variation in M for the different classes. No significant difference in metabolic rates existed between classes ($p = 0.18$).

Table 5. Calculated metabolic rates using Pandolf equation

Class Season	<i>n</i>	Mean + SD (W)*	Range (W)*
Spring	15	715 ± 47	660 to 819
Summer	20	728 ± 53	632 to 857
Winter	30	742 ± 54	619 to 849

* W = Watts

No significant differences ($p < 0.05$) in body composition, or fitness level as assessed by a self-reported two-mile run time, existed between classes (Table 6). Previous research has shown that a maximum effort two-mile run time can be used to estimate aerobic fitness (31).

Table 6. Student characteristics by class

Class	N	Age (yrs)	Height (cm)	Weight (kg)	Body Fat (%)	2-Mile Run (min:sec)
Spring	28	24.4 $\pm$ 3.9	175.3 $\pm$ 7.4	79.0 $\pm$ 8.4	15.2 $\pm$ 3.2	12:58 $\pm$ 0:50
Summer	25	25.6 $\pm$ 4.7	177.8 $\pm$ 5.3	79.3 $\pm$ 9.6	14.2 $\pm$ 3.6	12:52 $\pm$ 0:52
Winter	30	24.7 $\pm$ 4.2	178.6 $\pm$ 6.4	83.6 $\pm$ 9.0	16.6 $\pm$ 4.0	12:56 $\pm$ 0:58

It is important to consider the variability of the data when evaluating the accuracy of model predictions. Table 7 shows the mean, SD, and range of observed maximum T_{core} values for the three classes. Participant T_{core} values for the entire march were compared to HSDA predictions.

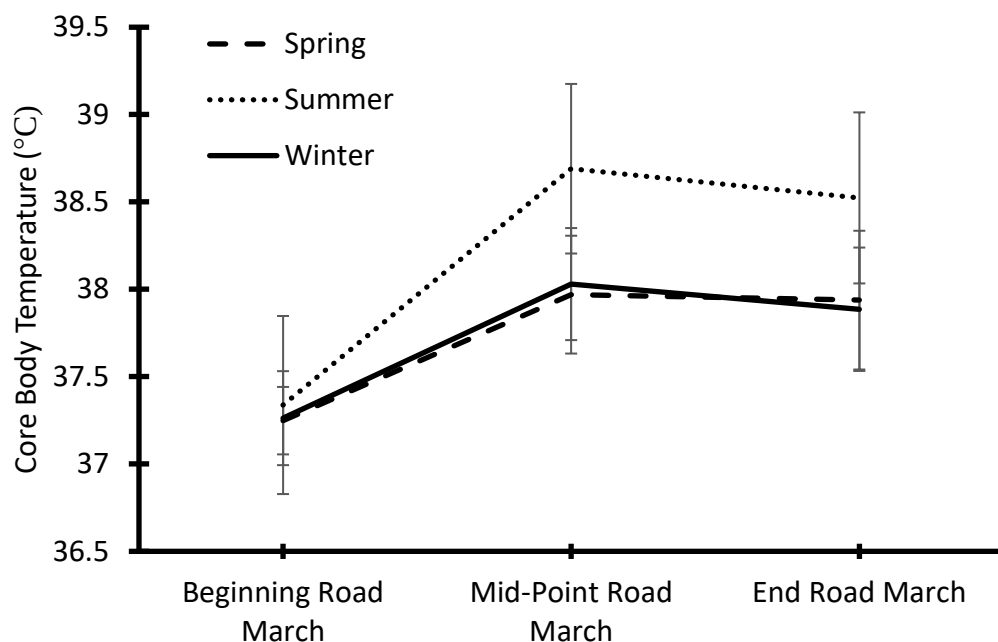
Table 7. Mean and range of observed T_{core} ($^{\circ}\text{C}$) by class

Class Season	n	Mean + SD ($^{\circ}\text{C}$)	Range ($^{\circ}\text{C}$)
Spring	15	37.94 $\pm$ 0.41	36.12 to 39.10
Summer	20	38.43 $\pm$ 0.63	36.03 to 39.55
Winter	30	37.96 $\pm$ 0.36	36.75 to 39.22

DIFFERENCES IN PHYSIOLOGICAL MEASUREMENTS DURING THE MARCH AND ACROSS CLASSES

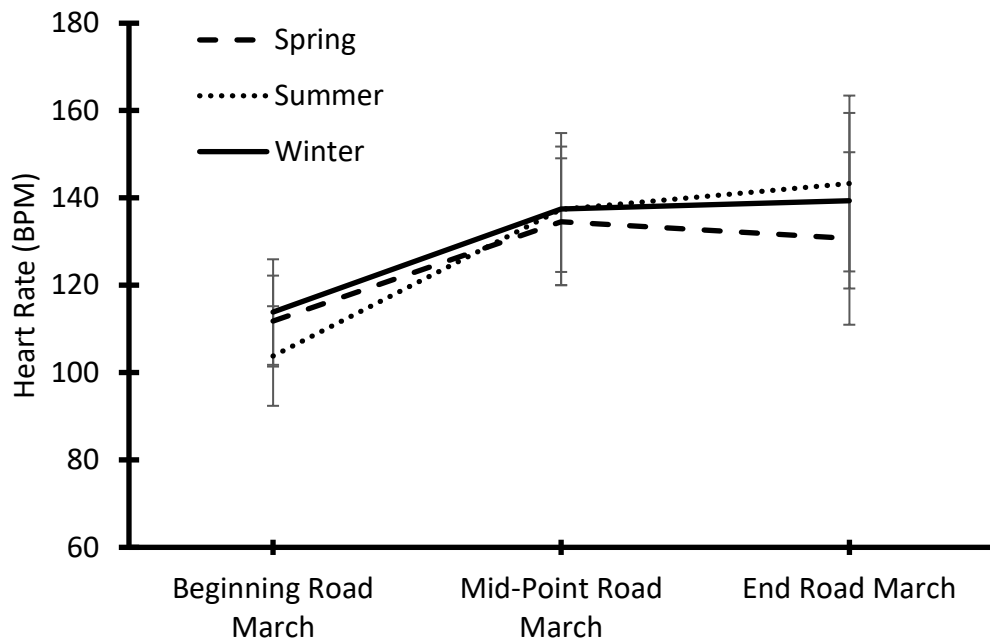
Figure 3 shows a main effect of time ($p < 0.001$), a main effect of class season ($p < 0.001$), and an interaction effect of time by class season ($p < 0.02$) for T_{core} pre-road march, at the mid-point of the road march (6 miles for Spring and Winter classes, 4 miles for Summer class), and at the end of the road march (12 miles for Spring and Winter classes, 8 miles for Summer class). Post hoc testing showed that for the main effect of time, T_{core} at the beginning of road march was significantly lower (37.3 ± 0.3 $^{\circ}\text{C}$; $p < 0.05$) than either the mid-point (38.2 ± 0.4 $^{\circ}\text{C}$) or the end of the road march (38.1 ± 0.4 $^{\circ}\text{C}$). No significant difference existed between the mid-point T_{core} and the end of the road march T_{core} . This suggests most participant's T_{core} values had reached equilibrium by mid-point of road march. The pattern of an increase in T_{core} in the Summer class was greater than either the Winter or Spring classes.

Figure 3. Core temperature by class at the beginning, mid-point, and at the end of the road march ($n = 65$)



Heart rate pre-road march, at the mid-point of the road march, and at the end of the road march showed a significant main effect of time ($p < 0.001$), and an interaction effect of time by class ($p < 0.05$) (Figure 4). Post hoc testing showed that for the main effect of time, the beginning of the road march heart rate was significantly lower (110 ± 11 beats per minute (bpm); $p < 0.05$) than either the mid-point (136 ± 15 bpm) or the end of the road march (138 ± 20 bpm). No significant difference existed between the mid-point heart rate and the end of the road march heart rate. Again, this suggests that most participants reached an equilibrium heart rate by mid-march. The interaction effect (Figure 4) shows that heart rate was lower at the beginning of the road march for the Summer class participants but increased more rapidly than the Spring or Winter class participants. Heart rate for the Spring class participants was noticeably lower at the midpoint and at the end of the road march when compared to the heart rates of the Summer and Winter class participants with estimated mean metabolic rates of $M = 715$ W for Spring, vs. $M = 728$ W for Summer, and $M = 742$ W for Winter classes (Table 5). The total amount of weight carried was greater and road march walking/running speed was slower for the Spring class.

Figure 4. Heart rate by class at the beginning, mid-point, and at the end of the road march ($n = 65$)



COMPARISON OF HEAT STRAIN DECISION AID (HSDA) PREDICTED CORE TEMPERATURE AND MEASURED CORE TEMPERATURE

Evaluation of Heat Strain Decision Aid – Metabolic Cost Input and Seasonal Differences

Figure 5 shows the actual and predicted T_{core} for all classes. Figures 6 to 8 show the same comparisons for each class (Spring, Summer, Winter). These figures show there are errors in predicted T_{core} , especially after the first hour of the road march. Statistical evaluations using Bias, *MAE*, *RMSD*, and the Non-Parametric Comparison technique detailed below will quantify these error levels.

Figure 5. Comparison of predicted (HSDA) to observed (Obs.) core temperature during the road march for all classes averaged together ($n = 65$)

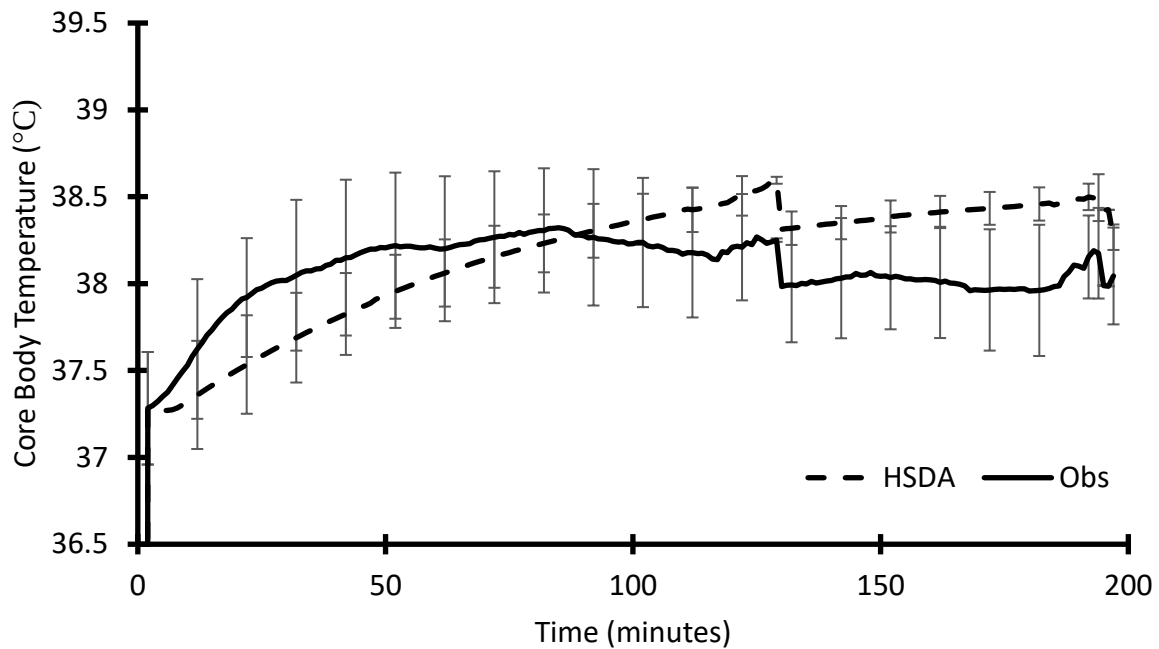


Figure 6. Comparison of predicted (HSDA) to observed (Obs.) core temperature during the road march for the Spring class ($n = 15$)

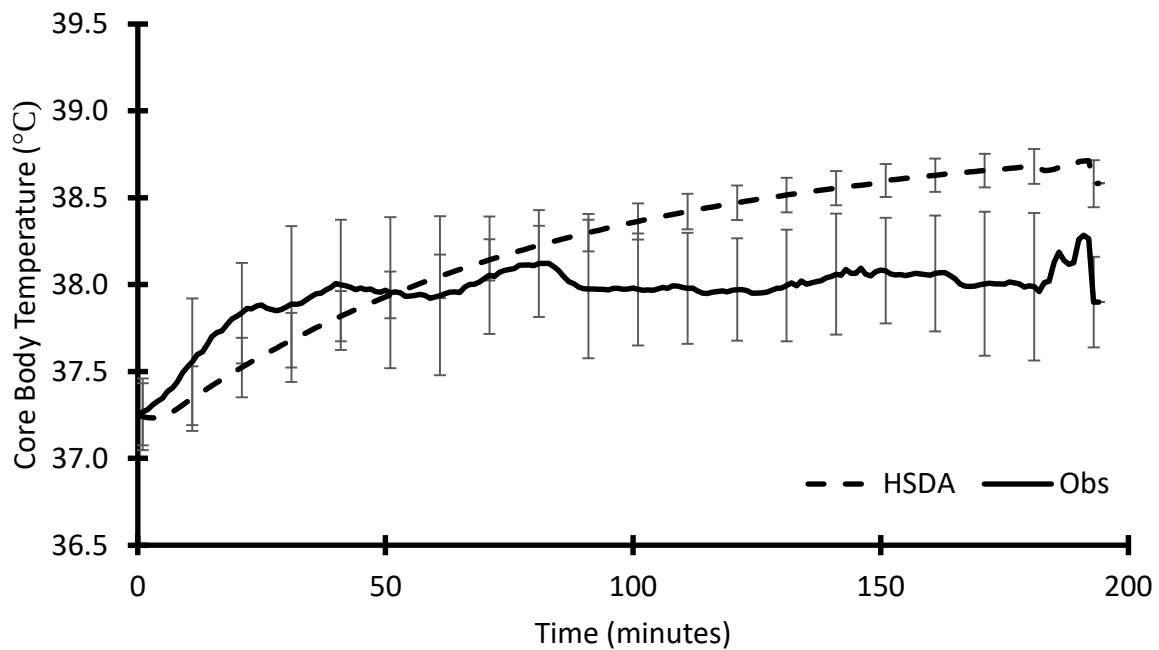


Figure 7. Comparison of predicted (HSDA) to observed (Obs.) core temperature during the road march for the Summer class ($n = 20$)

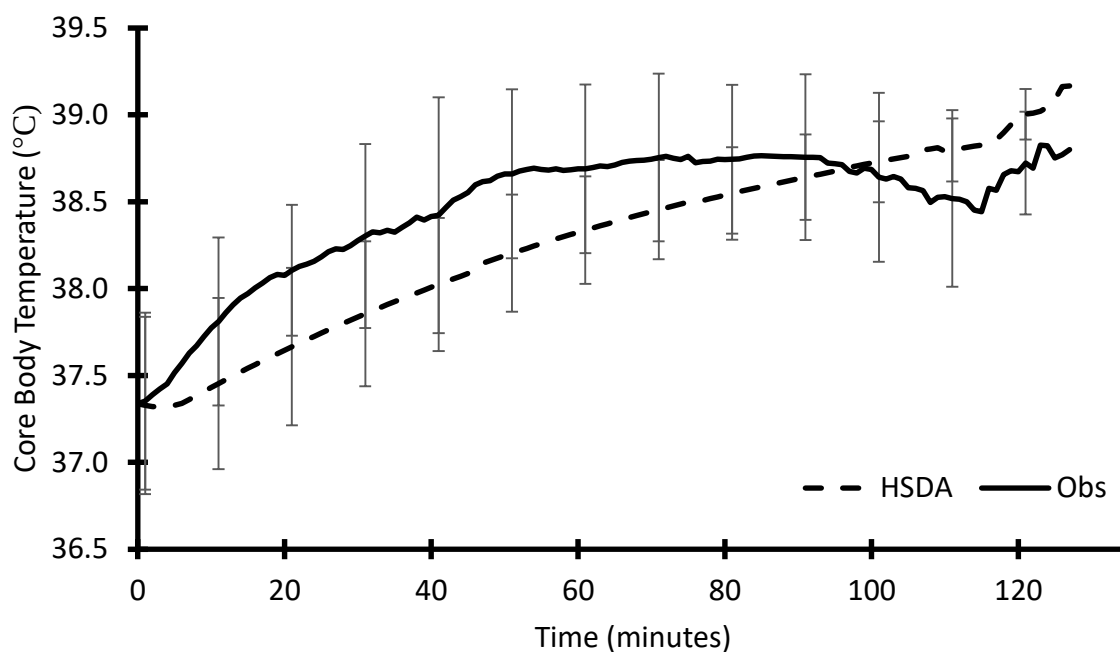
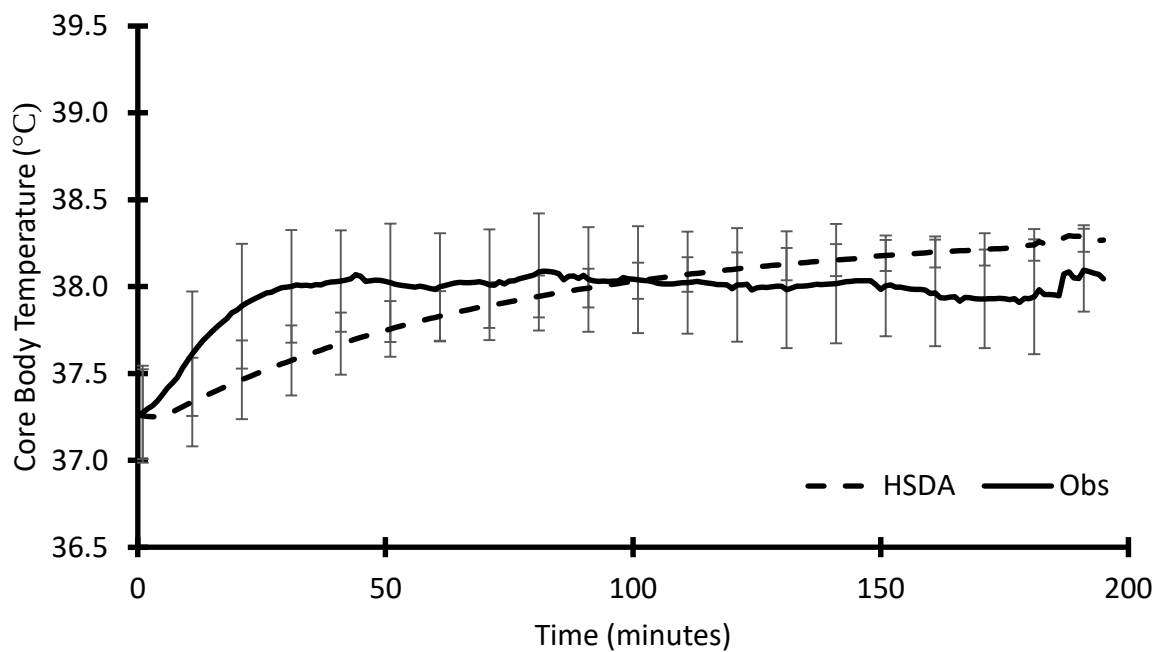


Figure 8. Comparison of predicted (HSDA) to observed (Obs.) core temperature during the road march for the Winter class ($n = 30$)



Bias, Mean Absolute Error (MAE) and Root Mean Square Deviation (RMSD)

Calculated Bias, MAE, and RMSD between predicted and actual T_{core} showed a calculated Bias of -0.02, MAE of 0.40, and RMSD of 0.45 °C for the three classes combined (Table 8). Each class and the aggregate met the Bias criterion of being within ± 0.27 °C. Using the comparison to the observed data SD, each of the classes and the aggregate MAE was within the observed SD. The aggregate of the classes RMSD was within the aggregate of the overall observed SD; while each individual class was within their respective observed SD with the exception of the Spring class being slightly over but less than $1.5 \times SD$ (0.41 to 0.49). For the RMSD, if ± 0.50 °C is used as the acceptable error, each class was within this criterion. However, RMSD does not differentiate for the trend of predictions being more accurate at the beginning of the road march when lower T_{core} are present (less critical time period) compared to near the end of the march when T_{core} are potentially higher (the more critical period).

Table 8. Error estimates of Bias, mean absolute error (MAE), root mean square deviation (RMSD), and Limits of Agreement (LoA) for predicted vs. observed core temperature by class

Class	Observed SD	<i>n</i>	Bias	MAE	RMSD	LoA
Spring	± 0.41	15	-0.22	0.40	0.49 ± 0.3	-1.09 to 0.65
Summer	± 0.63	20	0.22	0.53	0.50 ± 0.3	-0.68 to 1.12
Winter	± 0.36	30	0.05	0.26	0.35 ± 0.2	-0.62 to 0.73
Overall	± 0.47	65	0.02	0.40	0.45 ± 0.3	

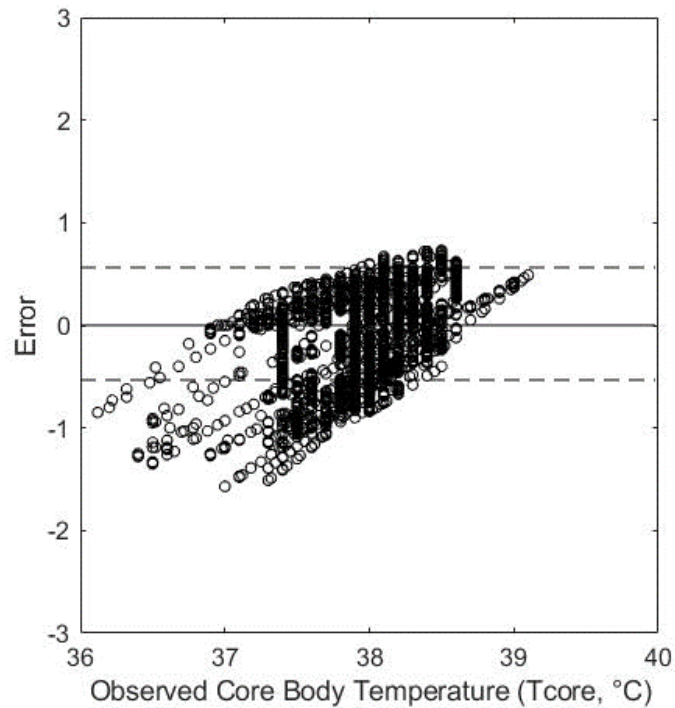
Non-Parametric Comparison

Non-Parametric Comparison method was used to show the deviations between the predicted and actual observed T_{core} . The percentage of T_{core} values for all individuals outside the accepted error criteria of 0.50 °C was 24% of all predicted values. Table 9 shows the percent of the time HSDA under- and over-predicted T_{core} relative to the acceptable error criteria by class. Additionally, the amount of over- and under-predicted values (error) based on the criterion measure of 0.50 °C is shown in Figures 9-11 for each class.

Table 9. Percent under-predicted and over-predicted core temperature (T_{core}) by Heat Strain Decision Aid (HSDA) using error acceptance criterion of 0.50 °C

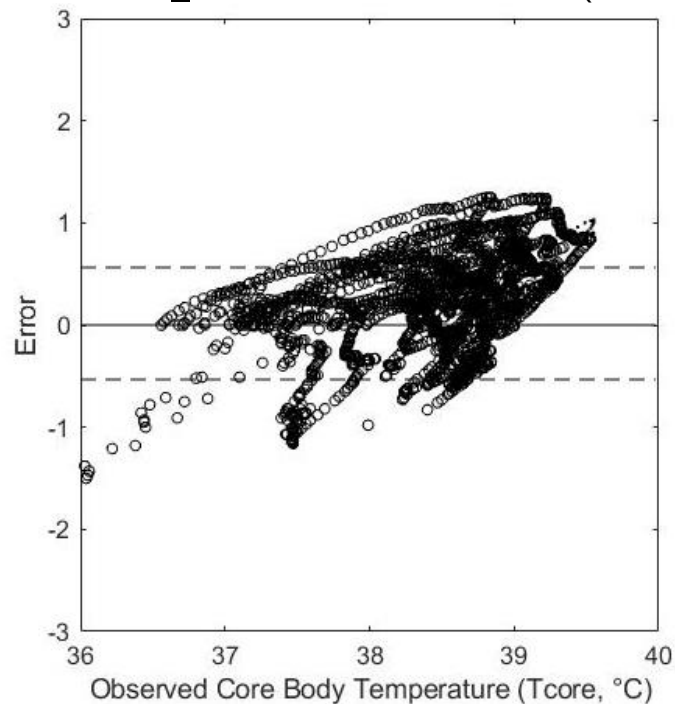
Class	% Under Predictions < -0.50 °C	% Over Predictions > +0.50 °C
Spring	29	3
Summer	5	29
Winter	5	10
Overall	12	12

Figure 9. Comparison of predicted vs. actual core temperature (error) with criterion measure of ± 0.50 °C for Spring class ($n = 15$)



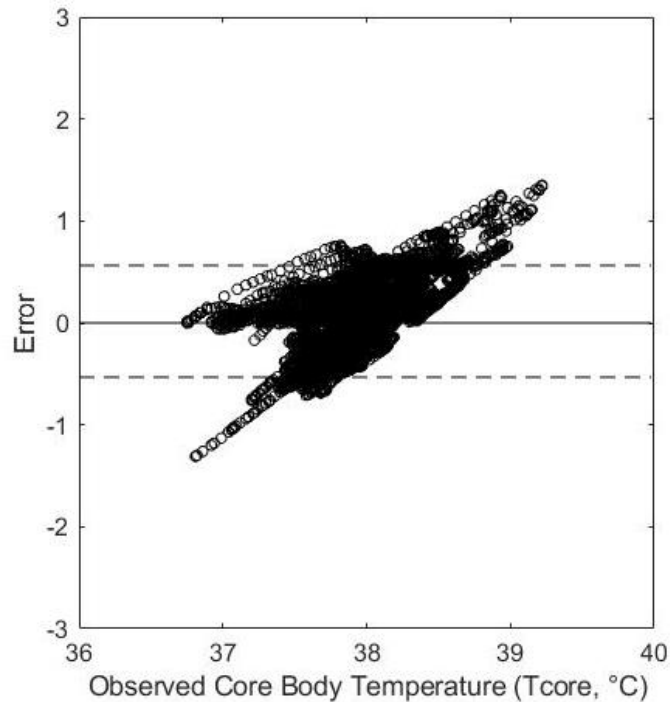
Note: Dashed lines represent the ± 0.50 °C criterion

Figure 10. Comparison of predicted vs. actual core temperature (error) with criterion measure of ± 0.50 °C for Summer class ($n = 20$)



Note: Dashed lines represent the ± 0.50 °C criterion

Figure 11. Comparison of predicted vs. actual core temperature (error) with criterion measure of ± 0.50 °C for Winter class ($n = 30$)



Note: Dashed lines represent the ± 0.50 °C criterion

Individual Variability

The ability of the HSDA to accurately model the observed T_c responses varied by individual. Figures 12-14 show observed (Obs.) and predicted (HSDA) T_{core} for individuals from each class (Spring, Summer, and Winter respectively). As can be seen from these figures, HSDA predicted T_{core} relatively accurately for many individuals but was not in close agreement for all.

Figure 12. Individual predictions (HSDA) (blue line) to observed (Obs) (orange line) core body temperatures for the Spring class ($n = 15$)

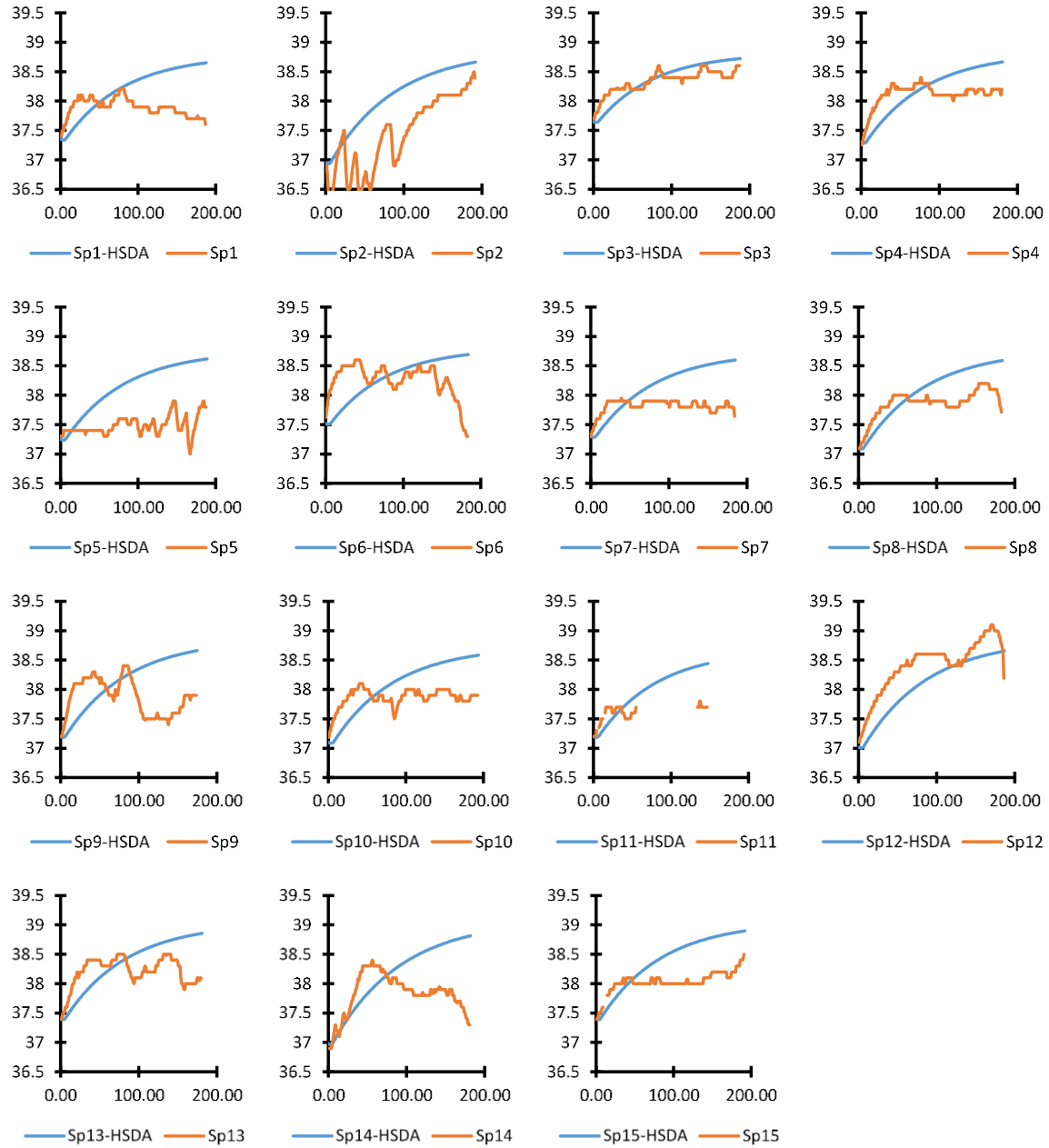


Figure 13. Individual predictions (HSDA) (blue line) to observed (Obs) (orange line) core body temperatures for the Summer class ($n = 20$)

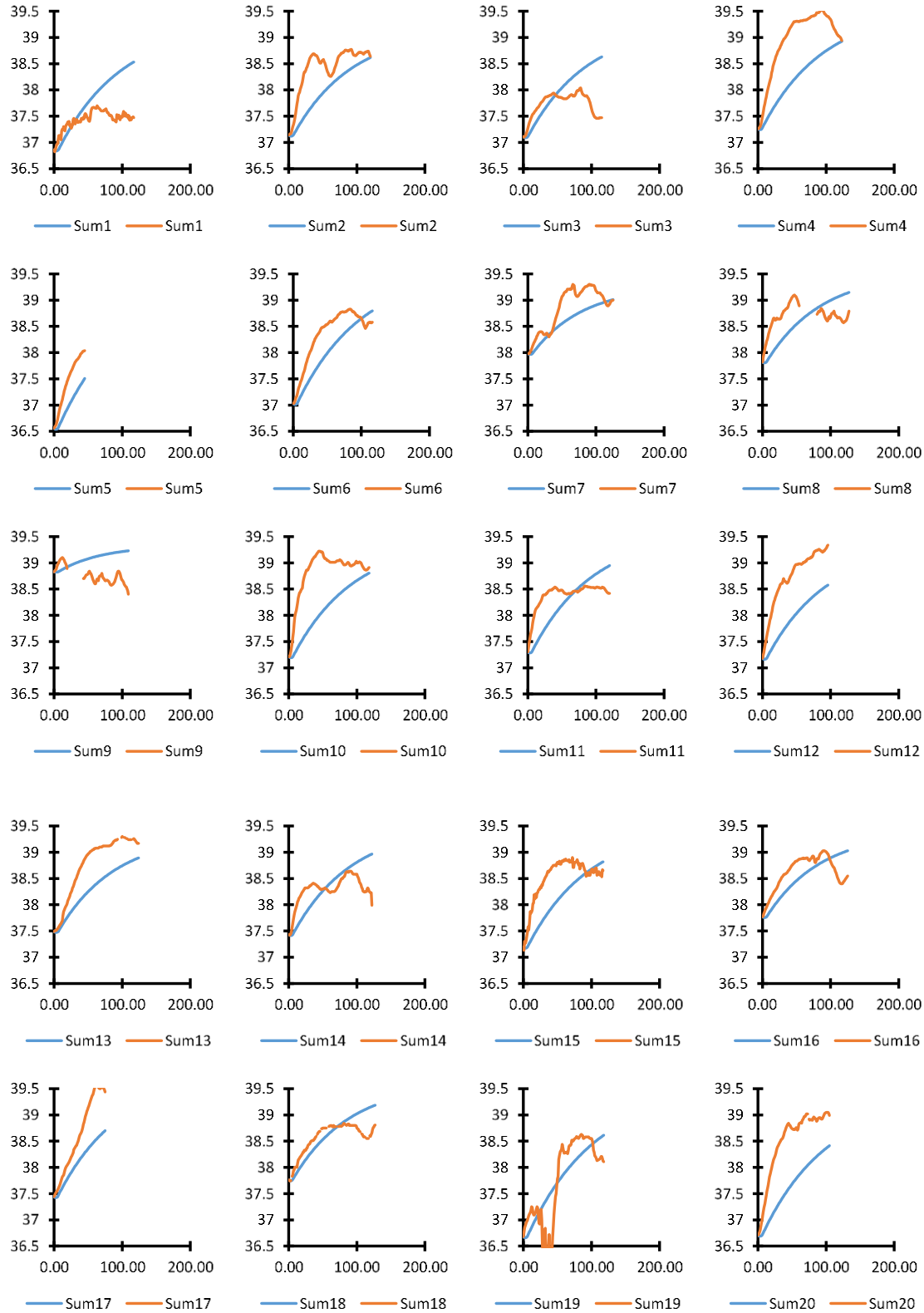


Figure 14a. Individual predictions (HSDA)(blue line) to observed (Obs) (orange line) core body temperatures for the Winter class ($n = 30$) (Volunteers 1-15)

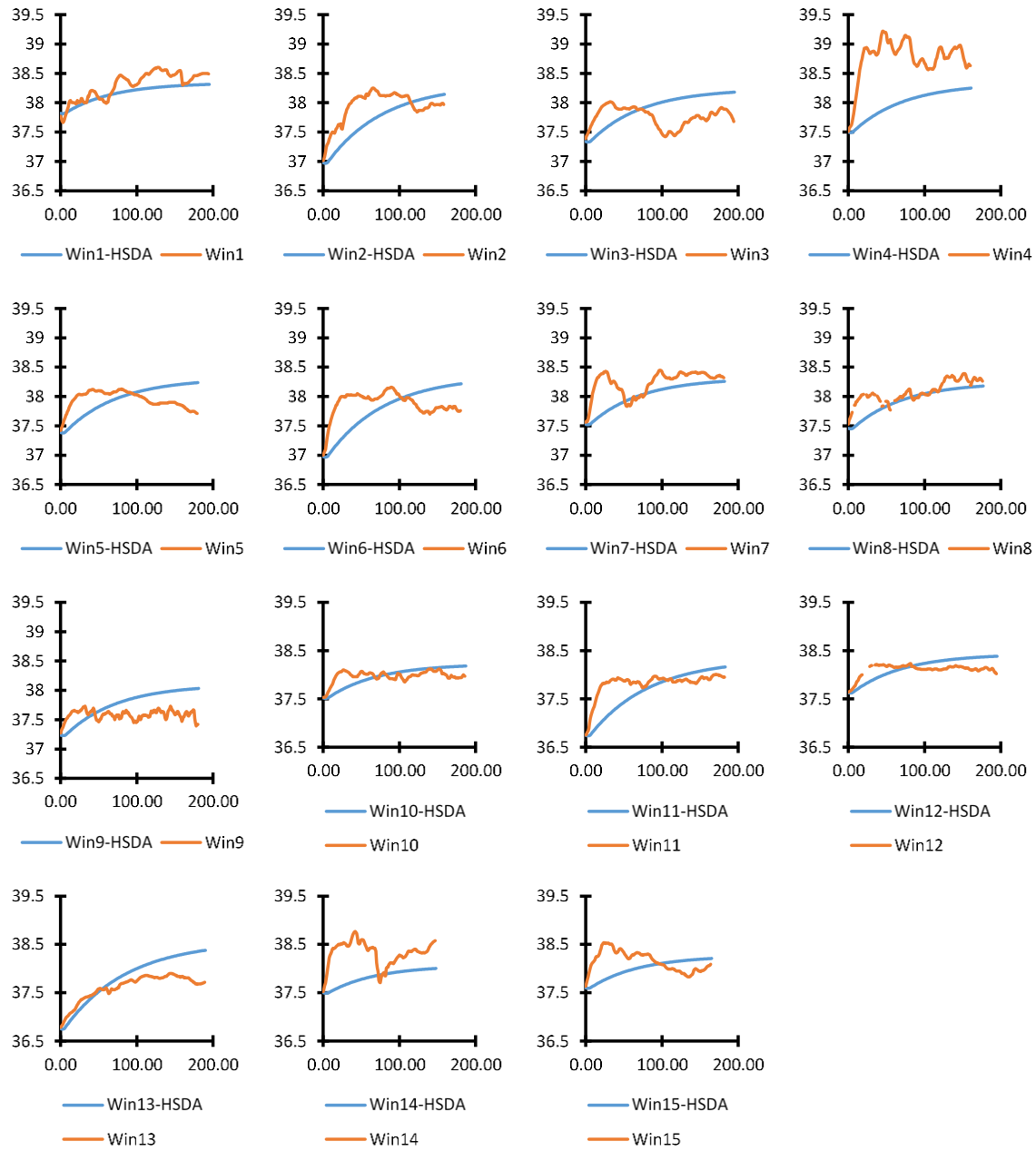
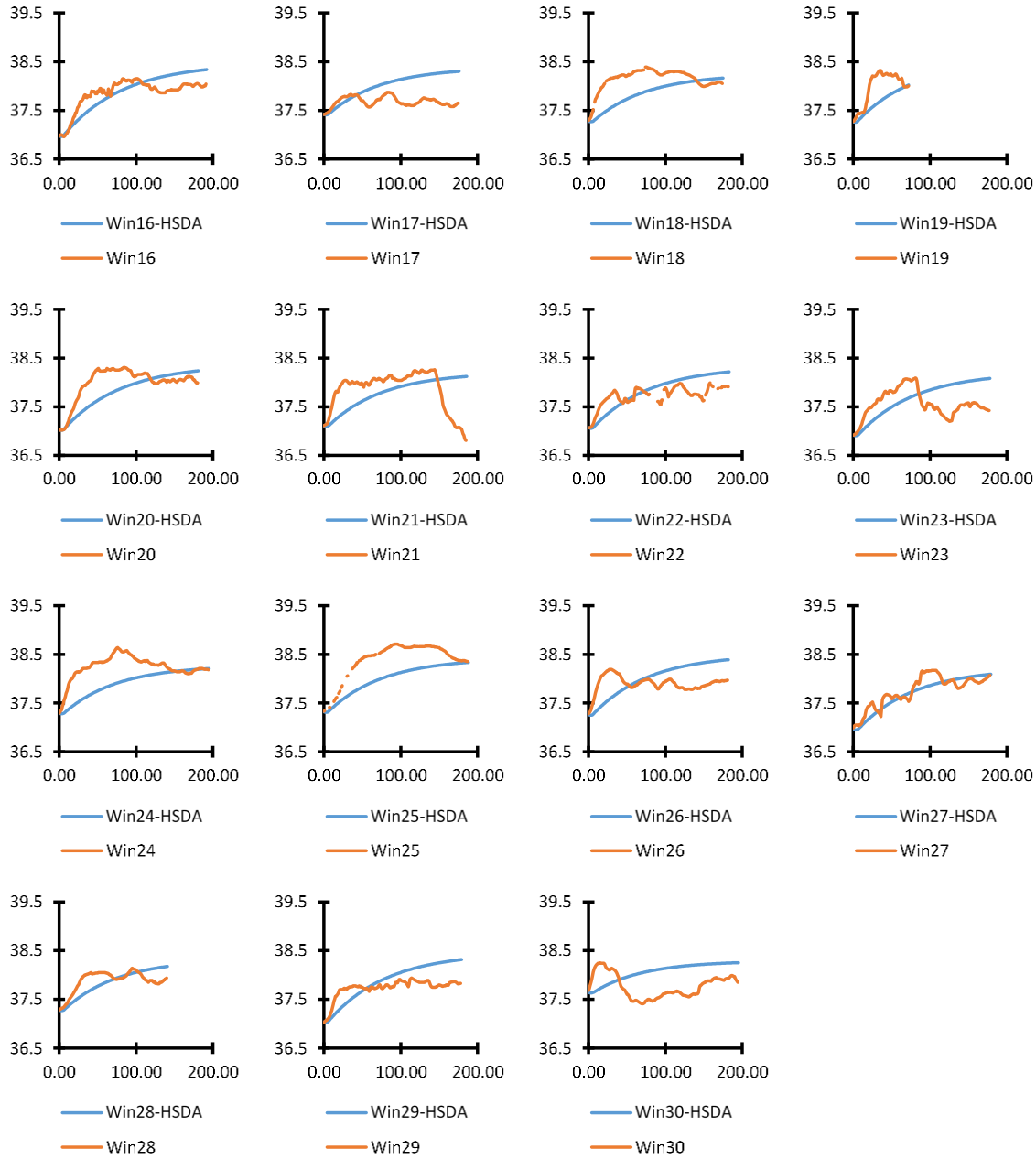


Figure 14b. Individual predictions (HSDA) (blue line) to observed (Obs) (orange line) core body temperatures for the Winter class ($n = 30$) (Volunteers 16-30)



DISCUSSION AND CONCLUSIONS

VALIDATION OF THE HEAT STRAIN DECISION AID (HSDA)

The HSDA model was chosen because it is easy to use and currently helps guide the recommendations made in TB-MED 507 (2). The results of the present study show that averaged inputs to HSDA predictions were within the pre-established statistical criterion. While some of the individual assessments showed inaccuracies over time (Figures 12-14), the model outcomes still fell within acceptable criterion limits and the outcomes were similar to other assessments for both individual (32) and group mean data (33). Some variance was expected, too, as many variables that affect heat production and heat loss were dynamically changing, i.e., pace, terrain grade and ground type, weather, clothing wetness, and hydration, whereas the predictions used time averaged pace, grade and terrain. In addition, variables that don't change over the mission did vary between individuals, or vary over time, such as percent body fat, fitness level and clothing wetness. Both these dynamic and static variables will influence the magnitude and time dynamics of the T_{core} observed during exercise.

Several aspects of the field test pushed the limits of the HSDA. For example, the original model was constructed using warm weather data. It was also created with Soldiers of average aerobic fitness. Therefore, applying it in cool conditions and above average aerobic fitness Soldiers, pushed the limits of the model. Interestingly, the HSDA predictions were most accurate during the Winter class. Yet, in all classes, as time elapsed, actual T_{core} plateaued while the model predicted T_{core} would continue to rise and to levels at end of exercise that were higher than observed. At least a portion of the difference in T_{core} early rise and during later stages of the marches is attributable to the Soldiers choosing a faster early pace (and higher energy expenditure) followed by slower pace, whereas the HSDA assumed the same average pace over the course of the march. The faster early pace would produce more heat and accelerate the T_{core} rise during first hour of exercise and during latter phases some accelerated cooling would be expected due to the relatively cool ambient conditions and wet clothing.

The influence of metabolic rate per se on HSDA prediction accuracy is confounded by the variable pacing. From Table 5 it can be seen that individual metabolic rates ranged from 619 to 857 W over the three classes. However, these ranges are the average metabolic rates by individuals over the whole road march. There was great variability over the pace as noted in Table 2 from the paper by Tharion et al. (8) that used data from this study. From that Table 2 (8) is a list of per mile pace by class and per mile. As can be seen, the students, in general, began the march at a brisk pace, slowed during the middle miles, and increased their pace near the end of the march. To compound the problem regarding model accuracy is that when students were nearing the end of the march many used different strategies. Some knew they would qualify to pass this Ranger School event, and they just maintained their pace. Others knew they were close to qualifying but were uncertain of their status, and as such might work as hard as physically possible to meet the Ranger School qualifying standard. Alternatively, when some individuals knew no matter what they did they would

not pass the standard when they got to a certain point, they effectively gave up and slowed during the final portion of the course. Unlike a civilian road race, where maximum performance is the goal of those running competitively, the goal of the march is to meet the qualifying standard. These students had other tasks to complete in that same training day (See Table 1) and almost two more months of training to undergo after this qualification road march. While the event was self-paced it was not an event where maximum performance of all students was expected. The high metabolic rates chosen by many during the initial minutes of the event, and in some cases maintained throughout, were near the upper range in which HSDA has been validated. The variable pacing created a second challenge to accurate modeling.

Despite these confounding factors, the HSDA predictions met many of the accuracy criteria used to determine acceptability. Table 10 presents a subjective evaluation (authors of this report) of model performance as evaluated by the various methods by class. If predicted values were within 5% of the criteria values classified for either under- or over-predicted, the model was deemed acceptable; otherwise it was considered unacceptable. The prevalence of acceptable markings suggest that the HSDA was reasonable for predicting the observed class average responses.

Table 10. Summary of Heat Strain Decision Aid (HSDA) performance assessed by the various methods and pre-established criteria by class

Class	Bias	MAE		RMSD		Non-Parametric Comparison	
		± Obs SD	± 0.50°C	± Obs SD	± 0.50°C	Under Predicted	Over Predicted
Spring	+	+	+	-	+	-	+
Summer	+	+	-	+	+	+	-
Winter	+	+	+	+	+	-	+
Total	+	+	+	+	+	+	-

(+) Equals acceptable performance and (-) equals unacceptable performance of the model

It should be noted there were great individual differences in the successful predictions from the model. While HSDA was not designed nor intended to predict individual responses to thermal stress, the large differences observed among individuals illustrates the problems HSDA will have in accurately predicting the thermal strain of a group of individuals that may have various individual differences in their physiology and behavioral histories. Previous research has shown that individual differences can affect prediction accuracy of thermal strain (34, 35).

The HSDA is an empirical model and therefore, its validity is dependent in large part on the large USARIEM database that was used to develop it. This database included thousands of exercise bouts performed in warm and hot environments while wearing various military clothing ensembles. This original developmental database did not include cold conditions because HSDA was originally intended for use in warm and

hot environments. Additionally, physiological responses to cold exposure differ from responses to heat exposure and thermally neutral environments. For these reasons, the HSDA input range has been traditionally limited to $T_a \geq 20^\circ\text{C}$. The T_a model inputs for the Winter and Spring classes are outside the bounds of HSDA accepted use limits, but were run anyway because of the expected high metabolic rates (and associated heat production) and the potential of using an App version of this model as an RTB planning tool. Because the Winter class actually had the most accurate predictions, the HSDA temperature range limit was not the limiting factor contributing to the inaccurate predictions observed. Rather, other factors, such as those mentioned above, and inaccurate input of hydration or acclimation state (these values were assumed) or individual physical or physiological differences in these Soldiers are likely the contributing factors to the errors associated with the predictions produced by HSDA. Error values associated with the Winter class were less than the Summer class where T_a was in the range where HSDA was developed.

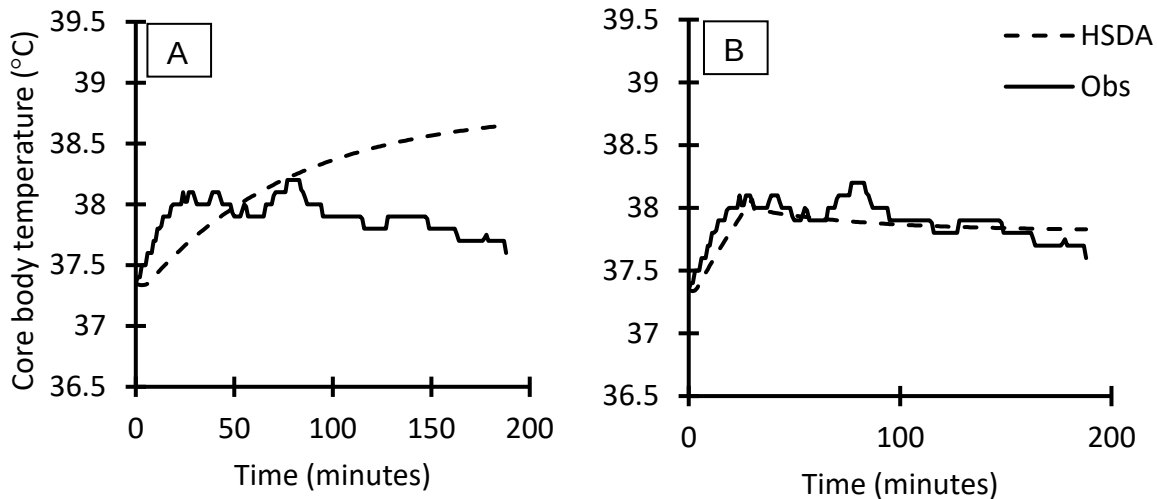
The acceptability of the HSDA group average predictions suggest that it could be used by the RTB to give a conservative rough estimate of the likely thermal strain the event will impose on the students. Moreover, the results from this study confirm that historical use of HSDA and TB-MED 507 (2) are meeting their intent, i.e., protect most Soldiers from heat injuries and provide a conservative estimates of work duration, before a rest break is required. In the scenario modeled, RTB students will have a low risk of experiencing a heat-related illness if they maintain an average pace, carry similar loads, and wear clothing that falls within the safe zone as predicted by HSDA for a given set of ambient conditions.

The HSDA model predictions were not accurate enough to allow a Ranger Instructor to determine the maximum load and fastest pace that an individual student could complete the road march without being at risk of experiencing a thermal injury. Likewise, HSDA, as used in this study, was not able to consistently predict the T_{core} response with the desired minute by minute accuracy. Other more sophisticated USARIEM thermoregulatory models (36-38) take into account individual characteristics and are more time sensitive to operational and environmental changes.

HSDA relies on several input variables and then uses a combination of equations to make the output predictions. The more accurate these inputs are to the observed data, the more closely the predictions should be to what is observed. However, in dynamic and real-world conditions, like these field based load carriage efforts, there are many elements that change in reality but are not easily captured within the model (e.g., non-steady-state pace, weather conditions, or changes to clothing properties overtime). These elements highlight both limitations and areas for potential improvement. For example, in the current study we used an average metabolic rate for each individual based on the distance and their individual time to complete the activity. While this is the more practical use model, it does create a higher predicted T_{core} initially and then a lower later T_{core} compared to the observed data (as students typically started at a higher pace and then slowed down). An example of this can be seen in Figure 15. Using Volunteer 1 during the Spring class, we can see the original prediction based on the

average metabolic rate (~700W) for the course (Fig. 15a). However, if we started with a higher metabolic rate (1200W) to meet the higher initial pace for the first 30 minutes and then dropped it to a lower rate (400W) for the remainder of the exercise (~160 minutes) we would see a much more accurate prediction comparison (Fig. 15 b). The challenge in this approach, as mentioned above, is that these patterns of work rate are not easily known at the beginning of the timed road march. Similarly, changes to the environmental conditions or clothing properties (e.g., wetted) that occur over the course of time are not easily accounted for in the model; while if available could be used to make time point corrections similar to the example shown in Figure 15. Wetted clothing in this study was a particular issue due to the high humidity, preventing evaporation of sweat and many students would dump water over their heads during various points of the march further wetting their clothing.

Figure 15. Example of differences in predictions based on average inputs (A) and mid-exercise adjustments (B) to metabolic rate



The HSDA version used in this comparison utilized a K_{work} equation to predict the time course of T_{core} rise after commencement of exercise. This equation is a substitute to the original “k” factor presented in the original paper of Givoni and Goldman (6). The K_{work} was introduced to broaden the applicability of HSDA, after it was observed that T_{core} rises at slower rate when Soldiers wear chemical protective clothing. Further experimentation will be needed to determine a more ideal method for capturing early rise in T_{core} across the spectrum of Soldier operations. Gonzalez et al., (9), modified the original “k” factor to better align to observed data from Soldiers wearing protective clothing. The current HSDA uses a K_{work} function which is provided in the equation below.

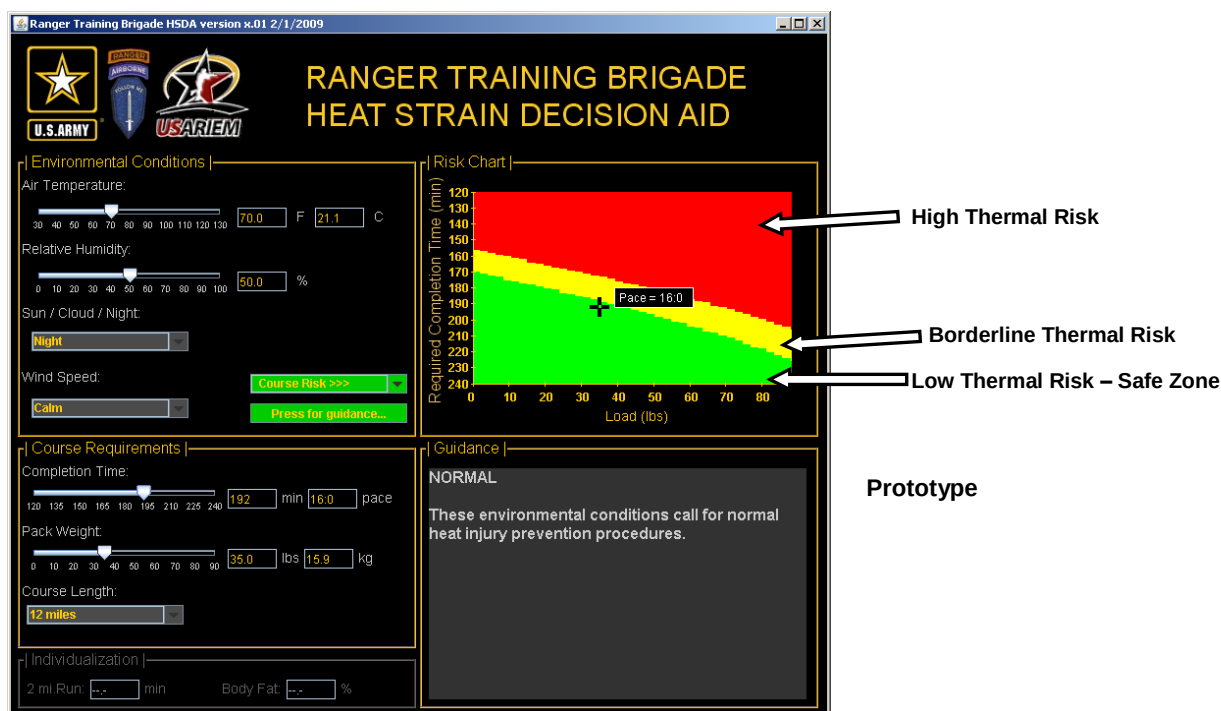
$$K_{work} = \frac{(1 + 3 \cdot EXP(0.3 \cdot (T_{ci} - T_{cfa})))}{225}$$

where $T_{ci} - T_{cfa}$ represents the change in final T_{core} value for acclimation and dehydration during exercise.

PROPOSED USE OF A MISSION PLANNING TOOL FOR THE RANGER TRAINING BRIGADE (RTB)

Pacing tables might be a useful tool for the RTB. Such a table can be generated using the HSDA. The produced tables whether computerized or paper-based are tables with a set of conditions forming the rows and columns and the corresponding pace or time it takes a runner or Soldier to complete a prescribed course in the body of the table. Pacing tables have been used for some time in guiding optimum training for distance runners. For example, tables have been generated based on age and body weight (39), maximal oxygen consumption (40), and normalized running speed and transient heart rate recovery times (41) to help equate performance times across athletes and across racing or training distances. Likewise this proposed application based on HSDA would provide the RTB guidance based on scientific principles as the environmental factors affecting thermal strain vary. The pacing tables could also include a selected risk tolerance variable. This risk level would then further refine best choice road march parameters such as course length, pace to cover the course, and weight to carry. Figure 16 illustrates a potential graphical user interface (GUI) for an application that would allow the instructor or those involved in mission planning to adjust course parameters.

Figure 16. Training aid interface of the Heat Strain Decision Aid (HSDA)



* Prototype Graphics Screen Developed by Dr. Mark Buller

FUTURE WORK

Trying to improve the HSDA model itself was beyond the scope of this research. However, it may be possible to improve the performance of HSDA by improving estimates for the metabolic cost of activities (M). A modification of the Pandolf equation or other existing metabolic equations may improve the accuracy of the M estimates. A study directly measuring the metabolic cost of the 8- to 12-mile march using portable oxygen uptake monitors would be useful. Recent work has been done (42-44) improving on the predictive methods of metabolic costs during military load carriage, body surface area calculations (45), and improvements specific to terrain for these types of estimation methods (25, 46). Additionally, there is work underway to incorporate all of these newer elements into one platform for modular updates and to further improve and evaluate the HSDA performance across a range of clothing configurations (47).

The use of non-direct measures are often ideal but can come with some significant limitations. This is especially true with respect to metabolic rates, as they have the greatest influence on heat gain for an individual. This influence is mathematically reflected in HSDA. For practical reasons, this study used the average movement speed for each individual as an input for predicting their individual metabolic rates. While the accuracy of HSDA was shown to be within the established statistical criterion; there are still areas that could be improved upon. Some research has shown that adjustments could be made to correct predictions of metabolic rates during dynamic activities by using GPS sensors (48). This type of adjustment could be used to correctly account for self-paced and complex movement activities.

The data set used in this report to validate HSDA could be used to evaluate other models. Volunteer characteristics and responses such as minute-to-minute heart rate, 2-mile run time, height, age, and percent body fat were collected even though HSDA does not use these parameters as inputs. These data may be useful as either inputs or outputs for other models.

RECOMMENDATIONS

- 1) The current HSDA computer application could be used with some caution as a general planning tool. Such precautions are applicable to any model, as all models provide only an approximation of the actual conditions. Most Ranger students will be safe with the prescribed pace and load for a given uniform and set of environmental conditions if the HSDA output pointer is in the green zone as indicated in Figure 16, the latest HSDA-RTB GUI.
- 2) Medical personnel could use HSDA to predict if and at what point in time during the road march students are likely to succumb to heat illness.
- 3) Use of HSDA to assess thermal injury risk for a particular individual may be used but should be done so with caution, as underlying inputs may not be easily known. However, HSDA was never intended for these purposes and the results within this report confirm that it does not fully support these applications.
- 4) Subsequent documentation using other USARIEM thermoregulatory models could be provided to assess thermal risk to the individual based upon individual fitness and anthropometrics.
- 5) Careful attention should be paid to the length of the road march and amount of weight carried if the RTB wants to ensure an equivalent thermal strain across classes. The data support the appropriate actions the RTB took by shortening the Summer road march to 8 miles from the 12 miles done by the Winter and Spring classes.

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