



U.S. Army Research Institute of Environmental Medicine

Natick, Massachusetts

TECHNICAL REPORT NO. T16-1

DATE October 2015

ADA

CORE TEMPERATURE AND SURFACE HEAT FLUX DURING EXERCISE IN HEAT WHILE WEARING BODY ARMOR

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

USARIEM TECHNICAL REPORT T16-1

**CORE TEMPERATURE AND SURFACE HEAT FLUX DURING EXERCISE IN HEAT
WHILE WEARING BODY ARMOR**

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October 2015

U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

REPORT DOCUMENTATION PAGE*Form Approved
OMB No. 0704-0188*

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1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)

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ACKNOWLEDGMENTS

No study can be successful without the willing participation and cooperation of the anonymous study volunteers. The authors would like to state their appreciation of those individuals, and thank them for their efforts and their service to the Nation as members of the US Army.

The authors would like to thank Mr. Tejash Patel, Mr. Christopher Carrigan, Ms. Stephanie Greene, and Ms. Cynthia Duhamel for their assistance in collecting, processing and analyzing the data.

EXECUTIVE SUMMARY

This report describes the physiological responses of soldiers wearing combat clothing and body armor (BA) while treadmill walking in a climatic chamber in warm and hot conditions. The specific objectives of the study were to (a) investigate methods for estimating core temperature (T_{core}) using measurements of skin temperature (T_s), surface heat flux (HF), and heart rate (HR), and (b) to develop a database, including direct measurements of surface heat loss, for the development, refinement, and validation of thermal models. This report is intended to serve as a reference document that describes the basic study and results. It does not describe the use of the data to develop methods for estimating T_{core} using heat flow, nor thermal modeling.

The basic test design consisted of test volunteers, dressed in combat clothing and equipment, including BA, following a test scenario consisting of two 1 h treadmill walks at a light-to-moderate (347 ± 28 W, WLK1) and moderate-heavy (537 ± 28 W, WLK2) work rates separated by a 30 min break. This core activity was bracketed by pre- and post-walk rest periods. The three chamber conditions were warm-neutral (WN25) (25°C , 50% RH), hot-humid (HH35) (35°C , 70% RH), and hot-dry (HD40) (40°C , 20% RH). T_{core} was measured using two telemetry pills; one was ingested (T_{c1}) and the other was used as a suppository (T_{c2}). Other data included height, weight, HF and T_s from 6 locations (forehead, sternum, pectoral muscle, scapula, rib, thigh), HR, and metabolic rates.

Nine male test volunteers were tested. As was expected, there were significant differences between WLK1 and WLK2 for the physiological parameters. The same observation is true for HR, T_{core} , and effective sweat rates. In addition, where there were differences between environmental conditions, the hot-humid (HH35) condition was generally more stressful than the hot-dry (HD40) and more moderate (WN25) conditions. An exception to the latter observation was for effective sweating rate during WLK1. Sweat loss was greater for HD40 relative to both WN25 and HH35, which indicates both greater potential for dehydration and more evaporative cooling.

Correlations of T_{core} to surface measurements of HF and T_s were calculated. In general, the values and pattern of the correlations (high and low values) were the same for T_{c1} and T_{c2} , and correlation values were greater between $T_s \times T_{\text{core}}$ than for HF $\times T_{\text{core}}$. For HF, the highest correlations were at the thigh and ribs locations. For T_s , the correlation for pectoral location was high, but the sternum and scapula value were essentially equivalent. A more refined analysis was required to derive an accurate prediction of T_{core} from non-invasive surface measurements (Xu et al., 2013).

In summary, this study provides a data set for further model development, refinement, and validation. Control data from test volunteers exercising without body armor will facilitate the development of non-invasive estimates of T_{core} . Such data for expanding, refining and/or validating the HF-based estimate of T_{core} can be collected as ancillary data during other thermal (heat and cold) studies.

INTRODUCTION

Purpose

This study was designed primarily to provide data for the development of methods for the early detection and prevention of heat illness using wearable sensors including a heat flow or flux sensor placed on the skin. The broad intent of this report is to provide the data needed to derive new methods for estimating T_{core} from heat flux (HF) (Xu et al., 2013), or to develop and/or validate other thermal models.

The study supports a secondary but valuable purpose, the expansion of the database for the development and validation of human thermal modeling. It is anticipated that the study results, with all personal identifiers removed, will become part of a human research database that will be used numerous times to support the development and validation of models that predict human physiological responses to exercise and environment.

HEAT INJURIES

Military Relevance

During training and combat operations in warm or hot environments, an underlying threat is the risk of heat illness, which may result in the loss of manpower, hospitalization, permanent disability or even death. In 2013, the overall incident of heat stroke for all services was 324 incidents and 1,701 other heat injuries at fixed (not deployed) locations (MSMR Mar 2014, pp 10-13). Over a five year period (2009-2013), there were a total 58 heat strokes, and 909 total heat injuries reported across services from service members deployed to Iraq or Afghanistan (MSMR, 2014). The report also noted that the rate of heat stroke increased for both Soldiers and Marines less than 20 years old. The prevention of heat illness is a Command responsibility, but those in positions of responsibility from squad leaders to Commanders need both knowledge and tools to assist them in mitigating the risks of heat illness.

The risk of heat illness is generally associated with conducting activities in warm or hot environments. This risk is significantly increased by greater physical exertion, carrying of heavy loads, including personal protective equipment (PPE), such as body armor (BA). During recent combat deployments to Iraq and Afghanistan some level of body armor is worn during most activities outside of major bases. In addition, heavy combat loads (e.g., 60kg) are commonly observed in dismounted infantry (Dean, 2003). Decisions regarding the combat load and PPE are the purview of the unit Commander. That individual faces a difficult decision regarding the value of equipment, including PPE, and the burdens imposed by that equipment, including the loss of maneuverability and the increased potential for heat illness.

Core Temperature (T_{core})

A primary goal of this study was to improve our ability to identify thermal strain continuously via physiological monitoring of military personnel during testing, training and operations. In general, wearable sensors that are suitable for use by the military may also be appropriate for athletes, police and firemen, and some industrial and agricultural workers. T_{core} is one of the best indicators of human heat status in warm or hot environments. Several non-invasive or minimally invasive methods have been used to approximate T_{core} , including axillary and forehead surface temperatures, oral temperature, and aural or tympanic temperature. By definition, the direct measurement of T_{core} requires invasive placement of a temperature sensor in locations such as the rectum, esophagus, gastrointestinal tract, and pulmonary artery (Moran & Mendal, 2002).

Physiological temperature measurements tend to be classified first, as above, by anatomical location, then sensor type (i.e., rigid, or flexible; hand-held, hard-wired, or transmitted; liquid, electronic - infrared, thermocouple, thermistor, etc.). Axillary temperature is recognized as a less accurate, but non-invasive method for estimating body temperature, and the process of checking for fever with a hand placed on the forehead is familiar to nearly everyone. Under some conditions, these site temperatures may be adequate, but a higher degree of agreement with T_{core} values will allow a more definitive evaluation of thermal status.

Oral and aural temperatures are also familiar non-invasive methods for assessing T_{core} . Oral temperature is generally recognized to be less accurate than more invasive methods and the placement of the sensor in the oral cavity is not acceptable for use by active individuals. The accuracy of aural and tympanic thermometers as representatives of T_{core} are a matter of debate in the literature (Moran & Mendal, 2002; Erickson & Kirklin, 1993; Childs et al., 1999; Kocoglu et al., 2002; Casa et al., 2007), and placement of the sensor in the ear may not be desirable during military training and operations. The debate over the validity of aural and tympanic measurements as a surrogate of T_{core} is clouded by claims regarding the characteristics of the specific device and its placement within the ear, and the context of the measurement. For active, continuous monitoring, such devices can be considered invasive.

As noted, T_{core} can be accurately measured through more invasive methods, (e.g., sensors placed to measure arterial blood, rectal (T_{re}) or esophageal (T_{es}) temperatures), but the use of these invasive research or clinical methods in field conditions ranges from difficult to near-impossible (pulmonary artery). A relatively recent innovation is to ingest a telemetry temperature pill. Local temperature is transmitted to a receiver as the pill migrates through the digestive tract until it is excreted from the body. The receiving device may display, record and/or transmit the temperature data. A telemetry pill may also be used to monitor temperature at a fixed site, such as the rectum (O'Brien et al., 1998).

The use of ingested telemetry temperature pills to measure T_{core} is considered invasive. However, the degree of health risk is low for most individuals, and has improved with the development of smaller thermometer pills from the larger analog HTI pills <http://www.hqinc.net/> to the smaller Minimitter/Phillips pills. At present the pills are not cost effective for use in a large population. In addition, temperature values will be influenced by the location of the pill within the digestive tract, and at least in the upper digestive tract, by the ingestion of liquids (Wilkinson et al., 2008). To limit the impact of ingested fluids, during studies, the pill is often administered 8-12 h before exposure to significant thermal stress related to environmental conditions and/or activity. Unfortunately, the pill sensor dwell time in the digestive system (~8-48 h) is variable, and some individuals may pass the pill before the onset of the exposure or activity.

An alternative to the ingested temperature pill for monitoring thermal status would be a surface mounted sensor that would be as durable and reliable as other physiological status monitoring (PSM) sensors (Tharion et al., 2013) while providing a reasonably accurate estimate of T_{core} ($\pm 0.2\text{-}0.5^{\circ}\text{C}$). It would also be an acceptable alternative to all of the invasive T_{core} sensors described previously, unless a very high degree of accuracy and/or a site specific parameter, such as a head or heart temperature, was a special research interest.

Given the desirability of obtaining an accurate, non-invasive estimate of T_{core} , there have been on-going efforts to search for techniques for non-invasive monitoring of core temperature (Yokota et al., 2006; Yokota et al., 2012; Buller et al., 2013). Gunga et al. (2008) demonstrated that HF, in conjunction with other non-invasive measures such as HR and T_{s} , may be used to estimate T_{core} . Other examples of non-invasive methods for approximating T_{core} are forehead skin and axillary temperatures. Thus there should be a reasonable expectation of a strong correlation between HF and T_{core} and this report will briefly consider the relationship.

STUDY ORIGINS AND DESIGN

The inspiration for the study design was in part derived from a field study of US Marines in Iraq (Buller et al., 2008) exposed to high temperatures while carrying heavy combat loads with BA. Based on values for walking speed and load, the metabolic cost of patrolling was estimated to be less than 300 W. Despite the relatively low metabolic cost, physiological monitoring indicated that the Marine volunteers were experiencing relatively high T_{core} , T_{s} , and HR, which are indicative of heat strain. These data were supplemented by local weather measurements.

Although the Marine study data provided excellent information, and demonstrated the value of body mounted sensors by providing real-time situational awareness regarding the physiological status of the study Volunteers, the use of ingested telemetry temperature pills to measure T_{core} is invasive, not cost effective, and the pill sensor dwell time (~8-48 h) is too variable. Therefore, monitoring thermal status using surface mounted sensors that are durable and reliable is more desirable.

Gunga et al (2008, 2009) developed a “Double Sensor” consisting of two temperature sensors separated by an insulating spacer for placement on the forehead or under a helmet to estimate T_{core} using HF. The present study used a single heat flow sensor to provide both HF and T_s surface temperature values. Surface mounted HF discs can be readily integrated in to the Hidalgo, Ltd. (Cambridge, UK) EquivalTM sensor suite without a requirement for an additional battery.

Field studies provide invaluable information, and serve as a reality check for researchers, but to collect the data imposes an additional task on units and individuals already burdened by the stress of combat operations. Field studies are thus invaluable in defining the problem in a military context, but the realities of military training and operations, as well as the variability of weather conditions, do not always provide optimal data for the development of models or sensors. Thus, field studies often need to be supplemented with more tightly controlled laboratory studies. As described in depth in the Methods section, the basic test design consisted of test volunteers, wearing combat clothing and body armor (BA) while treadmill walking in a climatic chamber in warm and hot conditions or environments.

The goal of the present research was to (a) develop an algorithm to estimate T_{core} from non-invasive measures of HF, HR, and T_s , and (b) generate de-identified data for future model development and validation. However, as noted earlier, the final derivation of non-invasive measurements to estimate T_{core} based on HF measurements is beyond the scope of this report; however this analysis is included in a separate publication by Xu et al., (2013).

METHODS

Volunteer Recruitment

Healthy, 18 to 35-year-old active duty military personnel were recruited from the Natick Soldier Systems Center, Human Research Volunteer Program to serve as test volunteers. Only soldiers who had passed their most recent Army Physical Fitness Test (APFT) were allowed to participate in studies involving physical activity. Prospective volunteers were briefed on the study and expressly assured that they were completely free to withdraw from participation in the study at any time. After giving their written informed consent, and prior to any participation in the study, potential Volunteers were medically screened by USARIEM medical staff to exclude individuals for whom the stress of the study could pose a greater hazard than that for normal, healthy persons.

Volunteer Safety

Volunteers ingested a telemetry pill the evening before testing. A second pill was inserted as a suppository the morning of each test day. If an ingested pill could not be

detected the morning of a test, the volunteer was given a new pill to ingest. Pill temperatures (T_{core}) were monitored throughout testing, and whenever either pill indicated a T_{core} of 39.5°C, the volunteer was removed. Any volunteer removed with a T_{core} of 39.5°C was monitored in the dressing area until the T_{core} values decreased to 39.2°C.

During all chamber testing, one or more staff members were present inside the chamber with the test volunteer. Although no threshold was specified, HR was closely monitored. Staff members inside the chambers were kept informed of both HR and T_{core} values by individuals in the control area who were monitoring the collected data. Staff members closely observed volunteers for other indicators of heat strain including gait changes and spoken responses.

Fluid consumption and body weights were recorded during the study. Volunteers were provided water or sports drink *ad libitum* prior to dressing and after exiting the chambers. In addition they were provided up to 600 ml at the mid-point of chamber testing. Volunteers were encouraged to drink when fluids were available, but consumption was not forced.

Test Design

The total study commitment for volunteers consisted of initial anthropometric data collection. At that time, volunteers were also fitted for BA, participated in a brief walk-through of chamber testing, and practiced walking on the treadmills. Volunteers then participated in three chamber test sessions. Chamber sessions were separated by at least 4 days to minimize acclimation effects. The evening before each chamber session (at ~1600 h), volunteers ingested a telemetry pill. Unless there was a make-up session, all chamber sessions followed the same order of presentation: 25°C, 50% RH; 35°C, 70% RH, and 40°C, 20% RH. Chamber air velocity (wind speed) was controlled at approximately 1.6 m/s. It was necessary to increase wind speed (~0.2 m/s) periodically to ensure adequate air mixing. If a volunteer exited the chamber before the second walking metabolic rate could be collected, the volunteer was asked to repeat the test session. After all chamber testing was completed, each volunteer participated in an informal out-briefing session that included a check for the presence of a telemetry pill.

Pre-Test Measures

Volunteer anthropometric parameters were characterized by height, weight and a Dual-Energy X-Ray Absorptiometry (DXA) scan to determine percent body fat (Model: GE Lunar iDXA Manufacturer: GE Healthcare, Waukesha, WI). Age, sex and self-reported 2-mile run time from the volunteers' last Army Physical Fitness Test (APFT) were recorded. The 2-mile run time was used to estimate $VO_2\text{max}$ (Mello et al., 1984). The waist and chest were tape measured to help ensure proper fit of the BA and to provide an alternative means of estimating body fat (Kujawa, 1998).

Chamber Test Sessions

Each chamber test session started with the arrival of the test Volunteers. Initially Volunteers were encouraged to use the rest room, unmonitored drinking water was provided, the Volunteers were questioned regarding any health problems, and an overview of the test session was provided. The formal test schedule (Table 1) began when Volunteers were weighed wearing only undershorts.

Table 1. Daily chamber test schedule

Phase	Duration	Location	*Measurements
Instrument and dress	~30 min	Dressing room	Weight (2), water
Sit	30 min	Dressing room	--- none ---
Stand	10 min	Chamber	Metabolic rate
Walk ~300 W	60 min	Chamber	Metabolic rate
Weights, toilet, return & sit	20 min	Dressing room & chamber	Weights (1), water
Stand	10 min	Chamber	Metabolic rate
Walk ~550 W	60 min	Chamber	Metabolic rate
Stand	10 min	Chamber	--- none ---
Sit	30 min	Dressing room	Weight (1), water
Remove equipment, sensors	~20 min	Dressing room	Weights (2)
*Measurements include core and skin temperature, heart rate, heat flux. Water indicates water or sports drinks were available for consumption. Weights indicate that Volunteers were weighed (1= clothed 2=both clothed and semi-nude weights).			

As described in more detail later, after dressing and instrumentation, Volunteers rested in the dressing area for 30 min before entering the chambers. Except for briefly exiting for weighing and restroom use, the full schedule was to remain standing, sitting or walking in the chambers for 190 min. Upon exiting, Volunteers were weighed with all clothing and equipment, and then sat for 30 min, before an additional clothed weight was taken. The Volunteers then removed clothing, equipment, and sensors, and a final weight was taken. If a Volunteer exited the chamber before the full chamber time was completed, the scheduled events in the dressing room were modified to accommodate specific concerns such as immediate removal of equipment and clothing to rapidly

dissipate heat. In general, an effort was made to observe and monitor Volunteers for at least 30 min after exiting the chamber.

Measurements During Chamber Test Days

Body weights and fluids

To quantify daily body weights, loads, fluid intake and estimate sweat and evaporative water, Volunteers and their load and clothing were weighted several times during testing. Table 1 indicates when Volunteer weights were taken and water given during daily testing. Clothing and load were weighed separately before and after testing. In addition, water consumption from the onset of data collection was measured. During the break between walking sessions, Volunteers were limited to a maximum intake of 600 ml, whereas fluids were provided *ad libitum* after they completed their chamber testing. All water intake was measured and recorded once the Volunteers were seated after dressing in their full ensemble of clothing and body armor. In addition, Volunteers were weighed before and after urination. As noted above, consumption of fluids was encouraged, but not forced. Total water loss (sweat) could only be approximated for the total time between the initial sedentary phase in the dressing room to the final semi-nude weight using body weight, water intake, and the change in clothing load weights to estimate sweat absorbed into those materials. Evaporative or effective water loss was estimated for walks from the changes in clothed weights.

Instrumentation for Chamber Testing

Heart rate (including ECG waveform), skin temperature, respiration rate (including respiration effort waveform), activity level using accelerometry data, and body core temperature were measured every 15 s by a chest belt monitoring system (Equivalital EQ-01, Hidalgo Ltd., Cambridge UK). Accelerometry was measured using a 3-axis accelerometer that measures movement in the X (left to right horizontal), Y (vertical) movement and Z (front to back) directions. The device is powered by two AAA alkaline batteries and weighs less than 200g. Core temperature was measured by both the ingestion of a telemetry thermometer pill (Jonah™ Core Temperature Pill, Respironics, Bend OR) administered the evening (~16 h) before a test session; and by the use of a second telemetry thermometer pill used as a suppository. In addition, a Vitalsense® physiological monitor (Mini-mitter, Bend, OR) was attached to the Body Armor (BA – described below) and other hand-held Vitalsense® units were used by staff in the chamber to monitor T_{core} . A ceramic heat flow sensor (FMS-060-TH44018-6, CE Concept Engineering, Old Saybrook, CT 0647), placed on the surface of the left pectoralis major muscle, was also incorporated into the Equivalital™ to measure the surface HF and T_s . Five additional sets of HF and T_s were collected with heat flow sensors on the surface of the sternum, left rib cage, left scapula, and left thigh (Figure 1) using a multi-channel data logger (Grant SQ2040-2F16, Grant Instruments, Hillsborough, NJ). The locations for the placement of the heat flux sensors were selected on the basis of proximity to important anatomical features, and the ability to consistently place the sensors based on anatomical landmarks. The heat flux sensors were mounted on the skin surface using an ECG foam adult monitoring electrode

(40493E, Philips Electronics, Andover, MA). A hole, the diameter of the sensor, was cut in the center of the electrode. This created an adhesive ring of foam material which held the sensor in place, but the top and bottom surfaces of the ceramic disc are fully exposed, Figure 2 shows a heat flow sensor and the surface mounts constructed from ECG electrodes.

Figure 1. Location of heat flow sensors indicating anatomical landmarks

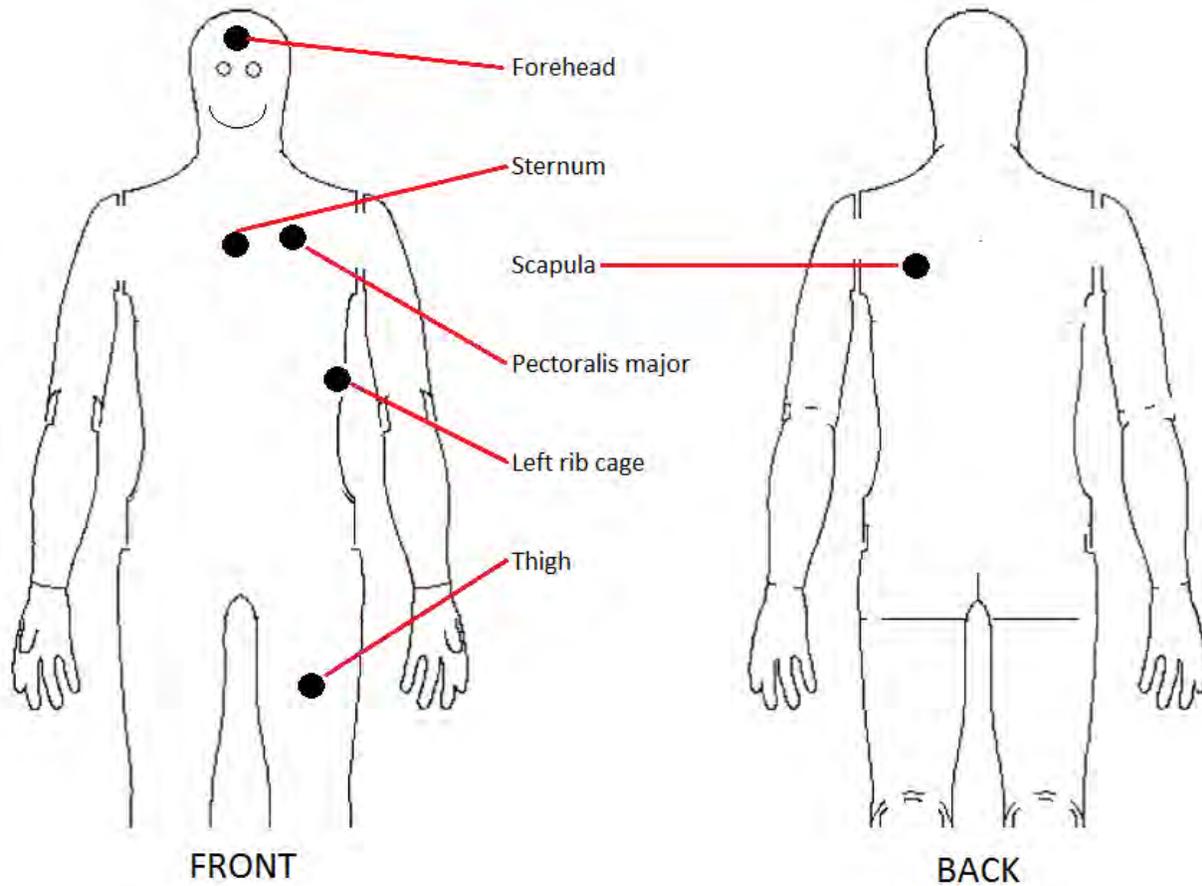
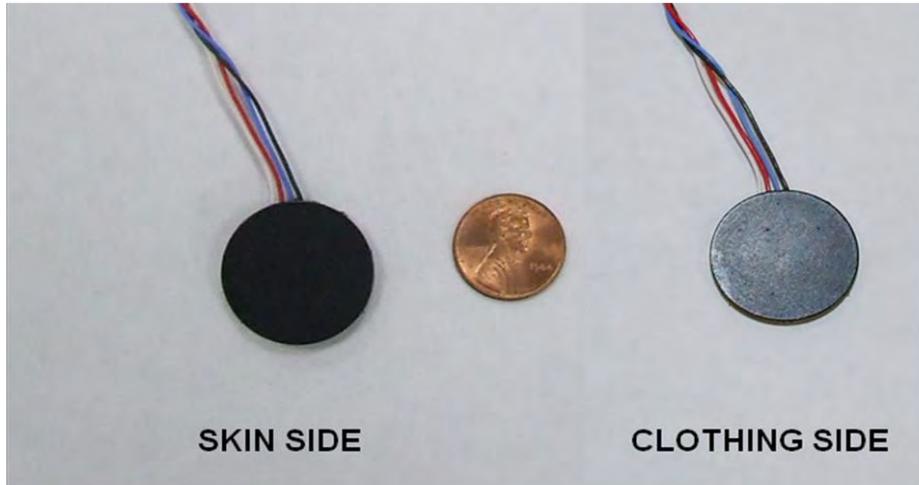
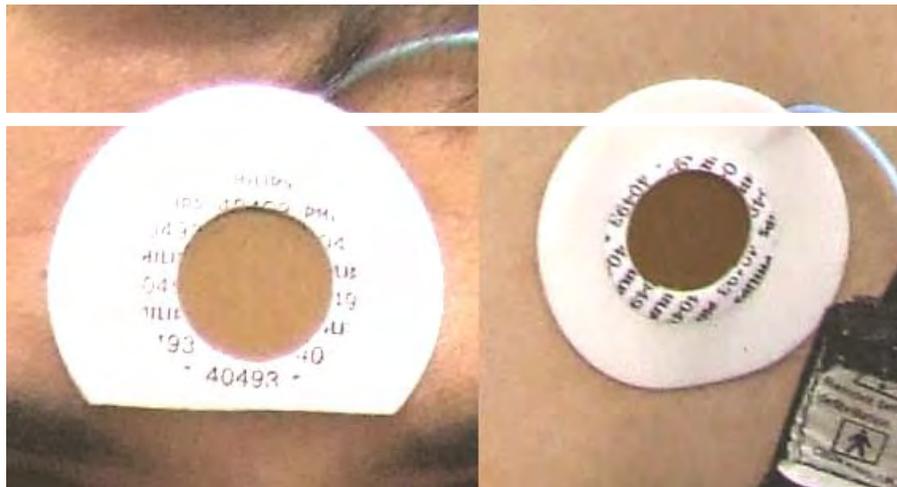


Figure 2. Mounting system for heat flux sensor. Part A. Ceramic heat flow sensors (FMS-060-TH44018-6, CE Concept Engineering, Old Saybrook, CT 0647) part B. Heat flow sensor surface mounts constructed using ECG electrodes.

A. Ceramic heat flow sensor - side facing skin is black



B. Heat flow sensor in surface mounted constructed using an ECG electrode



Clothing, Body Armor and Load

The Volunteers were fitted with Interceptor Body Armor, which included the armor vest with front, back and side Small Arms Protective Inserts (SAPI plates), and a Kevlar helmet. Table 2 provides weights for different combinations of actual armor and helmets. The Volunteers wore the BA kit over their own Army Combat Uniform (ACU) and footwear. After problems of blisters were experienced during initial testing, the footwear was switched from boots to running shoes. A Vitalsense® telemetry pill temperature monitor and recorder were attached to the BA. In addition, the total load included a frameless rucksack with a multi-channel datalogger inside used to monitor and record HF sensors, and the Equival™ EQ-01. The total weight carried consisted of the ACU, footwear, BA, rucksack, data loggers, and weights. No expendable items

(water or food) were carried during the study. The protocol design allowed the option of increasing the external load by adding weight to the ensemble worn by the Volunteers, but the load carried, less the ACU, footwear, and underwear, could not exceed 22.7 kg.

Table 2. Weights for Interceptor Body Armor (BA) components

Size	BA (kg)	SAPI (FB) (kg)	SAPI (S) (kg)	Helmet (kg)	Total (kg)
XL	6.27	6.40	2.30	1.68	16.64
L	5.70	5.59	2.30	1.63	15.21
M	5.34	4.91	2.30	1.42	13.97
S	5.00	4.32	2.30	1.42	13.03

BA= Body Armor w/o plates
 SAPI = Small Arms Protective Inserts
 FB = front and back plates
 S= 2 side plates
 Note: Sizes of components may be mixed for different Volunteers.

Metabolic Costs

Target whole body metabolic rates for the two walks were ~300 W and ~550 W. To achieve those targets, there were three options: (1) treadmill speeds could be selected between (2-4 mph), (2) treadmill slope could be raised from level up to 5% grade, and (3) weight could be added to the load, up to a maximum external load of 22.7 kg.

The Pandolf equation (PE)(Pandolf et al., 1977) uses inputs for body mass, external load, walking speed and slope grade to calculate the total metabolic cost. Smaller volunteers worked at a higher percentage of their aerobic capacity as the absolute target values for whole-body metabolic rates do not take body size differences into consideration. While other metabolic cost prediction methods exist, most alternatives do not provide the option of including an external load (Potter et al., 2013a).

Selection of treadmill settings: Using volunteer body weight and load carried as inputs, the PE was used to determine which combination of treadmill speeds and grade would provide metabolic rates of ~300 W and ~550 W. The chamber treadmills were adjusted before each walk to provide those approximate levels of activity.

Measurements: Metabolic rate measurements were obtained by collecting expired air samples in Douglas bags for 2 min during rest periods immediately prior to exercise and at approximately 20 minute into each exercise periods. The samples were then analyzed for oxygen uptake (VO₂) using a metabolic cart (True One 2400 Metabolic Measurement System, Parvo Medics Sandy, UT).

Test Duration and Re-Tests

Successful completion of a test session was defined by the collection of VO₂ during the second walk. The protocol allowed a retest in the event that this final value could not be collected. Two (2) individuals were retested. We were unable to retest the one individual who withdrew just before the VO₂ sample was taken in the hot-dry condition.

RESULTS

All study participants were healthy military personnel who had recently completed their Advanced Individual Training (AIT), and as noted earlier, had passed their most recent APFT. The data presented are for 9 male Volunteers that participated in all three chamber test days. Mean anthropometric parameters and estimated maximum VO₂ (VO₂max) (Mello et al, 1984) are given in Table 3.

Table 3. Anthropometric values and estimated VO₂max

	Age	*VO₂max	Height	Weight	Body Fat
	(yr)	(ml O ₂ /kg*min)	(cm)	(kg)	(%)
\bar{X}	22	49.75	175	76.44	23.4
SD	4	3.95	10	10.67	5.80
N	9	9	9	9	9

***Estimated using self-reported 2-mile run time and weight (Mello et al, 1984)**

The mean weight of clothing worn for all testing was 2.49 ± 0.43 kg and the mean load, excluding clothing was 18.43 ± 1.75 kg, for a total load of 20.92 ± 1.97 kg (n=9 test volunteers in each of the 3 environmental conditions). The range of values for the external load was 16.17 to 22.32 kg and 19.30 to 24.81 kg for the total load. Those values were computed from the difference between pre-test semi-nude and clothed weight of the Volunteers and a separate weighing of clothing. For control purposes, and to determine the absorption of sweat into the clothing and equipment, the clothing and other load components were weighed before dressing and post-test. Some data were lost when Volunteers were removed for safety concerns and/or the T_{core} met or exceeded the 39.5°C upper limit. Table 4 summarizes the treadmill settings.

Table 4. Summary of treadmill settings for all environments

	WALKING SPEED 1 (m/s)	GRADE 1 (%)	WALKING SPEED 2 (m/s)	GRADE 2 (%)
\bar{X}	1.10	0	1.30	3.67
SD	0.08	0	0.09	0.59
MIN	1.01	0	1.23	2.50
MAX	1.34	0	1.56	4.50
N	27	27	27	27

In the warm-neutral WN25 condition, all but one Volunteer completed the entire test session. Two (2) subjects re-tested in hot-humid HH35), but only three of nine volunteers were able to complete the full 60 min second walk. Due to a non-study related illness, 1 subject was unable to walk long enough in the hot-dry HD40 environment to provide the second walking VO₂ value. Of the remaining 8 Volunteers, 7 completed the entire test session. Table 5 presents the duration of the second walk and the total test duration or walk time. When the differences in duration for WLK2 and the total walk time are significant only between HH35 and HD40, but were close (p = 0.056) to being statistically significant across all three environments.

Table 5. Duration of second walk (D-WLK2) and total walk time (T-WLK) by environment. Maximum values set at 60 min and 120 min respectively.

	D-WALK2 (min)	T-WALK (min)*
WARM-NEUTRAL 25°C 50% RH		
\bar{X}	58	118
SD	5	5
N	9	9
HOT-HUMID 35°C 70% RH		
\bar{X}	48	108
SD	15	15
N	9	9
HOT-DRY 45°C 20% RH		
\bar{X}	55	115
SD	14	14
N	8*	8**
*WLK1+WLK2, not elapsed time		
**Volunteer removed due to illness in hot-dry environment – data not included in hot-dry sample population		

Metabolic Costs

Table 6 presents the mean observed and calculated metabolic costs of standing and walking by environment. STD1 and STD2 are the metabolic costs during the standing rest periods prior to the first and second walking periods. The corresponding metabolic costs of walking during the first and second walks are WLK1 and WLK2 respectively.

For the walking metabolic rates, WLK2 was, as expected, significantly greater than WK1. There was a significant difference for the energy costs (M) between the first and second standing measurements. Except for the difference between the humid and dry environments for the second standing measurement (STD2), Table 7, overall dry > humid, there were no significant differences for energy costs (M) between environments.

When compared to the estimated M costs calculated using PE (Table 7), overall there were significant differences for WLK1 (overall observed > calculated, mean difference = 43 (± 15) W, n=27). The differences between observed and calculated were also significant for the second standing period overall (mean difference 21(± 11), n=27), and in the dry environment (mean difference 22 (± 12) n=9). Otherwise, there were no significant differences in metabolic costs.

Table 6: Measured metabolic costs (W) during standing (STD) and walking (WLK)

		STD1†	STD2†	WLK1‡	WLK2‡
All Conditions	\bar{X}	124	145	347	537
	SD	16	20	28	28
	N	27	27	27	26
25°C, 50% RH	\bar{X}	124	145	350	536
	SD	15	20	26	32
	N	9	9	9	9
35°C, 70% RH	\bar{X}	125	138*	348	538
	SD	18	16	32	32
	N	9	9	9	9
40°C, 20% RH	\bar{X}	124	152*	346	530
	SD	18	22	29	32
	N	9	9	9	8

†significant difference between stand 1 and stand 2

‡ significant difference between walks

*significant difference between environments (ENV2 (35°C) x ENV3 (40°C))

Table 7. Comparison of observed metabolic rates and values predicted using the Pandolf equation (PE) for standing and walking periods

PE CALCULATED VALUES				OBSERVED DATA			
	STD	WLK1	WLK2	STD1	STD2	WLK1	WLK2
\bar{X}	130*	304†	531	124	145*	347†	537
SD	17	20	31	16	20	28	28
COUNT	27	27	26	27	27	27	26
*significant difference for Stand 2 between calculated and observed costs							
†Significant differences between calculated and observed values for Walk 1							

Heart Rate (HR)

As expected with an increase in walking speed and grade (Table 4), there was a significant difference between WLK1 and WLK2 for mean HR, the net change in HR and the final HR. Mean HR was significantly different between all environments for both WLK1 and WLK2 (Table 8A). For the final HR, the differences were significant between all environments for WLK1, and significantly different between 25°C and both 35° and 40°C conditions (Table 8B) for WLK2. Another indicator of increasing strain over time is the change (increase) in HR over the walk periods (Table 8C). There were significant differences between environments for WLK1, but not WLK2. The lack of any significance for the second walk may in part be due to the greater variability in HR during that period of greater activity.

Table 8. Mean, maximum and increase in Heart Rates: (\pm 1 SD) values in beats per minute by location and activity phase in test session. Unless otherwise noted, n=9

A. COMPARISON OF MEAN HEART RATES (HR) BY WALK AND ENVIRONMENT			
WALK 1 – MEAN HEART RATE (HR)			
CONDITION	25°C	35°C	40°C
\bar{X}	108*	124*	116*
SD	9	14	8
N	9	9	9
WALK 2-MEAN HEART RATE (HR)			
\bar{X}	135*	163*	153*
SD	20	12	12
N	9	9	9
*Significant differences between environments			

B. FINAL HEART RATE (HR) FOR WALK PERIOD, BY WALK AND ENVIRONMENT

WALK 1 FINAL HEART RATE (HR)			
CONDITION	25°C	35°C	40°C
\bar{X}	108*	137*	122*
SD	14	13	13
N	9	9	9
WALK 2 FINAL HEART RATE (HR)			
\bar{X}	132**	174**	164**
SD	32	15	18
N	8	8	8

* WLK1 Significant differences between all conditions, **WLK2 significant differences between WN25 x HH35, HD40

C. INCREASE IN HEART RATE (Δ HR) OVER WALK PERIOD BY ENVIRONMENT

WLK1 (Δ HR)			
CONDITION	25°C	35°C	40°C
\bar{X}	6*	32*	19*
SD	7	8	10
N	9	9	9
WLK2 (Δ HR)			
\bar{X}	23	44	37
SD	20	21	12
N	8	8	8

*WLK1 only, significant differences between all conditions

Core Temperatures (T_{core})

A number of metrics associated with T_{core} were evaluated including the mean (mT_c) and final (fT_c) values, and the absolute change (ΔT_c), all in °C, and rate of change/heat gain in T_{core} (ΔT_c in °C/min). Overall there were significant differences between WLK1 and WLK2 for all T_{core} variables for both temperature pills. One question of interest is the difference between measurement sites for the ingested and suppository temperature pills (T_{c1} and T_{c2}). When the data were separated by walk, the only significant differences between T_{c1} x T_{c2} were mT_c during WLK1 and fT_c for WLK2. When those data were analyzed for differences within the environments for those two cases, for mT_c , WLK1 and fT_c , WLK2, the only significant differences were in the more moderate, WN25 environment. For the purpose of further analysis, although there were no significant differences between T_{c1} and T_{c2} for most variables, the core temperature analysis examined each core temperature and walk data as discrete data sets. Tables 9A-9D present the descriptive statistics for the core temperature variables and indicate when there were significant differences between conditions.

For WLK1 there were no significant differences between conditions for mT_c, but at least one significant pair for all the other variables. For WLK2, there was at least one significant pair for all variables. Table 9 provides descriptive statistics for the core temperature variables by walk and pill location.

Summary analysis of core temperature variables

- Final core temperature (fT_c in °C), Table 9A: For WLK1 there are a few differences in significance between T_{C1} and T_{C2}. For T_{C1}, during WLK1, HH35 is significantly different from both WN25 and HD40. For T_{C2}, the difference between WN25 and HH35 is significant. For WLK2, all conditions are significantly different for both T_{C1} and T_{C2}.
- Mean core temperature (mT_c in °C), Table 9B: For WLK1 there were no significant differences between environments. For WLK2 all conditions are significantly different (T_{C1}, T_{C2})
- Change in core temperature (ΔT_c in °C), Table 9C. : For WLK1 there are significant differences between all environments for both T_{C1} and T_{C2}. For WLK2, the difference between HH35 and HD40 is significant.
- Rate of change (rT_c in °C/min), Table 9D: For WLK1, HH35 is significantly different from WN25 and HD40 for T_{C1}; all pairs are significantly different for T_{C2}. For T_{C2} in WLK1, and both T_{C1} and T_{C2} for WLK2, all conditions are significantly different.

Table 9. Core temperature variables by walk (WLK1, WLK2), pill location (T_{C1} = ingested, T_{C2} = suppository), and environments (ENV – chamber environmental WN25 = 25°C 50% RH; HH35 = 35°C 70% RH; HD40= 40°C 20% RH).

A. FINAL CORE TEMPERATURE (°C)						
ENV	WN25		HH35		HD40	
PILL	T _{C1}	T _{C2}	T _{C1}	T _{C2}	T _{C1}	T _{C2}
WALK 1						
\bar{X}	37.54 ^y	37.63 ^b	37.98 ^y	37.88 ^b	37.65 ^y	37.73 [*]
SD	0.18	0.16	0.41	0.19	0.19	0.16
N	8	9	9	8	8	8
WALK 2						
\bar{X}	37.96†	38.16†	39.20†	39.16†	38.69†	38.78†
SD	0.38	0.36	0.37	0.40	0.21	0.28
N	8	9	9	8	7	7
“y” WLK1 HH35 x WN25,HD40 are significantly different (T _{C1}) “b” WLK1 WN25 x HH35 are significantly different (T _{C2}) † WLK2 all conditions are significantly different (T _{C1} , T _{C2}) *not significantly different						

B. MEAN CORE TEMPERATURE (°C)						
ENV	WN25		HH35		HD40	
PILL	T _{C1}	T _{C2}	T _{C1}	T _{C2}	T _{C1}	T _{C2}
WALK 1						
\bar{X}	37.33*	37.46*	37.42*	37.45*	37.26*	37.32*
SD	0.13	0.20	0.31	0.35	0.19	0.19
N	8	8	9	9	8	7
WALK 2						
\bar{X}	37.74†	37.87†	38.42†	38.41†	38.06†	38.11†
SD	0.24	0.25	0.27	0.17	0.27	0.32
N	8	8	9	9	8	7
† WLK 2 all conditions are significantly different (T _{C1} , T _{C2}) *WLK 1 not significantly different						
C. CHANGE IN CORE TEMPERATURE (°C)						
ENV	WN25		HH35		HD40	
PILL	T _{C1}	T _{C2}	T _{C1}	T _{C2}	T _{C1}	T _{C2}
WALK 1						
\bar{X}	0.43†	0.37†	0.90†	0.88†	0.70†	0.70†
SD	0.12	0.16	0.33	0.22	0.14	0.19
N	8	9	9	8	8	8
WALK 2						
\bar{X}	0.68*	0.70*	1.28 ^z	1.20*	0.99 ^z	1.03*
SD	0.37	0.38	0.32	0.44	0.20	0.29
N	8	9	9	8	7	7
†WLK1 all significantly different (T _{C1} , T _{C2}) “z” WLK2 HH35 X HD40 are significantly different (T _{C1}) *not significantly different						
D. RATE OF CHANGE (°C/min)						
ENV	WN25		HH35		HD40	
PILL	T _{C1}	T _{C2}	T _{C1}	T _{C2}	T _{C1}	T _{C2}
WALK 1						
\bar{X}	0.008 ^a	0.007 ^b	0.018 ^a	0.017 ^b	0.013 ^a	0.013 ^b
SD	0.002	0.003	0.005	0.004	0.003	0.003
N	8	9	9	8	8	8
WALK 2						
\bar{X}	0.013†	0.013†	0.033†	0.027†	0.025†	0.024†
SD	0.008	0.007	0.011	0.004	0.011	0.006
N	8	9	9	8	7	7
“a” WLK1 HH35 x WN25, HD40 (T _{C1}) “b” WLK1 all pairs significantly different (T _{C2}) † WLK2 all conditions are significantly different (T _{C1} , T _{C2})						

Fluids / Sweat

For the rate of effective sweating (g/min) there was a significant difference between walks (Table 10). For the first walk there were significant differences between HD40, and WN25, HH35. For the second walk there were no significant differences despite the large apparent difference between WN25, HH35 and HD40.

Table 10. Rate of sweat loss (g/min) by walk

	WLK1			WLK2		
	WN25	HH35	HD40	WN25	HH35	HD40
\bar{X}	3.56 ^a	3.44 ^a	7.20 ^a	8.39 ^b	9.09 ^b	12.41 ^b
SD	0.45	0.64	0.66	2.08	2.43	2.85
N	9	9	9	9	7	9
^a WLK1 HD40 significantly different from WN25,HH35 ^b WLK2 HD40 significantly different from WN25						

Correlation of T_{core} to surface measurements of Heat Flux (HF) and skin temperature (T_s)

Table 11 summarizes the correlation between core temperatures (T_{c1} , T_{c2}) and heat flux (HF) and local skin temperature (T_s) for all site and data, and for only the data from the two walks (WLK1, WLK2). In general, the values and pattern of correlation (high and low values) were the same for T_{c1} and T_{c2} .

Table 11. Correlation of T_{core} ($^{\circ}C$) to surface measurements of Heat Flux (HF in W/m^2), and skin temperature (T_s in $^{\circ}C$)

	ALL DATA				WALKING DATA ONLY			
	T_{c1} x HF	T_{c1} x T_s	T_{c2} x HF	T_{c2} x T_s	T_{c1} x HF	T_{c1} x T_s	T_{c2} x HF	T_{c2} x T_s
PECTORAL	0.27	0.69	0.31	0.67	0.45	0.87	0.45	0.86
THIGH	0.51	0.63	0.54	0.60	0.73	0.73	0.75	0.73
SCAPULA	0.36	0.67	0.39	0.56	0.47	0.87	0.52	0.83
STERNUM	0.27	0.70	0.30	0.69	0.49	0.85	0.51	0.85
RIB	0.43	0.55	0.48	0.50	0.66	0.64	0.68	0.62
HEAD	0.34	0.43	0.37	0.39	0.60	0.68	0.60	0.70

In general the individual correlations were greater between T_s x T_{core} than for HF x T_{core} . The highest correlations for the more generalized, combined ALL DATA set for T_{c1} and T_{c2} x HF were the THIGH, and the RIB and HEAD locations was also relatively high. The lowest values for HF x T_{core} were obtained for the STERNUM location. For T_s , the STERNUM site had the highest correlation, but the value for the PECTORAL location was essentially equivalent. The lowest values for T_s x T_{core} were for the HEAD location.

For the more selective, energy-intensive WALK DATA, the correlations for both T_s and HF were stronger. For HF, the highest correlations were again at the THIGH and RIBS locations, and the lowest for the other locations on the torso. For T_s , the correlation for the PECTORAL location was high, but the STERNUM and SCAPULA value were essentially equivalent. The lowest values were for the HEAD and RIBS. In terms of specific measurements sites, Xu et al. (2013) performed a detailed analysis the relation between HF, T_s and T_{core} in order to develop a model to predict T_{core} using non-invasive measurements of HF and T_s . Their results are summarized in the Discussion section.

DISCUSSION

Body Armor

At present, most U.S. military operations are carried out by personnel wearing BA. Table 2 indicates the additional physical burden imposed by the weight of body armor. In addition the insulation and mass may have an influence on heat exchange, and may impede or hobble freedom of motion. Clothing insulation and water vapor permeability (i_m) are important data for thermal model development and testing (Potter et al., 2014). Values for the dry insulation value (clo) and maximum evaporative capacity (i_m/clo) for an ACU without BA are 1.08 clo and 0.47 clo^{-1} respectively and 1.18 clo and 0.41 clo^{-1} for the ACU with BA, including SAPI plates, both measured at 1.0 m/s (Santee & Friedl, 2014; Potter et al., 2013b).

In terms of the impact of body armor, as both physical effects on heat exchange and the impact of additional weight and hobbling, it would have been useful to run an additional control of the Volunteers in their uniforms without body armor in at least the moderate WN25 condition.

Physiological Responses (general)

In general, there were statistically significant differences between WLK1 and WLK2. In the warm-neutral (WN25 = 25°C, 50% RH) condition, all but 1 Volunteer completed the entire test session. Only 3 of 9 volunteers were able to complete the full 60 min second walk in the hot-humid (HH35 = 35°C, 70% RH) condition. Due to a non-study related illness, one subject was unable to walk long enough in the hot-dry environment to provide the second walking $\dot{V}O_2$ value. Of the remaining 8 Volunteers, 7 completed the entire test session in the hot-dry (HD40 = 40°C, 20% RH) condition. Table 8 presents the duration of the second walk and the total test duration or walk time. The differences in duration for WLK2 and the total walk time are only significant between HH35 and HD40, but were close ($p = 0.056$) to being significant among all three environment. The endurance times in Table 8 are indicative of a general observation that the warm-neutral (WN25) condition was the more moderate, and least stressful, environment whereas the hot-humid (HH35) condition, was the most stressful. Consequently, significant differences were more common between those extremes, with

values for HD40, the hot-dry environment, falling between the two other two environments.

In general, when there were significant differences between test conditions, these were most likely to be found between relative extremes, i.e. the conditions that were the least similar, i.e., the least stressful, more moderate 25°C, 50% RH condition (WN25) and the more stressful hot-humid 35°C, 70% RH condition (HH35). The hot-dry 40°C, 20% RH condition (HD40) was generally found to be between the two other conditions, and, in general, unless there was a significant difference between WN25 and HH35, there was no significant difference involving HD40. In addition, significant differences were more likely to occur during the second walk, when the metabolic rates were higher, and the Volunteers had already testing for over 90 min.

Metabolism

For this test design, there were no statistically significant differences in metabolic rate between the three environments. As per the test plan, there was a significant difference in metabolic rate between the two walks. The small increase in metabolic costs between the initial standing period and the standing data prior to the second walk may reflect a small thermoregulatory cost or a residual effect from the first walk and activity during the break period.

The PE underestimated metabolic costs for WLK1, but is in close agreement with the measured values for WLK2. For the standing metabolic costs PE underestimated the observed value for STD1, and significantly over-estimated it for STD2.

Response to Environmental Conditions

Given that metabolic heat production is equal for all three environments, following the basic principles of heat balance, differences in physiological responses are likely to be related to differences between the environments in terms of thermal stress, and more specifically to the potential for heat gain or loss between the body and the environment.

The WN25 25°C, 50% RH chamber condition was selected to minimize thermal strain relative to the two other more extreme chamber conditions. Thus significant differences between one or both the HH35 35°C, 70% RH and HD40 40°C, 20% RH conditions are also an expected result. In general the overall stress in the hot-humid conditions (HH35) were the most stressful, and thus the metrics for the physiological responses to hot-dry conditions often fell between the warm-neutral and hot-humid conditions. Overall the statistical analyses support these general observations.

Specific Physiological and Performance Measurements

Heart rate (HR) measurements clearly support the assumption that hot-humid conditions are more stressful than hot-dry and more neutral conditions. As expected with an increase in walking speed and grade (Table 4), there was a significant difference between WLK1 and WLK2 for mean HR, the net change in HR and the final

HR. Mean HR was significantly different between all environments for both WLK1 and WLK2 (Table 9A). For the final HR, the differences were significant between all environments for WLK1, and significantly different between 25°C and both 35° and 40°C (Table 9B) for WLK2. Another possible indicator of increasing strain over time is the change (increase) in HR over the walk periods (Table 9C). There were significant differences between environments for WLK1, but not WLK2. The lack of any significance for the second walk may in part be due to the greater variability in HR during that period of greater activity.

Duration or total walking time is confounded by the set maximum exposure time. If Volunteers had been able to continue walking beyond the 60 min limit for WLK2, the mean and final T_{core} values during the hot-dry exposure, their times would probably have been higher if the walk had continued. In contrast, Volunteers essentially reached their personal limits in the hot-humid conditions during WLK2. Therefore it may be more important to consider the rate of increase in T_{core} than the final or maximum T_{core} values.

T_{core} Measurements

T_{core} measurement sites: The best location for invasive measurements of core temperature is the subject of an on-going debate. The most common locations proposed are esophageal, aural or tympanic, and rectal. Although the investigators' perception was that the suppository T_{core} ($T_{\text{c}2}$) tended to be higher than the ingested T_{core} ($T_{\text{c}1}$), and there was an overall significant difference, when examined by environment, a significant difference was found only for the milder 25°C, 50% RH condition. One possible interpretation is that as stress and higher internal temperatures increased, tissue temperatures tended to be more homogeneous, and thus T_{core} values would converge.

Core temperature variables: In general, significant differences were more likely to occur during the more stressful WLK2, and between the environments generally considered to be the least (WN25) and most stressful (HH35). This pattern was observed for the final T_{core} (fT_{c}), the mean T_{core} (mT_{c}) and the rate of change in the T_{core} (rT_{c}). The exception is for the change in T_{core} (ΔT_{c}) during WLK2. One possible explanation is that all of the Volunteers completed WLK1, but only 3 Volunteers completed the full hour of testing in HH35, and 7 in HD40 (Table 5).

Core temperature based thresholds: The subjective observation that volunteers that reached a T_{core} of 39.5°C were essentially exhausted was consistent with observations made during many protective clothing laboratory studies in which the authors participated. However, some studies have concluded that lightly dressed, well-trained athletes can safely tolerate $T_{\text{core}} > 40^\circ\text{C}$ (Ely et al., 2009). The presence of heavier clothing in terms of weight and insulation, and reduced clothing permeability to water vapor may lower the T_{core} based threshold for heat tolerance. A variety of factors can influence heat tolerance beside T_{core} , including mean T_{s} , HR, uncompensable heat gain, individual fitness, and heat acclimatization. It is sometime useful to incorporate some of these factors by calculating a mean body temperature (T_{b}) using weighted

equations that use both T_{core} and mean T_{s} . The Physiological Strain Index (PSI) combines T_{core} and HR (Moran et al., 1998).

Fluid balance and sweating: The calculation of effective sweat loss or evaporative cooling is based on the change in weight at the beginning and end of the walks and break, less any water consumption or urine loss. Sweat loss was significantly greater in the hot, dry condition (HD40) where the environmental conditions were more favorable to evaporation. The increased evaporative cooling is reflected in the longer exposure time (Table 5) and lower T_{core} (Table 9) relative to the hot-humid condition (HH35), despite a higher air temperature.

Heat flux and skin temperature: The correlations for “all data” are more relevant to the development of a general relationship between HF, T_{s} and T_{core} . Xu et al. (2013) derived equations to predict T_{core} using a combination of HF and T_{s} for single locations and pairs of locations. The best single heat flux sensor site was the STERNUM, and the best set of combined set of locations were the STERNUM, SCAPULA and RIB locations. The worst location, possibly due to sweating effects, was the HEAD. The STERNUM was probably the best site, despite a relatively low correlation between T_{core} and HF due to the high correlation between T_{core} and T_{s} . The combined contribution of T_{s} and HF resulted in the best overall performance. A caveat was added to the results indicating that the findings were specific to the results for specific type of clothing ensembles (BA) tested.

Heat Flux, Skin Temperature and Heart Rate:

Given the results described for HR, adding a third variable, HR, to represent metabolic heat generation to predict T_{core} using only non-invasive physiological measurements, might further improve the accuracy of T_{core} predictions.

CONCLUSIONS

As noted, this is a descriptive paper primarily intended to document the study methods and initial results rather than the final products, which are envisioned to include a non-invasive predictor of T_{core} (Xu et al, 2013), a more accurate method to estimate of total body heat loss, and use of this data to develop and/or validate thermoregulatory models. These data will be especially useful for validating thermal models of individuals wearing body armor (BA).

- The preponderance of the statistical analyses regarding the effect of environmental condition on thermal strain support the conclusion that the hot-humid conditions were the most stressful in terms of T_{core} , HR and duration of exposure. As expected, water loss is greater in the hot-dry condition, but the net result is greater evaporative cooling (effective sweat) despite a higher air temperature and the presence of body armor.
- The correlation matrix for HF and T_s values indicates a stronger correlation between T_s and T_{core} than HF and T_{core} . A more refined analysis was required to derive an accurate prediction of T_{core} from non-invasive surface measurements (Xu et al., 2013).
- This study provides a data set for further model development, refinement, and validation.

RECOMMENDATIONS

In regard to the goal of developing a database for developing a non-invasive method for estimating T_{core} , an additional control set of treatments without body armor would be of value. Data for expanding, refining and/or validating the HF-based estimate of T_{core} could be collected as ancillary data during other ongoing USARIEM thermal (heat and cold) studies.

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