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THERMAL-WORK STRAIN DURING MARINE RIFLE SQUAD OPERATIONS IN AFHGANISTAN (MARCH 2010)

United States Army
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14. ABSTRACT

The United States Marine Corps (USMC) Program Manager Marine Expeditionary Rifle Squad (PM MERS) has conducted a series of in-theater equipment surveys and analyses with Regimental Combat Teams (RCT) stationed in Iraq and Afghanistan. Anecdotal evidence from 2007 suggested that Marines in Iraq experienced high heat strain while performing missions in full combat gear (assault loads), especially during the summer months. In conjunction with the United States Army Research Institute of Environmental Medicine (USARIEM), PM MERS successfully used ambulatory physiological monitors to evaluate thermal-work strain (heat strain) during Marine RCT missions in Iraq during the summer of 2008 [3]. The data collected during this time period confirmed that Marines experienced high levels of thermal-work strain even during low intensity missions. In 2009 the Marine Corps mission focus switched to Afghanistan. This technical report details the physiological status of Marines engaged in regular dismounted missions under spring time conditions in Afghanistan with 2nd Battalion 2nd Marines RCT 7 (March 2010).

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BACKGROUND

The United States Marine Corps (USMC) Program Manager Marine Expeditionary Rifle Squad (PM MERS) has conducted a series of in-theater equipment surveys and analyses with Regimental Combat Teams (RCT) stationed in Iraq and Afghanistan. Anecdotal evidence from 2007 suggested that Marines in Iraq experienced high heat strain while performing missions in full combat gear (assault loads), especially during the summer months. In conjunction with the United States Army Research Institute of Environmental Medicine (USARIEM), PM MERS successfully used ambulatory physiological monitors to evaluate thermal-work strain (heat strain) during Marine RCT missions in Iraq during the summer of 2008 [3]. The data collected during this time period confirmed that Marines experienced high levels of thermal-work strain even during low intensity missions. In 2009 the Marine Corps mission focus switched to Afghanistan. This technical report details the physiological status of Marines engaged in regular dismounted missions under spring time conditions in Afghanistan with 2nd Battalion 2nd Marines RCT 7 (March 2010).

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Special thanks to the test volunteers from the 2^{nd} Battalion 2^{nd} Marines Regimental Combat Team Seven (RCT-7) who made this study possible. The authors would also like to thank the 14^{th} Weather Squadron for providing the weather data necessary for modeling and Dr. Larry Berglund, Dr. William Santee, Dr. Miyo Yokota, and Mr. Julio Gonzalez for their assistance in preparing this technical report.

EXECUTIVE SUMMARY

The purpose of this study was to characterize the thermal-work strain of Infantry Marines in Afghanistan while performing dismounted activities. Originally, data collection was planned for both spring (baseline) and summer (high heat conditions) months. However, access to Afghanistan in 2010 was only granted for a spring study (March 2010). This technical report details the thermal-work strain experienced by Marines during spring RCT missions and uses physics and physiology based thermo-regulatory models to predict thermal-work strain for the summer months.

Heart rate (HR), core body temperature (Tcore), and activity counts were recorded from 31 USMC test volunteers from the 2nd Battalion 2nd Marines (2/2) Regimental Combat Team Seven (RCT-7). The test volunteers were stationed in COP Sher, Helmand Province, Afghanistan and data were collected while they engaged in regular mission duties from 19 to 24 March 2010. The environmental conditions the Marines operated in were temperate with mean air temperatures (Ta) between 15.6 ºC (60.1 ºF) and 25.5 ºC (77.9 ºF) and mean relative humidity (RH) between 20.2% and 48.4%. All mission periods occurred during "white" Wet Bulb Globe Temperature (WBGT) flag conditions [15]. The combination of combat load and mission demands resulted in mean estimated metabolic rates of between 230 and 530 W. Mean physiological strain index (PSI) values were between 1.5 and 5.2 PSI units, indicating overall low thermal-work strain [10]. However, there were instances of prolonged heavy work and acute very heavy work that resulted in moderate physiological strain levels no greater than 7 PSI units on a scale of 1 to 10.

Mission period metabolic rate profiles were calculated using heart rate and air temperature [1]. Data from the three most physically demanding Marine mission periods were used as inputs for the SCENARIO thermoregulatory rational model [6, 7] to estimate the Marines' Tcore and HR during an average summer (July) day in Afghanistan. Estimated summer weather conditions were not extreme as the mean air temperature was between 24.9 ºC (76.8 ºF) and 31.3 ºC (88.3 ºF) and mean relative humidity was between 18.0% and 31.5%. These weather conditions corresponded to "white" WBGT flag conditions [15] yet, both chronic heavy work (>600 W) and acute very heavy work (>800 W) could have resulted in significant thermal-work strain levels (PSI > 9).

The Marines we studied in Afghanistan wore C&IE ensembles including the less occlusive Scalable Plate Carrier (SPC) rather than the Modular Tactical Vest (MTV) worn by volunteers during the Iraq study. As both are currently available for use by Marines, we examined the thermal burden of each uniform system and found that the ensemble including the SPC was associated with lower Tcore and PSI values (0.4 to 1.4 °C and 0.8 to 2.4 PSI units respectively) but does not provide the same type of protection as the ensemble including the MTV (e.g., the SPC provides direct weapons fire protection while the MTV provides blast and fragmentation protection).

INTRODUCTION

The prevention and management of heat illness is an ongoing concern of the USMC, especially given their demanding training and mission requirements. This concern is well placed given that the USMC reports a significant rate of both heat stroke (0.33/1000 persons per year) and other heat injury (2.79/1000 persons per year) [11].

The USMC has led the way in implementing heat casualty prevention measures. The current military heat injury prevention guidelines [15] use environmental heat categories based upon the WBGT index to set mission work-rest schedules and water consumption guidelines. The WBGT index, developed by Yaglou and Minard [17, 18], used data from USMC training centers to provide a basis for adjusting physical work intensity to local environmental conditions. By adopting the WBGT system, the USMC was able to reduce the incidence of heat illness [8, 9]. However, the use of WBGT and adherence to military heat injury prevention guidelines (e.g., TB MED 507) has not eliminated all cases of heat illness [5].

Marines must often perform strenuous missions under hot “black flag” [3] conditions. In these circumstances, a need exists for more precise predictive models that provide detailed estimates of individual responses. Also, the ability to monitor and record thermal-work strain during Marine patrols provides data to update physiological models and could provide real time thermal-work strain awareness. Although the risk of heat illness injury can be mitigated through the use of WBGT, current work/rest schedules only provide rough guidance to limit heat casualties and do not indicate the level of strain experienced by individual warfighters. An assessment of U.S. Marines conducting normal patrols in Iraq during the summer of 2008 [3] found high levels thermal-work with PSI [10] values in excess of 7. This high strain occurred at the end of a slow foot patrol, where squad members had followed TB MED 507 work/rest schedules and water intake guidance. Rational physics and physiological based thermal models [2] were used to explore the amount of reserve time available to the Marines at the end of the patrol if they needed to increase their work rate. The analysis found that under the severe summer temperatures in Iraq that Marines had very limited work times (< 14 min) at high work rates (>600 W) before being at high risk of heat illness and exhaustion.

The purpose of the present study was to characterize the thermal-work strain of Infantry Marines performing dismounted activities in Afghanistan. Originally, it was anticipated that data collection would occur during both the spring (baseline) and summer (high heat conditions) months. However, access to Afghanistan was only granted for the March 2010 study. This technical report details the thermal-work strain of the Marines during spring time RCT missions and uses rational physics and physiology based thermo-regulatory models to predict thermal-work strain for the summer months.

METHODS

The thermal-work strain experienced by USMC volunteers located at COP Sher, Helmand Province, Afghanistan, was assessed during routine missions between the 19 and 23 March, 2010. Individual physiological data (heart rate, respiratory rate, core body temperature, and body motion) were collected using a chest-mounted physiological status monitor (PSM) sensor system, along with contextual information such as meteorology, clothing characteristics, individual equipment descriptions, and mission profiles.

VOLUNTEERS

Thirty-one USMC volunteers (age = 22.4 ± 2.7 yr, height = 180 ± 10 cm, weight = 82.4 ± 11.7 Kg, 3 mile run time = 20.3 ± 2.1 minutes) from 2nd Battalion 2nd Marines Regimental Combat Team Seven (RCT-7) stationed at COP Sher, Helmand Province, Afghanistan participated in this study. Participants volunteered for this study after being briefed on the research procedures and risks.

MISSIONS

Seven mission periods were recorded between 19 and 23 March, 2010. During missions, activities including dismounted and mounted patrols, guard duty, and rifle range/squad rush training with Afghani police forces.

SCIENTIFIC EQUIPMENT

Physiological Monitoring

Each volunteer wore a PSM comprised of a chest worn belt system (Equivital-1, Hidalgo Ltd. Cambridge UK) and ingested one or more thermometer pills (Jonah ™ Core Temperature Pill, Respironics, Bend OR). The PSM system measured heart rate (electrocardiogram waveform), respiration rate (from chest expansion/contraction waveform), activity level (three dimensional accelerometer waveforms), and core body temperature (from thermometer pill) every 15 seconds.

Meteorology

Meteorological data were collected at Kabul Airfield by the 14th Weather Squadron (Asheville, NC). Ambient temperature, dew point, wind speed (WS), and black globe temperature (Tbg) were provided for 19 to 23 March 2010 as well as for 17 to 25 July 2010. Relative humidity was calculated from air temperature and dew point using the National Weather Service's Meteorological Calculator [12]. The meteorological values recorded at the Kabul Airfield in July 2009 were averaged by hour to provide a composite 24 hour day that represented July weather (summer) in Kabul Afghanistan and the surrounding area.

MEASURES

Heart rate and core body temperature were used to document the thermal-work strain experienced by each Marine. The PSI [10], a measure combining HR and Tcore, was calculated as an overall indicator of thermal-work strain.

Height (self-report), body weight, and waist circumference at the navel (anthropometric tape measure) were measured to estimate percent body fat using Wright and Wilmore's technique [16]. Body weight (semi-nude with shorts and t-shirt) and fighting weight (total weight with combat clothing and equipment) were also measured for use as model inputs.

All test volunteers provided a self-reported 3-mile run time, a standard USMC physical training benchmark. The 3-mile run times were used as an indicator of aerobic fitness.

Clothing and individual equipment (C&IE) were recorded at the start of each mission by photograph and description. The clothing insulation (clo) and vapor permeability (Im) of Marine C&IE ensembles were estimated from existing copper manikin data, uniform descriptions, and the recorded in-field configurations.

Mission profiles (e.g., vehicle movement, foot patrol, rest) were recorded by the in-theatre investigator who accompanied the Marines on their mission. Additionally, three dimensional accelerometry data from the chest-mounted PSM device were used to provide an estimate of work intensity in the form of activity counts. Activity counts were calculated for each 15s sample period using the accelerometry wave forms (sampled at 25.6 Hz). Waveforms were normalized (differentiated) to remove the effect of gravity and activity counts were computed as follows:

Where *AC* = acceleration (mG), *t* = sample, *n* = accelerometer channel.

Metabolic rates ( ) for missions were estimated using individual subjects HR ratio (HRR) and Ta [1] (See Biomedical Modeling Analysis below).

PROCEDURES

Thermometer pills were orally administered to volunteers the evening prior to the initiation of data collection. The following morning volunteers would meet with study staff to don the PSM chest belt system according to the manufacturer's instructions and have waist circumferences and semi-nude weights measured. If time constraints did not allow for weight or waist circumference measurement prior to donning the PSM system, the measurements were obtained at the volunteers' convenience. On days one, two, and three of data collection, volunteers were instructed to wear the PSM chest belt for 24 hrs and record any physical activity (e.g., foot patrol, physical training) that they took part in during that time frame. The following morning volunteers returned the PSM chest belts to study staff. At this time an interview was conducted to determine type of physical activity, the time it took place, and the equipment worn. For subsequent data collection days, volunteers were instructed to wear the PSM during specific missions. Volunteers would don the PSM device and C&IE. At the conclusion of the mission, combat loads and body armor were removed.

BIOMEDICAL MODELING ANALYSIS

The USARIEM SCENARIO model [6] was used to predict the affect on Tcore of conducting the three most stressful mission profiles (determined by PSI) with environmental conditions likely to be experienced during a typical July day in Afghanistan. The effects of two clothing and equipment ensembles, one that was estimated from what Marines were observed to wear in Afghanistan and one previously observed in Iraq, were also examined. The SCENARIO model predicts Tcore given a number of input parameters such as: metabolic rate ( ), environmental parameters, clothing vapor permeability, clothing insulation, individual anthropometric measures (% body fat, height, and weight), and acclimation state (all subjects were modeled as acclimated). The only unknown parameter for our modeling effort was .

<u>Metabolic Rate Estimation</u>

Often, in the field can be estimated using the Pandolf equation [13] and global positioning system (GPS) data to estimate movement rates. However, due to operational security reasons, global positioning system (GPS) data loggers were not allowed on this study. We pursued an alternate approach by applying a technique used in the Initial Capability Decision Aid (ICDA) [19] that calculates metabolic rate from resting heart rate (RHR), HR, and Ta. This model uses a metabolic estimator developed by Berglund [1]:

(1)

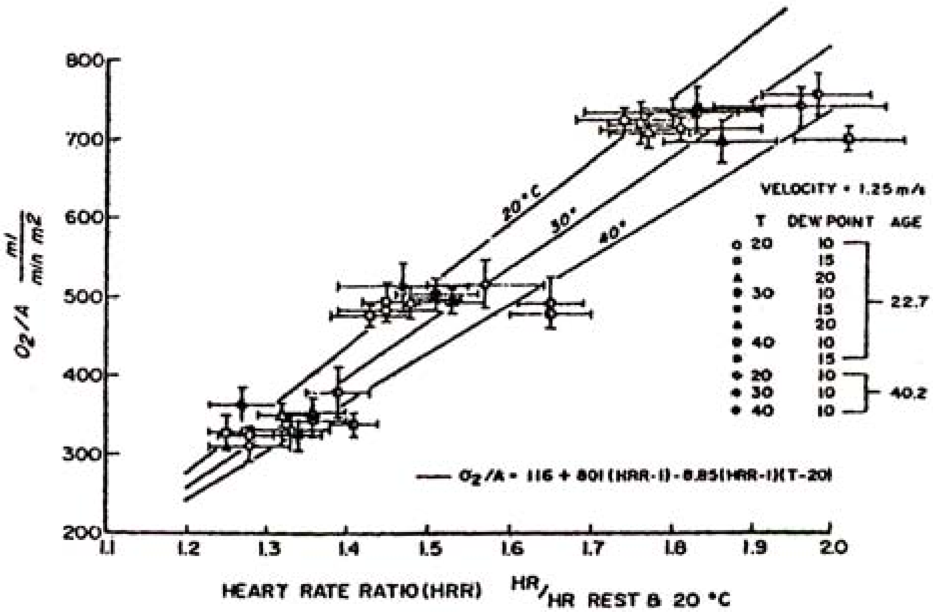
Where HRR is exercise heart rate divided by the resting heart rate at 20 °C and one MET unit is a normalized measure of energy production for a sedentary person. Thus:

Where *Da* = Dubois surface area which is calculated as:

Where *M* = body mass (kg), *H* = height (m).

This equation has been used successfully in the ICDA model, but can suffer from over estimations of under some conditions [4]. Overestimation errors are especially pronounced when the HRR exceeds 2. Figure 1, taken from Berglund's original paper, demonstrates that the original estimator is derived from data for which HRR are less than 2.0. Thus, to provide better estimates of we derived new tempered line equations for HRR values above 2.0.

Figure 1: O_2 Consumption Normalized to Body Surface Area by Heart Rate Ratio and Air Temperature from Berglund (1977).



The slope and intercept of each new linear equation was determined parametrically for each volunteer for each mission profile in the following way:

- When HRR ≤ 2.0 equation (1) was used to determine .
- When HRR > 2.0 the grade of the line was incrementally adjusted between 0 and the grade reported by Berglund.

For each test volunteer the metabolic rates generated by this series of linear equations were used as inputs for SCENARIO. The Tcore values SCENARIO returned were then compared to observed Tcore values. For HRR values greater than 2, the adjusted linear equation with the smallest Tcore root mean square error (RMSE) from the observed Tcore was selected and used at the corresponding Ta.

RESULTS

METEOROLOGICAL CONDITIONS

Table 1 shows the air temperature, relative humidity, wind speed, dew point and black globe temperatures for each of the mission periods, along with the WBGT and flag color [15]. Table 2, shows the summer environmental parameters derived for use in the SCENARIO model to estimate Tcore.

Table 1: March (spring) measured environmental conditions for each mission period (min to max and average ± standard deviation).

Activity Period	Air Temperature (°C)		Relative Humidity (%)		Wind Speed (m/s)		Dew Point (°C)		Black Globe (°C)		WBGT (°F)		Flag
	Min to Max	Average	Min to Max	Average	Min to Max	Average	Min to Max	Average	Min to Max	Average	Min to Max	Average	
A: March 19: 0800-1300 Stood Guard	14.0 - 25.0	20.3 ± 3.8	14.0 - 41.0	24.3 ± 9.2	1.0 - 3.6	2.0 ± 0.8	-4 - 1.0	-1.6 ± 1.6	22.5 - 51.5	40.8 ± 10.2	51.8 - 67.8	61.6 ± 5.7	White
B: March 19: 0800-1000 Dismounted Patrol	14.0 - 21.0	18.0 ± 3.2	21.0 - 41.0	29.3 ± 9.2	1.0 - 3.6	2.3 ± 1.1	-2.0 - 1.0	-0.8 ± 1.5	22.5 - 43.0	34.9 ± 9.5	51.8 - 62.2	58.3 ± 4.9	White
C: March 19: 1600-1900 Dismounted Patrol	23.0 - 27.0	25.5 ± 1.9	13.0 - 18.0	14.8 ± 2.2	1.5 - 6.1	2.9 ± 2.2	-7.0 - 1.0	-3.5 ± 2.5	23.5 - 45.0	33.6 ± 9.7	55.3 - 67.1	61.9 ± 5.2	White
D: March 20: 2200-0100 Dismounted/ Mounted Patrol	14.0 - 17.0	15.6 ± 1.1	42.0 - 59.0	48.4 ± 6.4	0.0 - 3.6	1.4 ± 1.3	4.0 - 6.0	4.6 ± 0.9	14.5 - 18.0	16.2 ± 1.3	51.5 - 53.6	52.5 ± 0.9	White
E: March 22: 0630-1130 Dismounted/ Mounted Patrol	11.0 - 21.0	16.0 ± 4.3	23.0 - 67.0	45.6 ± 18.4	1.0 - 2.6	1.8 ± 0.5	-1.0 - 5.0	3 ± 2.4	14.5 - 45.5	33.2 ± 13.3	48.9 - 64.0	58.1 ± 6.7	White
F: March 22: 1500-1830 Dismounted Patrol	21.0 - 22.0	21.4 ± 0.5	21.0 - 29.0	25.6 ± 3.4	3.6 - 8.7	5.3 ± 2.0	-2.0 - 3.0	0.8 ± 2.2	22.0 - 35.0	27.9 ± 5.9	55.3 - 62.2	58.7 ± 3.4	White
G: March 23: 0800-1700 Dismounted/ Mounted Patrol, Firing Range	13.0 - 22.0	19.6 ± 2.9	13.0 - 51.0	20.2 ± 10.8	1.0 -3.6	2.4 ± 0.8	-8.0 - 3.0	-5.1 ± 3.1	23.5 - 49.5	36.5 ± 8.0	52.8 - 63.9	58.2 ± 3.9	White

Table 2: July (summer) estimated environmental conditions for each mission period (min to max and average ± standard deviation).

Summer Activity Period	Air Temperature (°C)		Relative Humidity (%)		Wind Speed (m/s)		Dew Point (°C)		Black Globe (°C)		WBGT (°F)		Flag
	Min to Max	Average	Min to Max	Average	Min to Max	Average	Min to Max	Average	Min to Max	Average	Min to Max	Average	
A: 0800-1300 Stood Guard	24.6 - 31.7	28.6 ± 2.6	16.0 - 33.0	23.0 ± 2.6	1.4 - 4.1	2.9 ± 1.2	2.6 - 7.2	4.9 ± 3.1	40.1 - 50.5	47.7 ± 3.9	68.8 - 74.5	72.8 ± 3.1	White
B: 0800-1000 Dismounted Patrol	24.6 - 28.6	26.6 ± 2.0	22.0 - 33.0	27.7 ± 5.5	1.4 - 2.4	1.8 ± 0.5	5.0 - 7.2	6.3 ± 2.1	40.1 - 49.7	45.6 ± 5.0	68.8 - 73.7	71.6 ± 2.1	White
C: 1600-1900 Dismounted Patrol	28.7 - 32.0	30.4 ± 1.5	16 - 24	20.0 ± 3.4	5.8 - 6.8	6.2 ± 3.4	3.4 - 6.0	4.9 ± 2.1	30.2 - 43.3	37.1 ± 5.7	67.0 - 72.6	70.4 ± 2.1	White
D: 2200-0100 Dismounted/ Mounted Patrol	24.3 - 25.6	24.9 ± 0.6	30.0 - 34.0	31.5 ± 0.6	3.1 - 5.0	4.3 ± 0.3	5.4 - 6.9	6.2 ± 0.9	24.3 - 26.1	25.1 ± 0.6	62.5 - 63.4	63.0 ± 0.9	White
E: 0630-1130 Dismounted/ Mounted Patrol	22.0 - 29.7	26.3 ± 3.1	20.0 - 33.0	27.2 ± 6.1	1.1 - 4.3	2.4 ± 1.0	4.3 - 7.6	6.1 ± 2.6	30.9 - 49.7	43.4 ± 7.9	64.1 - 73.7	70.5 ± 2.6	White
F: 1500-1830 Dismounted Patrol	29.9 - 32.0	31.3 ± 1.0	16.0 - 21.0	18.0 ± 2.4	4.6 - 7.6	5.5 ± 0.7	3.2 - 5.6	4.2 ± 2.0	35 - 46.1	41.1 ± 4.8	69.2 - 73.4	71.6 ± 2.0	White
G: 0800-1700 Dismounted/ Mounted Patrol, Firing Range	24.6 - 32.3	29.9 ± 1.1	15.0 - 33.0	20.4 ± 5.9	1.1 - 5.0	3.7 ± 1.6	2.4 - 7.2	4.3 ± 2.9	39.9 - 50.5	46.5 ± 4.1	68.8 - 74.5	72.9 ± 2.9	White

MISSIONS

Table 3 presents the mission profiles for the seven mission periods during which data were collected. Missions consisted of patrols with mounted and dismounted portions, standing guard, and rifle range/squad rush training with Afghani security forces. All mission periods were reported by volunteers as light to moderate physical activity except for 0800-1700 on 23 March which had no description reported. Table A1 in Appendix A provides a list of military activities and associated metabolic rates for comparison.

Table 3: Mission description, number of subjects, self reported physical intensity levels, and mean metabolic rate estimate.

	Date	Time	Activity	N	Perceived Physical Intensity	Estimated Mean Metabolic Rate ± Standard Deviation (W)
A	19 March	0800-1300	Stood Guard	2	Not Reported	233 ± 67
B	19 March	0800-1000	Dismounted Patrol	7	Light to Moderate	434 ± 75
C	19 March	1600-1900	Dismounted Patrol	6	Not Reported	514 ± 71
D	20 March	2200-0100	Dismounted/ Mounted Patrol	4	Light	136 ± 22
E	22 March	0630-1130	Dismounted/ Mounted patrol*	5	Moderate	254 ± 56
F	22 March	1500-1830	Dismounted Patrol	5	Light to Moderate	529 ± 85
G	23 March	0800-1700	Dismounted/ Mounted Patrol, Firing Range**	5	Not Reported	321 ± 156

*Subjects engaged in different mounted and dismounted activities throughout this mission period (e.g., swept for IEDs, posted security, remained mounted, unloading equipment).
**Includes dismounted/mounted patrol periods, squad rush drills, and firing range assembly/disassembly.

During the 0630 to 1130 dismounted patrol on 22 March Mission Period E, mission activities were further specified as including sweeping for improvised explosive devices (IEDs), posting security, remaining mounted, and unloading equipment. The patrol on 23 March 2010, which had mounted and dismounted portions, was followed by the assembly of a firing range, marksmanship training, squad rush exercises, and firing range breakdown before the Marines remounted to return to base. Figure 2 shows photographs representative of mission environments and the vehicles used by the 2/2nd

Figure 2: Mission Area Photographs for the 2nd Battalion 2nd Marines. Panel A: Guard Post. Panel B: Dismounted Marines on patrol. Panel C: rest from movement and team vehicles. Panel D: guard post.

TEST VOLUNTEER CHARACTERISTICS

Table 4 presents volunteer characteristics (age, 3 mile run time, percent body fat, height, weight, load carried, and waist circumference) by mission period.

Table 4: Volunteer characteristics by mission period.

	Date, Time, and Mission Period							
	A 19 March Guard Duty 0800-1300 (N = 2)	B 19 March Patrol 0800-1000 (N = 7)	C 19 March Patrol 1600-1900 (N = 6)	D 20 March Patrol 2200-0100 (N = 4)	E 22 March Patrol 0630-1130 (N = 5)	F 22 March Patrol 1500-1830 (N = 5)	G 23 March Mult. Act. 0800-1700 (N = 5)	Combined Cohort (N = 31)
Age (yr)	25.0 ± 1.4	22.0 ± 2.9	22.0 ± 2.6	21.0 ± 1.8	22.3 ± 1.3 (N = 4)	22.4 ± 2.7	20.6 ± 1.5	22.4 ± 2.7 (N = 28)
3 Mile Run Time (min)	21.5 ± 0.0 (N = 1)	21.1 ± 2.1 (N = 6)	20.3 ± 1.3	17.7 ± 0.9 (N = 3)	20.1 ± 1.8	20.7 ± 1.5	19.2 ± 2.2 (N = 3)	20.3 ± 2.1 (N = 26)
Body Fat (%)	19.4 ± 2.6	12.5 ± 2.8	14.0 ± 2.6	14.8 ± 5.2	13.9 ± 7.2 (N = 4)	15.7 ± 3.5	14.0 ± 4.3	14.8 ± 5.0 (N = 28)
Height (m)	1.8 ± 0.0	1.8 ± 0.1 (N = 5)	1.8 ± 0.0 (N = 4)	1.8 ± 0.1	1.8 ± 0.0 (N = 4)	1.8 ± 0.0 (N = 4)	1.8 ± 0.1	1.8 ± 0.1 (N = 27)
Weight (kg)	89.1 ± 13.2	79.8 ± 3.4	79.3 ± 3.3	75.1 ± 8.6	84.2 ± 11.0 (N = 4)	82.4 ± 9.5	83.7 ± 16.3	82.4 ± 11.7 (N = 29)
Load (kg)	29.1 ± 2.1	31.0 ± 3.8	31.9 ± 3.8 (N = 5)	32.6 ± 9.3	24.5 ± 3.2 (N = 4)	30.8 ± 3.1	27.0 ± 3.1	28.6 ± 5.5 (N = 24)
Waist (cm)	89.2 ± 4.9	80.4 ± 2.0 (N = 6)	81.5 ± 2.4	82.8 ± 8.0	82.7 ± 9.9	83.7 ± 5.2	82.9 ± 8.4	83.7 ± 7.5 (N = 31)

If data is missing from one or more volunteers in a given mission period a new N value is listed.

CLOTHING AND EQUIPMENT CHARACTERISTICS

Volunteers from the 2/2nd reported wearing the Flame Retardant Organizational Gear (FROG) uniform, SPC, front, back and side Enhanced Small Arms Protective Insert (E-SAPI) plates, and a lightweight helmet. Figure 3 shows a typical C&IE configuration for the 2/2nd.

Figure 3: Typical Clothing and Individual Equipment Configurations for 2nd Battalion 2nd Marines and Vital Sign Detection System. Panels A, B, and D represent typical C&IE configurations. Panel C shows the PSM unit with prototype heat flux disc attached.

Various uniform configurations with their associated insulation factor and vapor permeability measured using the USARIEM copper manikins are shown in Table 5. For modeling purposes we used ensemble number 4 for the uniform configuration in Iraq, and ensemble number 2 for the uniform configuration used in Afghanistan. Figure 4 shows two types of protection ensembles worn over the Marine Corps Combat Utility Uniform (MCUU): Figure 4A is the MTV which protects against blast and fragmentation and was worn by our volunteers in Iraq. Figure 4B is the SPC which protects against direct weapons fire and was worn by our volunteers in Afghanistan (note: currently both SPC and MTV are worn in Afghanistan depending on the threat anticipated).

Table 5: Water vapor permeability and insulation values of various clothing and individual equipment ensembles.

Uniform Ensemble	Insulation Factor (clo)	Vapor Permeability (Im)	Im/clo
1. Army Combat Uniform (ACU) + t-shirt	1.08	0.50	0.46
2. ACU + t-shirt Interceptor Body Armor (IBA) w/ SAPI plates + Helmet + Green Socks + black leather boots	1.30	0.42	0.33
3. Flame Resistant ACU + t-shirt + IBA + Helmet	1.33	0.43	0.32
4. Flame Resistant ACU + t-shirt + IBA + Helmet + Weapon + Ammunition + Other encumbrances	1.52	0.40	0.29

Note: Im is a nondimensional index value where 0 = impermeable and 1 = bare skin. Clo measures total insulation of ensemble. Im/clo indicates the ratio approximate “cooling power” of ensemble. Values measured at 1.0 ms^{-1}.

Figure 4: Marine Corps Uniform Ensembles Worn in (A) Iraq and (B) Afghanistan

PHYSIOLOGY

Table 6 presents thermal-work strain (Tcore, HR and PSI) summary information for each of the mission periods.

Table 6: Mission period description and physiological statistics.

	Mission Period	Measure	Min	Max	Average
A	19 March 2010 0800-1300 Stood Guard	HR (bpm)	69	117	82 ± 7
		Tcore (°C)	37.1	37.5	37.4 ± 0.1
		PSI	1.5	3.2	2.2 ± 0.3
B	19 March 2010 0800-1000 Dismounted Patrol	HR (bpm)	84	128	105 ± 9
		Tcore (°C)	37.2	37.7	37.5 ± 0.1
		PSI	2.7	4.2	3.4 ± 0.3
C	19 March 2010 1600-1900 Dismounted Patrol	HR (bpm)	94	149	121 ± 15
		Tcore (°C)	37.8	38.4	38.1 ± 0.2
		PSI	3.9	6.5	5.2 ± 0.8
D	20 March 2010 2200-0100 Dismounted/Mounted Patrol	HR (bpm)	68	86	75 ± 4
		Tcore (°C)	36.9	37.4	37.1 ± 0.2
		PSI	1.0	2.2	1.5 ± 0.4
E	22 March 2010 0630-1130 Dismounted/Mounted Patrol	HR (bpm)	62	99	77 ± 6
		Tcore (°C)	36.9	37.2	37.0 ± 0.1
		PSI	1.0	2.9	1.8 ± 0.4
F	22 March 2010 1500-1830 Dismounted Patrol	HR (bpm)	85	134	115 ± 12
		Tcore (°C)	37.6	38.1	37.8 ± 0.14
		PSI	2.1	5.5	4.2 ± 0.8
G	23 March 2010 0800-1700 Dismounted/Mounted Patrol, Firing Range	HR (bpm)	70	162	96 ± 20
		Tcore (°C)	37.0	38.3	37.5 ± 0.3
		PSI	0.5	6.5	2.3 ± 1.4

Figures 5 through 11 show mean Tcore, HR, PSI, and accelerometer activity counts for each of the seven mission periods. Where data are available, changes in activity are indicated by vertical dotted lines, and error bars represent one standard deviation. Data were dropped from the charts under two conditions: (1) where the Tcore thermometer pill was ingested close to the mission period and Tcore data was affected by ingesting water, and (2) if the PSM device malfunctioned and failed to record a parameter. Specifically, data were dropped for the following reasons:

1600-1900 19 March 2010: Thermometer pill passed or failed prior the mission period and Tcore was not recorded by the PSM.

1500-1830 22 March 2010: Thermometer pill provided erroneous Tcore due to ingested fluids. PSM unit malfunctioned.

0800-1600 23 March 2010: Thermometer pill passed or failed prior to the mission period and Tcore was not recorded by the PSM.

Figure 5: Mean Thermal-Work Strain Parameters for Mission Period A: 0800-1300 19 March 2010 Guard Duty (N=2).

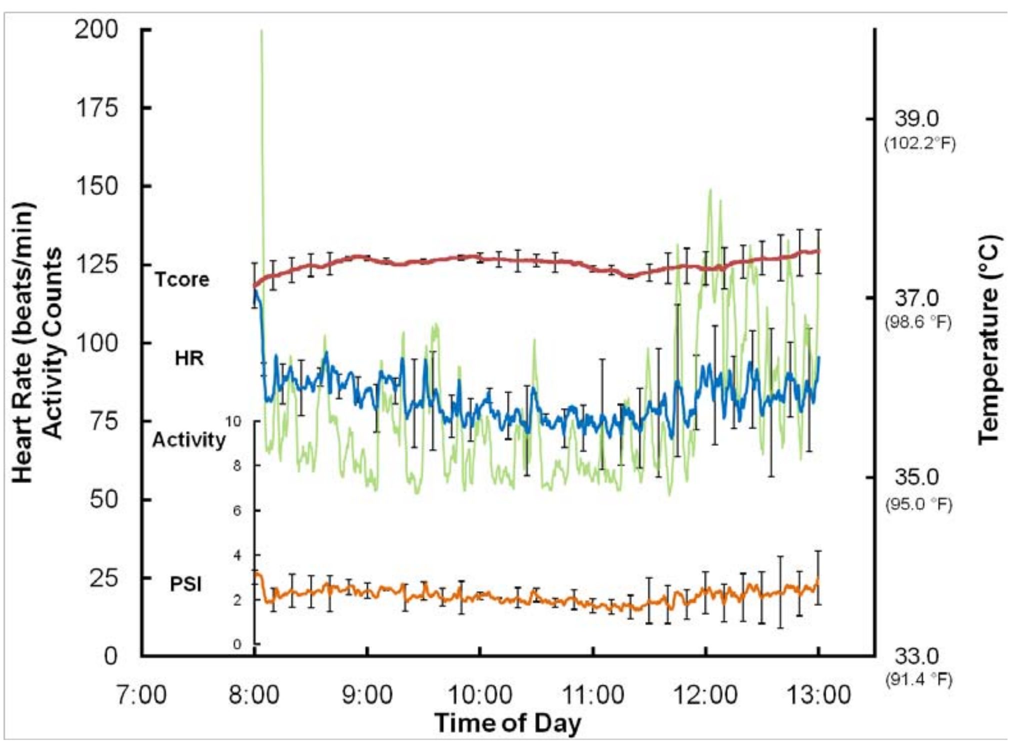


Figure 6: Mean Thermal-Work Strain Parameters for Mission Period B: 0800-1000 19 March 2010 Dismounted Patrol (N = 7).

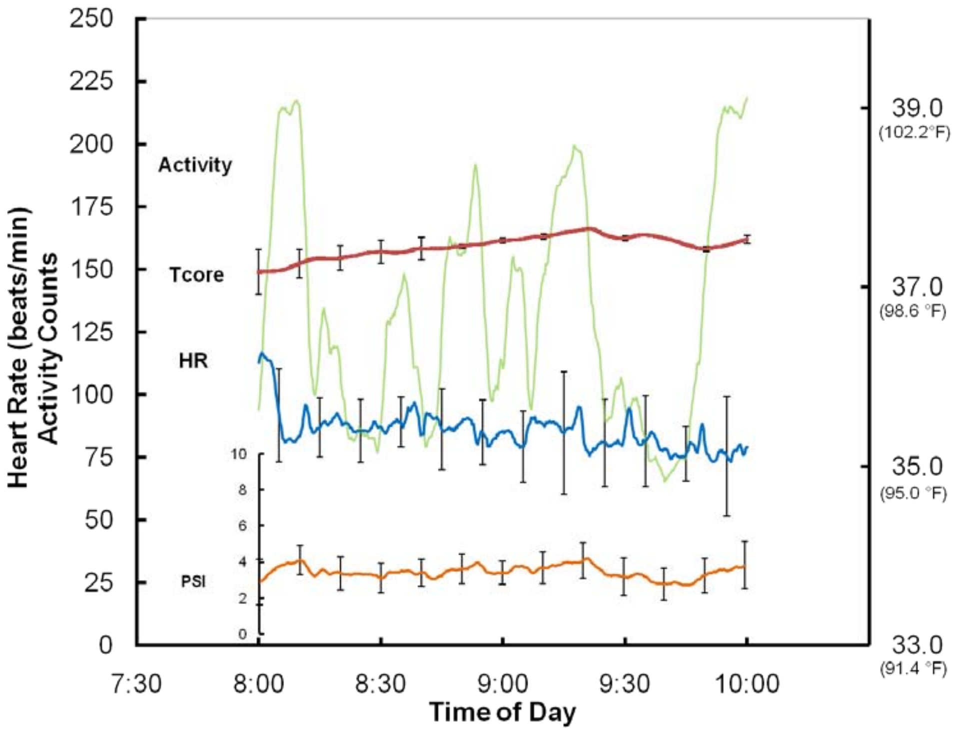


Figure 7: Mean Thermal-Work Strain Parameters for Mission Period C: 1600-1900 19 March 2010 Dismounted/Mounted Patrol (N = 6).

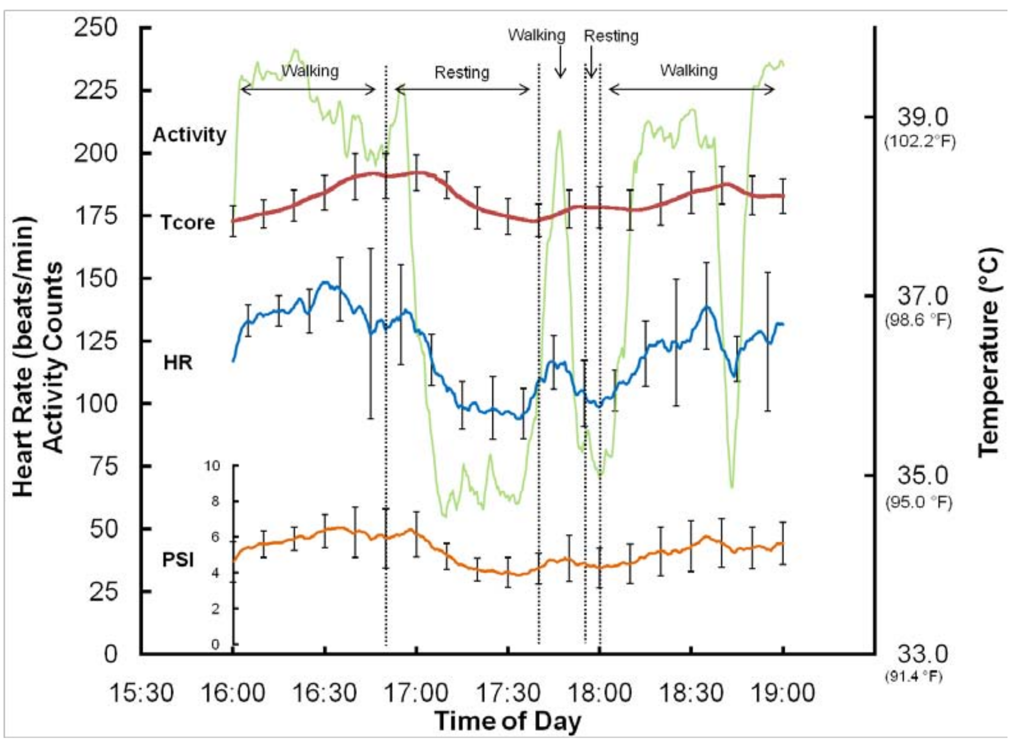


Figure 8: Mean Thermal-Work Strain Parameters for Mission Period D: 2200-0100 20 March 2010 Dismounted/Mounted Patrol (N = 4). Note: Large standard deviations are due to subjects engaging in different activities including sweeping for IEDs, posting security, remaining mounted, and unloading equipment.

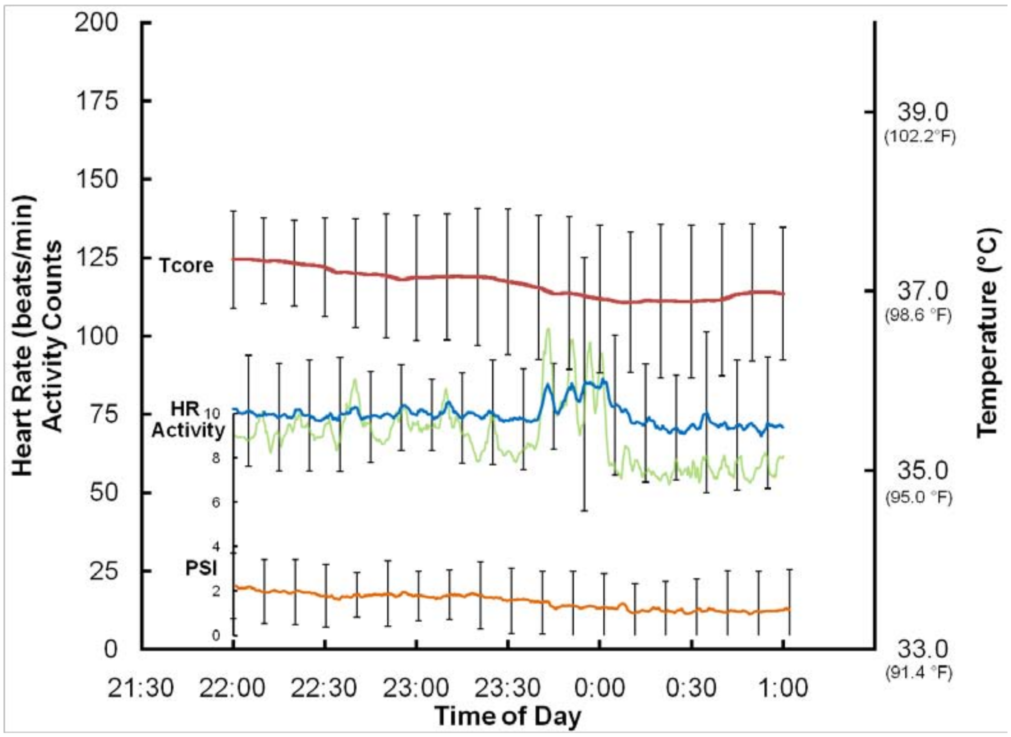


Figure 9: Mean Thermal-Work Strain Parameters for Mission Period E: 0630-1130 22 March 2010 Dismounted/Mounted Patrol (N = 5).

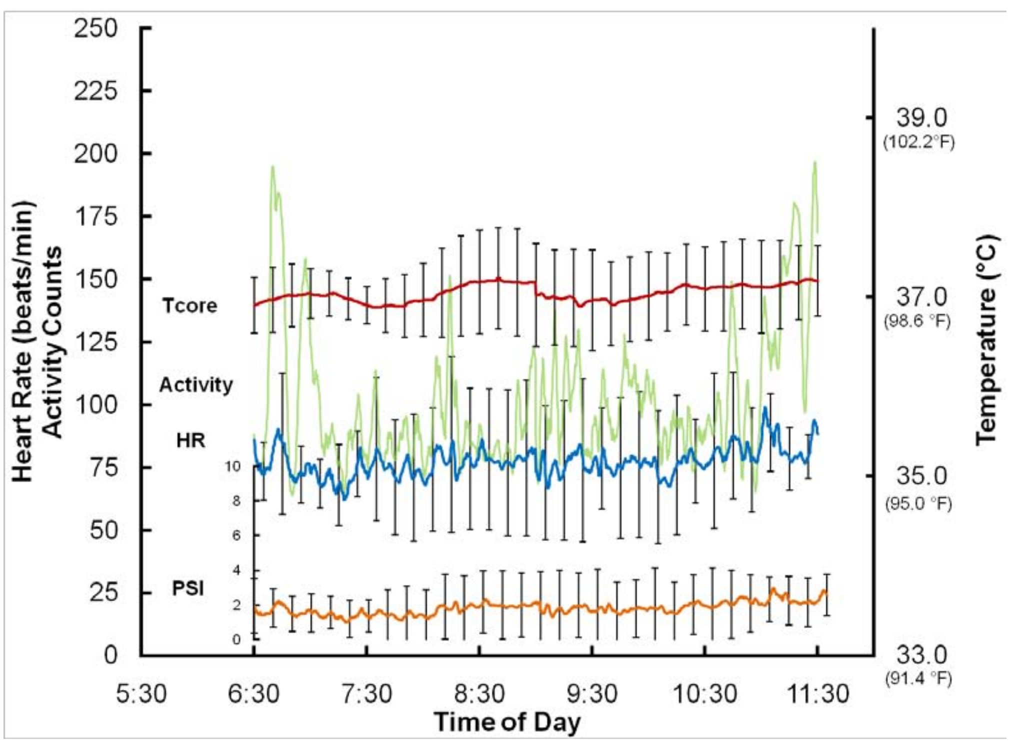


Figure 10: Mean Thermal-Work Strain Parameters for Mission Period F: 1500-1830 22 March 2010 Dismounted Patrol (N = 5).

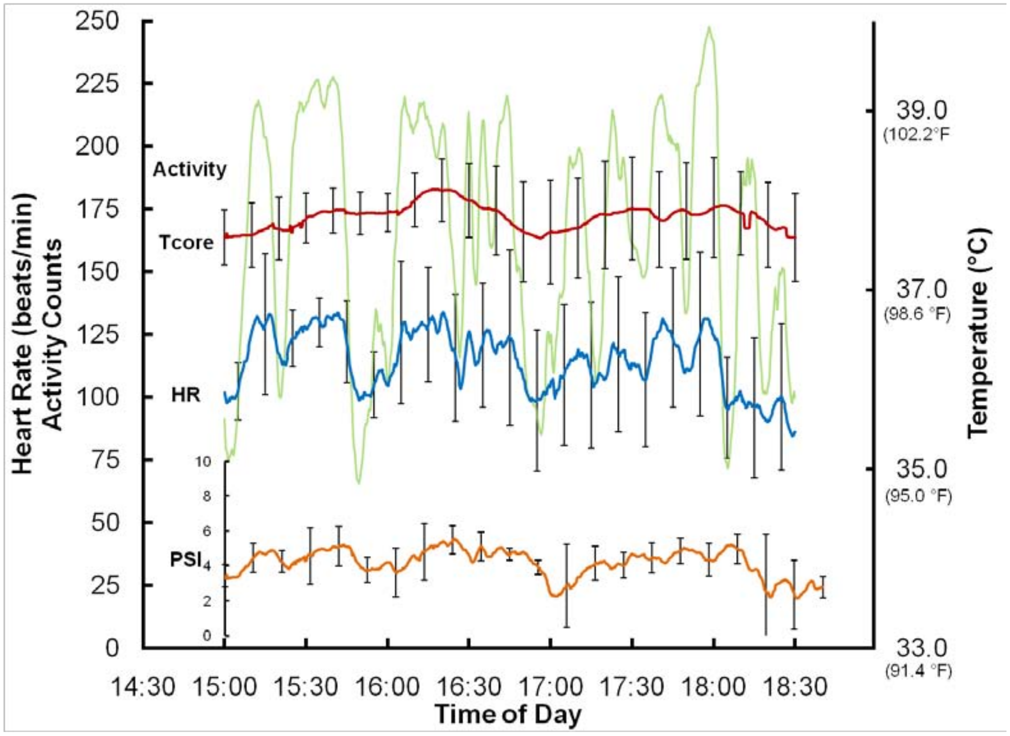
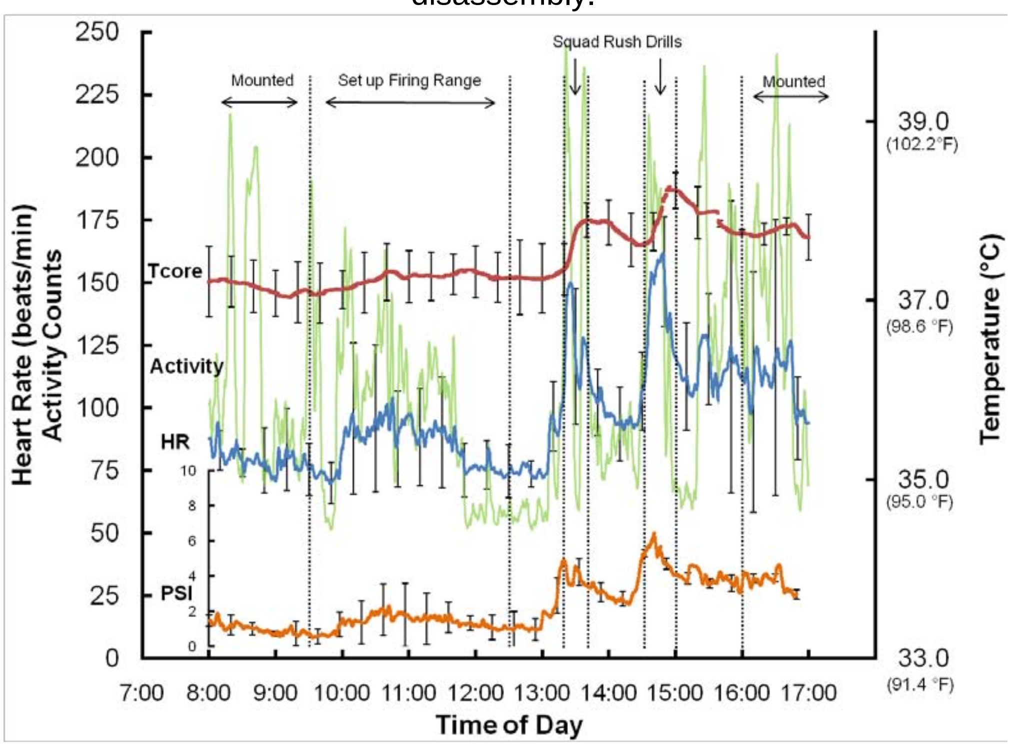


Figure 11: Mean Thermal-Work Strain Parameters for Mission Period G: 0800-1700 23 March 2010 Dismounted/Mounted Patrol, Firing Range, and Squad Rush Drills (N = 5). Note: Unlabeled portions of time include unreported activity and firing range disassembly.



BIOMEDICAL MODELING ANALYSIS

Metabolic Rate Estimation

Table 7 shows the metabolic rate estimation regression lines used when HRR exceeded 2.0. For the three selected modeling periods (1600-1900 19 March, 1500-1830 22 March, and 0800-1800 23 March) the SCENARIO model estimated Tcore with RMSE values of 0.27 ± 0.15, 0.15 ± 0.10, and 0.15 ± 0.10 respectively (Table 8). These lines were used to estimate metabolic rate for each individual volunteer. Figures 13 through 15 show the mean metabolic rate estimations for each of the mission periods and the corresponding accelerometry activity counts.

Table 7: Modified metabolic rate regression lines by ambient temperature rate.

	Mission Period	Temperature (°C)	Slope	Intercept
C	1600-1900 19 March 2010 Dismounted Patrol	25.5	0.3	4.484
F	1500-1830 22 March 2010 Dismounted Patrol	21.4	0.4	4.497
G	0800-1700 23 March 2010 Dismounted/ Mounted Patrol, Firing Range	19.6	0.4	4.589

Table 8: Root mean square error of SCENARIO prediction versus observed data by individual and mission period (average ± RMSE).

	Mission Period	Individual Subject RMSE	Overall Period RMSE
C	1600-1900 19 March 2010 Dismounted Patrol	0.23 ± 0.18 0.35 ± 0.24 0.42 ± 0.25 0.32 ± 0.28 0.25 ± 0.16	0.31 ± 0.08
F	1500-1830 22 March 2010 Dismounted Patrol	0.21 ± 1.29 0.25 ± 0.22 0.18 ± 1.32 0.16 ± 0.09	0.20 ± 0.04
C	0800-1700 23 March 2010 Dismounted/ Mounted Patrol, Firing Range	0.16 ± 0.11 0.32 ± 0.18 0.11 ± 0.09	0.20 ± 0.11

Figure 12: Accelerometer counts and Estimated Metabolic Rate Data for Mission Period C: 1600-1900 19 March 2010 Dismounted/Mounted Patrol (N = 4).

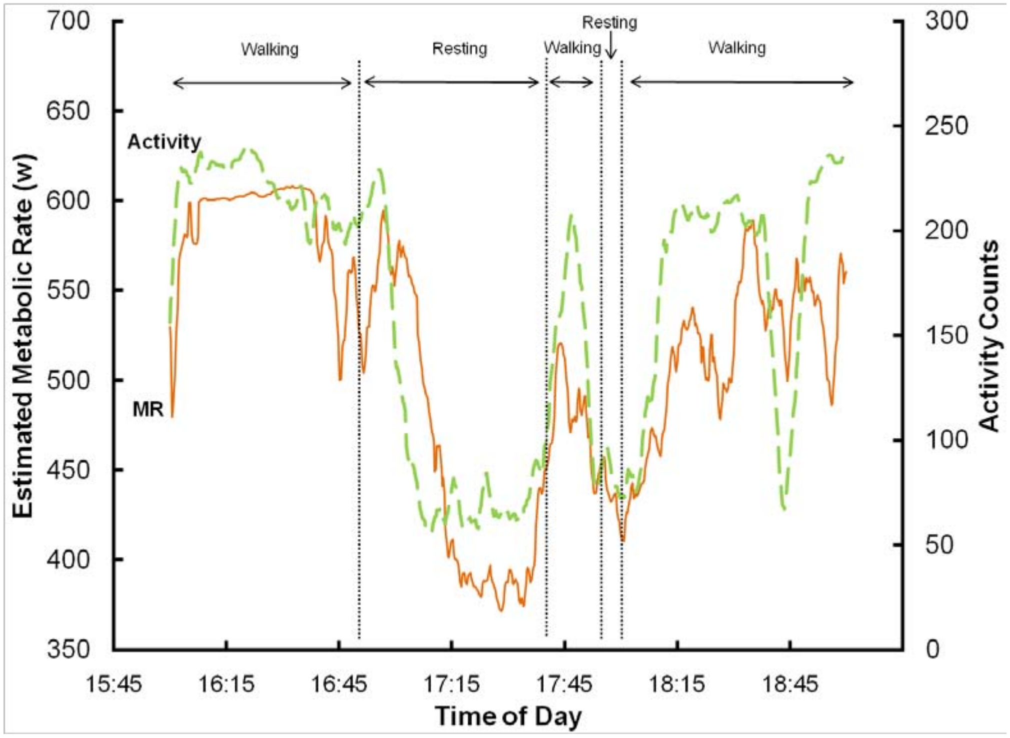


Figure 13: Accelerometer and Estimated Metabolic Rate Data for Mission Period F: 1500-1830 22 March 2010 Dismounted Patrol (N =4).

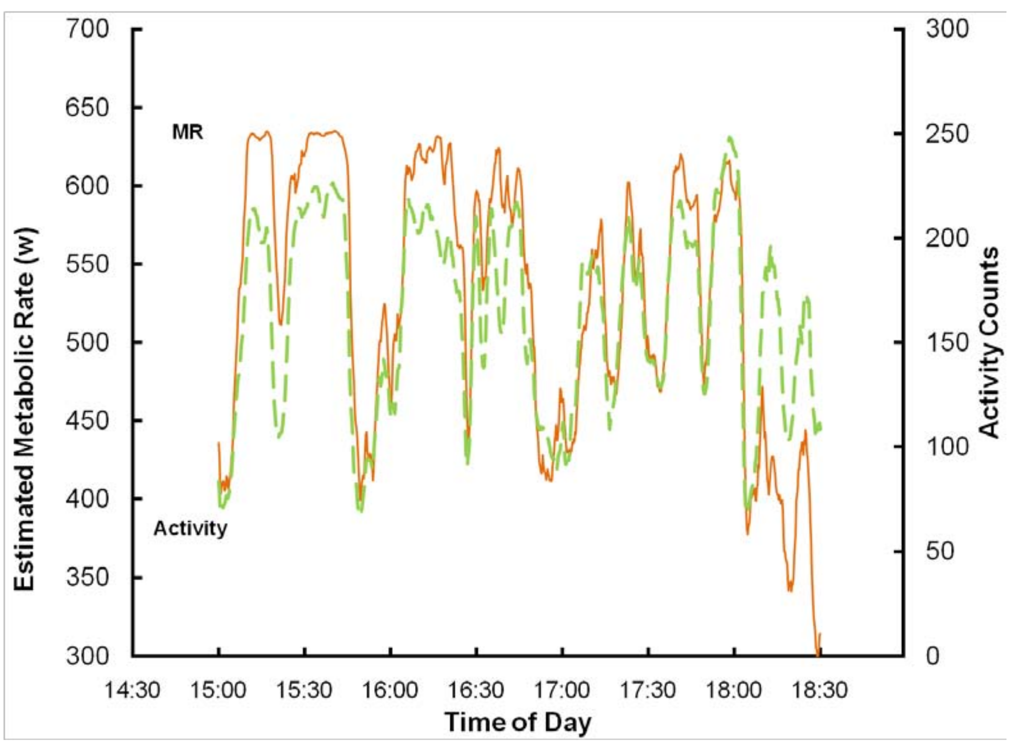
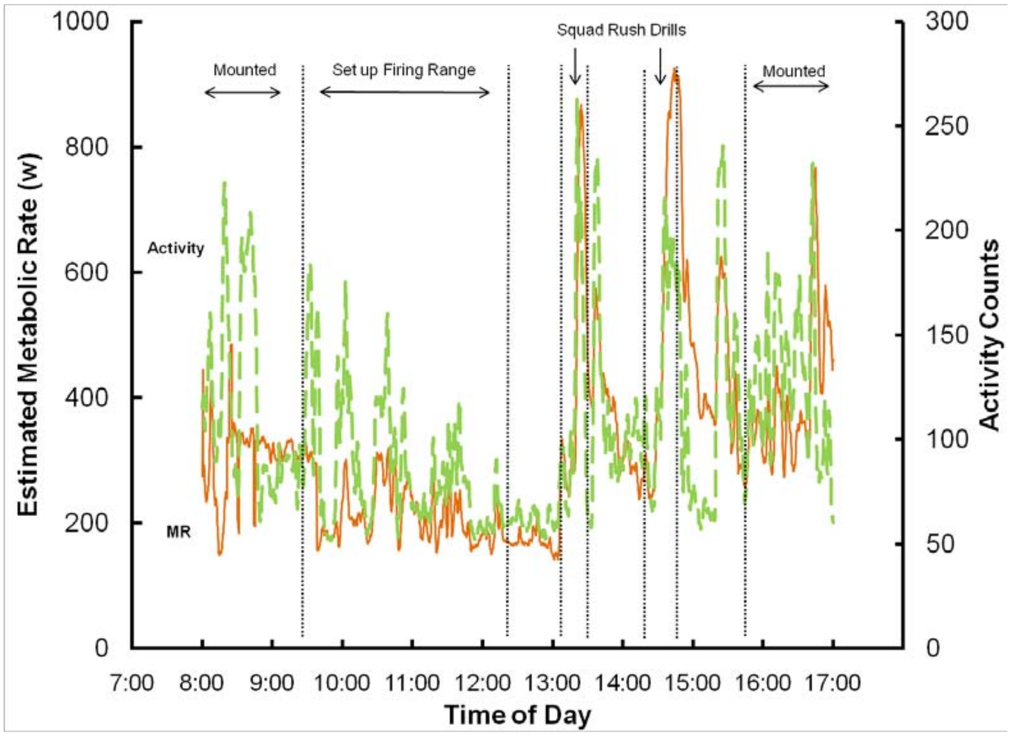


Figure 14: Accelerometer and Estimated Metabolic Rate Data for Mission Period G: 0800-1700 23 March 2010 Dismounted Patrol (N =3).



Mission Modeling

The three most demanding mission periods, i.e., those with the highest PSI, were selected for modeling in SCENARIO. Figures 15 through 17 compare the observed HR and Tcore values, and the HR and Tcore values estimated using SCENARIO for the March (spring) and July (summer) environments and for the different C&IE configurations worn in Afghanistan (SPC) and Iraq (MTV). Table 9 shows the min, max, and mean modeled HR, Tcore, and PSI for summer environmental conditions while wearing either the estimated SPC ensemble or the MTV Marine ensemble.

Figure 15: Observed versus modeled physiology data for Period C: 1600-1900 19 March 2010 Dismounted Patrol (N =5). (A) March 2010 and Summer Environments. (B) March 2010 and Summer Environments with Scalable Plate Carrier versus Modular Tactical Vest Clothing and Individual Equipment Ensembles.

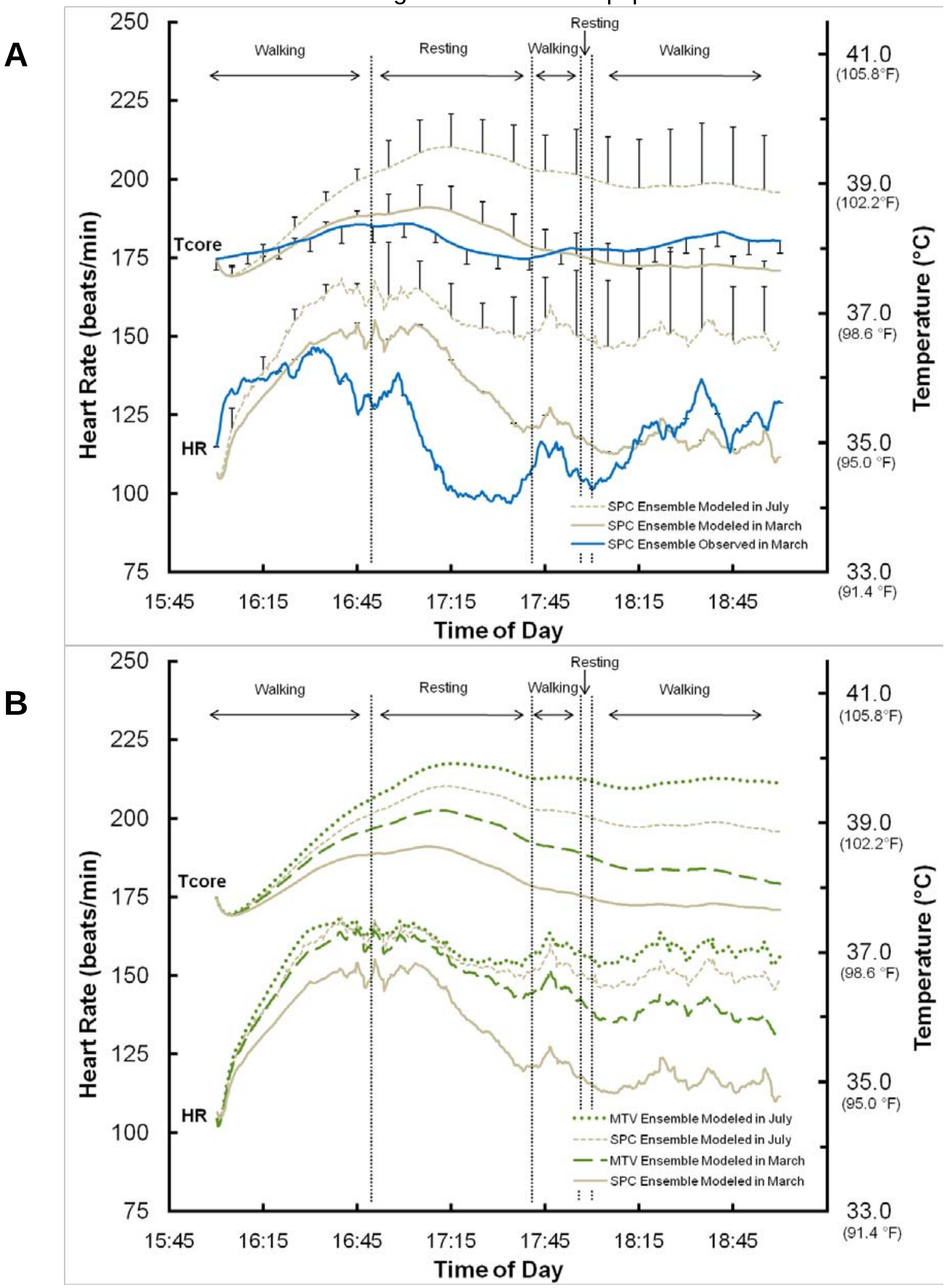
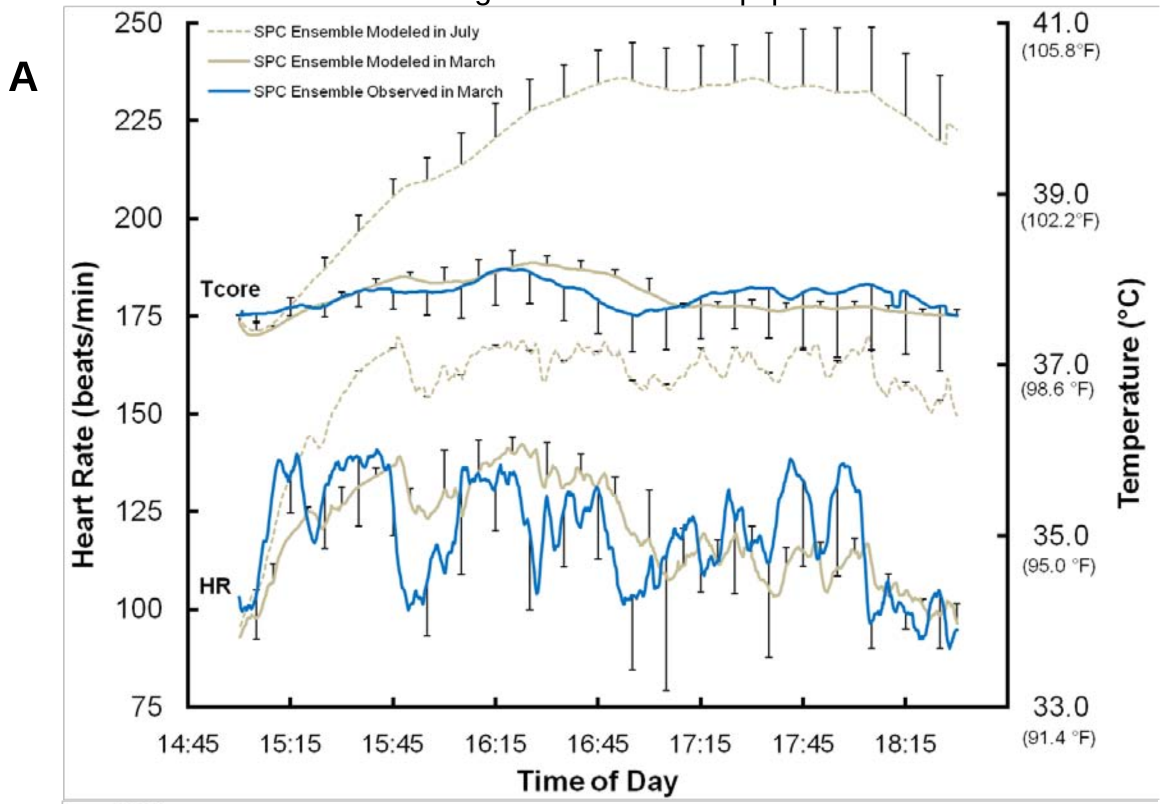


Figure 16: Observed versus modeled physiology data for Period F: 1500-1830 22 March 2010 Dismounted Patrol (N =4). (A) March 2010 and Summer Environments. (B) March 2010 and Summer Environments with Scalable Plate Carrier versus Modular Tactical Vest Clothing and Individual Equipment Ensembles.



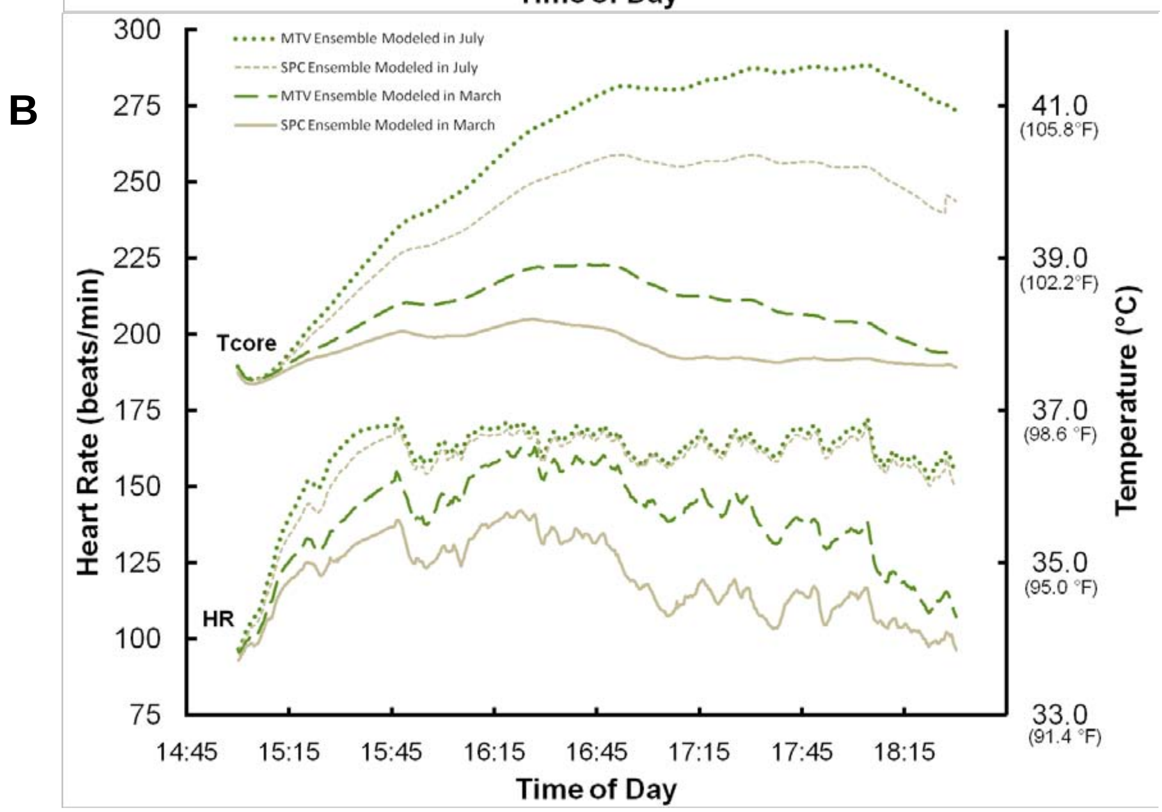
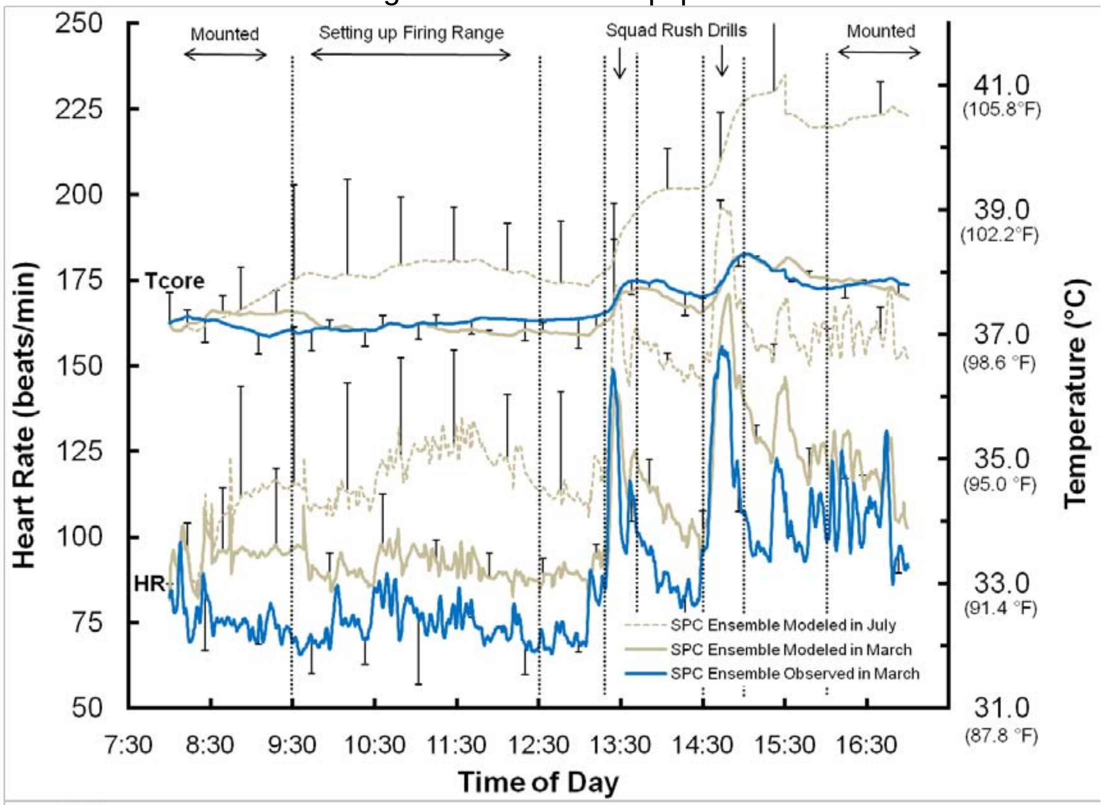


Figure 17: Observed versus modeled physiology data for Period G: 0800-1800 23 March 2010 Dismounted Patrol (N =3). (A) March 2010 and Summer Environments. (B) March 2010 and Summer Environments with Scalable Plate Carrier versus Modular Tactical Vest Clothing and Individual Equipment Ensembles.

A



B

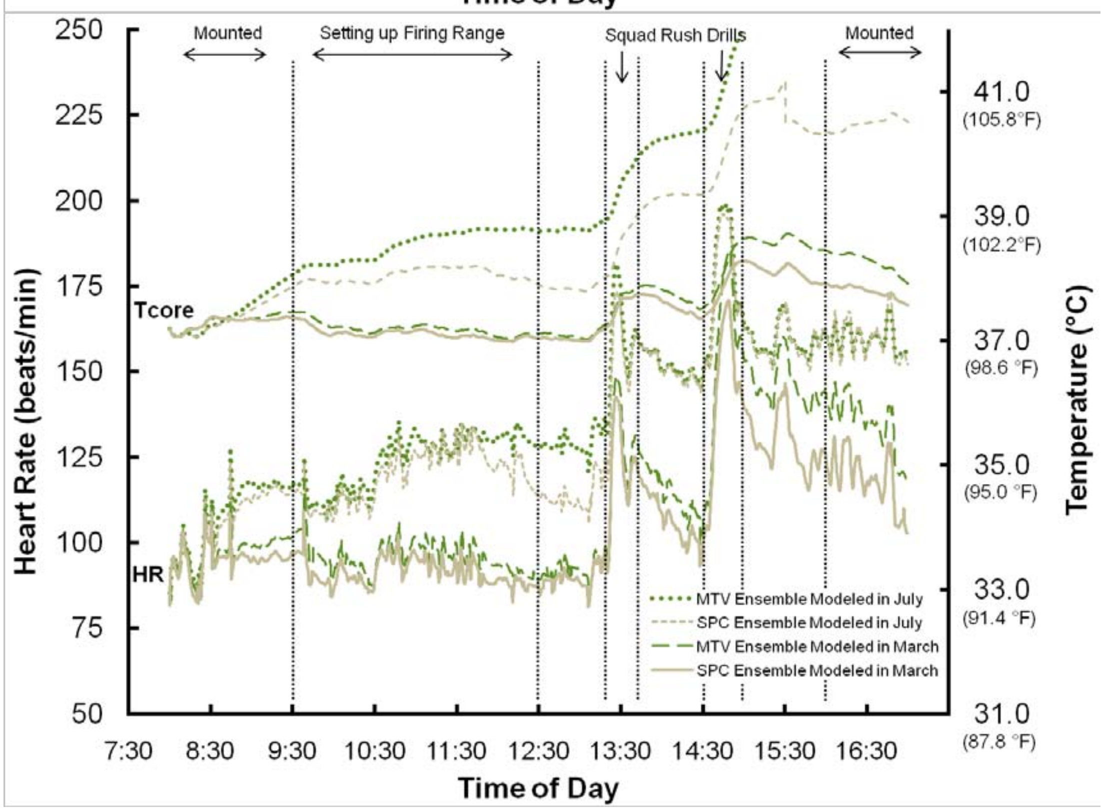


Table 9: SCENARIO physiological data for scalable plate carrier and modular tactical vest ensembles modeled during July (summer) mission periods.

Mission Period		Ensemble	Measure	Min	Max	Average
C	Summer 1600-1900 Dismounted Patrol	SPC Ensemble	HR (bpm)	105	169	152 ± 11
			Tcore (°C)	37.6	39.6	38.9 ± 0.5
			PSI	4.0	9.3	7.9 ± 1.2
		MTV Ensemble	HR (bpm)	103	168	156 ± 11
			Tcore (°C)	37.6	39.9	39.3 ± 0.7
			PSI	3.9	9.9	8.7 ± 1.4
F	Summer 1500-1830 Dismounted Patrol	SPC Ensemble	HR (bpm)	96	170	157 ± 14
			Tcore (°C)	37.4	40.4	39.6 ± 0.9
			PSI	3.25	10.8	9.1 ± 1.9
		MTV Ensemble	HR (bpm)	97	173	160 ± 14
			Tcore (°C)	37.4	41.5	40.4 ± 1.3
			PSI	3.3	13.0	10.5 ± 2.5
G	Summer 0800-1700 Dismounted/Mounted Patrol, Firing Range	SPC Ensemble	HR (bpm)	82	196	133 ± 24
			Tcore (°C)	37.1	41.2	38.7 ± 1.2
			PSI	1.3	12.7	6.5 ± 3.2
		MTV Ensemble	HR (bpm)	70	162	96 ± 20
			Tcore (°C)	37.1	46.3	40.1 ± 2.5
			PSI	1.4	21.0	8.9 ± 5.3

DISCUSSION

The environmental conditions during the March 2010 study were mild, resulting in limited thermal-work strain. The WBGT flag condition was white, even accounting for the addition of 5°F for individuals wearing body armor. Similarly, a typical summer day was predicted to impose limited thermal stress, with a body armor adjusted WBGT flag condition of white.

Seven distinct mission periods were monitored. Of these periods, according to TB MED 507, two mission periods (C and F) either contained periods of heavy work or sustained heavy work (>513 W). The remaining periods consisted of, on average, light work (<338 W). Additionally, mission period G contain two instances of very heavy work (>800 W) during a training event where Marines conducted squad rushes.

As expected, the mean PSI was less than 2.6 (low thermal-work strain) during mission periods with light work. Periods with chronic heavy work had mean PSI values up to 5.5 (moderate physiological strain). For all data collected, PSI levels approached but did not exceed 6.8 (high thermal-work strain).

The metabolic rate profiles developed using the adapted Berglund method [1] appeared reasonable as they allowed SCENARIO to model Tcore estimates of 11 out of 12 volunteers to within 0.11 to 0.35 RMSE of observed Tcore. The 12th volunteer's SCENARIO estimated Tcore had a RMSE of 0.42 (Table 8). The average summer environmental conditions, while warmer (+~8°C) with more solar radiation (+~10°C black globe) than March conditions, did not pose a thermal risk with an overall WBGT flag condition of white. However, these warmer conditions, if combined with the chronic heavy workloads and acute very heavy workloads lead to predicted PSI values (>9) typically associated with a high risk of thermal-work strain, heat illness, syncope (fainting), and heat exhaustion.

The three mission periods modeled represent three different categories of work. Mission period "C" consists of a ~60 minute initial period of heavy work, followed by a ~45 minute rest period, and ending with a ~60 minute period of moderate work. Mission period "F" shows four hours of heavy work interspersed with shorter periods of moderate work. Finally mission period "G" shows several hours of low intensity work followed by two periods of very heavy work in the form of squad rush drills. In all these scenarios Tcore values modeled with the composite summer time (July) environmental data resulted in predicted Tcore values of >39.5°C. It is likely that under the warmer summer conditions Marines would self-adjust their operational tempo to moderate their thermal-work strain as they did during foot patrols in Iraq. This would result in lower Tcore values, and thus lower PSI values. Nevertheless, this modeling effort raises an important point: that while the Afghani summer environmental conditions appear unlikely to cause thermal-work strain (as determined by the WBGT flag scale), missions that involve chronic heavy work or acute very heavy work could pose a significant thermal-work strain risk. Schickele [14] notes in her examination of heat stroke fatalities during training that "most fatalities associated with heavy exercise can occur at relatively low [air] temperatures, when the total heat strain is commonly underestimated."

Additionally, we modeled the mission scenarios using the summer environmental conditions with estimated clothing parameters of the uniform worn by Marines during their tour in Iraq (2008). As can be seen from Figure 4 the Iraq ensemble (figure 4A) contains the more occlusive MTV and would likely have a higher insulation factor and lower vapor permeability when compared to the ensemble (containing the SPC) worn during this study (figure 4B). The change in uniform configurations from MTV to SPC, along with corresponding lighter load reduced, the thermal-work strain in the simulated summer period (by 0.8 PSI units in mission period C, 1.4 in mission period F, and 2.4 in mission period G). However, this should not be interpreted as a prescription for wear under certain thermal conditions. The threat scenario, vice the thermal scenario, prescribes which protective vest is worn (MTV – blast and fragmentation; SPC – direct fire).

CONCLUSIONS

Under the temperate spring weather conditions (WBGT white flag), missions with heavy and very heavy work resulted in physiological strain index values no greater than 6.8 (high physiological strain). However, when the same mission scenarios are modeled under summer environmental conditions (still WBGT white flag), average PSI values peak at > 9, indicating a strong likelihood of heat exhaustion or heat illness if work rates are not moderated. The combination of less occlusive uniforms and lighter carried weight can reduce the predicted thermal-work strain but may not be feasible depending on anticipated threat scenarios and desired protection level.

RECOMMENDATIONS

The mission scenarios used for modeling in this report provide an activity baseline that can be used for future experiments. If physiological data are collected from similar mission profiles (e.g., intermittent heavy work with rest periods, continuous heavy work, and light work with periods of acute very heavy work) changes in PSI can function as the metric by which unit leaders quantify the physiological impact of changes in environmental conditions, C&IE (e.g., the SPC for direct weapons fire versus the MTV for blast and fragmentation protection), and operational tempo to thermal-work strain.

As Marine Corps uniform configurations change the thermal properties of these uniforms should be assessed using thermal manikin protocols. Once these properties are known the mission scenarios recorded in this baseline can be used to examine the change in PSI under different environmental conditions and levels of threat protection.

DISCLAIMER

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25 and SECNAVINST 3900.39D, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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Appendix A: Table of Military Activities and Associated Metabolic Rate

Table A1: Metabolic Rate for Easy/Light, Moderate, and Hard Work With Examples

Easy/Light Work (250 W)	Moderate Work (425 W)	Hard Work (600 W)
Weapon Maintenance	Walking loose sand 2.5 mph no load	Walking loose sand at 2.5 mph with load
Walking hard surface at 2.5 mph, load < 30 lb	Walking hard surface at 3.5 mph, load < 40 lb	Walking hard surface at 3.5 mph, load > 40 lb
Manual of arms	Calisthenics	Field Assaults
Marksmanship Training	Patrolling	
Drill and Ceremony	Individual movement techniques of low and high crawl	
	Defensive position construction	