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THERMAL-WORK STRAIN AND ENERGY EXPENDITURE DURING MARINE RIFLE SQUAD OPERATIONS IN AFGHANISTAN (AUGUST 2013)

United States Army
Medical Research & Materiel Command

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14. ABSTRACT
Marines in-theater must often accomplish demanding mission goals in extreme environments. The collection of physiological and metabolic data provides a means to characterize, and potentially mitigate, thermal-work strain. Heart rate (HR), core body temperature (Tcore), skin temperature (Tskin), activity counts, and average total daily energy expenditures (TDEE) were collected from 19 USMC test volunteers in the 2nd Battalion 2nd Marines (2/2), Fox Company during regular patrols as well as non-mission activities while stationed in Afghanistan. All mission periods occurred during white/green or yellow Wet Bulb Globe Temperature (WBGT) flag conditions. Test volunteers (n = 13) experienced low levels of thermal-work strain during missions as indicated by mean physiological strain index (PSI) values between 2.7 and 3.6 PSI units with a maximum of 4.6. The combination of combat load and mission demands resulted in a mean TDEE of 13.20 ± 1.41 MJ/day (3150 ± 630 kcal/day, mean ± standard deviation, n = 17) as determined by doubly labeled water (DLW) over four days. Metabolic rates for mission activities were back calculated using Tcore and environmental data as inputs for the SCENARIO thermo-regulatory model. Mean modeled TDEE values were 13.18 ±

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BACKGROUND

The United States Marine Corps (USMC) Marine Expeditionary Rifle Squad (MERS) and the U.S. Army Research Institute of Environmental Medicine (USARIEM) have conducted a series of in-theater equipment surveys and physiological data collections with Regimental Combat Teams (RCT) stationed in Iraq and Afghanistan. These studies focused primarily on thermal-work strain levels [4,19] recorded by ambulatory physiological status monitors. However, metabolic rates were not measured or were only roughly estimated. This report details the total daily energy expenditures and physiological profiles (heart rate, core temperature, and accelerometry counts) of Marines during two ten hour patrols on two separate days as well as their estimated average total daily energy expenditure over a four day period.

ACKNOWLEDGMENTS

Special thanks to the test volunteers from the 2nd Battalion 2nd Marines Fox Company who made this study possible. The authors would also like to thank the 14th Weather Squadron for assistance with weather data collection and preparation and Mr. Anthony Karis for thermal manikin analysis of various Marine ensembles including the one used for data analysis in this report.

EXECUTIVE SUMMARY

The purpose of this study was to characterize the thermal-work strain and total daily energy expenditures (TDEE) of Infantry Marines in Afghanistan. Additionally, we report a novel use of the SCENARIO physics and physiology based thermo-regulatory model to estimate metabolic rate from core body temperature.

Heart rate (HR), core body temperature (Tcore), skin temperature (Tskin), activity counts, and average total daily energy expenditures (TDEE) were collected from 19 USMC test volunteers in the 2nd Battalion 2nd Marines (2/2), Fox Company. The test volunteers were stationed at Patrol Base Boldak, Helmand Province, Afghanistan. Physiological data (HR, Tcore, and Tskin) were collected using the chest-worn Equivital-2 (Hidalgo Ltd., Cambridge UK) physiological status monitoring (PSM) system during regular patrols on the 28th and 29th as well as non-mission activities on the 30th and 31st of August 2013. The environmental conditions the Marines operated in were warm and dry with mean air temperatures (T_A) between 33.6 ºC (92.5 ºF) and 34.0 ºC (93.2 ºF) and mean relative humidity (RH) between 9.3% and 11.6%. All mission periods occurred during white/green or yellow Wet Bulb Globe Temperature (WBGT) flag conditions. Test volunteers (n = 13) experienced low levels of thermal-work strain during missions as indicated by mean physiological strain index (PSI) values between 2.7 and 3.6 PSI units with a maximum of 4.6.

The combination of combat load and mission demands resulted in a mean TDEE of 13.20 ± 1.41 MJ/day (3150 ± 630 kcal/day, mean ± standard deviation, n = 17) as determined by doubly labeled water (DLW) over four days. Observed physiology and thermal-work strain data for mission and non-mission days were similar. Metabolic rates for mission activities were back calculated using Tcore and environmental data as inputs for the SCENARIO thermo-regulatory model. Mean modeled TDEE values were 13.18 ± 2.54 MJ/day (3160 ± 340 kcal/day) (n = 13), corresponding well to mean TDEE values measured by the criterion DLW method. However, the large standard deviation of percent error (-1.59 ± 18.58 %, -0.21 ± 2.49 MJ) suggests that this model of metabolic rate estimation may not be appropriate for individuals.

INTRODUCTION

Marines in-theater must often accomplish demanding mission goals in extreme environments. The risk of heat illness or heat injury is significant despite following heat injury prevention guidelines for water consumption and work rest scheduling [8,12,13,15]. The collection of physiological and metabolic data in-theater provides a means to characterize, and potentially mitigate, thermal-work strain.

Previously it has been shown that Marines on dismounted hot weather patrols in Iraq reached high levels of thermal-work strain by the end of a slow foot patrol [4] even though they followed TB MED 507 work-rest and water intake guidance. It was also predicted that dismounted Marine missions with periods of hard work (> 600W work rate) could result in high thermal-work strain even during White/Green flag WBGT conditions common to Afghanistan during the Spring and Summer (March, July) [20]. In both instances, physiological data including core body temperature (Tcore), skin temperature (Tskin), and heart rate (HR) were collected in-theater and used to quantify the thermal-work strain experienced by the Marines. During both studies metabolic rate ($\dot{M}$) was estimated but, not measured.

The metabolic energy expenditures of Warfighters during a variety of different training events and exercises have been characterized [18], but to our knowledge very little energy expenditure data have been collected in-theater or during actual missions. This is not surprising given the difficulties inherent to collecting data under the constraints imposed by in-theater operations. For example, measuring oxygen consumption requires a whole room calorimeter or a worn/tethered breathing apparatus, the intake-balance method requires detailed and long term records of caloric intake and changes in body composition, and the factorial method requires a detailed recording of activity type and duration. The use of doubly labeled water (DLW) is tenable during field operations as it only requires the collection of periodic urine samples for later analysis. However, the DLW method typically provides a measure of total daily energy expenditure (TDEE) over a minimum interval of one to two days. A more detailed view of Warfighter thermal-work strain and metabolic rate can be provided by a combination of DLW data, wearable physiological status monitoring (PSM), and mathematical modeling of human thermo-regulatory physiology.

The purpose of the present study was to characterize the physiology and energy expenditures of Marines during in-theater missions in Afghanistan. This report details the average total daily energy expenditures of Marines across four days. Subjects engaged in ten hour patrol missions on the first two days and spent the remaining two days “behind the wire” at their patrol base. Physiological and thermal-work strain data are also presented for the patrol mission periods. This report also examines the novel use of the SCENARIO thermo-regulatory model and observed Tcore as a means to estimate energy expenditure over the course of missions.

METHODS

The thermal-work strain experienced by USMC volunteers operating out of Patrol Base Boldak (Helmand Province, Afghanistan) was assessed during routine patrol missions on 28 and 29 August, 2013 between the hours of 0600 and 1600. Individual physiological data (HR, respiratory rate, Tcore, Tskin, and body motion) were collected using a chest-mounted Equivital-2 (Hidalgo Ltd., Cambridge UK) physiological status monitoring (PSM) system, along with contextual information such as meteorology, clothing characteristics, individual equipment descriptions, and TDEE as determined by DLW. These data were also collected while volunteers were at their patrol base on 30 and 31 August, 2013.

PROCEDURES

The afternoon and evening of August 27th (1500-2130), prior to the initiation of data collection, volunteers were briefed and provided their informed consent. Following informed consent, thermometer pills were orally administered, volunteers provided an initial urine sample, consumed their DLW dose (see below), and were fitted with PSM systems. Each subsequent morning, urine samples were collected and temperature pill presence was checked. Volunteers were instructed to wear the PSM belts for the entirety of each day. PSM systems were swapped each evening enabling daily data downloads and battery recharging. Equipment inventory and anthropometric measures were collected throughout the day on August 30th as the volunteers' duty requirements permitted. Urine samples were collected each day from 28 to 31 August.

METEOROLOGICAL CONDITIONS

Hourly meteorological data were collected at the Camp Bastion Airfield and provided by the 14th Weather Squadron (Asheville, NC). Air temperature (T_A), dew point, wind speed (WS), black globe temperature (T_{BG}), and relative humidity (RH) were provided for the month of August, 2013.

MISSION GROUPS AND VOLUNTEERS

Nineteen USMC volunteers (age = 21.7 ± 3.8 yr, height = 168.4 ± 38.5 cm, weight = 76.8 ± 17.7 Kg, waist circumference = 81.7 ± 6.6 cm, 3 mile run time = 19.8 ± 3.2 minutes) from Fox Company, 2nd Battalion 2nd Marines Regimental Combat Team stationed at Patrol Base Boldak participated in this study. Participants volunteered for this study after being briefed on the research procedures, risks, and benefits. The investigators 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.

Height (self-report), body weight (semi-nude with shorts and t-shirt), and waist circumference at the navel (anthropometric tape measure) were recorded to estimate percent body fat using Wright and Wilmore's technique [20]. Fighting weight (total weight with combat clothing and equipment) were also measured when possible. In addition to these data, all test volunteers provided a self-reported 3-mile run time, a standard USMC physical training benchmark.

Data were collected during two patrols (~10 hours each, 28 and 29 August, 2013). Patrols on both days were performed by two groups of volunteers (labeled group 1 and group 2) and included mounted and dismounted operations. Additional data were collected on 30 and 31 August, 2013 when all volunteers remained at Patrol Base Boldak or, in the case of one evacuated subject, at a nearby medical facility.

Full data sets were not collected for all nineteen volunteers. Two volunteers received placebos in place of DLW doses to control for local baseline isotope abundances (see Physiological Measures/Energy Expenditure section for explanation) resulting in an N of 17 for TDEE data. Additionally, physiological data from six subjects, including the two given placebos, were discarded due to one or more of the following issues: loss of temperature pill data, poor quality HR data (complications with load carriage/shifting of Equivital belt during wear), and equipment malfunction (e.g., battery failure, device damage). Overall, this resulted in DLW data being collected for 17 volunteers and full physiological datasets for 13 volunteers.

CLOTHING AND EQUIPMENT CHARACTERISTICS

Total clothing insulation ($I_{tot,clo}$) and water vapor permeability index (i_m) of the Marine ensemble were measured via thermal manikin (Newton Manikin System, Thermetrics; Seattle, WA) by USARIEM personnel according to ASTM standards [1, 2]. A clo is a unit of thermal resistance defined as the insulation required to keep a resting man comfortable at 21 ºC [2]. A clo value of 1 is equal to 0.155 $K \bullet m^2/W$ [2] and roughly equivalent ($I_{tot,clo}$ = 1.17 clo) to wearing an ensemble including men's underwear briefs, khaki pants, belt, socks, athletics shoes, and a short-sleeved shirt [2]. The permeability index is a non-dimensional index from 0 to 1 where 0 indicates a garment or ensemble is impermeable to vapor transfer and allows for no evaporative heat transfer. An i_m of 1 indicates the theoretical maximum of evaporative heat loss given the worn ensemble's insulation [3]. The ratio of $i_m/I_{tot,clo}$ indicates the "cooling power" of an ensemble [3]. Photos and descriptions of typical ensembles were also taken when possible (e.g., Figure 1).

PHYSIOLOGICAL MEASURES

Energy Expenditure – Doubly Labeled Water

Doubly labeled water containing the stable, naturally-occurring isotopes $H_2{}^{18}O$ and ^2H_2O in known proportions, (Cambridge Isotopes, Cambridge, MA) was given to volunteers to determine total energy expenditure during the study. Urine samples were collected and stored in urine sample tubes and ^{18}O and ^2H isotope abundances were measured on a Stable Isotope Ratio Mass Spectrometer (MAT 252, Thermo Fisher Scientific; Waltham, MA) at the Stable Isotope Laboratory Pennington Biomedical Research Center (Baton Rouge, LA).

The DLW method of measuring total energy expenditure [16] is based on the assumption that an initial oral dose of stable $^2H_2{}^{18}O$, deuterium (^2H) is eliminated from the body as water, whereas ^{18}O leaves as both water and exhaled carbon dioxide (CO_2). The rate of CO_2 production ($\dot{V}CO_2$) can be calculated from the difference in the elimination rates of the two isotopes. Energy expenditure is calculated from $\dot{V}CO_2$ using a metabolic fuel quotient (calculated from the food quotient (FQ) or assumed to be a standard western FQ) and conventional indirect calorimetric relationships. The mean daily CO_2 production ($r\ CO_2$ mol/day) is calculated according to Schoeller (1988) [17]:

$$r\ CO_2 = (N/2.078) * (1.007\ k_0 - 1.041\ k_d) - 0.0246\ rH_2O_t \qquad (2)$$

where,

$r\ CO_2$ = rate of CO_2 in mol/day
N = average of initial and final estimated total body weight (TBW)
k_0 = $H_2{}^{18}O$ elimination rate
k_d = ^2H_2O elimination rate
rH_2O_t = rate of fractionated evaporated water loss estimated as 1.05 N * (1.01 k_0 – 1.04 k_d) [5]

Water turnover for a given period of time is determined by multiplying TBW by k_d. Total daily energy expenditure is calculated using the two-point methods described by Schoeller, et al. (1986) [16]. The calculations are done via the equation:

$$k = [\ln(\sigma_i - \sigma_b) - \ln(\sigma_f - \sigma_b - \Delta\sigma_c)]/t \qquad (3)$$

where,

k = isotopic elimination rate
σ_i = initial isotopic abundance (%)
σ_b = pre-dose baseline isotopic abundance (%)
σ_f = final isotopic abundance (%)
σ_c = corresponding change in mean baseline isotopic abundance (%) in control group that did not receive $H_2{}^{18}O$
t = time period between the initial and final samples of the energy expenditure period

Abrupt changes in ^2H and ^{18}O are often unavoidable when sources of drinking water change [7]. Therefore, isotopic elimination rates for ^2H and ^{18}O were corrected for changes in baseline isotopic abundances (Schoeller et al., 1986) [16], with two volunteers drinking local water (i.e., not dosed with DLW). Energy expenditure data were calculated by multiplying rCO_2 by the energy equivalent of CO_2 for an assumed Respiratory Quotient (RQ) of 0.83 or an RQ calculated from the FQ of the foods consumed, and the estimated changes in body energy stores during the study (DeLany et al., 1989) [5].

Thermal-Work Strain Physiological Parameters

Each volunteer wore a chest belt PSM system (Equivital-2, Hidalgo Ltd. Cambridge UK) and ingested a thermometer pill (Jonah ™ Core Temperature Pill, Respironics, Bend OR). The PSM system measured heart rate (derived from electrocardiogram waveform), respiration rate (derived from chest expansion/contraction waveform), activity level (derived from tri-axial accelerometer waveforms), skin temperature (infrared thermometer), and core body temperature (thermometer pill). All PSM data was collected at least every 15 seconds.

Heart rate, Tskin, and Tcore were used to characterize the thermal-work strain experienced by each volunteer. The Physiological Strain Index (PSI) [14], a measure combining HR and Tcore, was calculated as an overall indicator of thermal-work strain on a scale from 0 to 10.

Due to mission and time constraints (volunteers had strict departure time requirements and could not adjust the PSM system once on patrol), routine functionality checks for the PSM system (i.e., viewing the electrocardiogram to ensure that the PSM belt was collecting clean data and that the core temperature pill was present and broadcasting) were not always possible. In at least one case, a PSM system malfunctioned, most likely due to a damaged battery, and failed to record data properly. Thus, full PSM datasets were collected for 13 of our 19 volunteers.

Activity Monitoring

Three dimensional accelerometry data from the chest-mounted PSM device were used to estimate 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). Activity counts were computed as follows:

$$ActivityCounts = \sqrt{\sum_{n=1}^{3}\sum_{t=1}^{383}\left|AC_{nt} - AC_{nt+1}\right|} \qquad (4)$$

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

Activity counts provide an estimate of total activity based on the difference between each accelerometry axes' data sample within a 15 second period. The AC value is a representation of total accelerations on all three axes which increases as there are more and larger changes in accelerations.

METABOLIC RATE ESTIMATION USING THERMOREGULATORY MODEL

The SCENARIO model predicts core temperature given a number of inputs in addition to $\dot{M}$, including: environmental parameters (T_A, T_{BG}, WS, and RH), worn ensemble characteristics (i_m, $I_{tot,clo}$), and individual anthropometrics (height, weight, and % body fat). SCENARIO takes inputs and produces outputs for one minute time steps. With the exception of $\dot{M}$, all input values for SCENARIO were collected in the field.

Metabolic rate was modeled by matching the modeled Tcore output by SCENARIO to the observed Tcore of a given volunteer. At each time-step, $\dot{M}$ input values ranged from a volunteer's estimated resting metabolic rate (SCENARIO estimates this as 1.5 x body weight (kg), ~115 W) up to 1000 W. These $\dot{M}$ values were input along with the volunteer's anthropometrics, clothing, and environmental data. Root mean squared error (RMSE) between the observed Tcore and each modeled Tcore generated by the range of $\dot{M}$ values were calculated. The $\dot{M}$ with the lowest error was retained for each time-step.

Initially, matching $\dot{M}$ rates using SCENARIO's default minute-to-minute time step resulted in physiologically unlikely metabolic profiles. These profiles were characterized by extreme metabolic "yoyo-ing" or railing where modeled $\dot{M}$ would alternate between resting or near resting $\dot{M}$ (~115 W), ~255 W, and 1000 W. This railing effect was due to the first order change-of-state lags built into SCENARIO to counteract large and sudden changes in $\dot{M}$, blood flow, and stroke volume [9] by effectively smoothing transitions between different $\dot{M}$ values. The first order lag function is defined as:

$$\mathrm{X}_{\mathrm{m}+1} = \mathrm{X}_{\mathrm{m}} + (\mathrm{X}_{\mathrm{new}} - \mathrm{X}_{\mathrm{old}}) \bullet \left[1 - exp\left(\frac{-0.693 t_m}{t_{0.5}}\right)\right] \qquad (5)$$

where, X_{m+1} is the new time-lagged value, X_m is the previously lagged value, X_{new} is the new non-lagged value, X_{old} is the previous non-lagged value, t_m is the elapsed time, and $t_{0.5}$ is the response half-time (30 seconds in the case of $\dot{M}$),

While railing between minimum and maximum $\dot{M}$ inputs is explained by SCENARIO attempting to mute the magnitude of the metabolic transitions, we hypothesize that the prevalence of 255 W outputs is likely due to the use of 255 W in the original validation of SCENARIO and the generation of some of its internal set points (e.g., work rates were modulated between resting and 255 W during several of the validation studies) [9,10].

To achieve a gradual $\dot{M}$ profile and reduce the effects of the change-of-state lags, we incrementally increased the $\dot{M}$ time step from 1 minute to 5, 10, 15, 20, and 25 minutes thereby reducing the number of $\dot{M}$ transitions. Twenty minute time steps resulted in the lowest mean Tcore RMSE across volunteers (Figures 10 through 17) while generating smooth and stable $\dot{M}$ profiles. Using these $\dot{M}$ profiles we calculated modeled mission $\dot{M}$ energy expenditure ($\dot{M}_{MEE}$) and total mission energy expenditures in megajoules.

For comparison to DLW total daily energy expenditure ($TDEE_{DLW}$) data, we calculated estimated total daily energy expenditure ($TDEE_{EST}$) by summing three values: SCENARIO modeled mission $\dot{M}$ values ($\dot{M}_{MEE}$), estimated resting energy expenditures ($\dot{M}_{REE}$), and estimated non-exercise activity thermogenesis (NEAT) energy expenditures ($\dot{M}_{NEAT}$). Resting energy expenditure, the number of calories required to sustain the body while non-active, were calculated using Mifflin et al. [11] using equation 6:

$$\dot{\mathrm{M}}_{\mathrm{REE}} = (10 \bullet \mathrm{BW} + 6.25 \bullet \mathrm{HT} - 5 \bullet \mathrm{age} + 5) \bullet \frac{4184}{24 \bullet 60^2} \qquad (6)$$

where BW is body weight in kilograms, HT is height in centimeters, age is in years, and the fraction at the end converts between kilocalories and watts (Js^{-1}). Non-exercise activity thermogenesis energy expenditures include any activities that are not sleeping, eating, or volitional exercise. This includes sitting, standing, maintaining non-recumbent body positions, changing body positions, fidgeting, and spontaneous muscle contraction [6]. Equation 7 calculates NEAT in Watts as:

$$\dot{\mathrm{M}}_{NEAT} = (1.5 \bullet BW + 2.0 \bullet (BW + L)\ (L/BW)\hat{}2\ + \dot{\mathrm{M}}_{\mathrm{REE}})/2 \qquad (7)$$

where L is load carried in kilograms.

The in-theater investigator noted that missions lasted approximately 10 hours and we assumed an additional half hour of mission $\dot{M}$ values due to equipment stowage and walking movement between activities post and pre mission. The remaining 13.5 hours were broken down into 5 hours of $\dot{M}_{REE}$ and 8.5 hours of $\dot{M}_{NEAT}$ activities. Because we had no logs of any non-mission activities, including sleep, we estimated 5 hours of sleep by averaging length of time in the evening during which HR dropped below 60 beats per minutes while coinciding with low accelerometry counts. Thus, $TDEE_{EST}$ was calculated in megajoules as:

$$\mathrm{TDEE}_{\mathrm{EST}} = (10.5 \bullet \dot{\mathrm{M}}_{\mathrm{MEE}} + 5.0 \bullet \dot{\mathrm{M}}_{REE} + 13.5 \bullet \dot{\mathrm{M}}_{NEAT}) \bullet \frac{60^2}{10^6} \qquad (8)$$

This allowed us to estimate $\dot{M}$ for each individual and mission period as well as estimate TDEE (Figures 6-9, Table 5). We also calculated the percent error of $TDEE_{EST}$ compared to $TDEE_{DLW}$. Conversions from megajoules to kilocalories can be made using equation 9 below.

$$kcal = MJ \bullet \frac{10^6\ \mathrm{J/MJ}}{4184\ \mathrm{J/kcal}} \qquad (9)$$

RESULTS

METEOROLOGICAL CONDITIONS

Table 1 shows air temperature, relative humidity, wind speed, black globe temperatures, and WBGT for each of the mission periods. Meteorological data used for modeling purposes were collected during mission periods. Flag conditions were calculated from WBGT with an added 2.8 °C to account for body armor [15]. Overall, flag conditions did not exceed yellow although recorded temperatures reached as high as 40 °C.

Table 1: Environmental conditions for patrols on 28 and 29 August 2013.

Mission Period		Air Temp. (°C)	Relative Humidity (%)	Wind Speed (m/s)	Black Globe (°C)	WBGT (°C)	Flag Cond.*
28 AUG 0600-1600	MIN	22.0	5.0	1.5	26.0	14.0	No Flag
	MAX	40.0	17.0	5.7	60.5	26.7	Yellow
	MEAN	34.0	9.3	3.6	43.8	22.1	No Flag
	STD	5.6	4.2	1.2	10.3	3.7	-
29 AUG 0600-1600	MIN	23.0	7.0	0.5	28.0	14.1	No Flag
	MAX	38.0	20.0	5.7	58.5	27.2	Yellow
	MEAN	33.6	11.6	3.0	43.1	22.4	No Flag
	STD	4.3	3.6	1.5	9.4	3.7	-

*Note: flag condition takes into account adding 2.8 °C to WBGT to account for the effects of wearing body armor.

MISSION GROUPS AND TEST VOLUNTEERS

Table 2 presents volunteer characteristics (age, height, weight, percent body fat, 3 mile run time, and load carried). Volunteers in separate groups (G1, G2) engaged in separate mission activities and had different mission start and end times. Waist circumferences were 80.2 ± 5.2 cm, 83.2 cm, 81.5 ± 9.9 cm, and 81.9 ± 3.4 cm (mean ± standard deviation) for groups 1 and 2 on August 28th and August 29th respectively.

Table 2: Volunteer characteristics by patrol group and day.

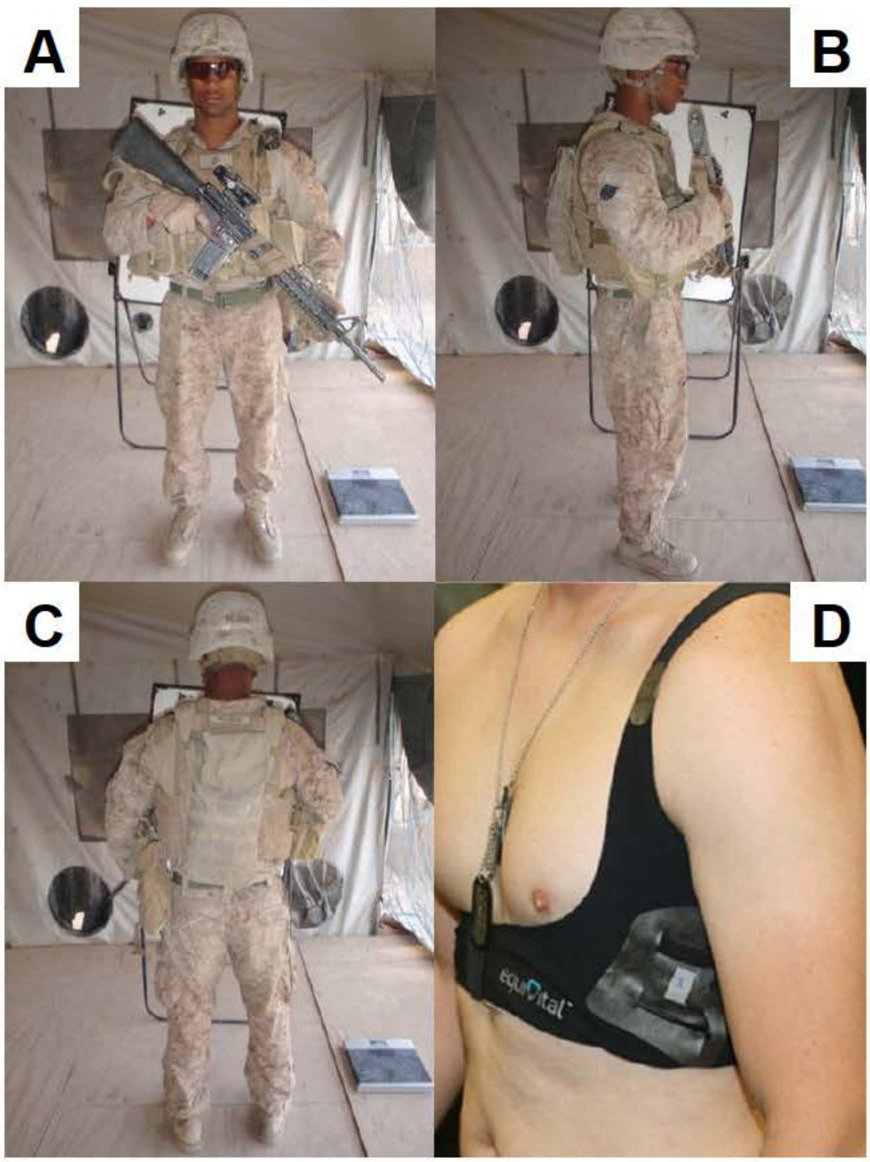
Day & Group		N	Age (yr)	Height (cm)	Weight (kg)	Body Fat (%)	3 Mi. Run Time (min)	Load (kg)
28 Aug	G1	5	22.0 ± 3.5	182.0 ± 5.3	78.3 ± 6.7	14.2 ± 5.0	20.8 ± 1.0	22.8 ± 4.8
	G2	1	20.0	69.0	82.6	13.9	19.5	Not recorded*
29 Aug	G1	8	20.7 ± 2.0	176.7 ± 9.8	81.1 ± 14.4	12.0 ± 4.7	20.3 ± 3.3	22.7 ± 5.0
	G2	5	21.2 ± 2.2	178.3 ± 5.5	79.4 ±4.0	13.4 ± 2.0	19.3 ± 0.8	27.2 ± 5.8

Note: for 28 August 2013 group 2, only one subject's data was useable for modeling and no load data was recorded for this volunteer (22.7kg was estimated*). G1 indicates group one and G2 indicates group two. Values shown are mean ± standard deviation.

CLOTHING AND EQUIPMENT CHARACTERISTICS

Volunteers from Fox Company 2/2nd reported wearing the Flame Retardant Organizational Gear (FROG) uniform, Scalable Plate Carrier (SPC), front, back and side Enhanced Small Arms Protective Insert (E-SAPI) plates, and Kevlar combat helmet. Figure 1 shows a typical C&IE configuration for the 2/2nd, and the physiological status monitor used to collect physiology data. Thermal manikin analysis found the Marine ensemble to have an insulation factor ($I_{tot,clo}$) of 1.34 clo, a permeability index (i_m) of 0.39, and an i_m/ $I_{tot,clo}$ ratio of 0.26 at a wind speed of 1.0 m/s.

Figure 1: Typical clothing and individual equipment configurations (A, B, and C) for Fox Company 2nd Battalion 2nd Marines and physiological status monitoring (PSM) system (Hidalgo EQ-02, D).



PHYSIOLOGICAL MEASURES

Table 3 presents observed physiological thermal-work strain data (HR, Tcore, Tskin, and PSI) by study day. Groups one and two were combined for each day.

Table 3: Heart rate, core temperature, skin temperature, and physiological strain index (PSI) (mean ± 1 standard deviation) for all study days between 0600 and 1600.

Day	Measure	Mean ± SD	Min	Max
28 AUG (n = 6)	HR (bpm)	84 ± 9	66	134
	Tcore (°C)	37.3 ± 0.1	37.2	37.4
	Tskin (°C)	36.6 ± 0.3	34.8	37.1
	PSI	2.6 ± 0.4	1.8	4.8
29 AUG (n = 13)	HR (bpm)	84 ± 7	69	111
	Tcore (°C)	37.2 ± 0.2	37.0	37.7
	Tskin (°C)	36.4 ± 0.6	34.2	36.9
	PSI	2.3 ± 0.5	1.3	4.0
30 AUG (n = 8)	HR (bpm)	77 ± 11	51.6	124
	Tcore (°C)	36.9 ± 0.1	36.8	37.2
	Tskin (°C)	35.4 ± 1.0	32.8	36.5
	PSI	2.4 ± 0.8	0.9	4.8
31 AUG* (n = 2)	HR (bpm)	85 ± 10	61	119
	Tcore (°C)	37.1 ± 0.2	36.7	37.4
	Tskin (°C)	36.0 ± 0.7	30.7	37.1
	PSI	2.5 ± 1.1	0.8	6.4

SD = standard deviation.
*The data collected on the 31st was incomplete and noisy. This is reflected by the high max PSI despite similar mean and standard deviations for all other measures.

Table 4 presents observed physiological thermal-work strain (HR, Tcore, Tskin, and PSI). Figures 2 through 9 show mean HR, Tcore, Tskin, PSI, and accelerometer activity counts for both groups on each mission day. Error bars representing one standard deviation are present for all data except for accelerometry counts.

Table 4: Heart rate (HR), core temperature (Tcore), skin temperature (Tskin), and physiological strain index (PSI) (mean ± 1 standard deviation) for patrol days between 0600 and 1600.

Day	Group & Time	Measure	Mean ± SD	Min	Max
28 AUG	G1 (n = 5) 0600-1600	HR (bpm)	84 ± 10	66	134
		Tcore (°C)	37.3 ± 0.1	37.1	37.4
		Tskin (°C)	36.6 ± 0.3	35.7	37.1
		PSI	2.5 ± 0.5	1.8	4.8
	G2 (n = 1) 0600-1600	HR (bpm)	87 ± 15	63	136
		Tcore (°C)	37.5 ± 0.2	37.1	37.8
		Tskin (°C)	36.8 ± 0.6	34.9	37.7
		PSI	2.8 ± 0.7	1.5	4.9
29 AUG	G1 (n = 8) 0600-1600	HR (bpm)	80 ± 5	69	97
		Tcore (°C)	37.2 ± 0.2	36.9	37.7
		Tskin (°C)	36.7 ± 0.3	36.1	37.2
		PSI	2.2 ± 0.7	1.1	4.0
	G2 (n = 5) 0600-1400*	HR (bpm)	84 ± 12	61	129
		Tcore (°C)	37.2 ± 0.1	37.0	37.4
		Tskin (°C)	36.4 ± 0.4	35.6	37.0
		PSI	2.5 ± 0.6	1.4	4.4

SD = standard deviation.
*No data available for mission after 1400 for Group 2.

Figure 2: Core temperature (Tcore), skin temperature (Tskin), and heart rate (HR) (mean ± 1 standard deviation) for group 1 (n = 5) during patrol on 28 August 2013: 0600-1600.

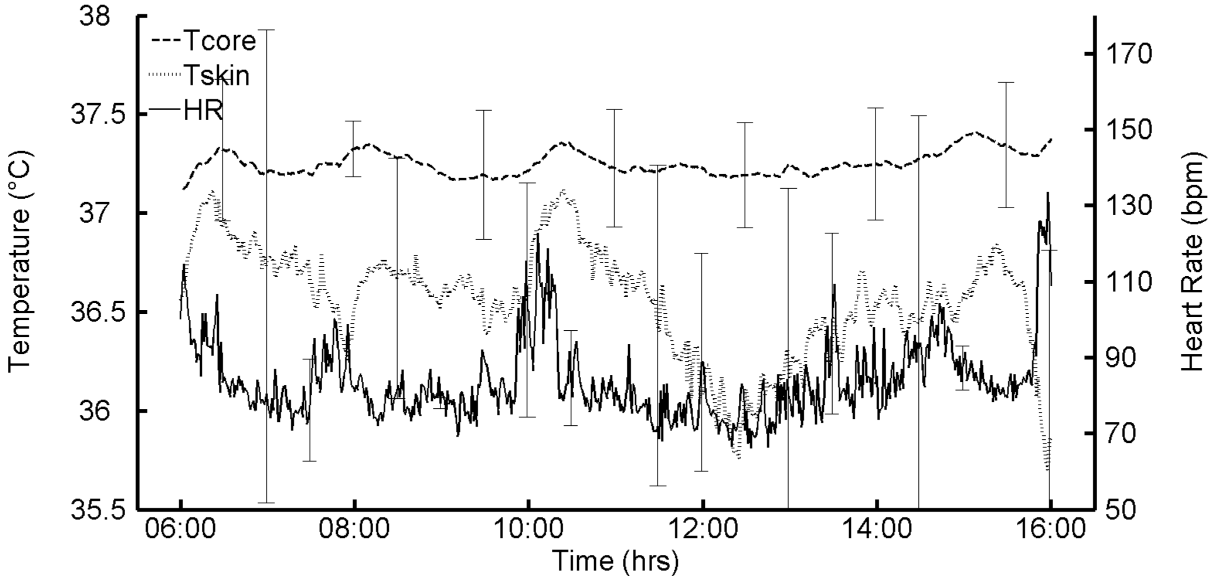


Figure 3: Physiological strain index (PSI) (mean ± 1 standard deviation) and mean accelerometry counts for group 1 (n = 5) during patrol on 28 August 2013: 0600-1600.

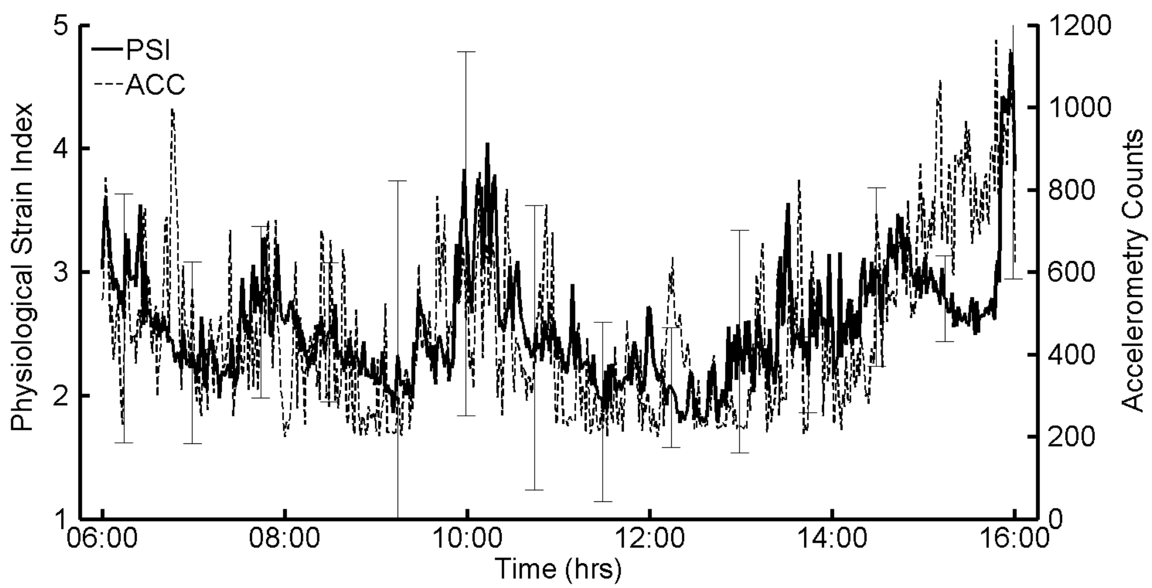


Figure 4: Core temperature (Tcore), skin temperature (Tskin), and heart rate (HR) (mean ± 1 standard deviation) for group 2 (n = 1) during patrol on 28 August 2013: 0600-1600. Note: HR data was lost at ~1300.

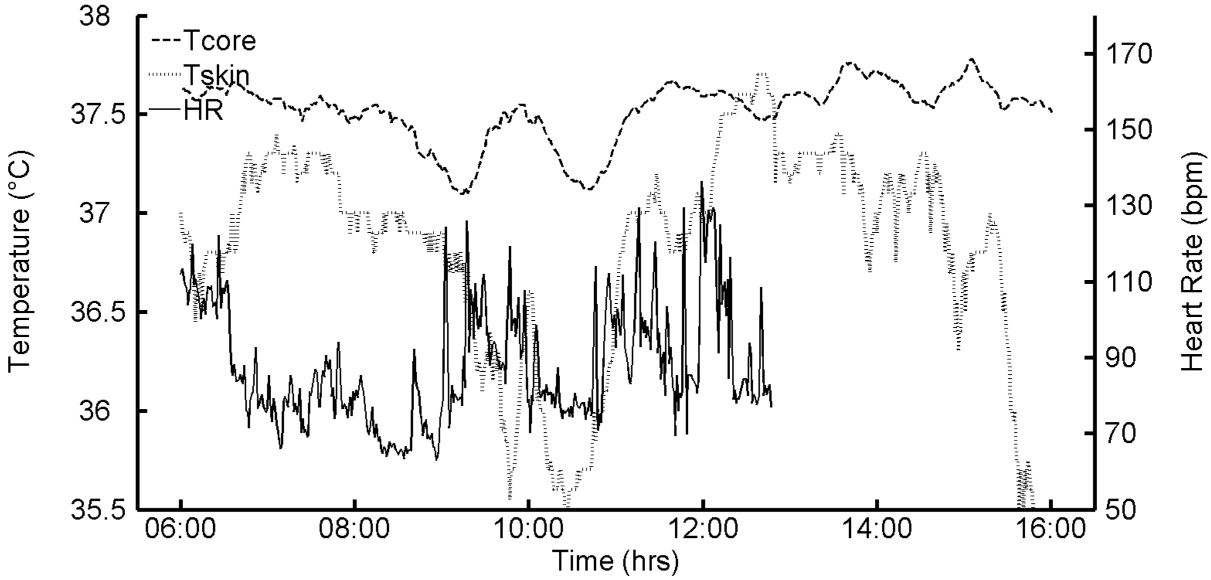


Figure 5: Physiological strain index (PSI) (mean ± 1 standard deviation) and mean accelerometry counts for group 2 (n = 1) during patrol on 28 August 2013: 0600-1600. Note: HR data was lost for the only volunteer at ~1300 hours but the accelerometry data for 1300 on suggests a high degree of either movement or mounted transport.

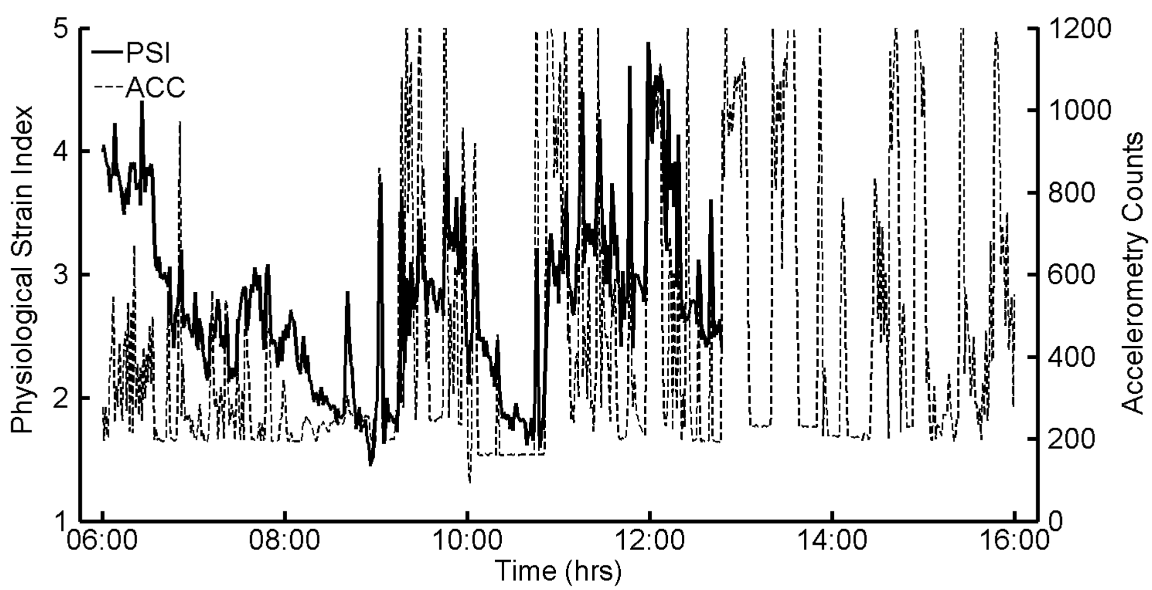


Figure 6: Core temperature (Tcore), skin temperature (Tskin), and heart rate (HR) (mean ± 1 standard deviation) for group 1 (n = 8) during patrol on 29 August 2013: 0600-1600.

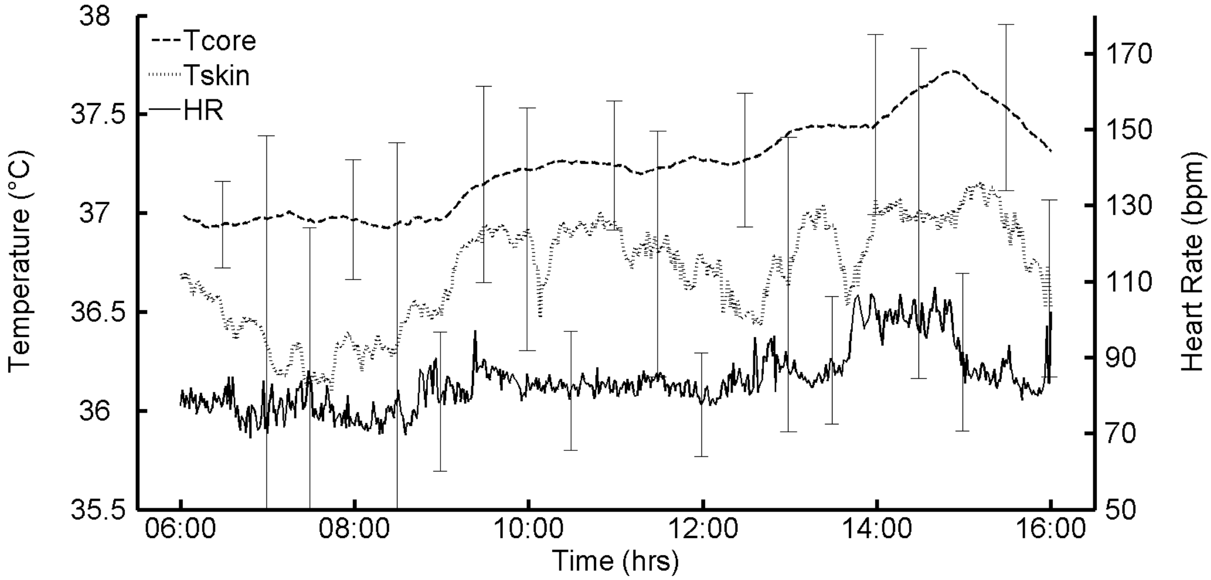


Figure 7: Physiological strain index (PSI) (mean ± 1 standard deviation) and mean accelerometry counts for group 1 (n = 8) during patrol on 29 August 2013: 0600-1600.

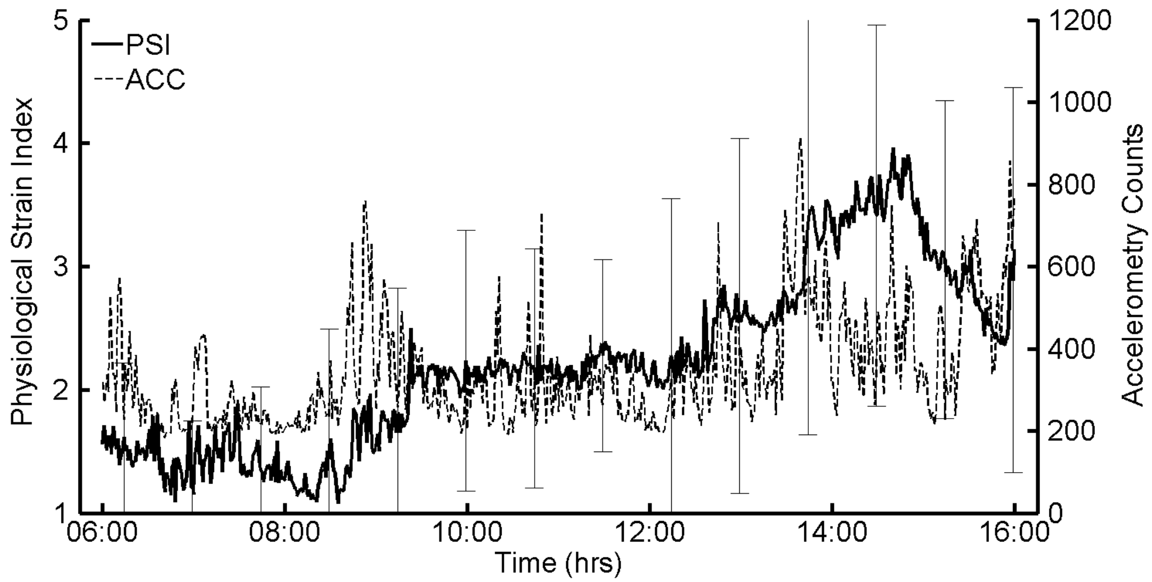


Figure 8: Core temperature (Tcore), skin temperature (Tskin), and heart rate (HR) (mean ± 1 standard deviation) for group 2 (n = 5) during patrol on 29 August 2013: 0600-1600.

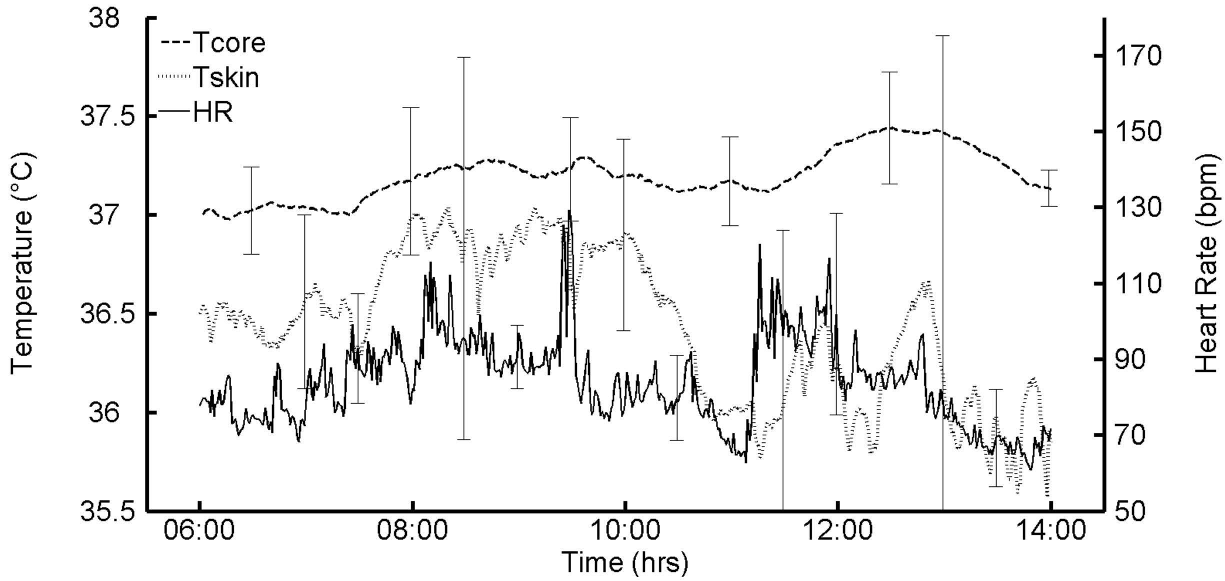
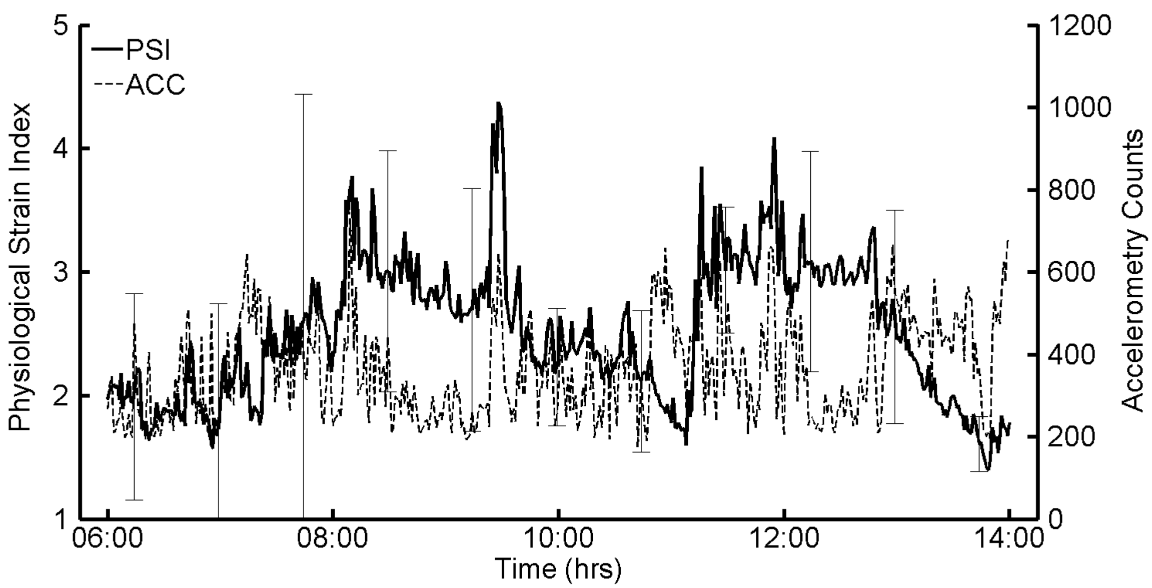


Figure 9: Physiological strain index (PSI) (mean ± 1 standard deviation) and mean accelerometry counts for group 2 (n = 5) during patrol on 29 August 2013: 0600-1600.



METABOLIC RATE ESTIMATION USING THERMOREGULATORY MODEL

Table 5 presents modeled physiological and metabolic summary information (Tcore, HR, PSI, and $\dot{M}$) for each mission period and group. Metabolic rate ($\dot{M}$) in this table is the metabolic rate in watts, not TDEE in kilocalories. Metabolic rate values were used in the estimation of TDEE using equations 6, 7, and 8.

Table 5: Heart rate (HR), core temperature (Tcore), physiological strain index (PSI), and mission metabolic rate ($\dot{M}$) for patrols on 28 and 29 August 2013: 0600-1600.

Mission Period	Group & Time	Measure	Mean ± SD	Min	Max
28 AUG	Group 1 (n = 5) 0600-1600	HR (bpm)	96 ± 4	81	107
		Tcore (°C)	37.3 ± 0.1	37.2	37.7
		PSI	3.1 ± 0.2	2.5	3.8
		$\dot{M}$ (W)	222 ± 53	124	333
	Group 2 (n = 1) 0600-1600	HR (bpm)	106 ± 8	87	130
		Tcore (°C)	37.5 ± 0.2	37.1	37.7
		PSI	3.6 ± 0.5	2.2	4.6
		$\dot{M}$ (W)	290 ± 85	124	476
29 AUG	Group 1 (n = 8) 0600-1600	HR (bpm)	94 ± 11	77	121
		Tcore (°C)	37.3 ± 0.2	37.0	37.7
		PSI	2.7 ± 0.7	1.6	4.5
		$\dot{M}$ (W)	215 ± 41	149	264
	Group 2 (n = 5) 0600-1400	HR (bpm)	96 ± 6	84	108
		Tcore (°C)	37.2 ± 0.1	37.1	37.4
		PSI	2.8 ± 0.4	2.1	3.6
		$\dot{M}$ (W)	223 ± 25	185	264

SD = standard deviation.
$\dot{M}$ = Metabolic rate during mission.

Table 6 shows subject energy expenditure data as determined by DLW, Mifflin et al., Hoyt et al., and SCENARIO modeling. REEs were calculated using Mifflin et al [11] assuming 5 hour resting periods. Mission energy expenditures were calculated using SCENARIO assuming 10 hour missions with an additional 0.5 hours of similar work rates pre and post mission. The remaining 8.5 hours were assumed to be NEAT and were calculated using Hoyt et al. The $TDEE_{EST}$ was calculated by summing resting, NEAT, and mission energy expenditures (Equation 8). Percent error was calculated for $TDEE_{EST}$ versus $TDEE_{DLW}$. A two tailed paired t-test of modeled $TDEE_{EST}$ and $TDEE_{DLW}$ resulted in a p-value of 0.74 indicating that $TDEE_{EST}$ values were not significantly different from $TDEE_{DLW}$.

Mission energy expenditures modeled by matching observed Tcore values to SCENARIO modeled Tcore had RMSE values of 0.12 ± 0.03, 0.15 ± 0.11, and 0.12 ± 0.04 (mean ± SD) for group 1 on the 28th and groups 1 and 2 on the 29th of August respectively. Group 2 on the 28th of August was comprised of only one volunteer with an RMSE of 0.07. Mean RMSE across all volunteers was 0.13 ± 0.08.

Table 6: Total daily, resting, non-exercise activity thermogenesis (NEAT), and mission energy expenditures*.

	Estimated Energy Expenditures				$TDEE_{DLW}$ (MJ)	$TDEE_{EST}$ % Error
	Resting (MJ)	NEAT (MJ)	Mission (MJ)	$TDEE_{EST}$ (MJ)		
	1.69	3.51	8.61	13.81	13.50	2.28
	1.61	3.29	7.91	12.81	13.78	-7.07
	1.54	3.15	6.19	10.88	14.68	-25.90
	1.51	3.00	11.49	16.00	11.94	34.08
	1.56	2.95	6.39	10.90	13.34	-18.34
	1.84	4.01	11.17	17.03	15.37	10.78
	1.58	3.19	11.50	16.27	13.25	22.80
	1.33	2.55	4.13	8.01	9.90	-19.03
	1.59	3.25	10.75	15.59	13.74	13.51
	1.50	3.01	9.14	13.66	14.15	-3.43
	1.61	3.32	8.65	13.58	12.74	6.60
	1.57	3.11	7.60	12.28	14.32	-14.24
	1.60	3.12	5.84	10.56	13.66	-22.67
Mean	1.58	3.19	8.41	13.18	13.41	-1.59
SD	0.11	0.32	2.28	2.54	1.30	18.58
	**	**	**	**	12.51	**
	**	**	**	**	10.56	**
	**	**	**	**	14.38	**
	**	**	**	**	12.63	**
Mean	**	**	**	**	13.20	**
SD	**	**	**	**	1.41	**

* Resting Energy Expenditures were calculated using Mifflin et al. (1990) assuming 5 hours of rest. Estimated Mission Energy Expenditures were calculated using the SCENARIO model assuming 10 hour mission periods plus an additional 0.5 hours of post and pre mission movement. NEAT estimated energy expenditures were calculated using Hoyt et al. (2004). $TDEE_{EST}$ is the sum of Resting, NEAT, and Mission estimated energy expenditures. $TDEE_{DLW}$ is the total daily energy expenditure as measured by doubly labeled water. $TDEE_{EST}$ % Error = ($TDEE_{EST}$–$TDEE_{DLW}$) /$TDEE_{DLW}$ • 100. SD = standard deviation.
** Values were not calculated because physiological data for subject were lost/corrupt/discarded.

Figure 10: Observed (Obs) and modeled (Mod) core temperature(Tcore) and heart rate (HR) (mean ± 1 standard deviation) for group 1 (n = 5) on patrol on 28 August 2013: 0600-1600.

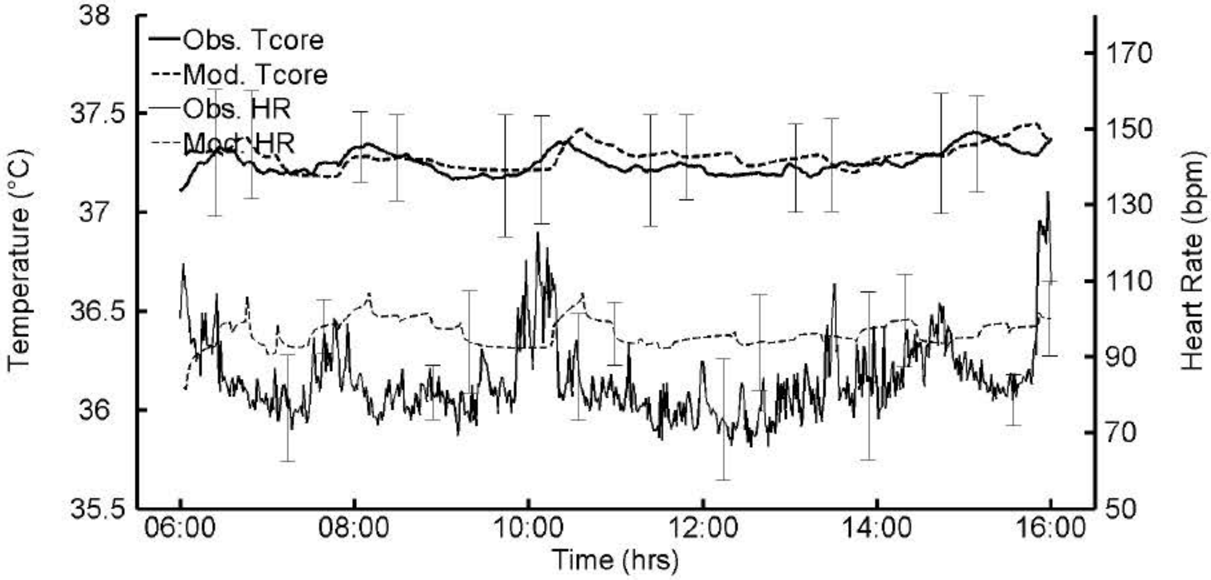


Figure 11: Observed (Obs) and modeled (Mod) physiological strain index (PSI) and modeled metabolic rate ($\dot{M}$) (mean ± 1 standard deviation) for group 1 (n = 5) on patrol on 28 August 2013: 0600-1600. Note: the grey box highlights a time step lag between modeled and observed PSI created by using a time step of 20 minutes. Further explanation is given in the discussion.

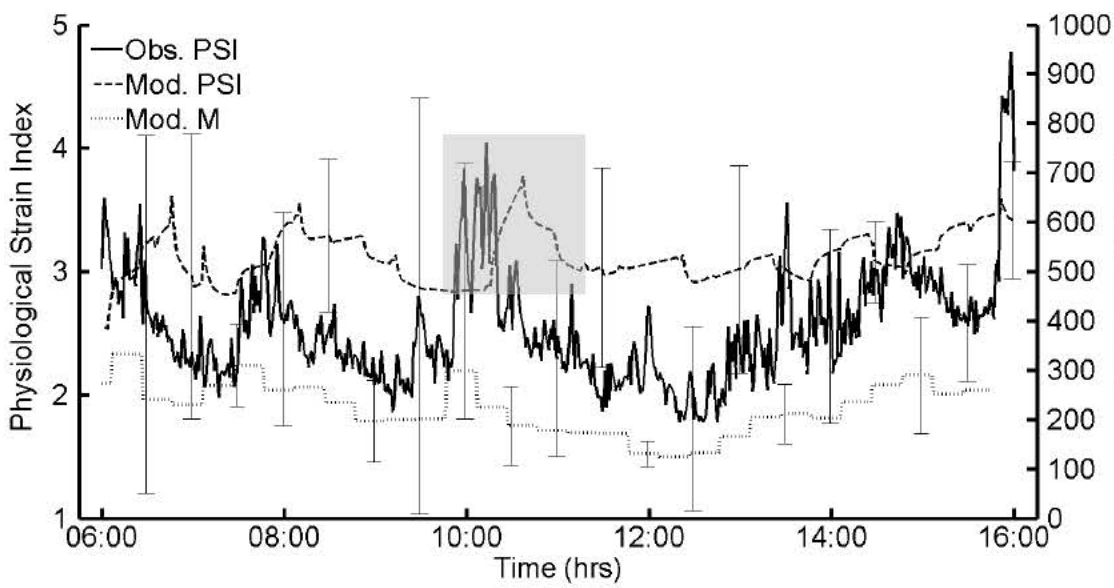


Figure 12: Observed (Obs) and modeled (Mod) core temperature (Tcore) and heart rate (HR) (mean ± 1 standard deviation) for group 2 (n = 1) on patrol on 28 August 2013: 0600-1600.

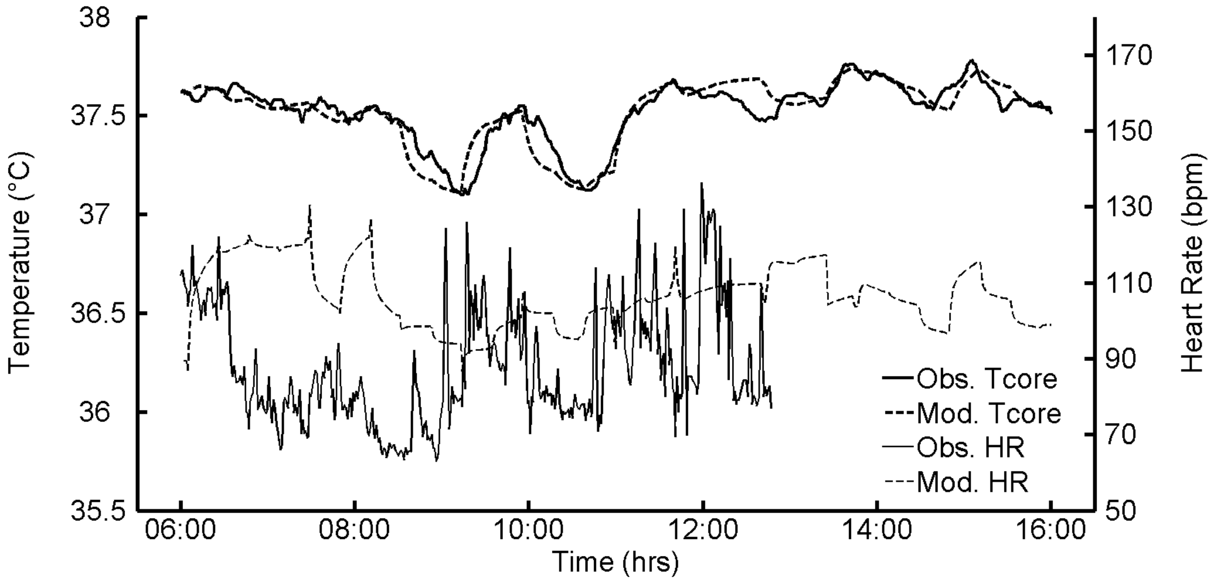


Figure 13: Observed (Obs) and modeled (Mod) Physiological Strain Index (PSI) and modeled $\dot{M}$ (mean ± 1 standard deviation) for group 2 (n = 1) on patrol on 28 August 2013: 0600-1600.

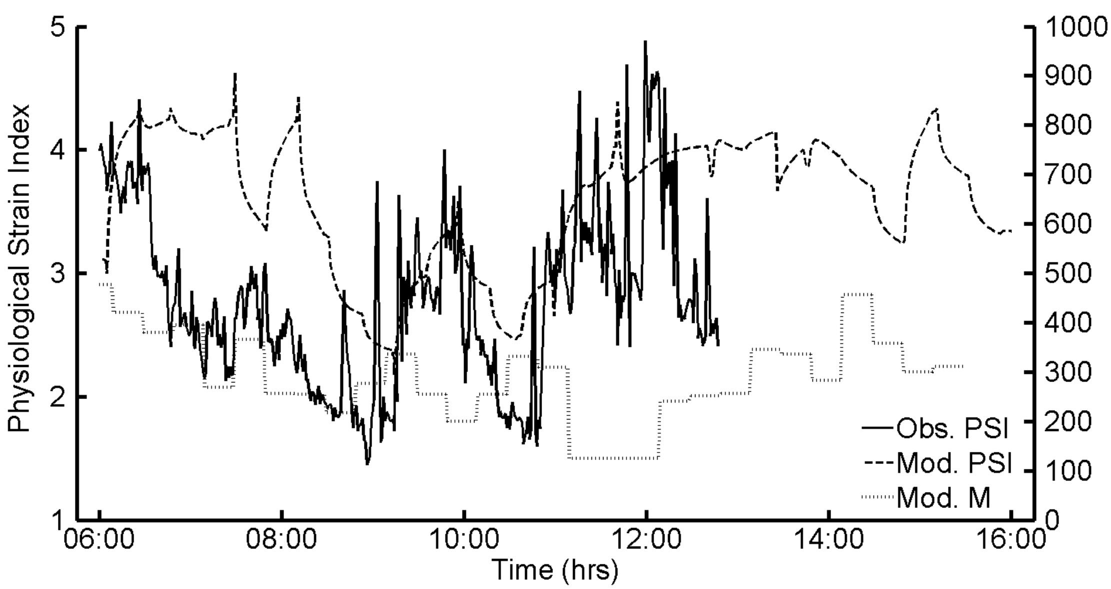


Figure 14: Observed (Obs) and modeled (Mod) core temperature (Tcore) and heart rate (HR) (mean ± 1 standard deviation) for group 1 (n = 8) on patrol on 29 August 2013: 0600-1600. Note: the grey box highlights a time step lag between modeled and observed physiological strain index (PSI) created by using a time step of 20 minutes. Further explanation is given in the discussion.

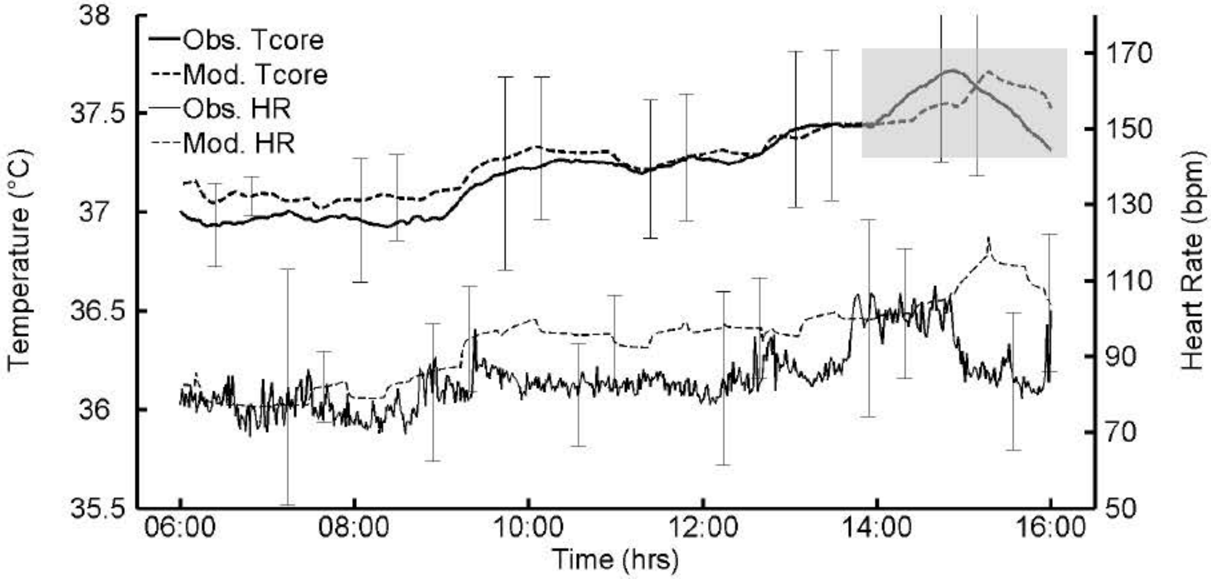


Figure 15: Observed (Obs) and modeled (Mod) physiological strain index (PSI) and modeled metabolic rate ($\dot{M}$) (mean ± 1 standard deviation) for group 1 (n = 8) on patrol on 29 August 2013: 0600-1600.

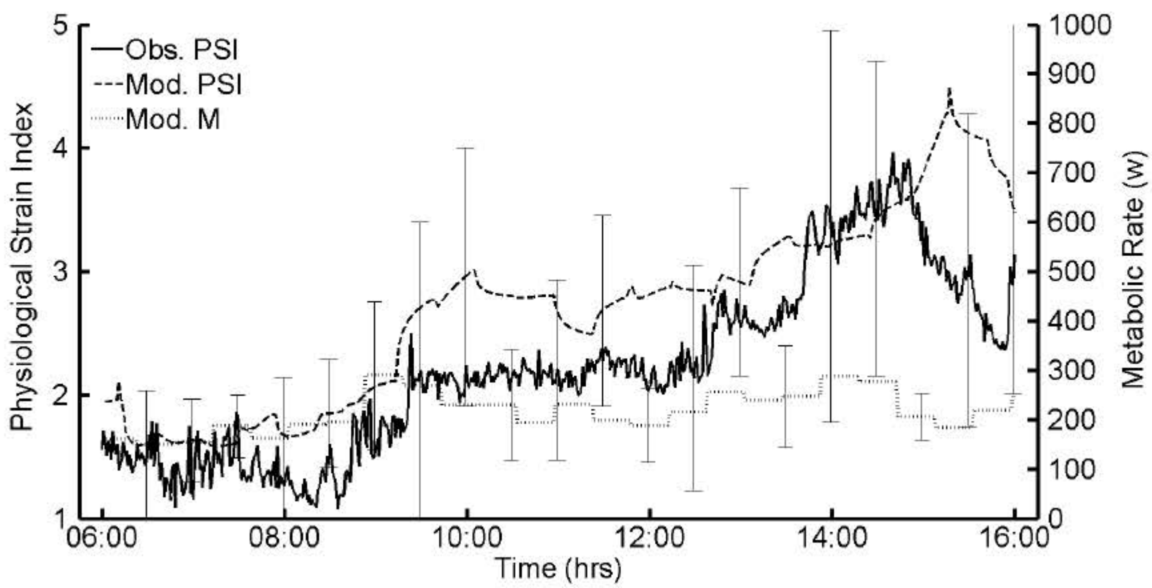


Figure 16: Observed (Obs) and modeled (Mod) core temperature (Tcore) and heart rate (HR) (mean ± 1 standard deviation) for group 2 (n = 5) on patrol on 29 August 2013: 0600-1400.

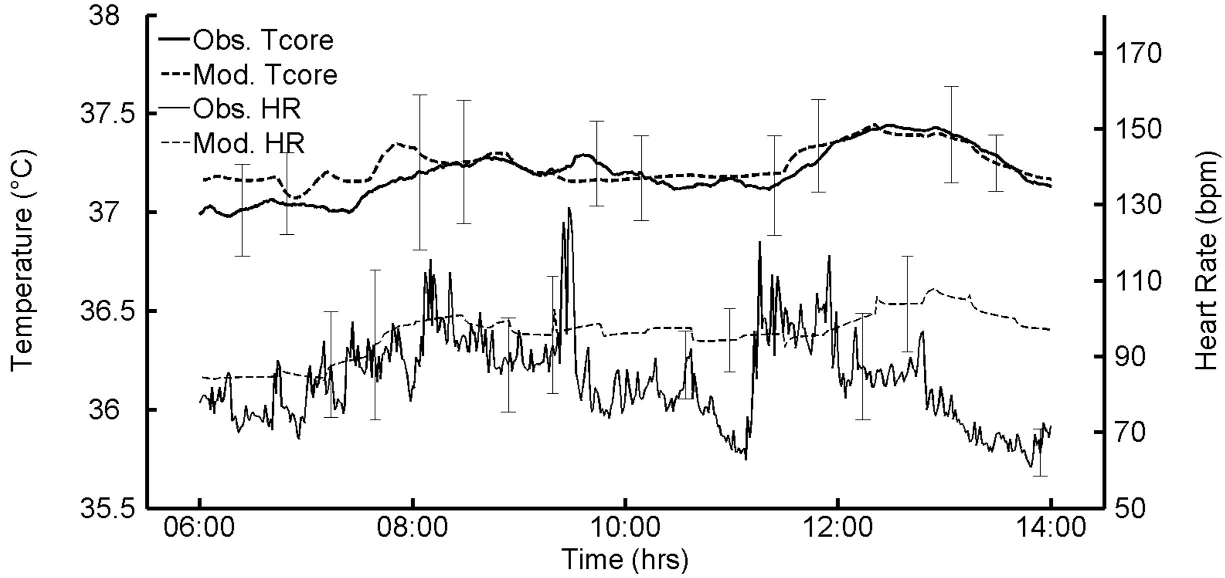
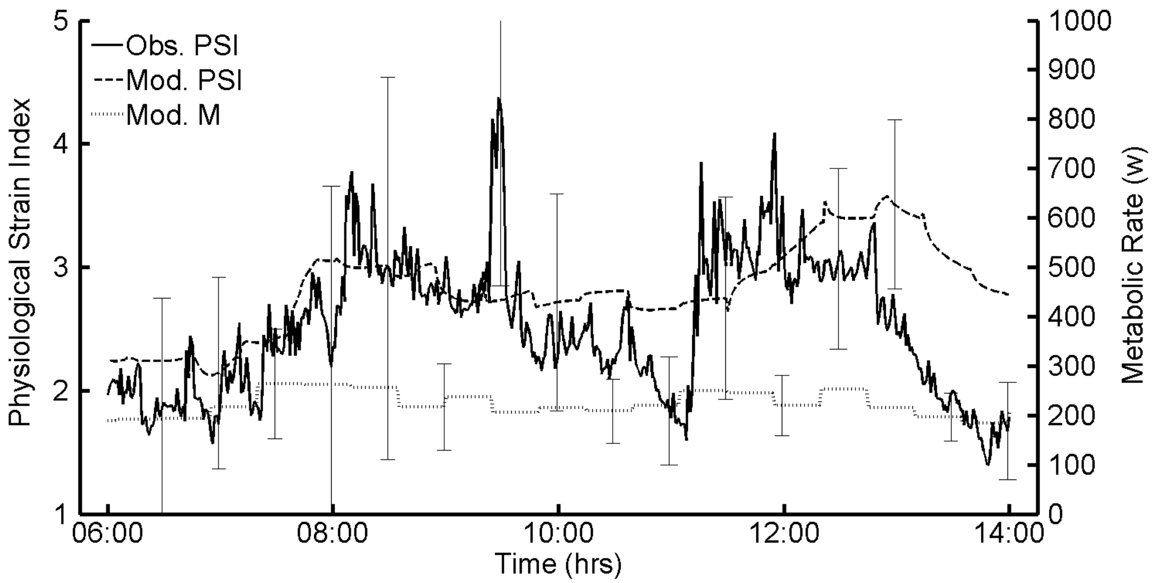


Figure 17: Observed (Obs) and modeled (Mod) physiological strain index (PSI) and modeled metabolic rate ($\dot{M}$) (mean ± 1 standard deviation) for group 2 (n=5) on patrol on 29 August 2013: 0600-1400.



DISCUSSION

Thermal-Work Strain

The environmental conditions during the August 2013 missions were temperate and the Marine test volunteers experienced limited thermal-work strain. Mean WBGT for both patrol Day 1 and patrol Day 2 (28^{th} and 29^{th} of August) were 22.1 ± 3.7 °C and 22.4 ± 3.7°C. Mean PSI values for both days indicated low thermal-work strain with values of 2.5 ± 0.5 and 3.1 ± 1.1 for groups 1 and 2 on Day 1 and values of 2.2 ± 0.7 and 2.5 ± 0.6 on Day 2. Observed PSI reached a maximum of 4.9 on Day 1 for group 2 indicating a short period of low to moderate thermal-work strain.

Physiological data for all study days also reflected low levels of thermal-work strain. Core temperature and HR never exceeded 37.8 °C and 136 beats per minute respectively despite the in-theater investigator describing mission events including sniper fire, securing weapon caches, and an IED explosion. In fact, mean mission physiological data were similar to mean data for non-mission days. Core temperature ranged from 36.7 to 37.7 ºC and HR from 52 to 134 bpm over the four day period (Table 4). Low Tcore and HR data may be partially explained by prolonged periods of mounted travel as well as the loss of data during periods of greater activity (due to disruption by load carriage and movement) but overall suggest a relatively low level of physiological exertion.

Metabolic Modeling and Estimation

Overall low thermal-work strain levels seem reasonable given the moderate energy expenditures observed. The slopes for ^{2}H and ^{18}O elimination were consistent across subjects over the four days of data collection resulting in a mean $TDEE_{DLW}$ (13.20 ± 1.41 MJ) similar to values documented for Marine construction missions (13.0 ± 2.30 MJ). In comparison, energy expenditures observed during combat unit training have been observed to be in the 14.0 – 20.0 MJ/day range [18].

Estimated TDEE values also appear reasonable given the accuracy with which we modeled Tcore. Back calculation of $\dot{M}$ using the SCENARIO thermo-regulatory model [9,10] resulted in low observed versus modeled Tcore RMSE values (0.13 ± 0.08) and a p-value of 0.74 (two tailed paired t-test) indicating that estimated versus observed TDEE values are not significantly different across subjects. However, the large standard deviation of percent error (-1.59 ± 18.58 %, -0.21 ± 2.49 MJ) suggests that estimating $\dot{M}$ using SCENARIO may not be suitable for individuals. Furthermore, because volunteers did not log their non-mission activities, we have no way to verify how accurate our estimations of NEAT and resting time periods were.

Our metabolic rate modeling efforts yielded several interesting but unexpected results. Initial attempts to back calculate $\dot{M}$ using 1-10 minute bins or “epochs” resulted in highly variable and physiologically unlikely, if not impossible, $\dot{M}$ profiles. This was due to the first order change-of-state lags built into SCENARIO designed to prevent physiologically unrealistic changes in $\dot{M}$, stroke volume, and blood flow. It was only by increasing the time step length to 15-25 minutes that $\dot{M}$ outputs began to stabilize into profiles which reflected our DLW results while still matching modeled Tcore to observed. SCENARIO also consistently over estimated HR values which may suggest an underlying issue in one or more of SCENARIO's physiological heat transfer components.

Although the $\dot{M}$ time step length (20 minutes) created a generally smoother and more stable $\dot{M}$ profile, it also introduced errors into the modeled data. When observed Tcore rose or fell rapidly, larger time steps created modeling errors by reducing a region of rapid metabolic change to only one $\dot{M}$ value. These errors are visible as delays in the modeled Tcore and PSI (Figure 11 and 14, highlighted regions). Modeling lags could potentially be reduced using several methods including matching the size of the time step to the rate of change of observed Tcore, using a set of $\dot{M}$ transition probabilities to select an appropriate range of $\dot{M}$ values each time step, or removing the change-of-state lags built into the SCENARIO model.

Future work will include improving the SCENARIO model by using a dataset containing higher resolution $\dot{M}$ data. Specifically, we hope to compare SCENARIO's physiological outputs to observed values using an observed $\dot{M}$ profile with a resolution of minutes rather than days. By examining SCENARIO's internal variables and outputs, we hope to determine which sub components (active physiology versus passive heat transfer) produce anomalous heat balance or physiology values.

CONCLUSIONS

The mean $TDEE_{DLW}$ of in-theater Marines who engaged ten hour patrols on two days followed by two days on base was 13.20 ± 1.41 MJ (n = 17). This metabolic rate is comparable to rates observed during Marine construction missions. Volunteers experienced mostly low to moderate thermal-work strain levels during both patrol mission periods and the days spent on base.

Accurately determining $\dot{M}$ in the field remains a challenge to scientists. Developing a method of estimating $\dot{M}$ using accepted thermo-regulatory models and physiological data may provide a valuable tool for modeling and planning purposes in environments where accurate methods of measuring metabolic rate are otherwise precluded. Our approach of back-calculating $\dot{M}$ using a validated thermo-regulatory model shows agreement for group means but needs further work for extension to individuals.

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