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SIMULATION OF THERMAL-WORK STRAIN OF DISMOUNTED MARINES WEARING DIFFERENT BODY ARMOR PROTECTION LEVELS IN A JUNGLE ENVIRONMENT

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ABSTRACT

Dismounted warfighters often experience thermal-work strain when performing missions in hot and humid jungle environments. Under these conditions, the survivability benefits provided by increased body armor protection levels (BAPL) must be carefully balanced with their associated thermal and metabolic burdens and avoid thermal injury. **PURPOSE:** Model the effects of increased BAPL on the thermal-work strain of U.S. Marines engaged in dismounted training activities at Camp Gonsalves, Okinawa, Japan (June, 2013). **METHODS:** Core temperature (T_C), heart rate (HR), and accelerometry data were collected over 3 days (5-9 hr/day) from U.S. Marines (N = 11, age = 21 ± 2 yr, ht = 172 ± 4 cm, wt = 78.2 ± 1.9 kg, $\bar{x}$ ± SD) using chest-worn physiological monitors and ingested thermometer pills. Metabolic rates, estimated from accelerometry data by matching modeled to observed T_C values using a thermoregulatory model, used to predict the physiological effects of increased BAPL under jungle conditions (air temperature = 28.3 ± 0.8 ºC, relative humidity = 91 ± 7 %). **RESULTS:** Root mean square error between observed and modeled T_C was 0.24 ± 0.09 ºC for BAPL 0, indicating reasonable metabolic rate estimations. Mean daily increases in T_C were 0.3 ± 0.4 ºC, 0.7 ± 0.4 ºC, 2.8 ± 0.9 ºC, and 3.2 ± 0.9 ºC for observed data and data modeled with BAPL 0, 3, and 5 respectively. Modeling BAPL 0 with either increased load or reduced vapor permeability resulted in T_C increases of 2.9 ± 0.8 ºC and 1.4 ± 0.6 ºC respectively. Differences between BAPL resulted in Modeled T_C values > 39.5 ºC at 238 ± 65 minutes and 188 ± 42 hrs for BAPL 3 and 5. **CONCLUSION:** Predictive modeling indicates that the risk of thermal-work strain is severe given jungle conditions and increased BAPL. The mass of BAPL ensembles contributes more to thermal-work strain than reductions in ensemble permeability and evaporative heat loss.

Keywords: thermal-work strain, metabolic rate, modeling, thermal performance

INTRODUCTION

The use of body armor has become common place in recent military engagements and a great deal of literature and doctrine has accumulated on the topic of the tactical advantages and challenges of its deployment [1,2,3]. However, in thermally-challenging environments with high air temperatures, high relative humidities, and rugged terrain and vegetation that can greatly increase the metabolic cost of movement, the thermal burden of body armor must be carefully considered. This is particularly true during Warfighter jungle operations which have been described as "consist[ing] essentially of the coordinated action of small groups of infantry armed with the weapons they are able to carry on their backs" [4] during which "heat prostrations and cases of sheer physical exhaustion are common" [4].

These observations and warnings appear sensible given that jungle environments typically have constant high temperatures between 25.5 to 30 ˚C and relative humidity from 65 to 90% depending on season and time of day. Operations in these thermally-challenging environments can be further complicated by jungle canopies capable of blocking or diffusing most direct sunlight and nearly all wind. The combination of high humidity and lack of air movement can greatly reduce the potential for evaporative cooling from sweating.

Neither the US Army Field Manual (FM) on jungle operations [5] nor the Fleet Marine Force Reference Publication (FMFRP) 12-9 [4] mention or describe the use of body armor. Instead, body armor protection level (BAPL) guidance has taken the form of general directives moving away from a "one-size-fits-all" mentality towards reliance upon "mission analysis and military judgement" to determine appropriate personal protective posture and equipment [6,7]. This work models the thermal-work strain associated with encapsulation and load carriage burdens imposed by BAPL during dismounted training operations in a jungle environment.

METHODS

Data were collected from 33 U.S. Marine participants across 13 days during dismounted training missions at the Jungle Warfare Training Center (JWTC), Camp Gonsalves, Okinawa. Participants were volunteers recruited under a protocol approved according to the policies for protection of human subjects as prescribed in Army Regulation 70-25 and in adherence to the provisions of 32 CFR part 219. Prior to the initiation of data collection, volunteers were briefed and provided their informed consent.

Each participant wore six different uniforms for at least 48 hours per uniform. During this time, they also completed jungle warfare training activities including patrolling with varying loads, rappelling, establishing patrol bases, combat life saver training, and jungle survival training.

To simplify our modeling process and control against differences between activities, amounts of load carried, and ensemble characteristics, we used a subset of 11 participants wearing the Marine Corps Combat Utility Uniform (MCCUU) over 3 days where the dominant activity was patrolling without a backpack or body armor (minimal load similar to body armor protection level (BAPL) 0). The MCCUU was selected as our baseline ensemble as we have previously determined that its insulation and permeability characteristics are similar to values reported by Potter et al. [8] for BAPL 0 (Table 2).

Volunteer Characteristics

Age (self-report), height (anthropometric tape measure), semi-nude weight (shorts and t-shirt), and circumferences at the navel and chest (anthropometric tape measure) were recorded for each volunteer (N = 11, age = 21 ± 2 yr, ht = 172 ± 4 cm, wt = 78.2 ± 1.9 kg, waist circ = 85 ± 8 cm, chest circ = 98 ± 7 cm, $\bar{x}$ ± standard deviation (SD)).

Environmental Conditions

Due to its relative proximity to Camp Gonsalvez, hourly meteorological data were requested from Kadena Air Force Base, Kadena, Japan. The 14th Weather Squadron (Asheville, NC), provided air temperature (T_A), dew point, wind speed (WS), black globe temperature (T_{BG}), relative humidity (RH), and wet black globe temperature (WBGT) data for the month of June, 2015. During the modeling process T_{BG} was assumed to be the same as T_A (minimal solar load) and WS was assumed to be 0.4 ms-1 (still air). These changes were to account for the effects of the jungle canopy blocking some solar load and air movement. Figure 1 shows the typical study environment.

Clothing Ensemble Characteristics

Clothing insulation (clo), water vapor permeability index (i_m), and evaporative potential (i_m/clo) values for each of the Body Armor Protection Levels (BAPL) reported by Potter et al. [8] were used as model inputs. A clo is a unit of thermal resistance defined as the insulation required for keeping a resting man comfortable at 21 ˚C [9]. One clo is equal to 0.155 K•m2W-1 and roughly equivalent (1.17 clo) to wearing men's underwear briefs, khaki pants, belt, socks, athletics shoes, and a short-sleeved shirt [9]. The vapor permeability index, i_m, is a non-dimensional index from 0 to 1 where 0 indicates that an ensemble is impermeable to vapor transfer and subsequently does not permit evaporative heat transfer [10]. An i_m of 1 indicates the theoretical maximum of evaporative heat loss given the ensembles insulation [10]. The ratio of im/clo indicates the "evaporative potential" of an ensemble [11].

In addition to values reported by Potter et al., biophysical characteristics (clo, i_m) of the Enhanced Flame Resistant Combat Ensemble (EFRCE) and MCCUU were tested via thermal manikin using American Society of Testing and Materials (ASTM) standards [9,10]. Both the EFRCE and MCCUU (Figure 2) were tested to determine how similar their biophysical properties were to BAPL 0. Table 1 contains the corresponding insulation and vapor permeability values for each of the BAPL, BAPL 0 variants, the EFRCE, and the MCCUU.

Figure 1. Study participants engaged in training exercises in the Jungle Warfare Training Center.

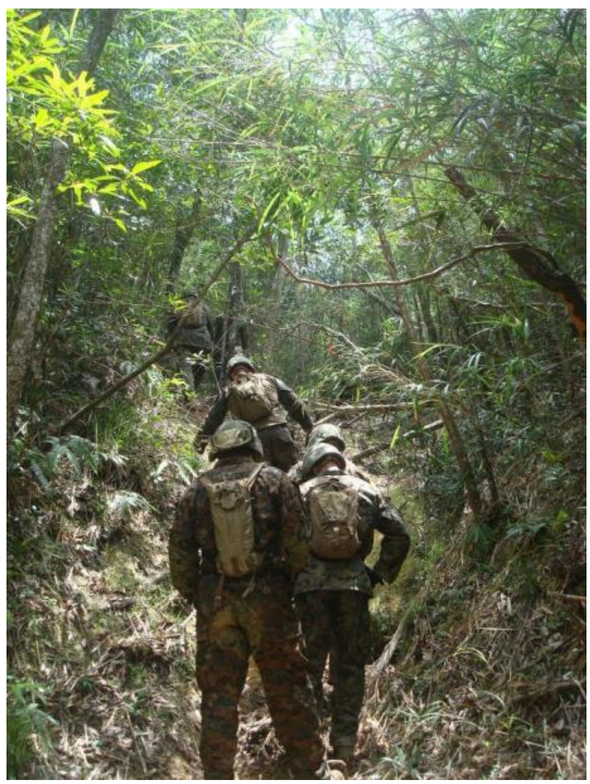


Table 1. Ensemble insulation (clo) and evaporative potential (i_m/clo) measured at 0.4 ms^{-1} wind speed ensemble and mass values for various body armor protection levels and variants.

Body Armor Protection Level (BAPL)	Ensemble Configuration	clo	i_m/clo	Armor Mass (kg)
EFRCE*	Enhanced Flame Resistant Combat Ensemble (EFRCE), no body armor.	1.17	0.48	0.0
MCCUU*	Marine Corps Combat Utility Uniform (MCCUU), no body armor.	1.26	0.36	0.0
BAPL 0	Army Combat Shirt (ACS), no body armor.	1.37	0.28	0.0
BAPL 1	ACS, Interceptor Outer Tactical Vest (IOTV) with no plates.	1.59	0.25	4.8
BAPL 2	ACS, Plate Carrier (PC) vest with front and back plates.	1.58	0.24	8.2
BAPL 3	ACS; PC with front, back, and side plates.	1.57	0.24	10.4
BAPL 4	ACS; IOTV with front and back plates.	1.58	0.22	12.7
BAPL 5	ACS; IOTV with front, back, and side plates.	1.58	0.22	14.5
BAPL 0 WT 3	BAPL 0 variant, modified armor weight.	1.37	0.28	10.4
BAPL 0 OC 3	BAPL 0 variant, modified i_m/clo.	1.57	0.24	0.0
BAPL 0 WT 5	BAPL 0 variant, modified armor weight.	1.37	0.28	14.5
BAPL 0 OC 5	BAPL 0 variant, modified i_m/clo.	1.58	0.22	0.0

Note: all ensembles were tested with FRACU pants, ACS, poly boxer briefs, green cotton socks, combat helmet, Max Grip combat gloves, and desert hot weather suede combat boots except those indicated with an asterix. The EFRCE and MCCUU ensembles were tested without under garments, socks, boots, gloves, or helmet resulting in lower insulation (clo) and higher evaporative potential (i_m/clo) values.

Figure 2. Two of the ensembles volunteers wore during data collection, the Enhanced Fire Resistant Outer Garment (EFRCE, left) and the Marine Corps Combat Utility Uniform (MCCUU, right).

In addition to BAPL 0 through 5, four modified variants were modeled. These variants used BAPL 0 ensemble characteristics with either their weight or i_m/clo modified to match that of BAPL 3 or 5 (e.g., BAPL 0 WT 3 uses BAPL 0 i_m/clo and BAPL 3 load; BAPL 0 OC 3 uses BAPL 0 load and BAPL 3 i_m/clo, Table 1). The abbreviation WT indicates BAPL 0 variants with modified load values and OC indicates BAPL 0 variants with modified occlusivity (i_m/clo).

Physiological Measures

Individual physiological data were collected using chest-belt physiological status monitoring (PSM) systems (Equivital-2; Hidalgo Ltd., Cambridge, UK) and ingestible core temperature pills (Vital Sense Core Temperature Pill; Philips Respironics, Bend, OR). Data collected included heart rate (HR), core temperature, skin temperature (T_{Sk}), and tri-axial accelerometry counts (AC). Data were collected at 15 sec intervals. Core temperature was used to characterize the thermal strain experienced by each volunteer and tri-axial accelerometry data were used to estimate Metabolic Rate ($\dot{M}$) in Watts.

Metabolic Rate Estimation

The thermoregulatory model [12] used to predict the effects of BAPL on participants during jungle training exercises requires $\dot{M}$ as an input. However, we were unable to directly measure $\dot{M}$ in the field. To establish reasonable $\dot{M}$ profiles for each participant, $\dot{M}$ was estimated from accelerometry data in four steps: (1) calculation of AC from accelerometry data, (2) scaling the calculated AC values, (3) using the scaled AC values as $\dot{M}$ inputs for the thermoregulatory model, (4) comparing modeled T_C outputs to observed T_C and selecting the scaling coefficient corresponding to the least error between the two.

Accelerometry counts were calculated from raw acceleration data as follows:

$$AC = \sqrt{\sum_{n=1}^{3}\sum_{t=1}^{384} a_{nt} - a_{nt+1}}$$

where a = acceleration (mG), t = sample (25.6 hz sampling per 15s period), n = accelerometer axis channel. Calculating AC in this way provides 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; AC increases with more and/or larger changes in accelerations.

Accelerometry count data for each participant were scaled, using a range of coefficients (0.1 to 1.5 in 0.1 increments). Each set of scaled AC values were used as $\dot{M}$ input to the thermoregulatory model and generated a corresponding output of T_C predictions while wearing BAPL 0 (one T_C predictions per coefficient). Each volunteer's modeled T_C predictions were then compared to their corresponding observed T_C values and a root mean square error (RMSE) value was calculated. The coefficient resulting in the lowest RMSE for a given participant across all of that volunteer's data was selected for use in estimating that participant's $\dot{M}$ profile for BAPL 0. Thus, a single coefficient was chosen for each volunteer using data from multiple days but a different coefficient was potentially selected for each volunteer.

Thermoregulatory modeling of body armor protection levels

A physics and physiology based thermoregulatory model [12] was used to predict T_C values at minute intervals given inputs including $\dot{M}$, clothing biophysical characteristics (im, clo), environmental characteristics (T_A, T_{BG}, WS, RH), and individual anthropometrics (height, mass, % body fat). Two distinct sets of predictive model results were generated to examine the thermal effects of BAPL under jungle conditions: (1) predicted effects of increased BAPL on study participants during jungle warfare training, (2) a comparison of the thermal effects over of a range of ensemble im/clo values and ensemble weights at two different $\dot{M}$ (300 and 400 W) and RH values (50 and 92%).

The effect of increased BAPL on participants during training exercises was modeled by rerunning the thermoregulatory model for each individual and BAPL (and BAPL variant). The non-ensemble inputs were kept the same for each individual while the clothing variables (i_m, clo) were those of the current ensemble being modeled. For ensembles with an armor mass greater than 0 kg (Table 2, Figure 3), a fixed metabolic load carriage cost (≤ 65 W) was added to the BAPL 0 metabolic profile to reflect the work associated with carrying additional mass.

Comparing the effects of ensemble i_m and mass under a single set of conditions was done by holding $\dot{M}$ steady while modeling different combinations of i_m and ensemble mass. To generate 10,000 combinations of mass and i_m, the i_m value for each BAPL was incremented from 0.15 to 0.5 (100 increments) and ensemble mass was incremented from 0 to 20 kg (100 increments). Each combination of these ranges of i_m and ensemble mass were used as model inputs. The model was also input with a base $\dot{M}$ of 300 or 400 W and one of two humidity conditions, 50% or 92% RH. An additional $\dot{M}$ associated with carrying an ensemble's mass (0 to 20 kg) was added to the base rate (≤ 65 W) and ensemble insulation was input as 1.5 clo. Anthropometric inputs were those of the "standard man," (25 yr, 70 kg, 1.7m, 15% body fat). The final T_C values at minute 60 for each combination of i_m/clo, ensemble mass, $\dot{M}$, and RH were used to produce T_C transition surfaces (Figures 4 and 5).

RESULTS

Environmental Conditions

Mean T_A, RH, WS, T_{BG}, and WBGT for each mission day are shown in Table 2. Mean meteorological data values for each mission day were used as model inputs as opposed to hourly values. Although T_{BG} values measured at Kadena Air Force Base were greater than observed T_A values, T_{BG} was assumed to be the same as T_A for the purpose of modeling under the jungle canopy (reduced solar load). Sub-canopy wind speed was modeled as 0.4 ms^{-1} (still air) due to thick jungle vegetation reducing air movement.

Thermoregulatory modeling of body armor protection levels using physiological data

Table 3 contains the observed and predicted mission physiological data (T_C, T_{Sk}, HR, $\dot{M}$) for each day of training operations. The RMSE values reported in Table 3 are calculated between observed and modeled T_C values using estimated $\dot{M}$ and BAPL 0 ensemble characteristics as inputs. The comparison of observed T_C values and those predicted for BAPL 0 provides a baseline for determining if model predictions are realistic and if so, a means for comparing the effects of the other BAPL variants on T_C.

Table 2. Environmental conditions (mean ± standard deviation) and flag color for Kadena Air Force Base during study training days.

Day	Air Temperature (T_A, ˚C)	Relative Humidity (RH, %)	Black Globe Temperature (T_{BG}, ˚C)	Wet Bulb Globe Temperature (WBGT, ˚C)	Flag Color
1	28.7 ± 1.2	95 ± 7	32.5 ± 4.7	29.0 ± 1.3	Red
2	28.7 ± 1.2	96 ± 6	31.9 ± 5.4	28.8 ± 1.6	Red
3	28.8 ± 1.6	86 ± 3	34.4 ± 6.9	28.6 ± 2.1	Red
Mean	28.7 ± 0.0	92 ± 6	32.9 ± 1.3	28.8 ± 0.2	Red

Note: WBGT Flag colors white, green, yellow, red, and black correspond to the following WBGT ranges: ≤ 26.6, 26.7-29.3, 29.4-31.0, 31.1-32.1 and ≥32.2 ˚C. Flag colors have been adjusted by adding 2.8˚C WBGT but reported values are as measured. A WBGT flag color of red corresponds to a 25% work 75% rest schedule. Heat stroke possible with continued exposure.

Table 3. Observed (O) physiological data and those predicted (P) for body armor protection level 0 (BAPL 0).

Day	N	Obs. v Pred.	Core Temperature (T_C, ˚C)	Heart Rate (HR, bpm)	Skin Temperature (T_{Sk}, ˚C)	Predicted Metabolic Rate ($\dot{M}$)	Root Mean Square Error (RMSE)
1	5	P	37.7 ± 0.1	110 ± 3	36.6 ± 0.3	250 ± 54	0.27 ± 0.09
		O	37.8 ± 0.1	108 ± 7	36.5 ± 0.2	-	
2	2	P	37.3 ± 0.1	94 ± 4	35.6 ± 0.1	213 ± 54	0.15 ± 0.07
		O	37.3 ± 0.1	96 ± 10	36.6 ± 0.3	-	
3	4	P	37.5 ± 0.1	103 ± 4	36.1 ± 0.1	231 ± 45	0.25 ± 0.08
		O	37.6 ± 0.1	103 ± 9	36.1 ± 0.2	-	
Mean	11	P	37.5 ± 0.4	103 ± 16	36.1 ± 1.0	230 ± 105	0.24 ± 0.09
		O	37.6 ± 0.9	103 ± 23	36.3 ± 0.9	-	

Note: no observed metabolic rate values are available. RMSE values are only available for T_C modeled with body armor protection level 0 (BAPL 0).

Figure 3 shows an example of observed and predicted T_C values (± SD) for each BAPL and variant during day 3 of training exercises. Across all days, observed and predicted T_C values for BAPL 0 never exceed 39.5 ˚C, a core temperature cutoff associated with hyperthermia [13]. Volunteers modeled wearing BAPL 3 and 5 reached mean T_C values > 39.5 ˚C at 238 ± 65 and 188 ± 42 minutes respectively. Mean T_C predictions for BAPL 0 WT variants (3, 5) exceeded 39.5 ˚C at 316 ± 0 and 225 ± 65 minutes (note, only on day 3 did the BAPL 0 WT 3 variant exceed 39.5 ˚C) while predictions for BAPL 0 OC variants (3, 5) never exceeded 39.5 ˚C.

Change in core temperature (ΔT_C) was calculated by subtracting initial from final T_C for each of the study days. Table 4 contains observed ΔT_C as well as ΔT_C predicted for each BAPL and the BAPL variants (OC and WT). The ΔT_C values for the BAPL weight variants (BAPL 0 WT 3, BAPL 0 WT 5) were at least two times greater than their corresponding occlusive variants (BAPL 0 OC 3, BAPL 0 OC 5; Table 4).

Figure 3. Observed core temperature (T_C; bold solid line labeled: Obs) and predicted T_C for each body armor protection level (BAPL; solid lines labeled: 0, 1, 2, 3, 4, 5) and BAPL variants with modified weight (WT) and vapor permeability (OC ; dashed lines labeled: 0 OC 3, 0 OC 5, 0 WT 3, 0 WT 5) during training on day three.

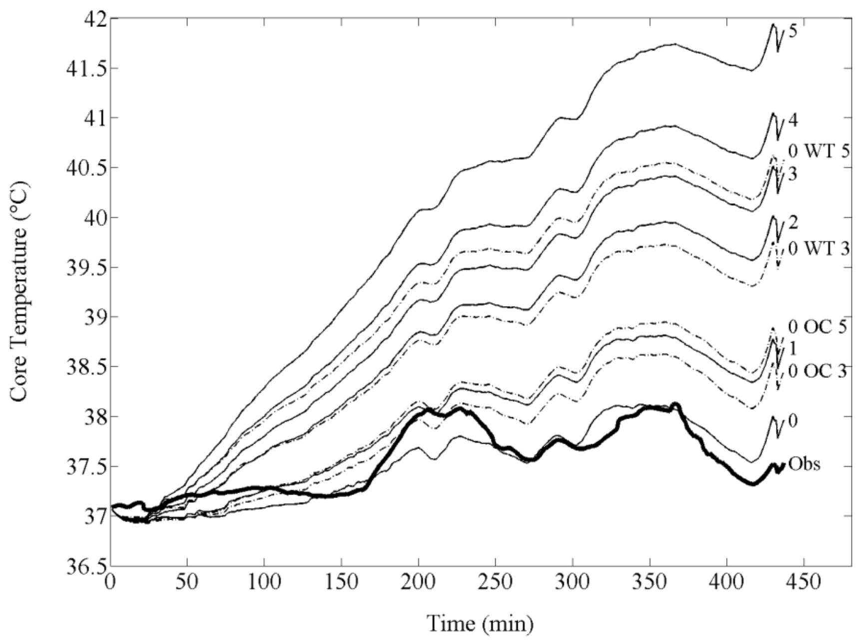


Table 4. Observed and predicted changes in core temperature (ΔT_C, ˚C) for each of the body armor protection levels (BAPL) and modified variants each day (mean ± standard deviation).

Day	Obs. Core Temperature Change (ΔT_C, ˚C)	Body Armor Protection Level (BAPL) and Variant Data						
		0	3	5	0 WT 3	0 OC 3	0 WT 5	0 OC 5
1	-0.14 ± 0.3	0.3 ± 0.4	1.9 ± 0.4	2.2 ± 0.3	1.5 ± 0.3	0.6 ± 0.3	2.0 ± 0.3	0.8 ± 0.3
2	0.4 ± 0.2	0.6 ± 0.2	2.9 ± 0.2	3.4 ± 0.1	2.3 ± 0.1	1.1 ± 0.2	3.1 ± 0.1	1.4 ± 0.2
3	0.5 ± 0.1	1.1 ± 0.2	3.6 ± 0.2	4.1 ± 0.2	2.8 ± 0.2	1.6 ± 0.2	3.7 ± 0.2	2.0 ± 0.2
Mean	0.3 ± 0.4	0.7 ± 0.4	2.8 ± 0.9	3.2 ± 0.9	2.2 ± 0.7	1.1 ± 0.5	2.9 ± 0.8	1.4 ± 0.6

Figure 4 shows a T_C transition surface of modeled T_C (z-axis) versus ensemble permeability (i_m, x-axis) and ensemble load (y-axis) with the relative location of BAPL and BAPL variants indicated. Figure 5 presents a "birds-eye" view of four T_C transition surfaces (gridlines removed) at 300 and 400 W $\dot{M}$ values and 50 and 92% RH.

Figure 4. Core temperature (T_C) transition surface for body armor protection level (BAPL: 0, 1, 2, 3, 4, 5, 0 WT 3, 0 OC 3, 0 WT 5, 0 OC 5) characteristics (i_m/clo and load) and configurations at 28 °C black globe and air temperature (T_{BG}, T_A), 92% relative humidity (RH), 0.4 ms^{-1} wind speed (WS), an initial T_C of 37 ˚C, 300 W base metabolic rate ($\dot{M}$), and 60 minutes elapsed time.

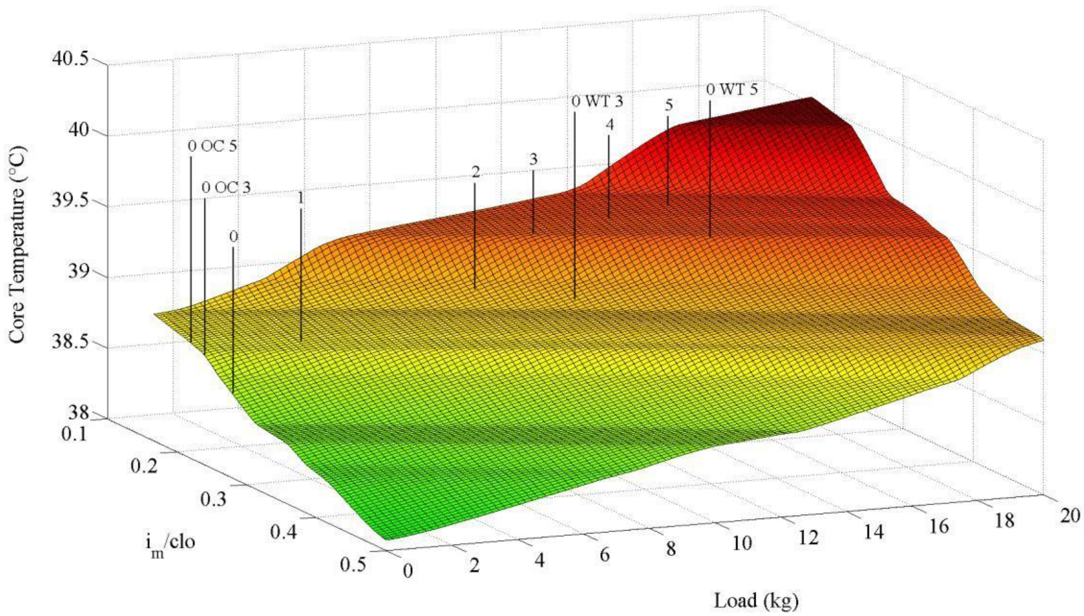
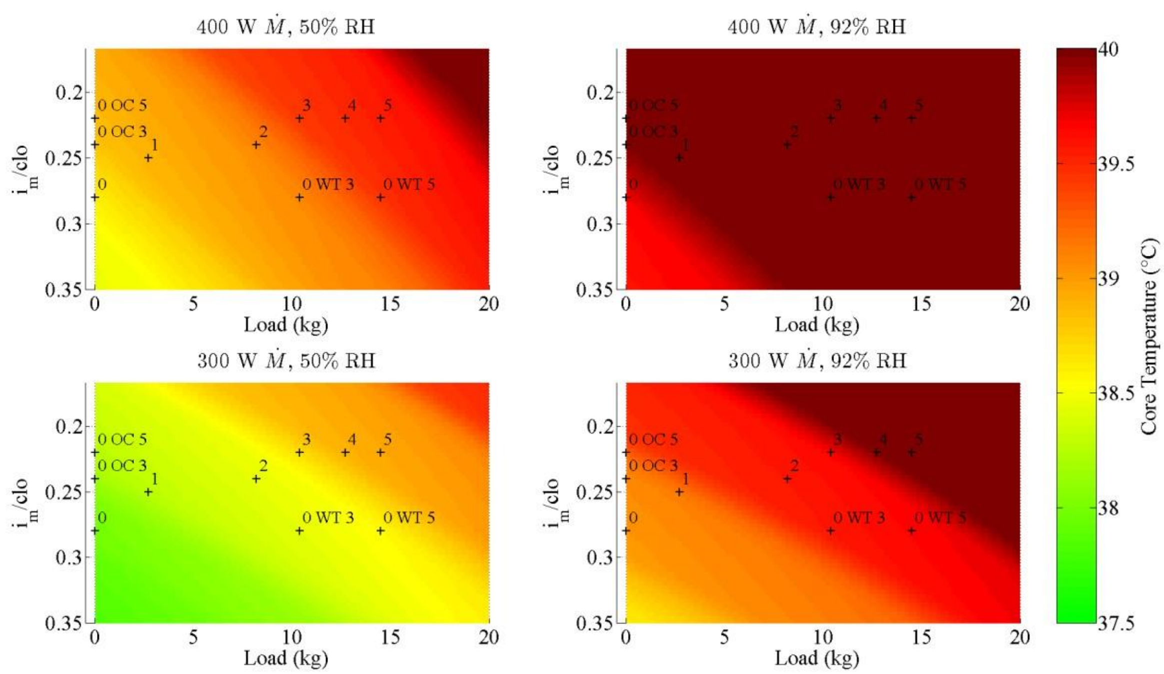


Figure 5. Core temperature (T_C) transition surfaces viewed from above for body armor protection level (BAPL: 0, 1, 2, 3, 4, 5, 0 WT 3, 0 OC 3, 0 WT 5, 0 OC 5; indicated by "+") characteristics (i_m/clo and load) and configurations at 400 and 300 W metabolic rates ($\dot{M}$, top and bottom rows) and 50 and 92% relative humidity (RH, left and right columns).



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DISCUSSION

The thermal modeling results reveal a clear and perhaps common sense pattern, that as BAPL increases (Levels 0, 3, 5; Table 4) so too does thermal burden (ΔT_C). This appears reasonable considering that as BAPL increases ensemble vapor permeability decreases (i_m, i_m/clo) and the load carried increases. Reducing an ensemble's vapor permeability reduces the potential rate of evaporative cooling from sweating. Increased load requires an increased metabolic rate to achieve the same rate of movement (with some assumptions about what type of activity is being done), and increased metabolic rate requires increased thermogenesis. Therefore, the reduction of the ability to shed heat by sweating, coupled with increased metabolic rate, leads to higher T_C values. However, the results of modeling BAPL variants (BAPL 0 WT 3, etc.) illustrate that under jungle conditions the load carriage associated with increasing BAPL has a greater effect on ΔT_C than ensemble occlusivity (i_m, i_m/clo). The heavier BAPL 0 variants (WT 3, 5) resulted in over twice the ΔT_C during training exercises as their corresponding occlusive variants (e.g., BAPL 0 WT 3 versus BAPL 0 OC 3; Table 4). Similarly, when modeling BAPL variants, participants only reached the T_C value of 39.5˚C while wearing the WT variants.

Final T_C values for each BAPL were first ordered by increasing load and only ordered by i_m/clo within groups that had the same armor weight (Figure 3). The T_C transition plot (Figure 4) parallels these results as predicted T_C (under steady state model inputs: base $\dot{M}$, T_A, WS, etc.) is always higher for BAPL with heavier load and increased vapor permeability (e.g., 14.5 kg, 0.28 i_m/clo) than those with no load and reduced permeability (e.g., 0 kg, 0.22 i_m/clo; Figures 4, 5). This pattern is also observed when RH is dropped to 50% and/or $\dot{M}$ is increased to 400W (Figure 5).

CONCLUSIONS

Given the jungle environmental conditions and ensemble characteristics described above, BAPL ensemble weight plays a greater role than BAPL vapor permeability in determining the rate of T_C rise. This suggests that under hot and humid conditions where there is limited potential for evaporative cooling close attention must be paid to the tradeoff between increased ballistic protection and increased thermal-work strain. Specifically, the metabolic cost of carrying body armor, whether donned or stored (e.g., in a backpack), makes a greater contribution to increases in core temperature than the corresponding decrease in permeability due to wearing that body armor.

In light of these findings, two important points should be made: (1) that while the greatest reductions in thermal-work strain can be achieved by reducing the metabolic cost of carrying the ensemble itself, increasing an ensemble's permeability can still provide tangible reductions in thermal-work strain, and (2) that the lifesaving benefits of ballistic and fragmentation protection provided by increased BAPL may outweigh reductions in thermal-work strain associated with reduced BAPL.

Future work includes examining how the relationship between permeability and load changes in different environments (e.g., cooler less humid environments with greater wind speeds) as well as determining a range of biophysical properties and values materiel developers and leaders should be targeting to offset the metabolic burden of wearing body armor. Further development of thermoregulatory models may enable the identification of break-even points between vapor permeability and weight that optimize cooling power per pound carried.

Core temperature transition surfaces (e.g., Figures 4, 5) could potentially be used to provide a better understanding of, or decision aid for, the thermal-work strain warfighters may experience given an environment, ensemble, and mission tempo. Using software designed to generate a T_C transition surface, unit leaders and materiel developers could enter estimates of environmental conditions, expected work rate (including length of time and work-rest schedule), and output a visual representation of expected T_C given a range of ensembles. This would allow them to not only select an existing ensemble which best meets mission requirements and personal protection needs but also target improvements to existing ensembles (e.g., by reducing load or increasing permeability).

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