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COMPARISON OF BIOPHYSICAL CHARACTERISTICS AND PREDICTED THERMOPHYSIOLOGICAL RESPONSES OF THREE PROTOTYPE BODY ARMOR SYSTEMS VERSUS BASELINE U.S. ARMY BODY ARMOR SYSTEMS

United States Army
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Modern day dismounted military are commonly required to perform high physical work at high intensities in a variety of environmental conditions while facing challenging training and combat engagements. To optimize warfighter physical performance while providing protection from kinetic threats, tradeoffs must be made between physical performance and the adverse effects of the weight and functional characteristics of equipment and clothing carried and worn by the individual Soldiers.

The work outlined in this report provides: 1) a quantitative assessment of the biophysical characteristics of three prototype body armor configurations, 2) a comparison to current baseline U.S. Army body armor systems, and 3) mathematical predictions of maximal work times in three different environmental conditions. This work provides a cost effective and scientifically valid method of making comparisons of clothing and equipment changes prior to conducting human research.

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EXECUTIVE SUMMARY

Modern day dismounted military are commonly required to perform high physical work at high intensities in a variety of environmental conditions while facing challenging training and combat engagements. To optimize warfighter physical performance while providing protection from kinetic threats, tradeoffs must be made between physical performance and the adverse effects of the weight and functional characteristics of equipment and clothing carried and worn by the individual Soldiers.

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INTRODUCTION

Modern day dismounted military are commonly required to perform high physical work at high intensities in a variety of environmental conditions while facing challenging training and combat engagements. To optimize warfighter physical performance while providing protection from kinetic threats, tradeoffs must be made between physical performance and the adverse effects of the weight and functional characteristics of equipment and clothing carried and worn by the individual Soldiers.

The work outlined in this report provides: 1) a quantitative assessment of the biophysical characteristics of three prototype body armor configurations, 2) a comparison to current baseline U.S. Army body armor systems, and 3) mathematical predictions of maximal work times in three different environmental conditions. This work provides a cost effective and scientifically valid method of making comparisons of clothing and equipment changes prior to conducting human research.

METHODS

Ensembles

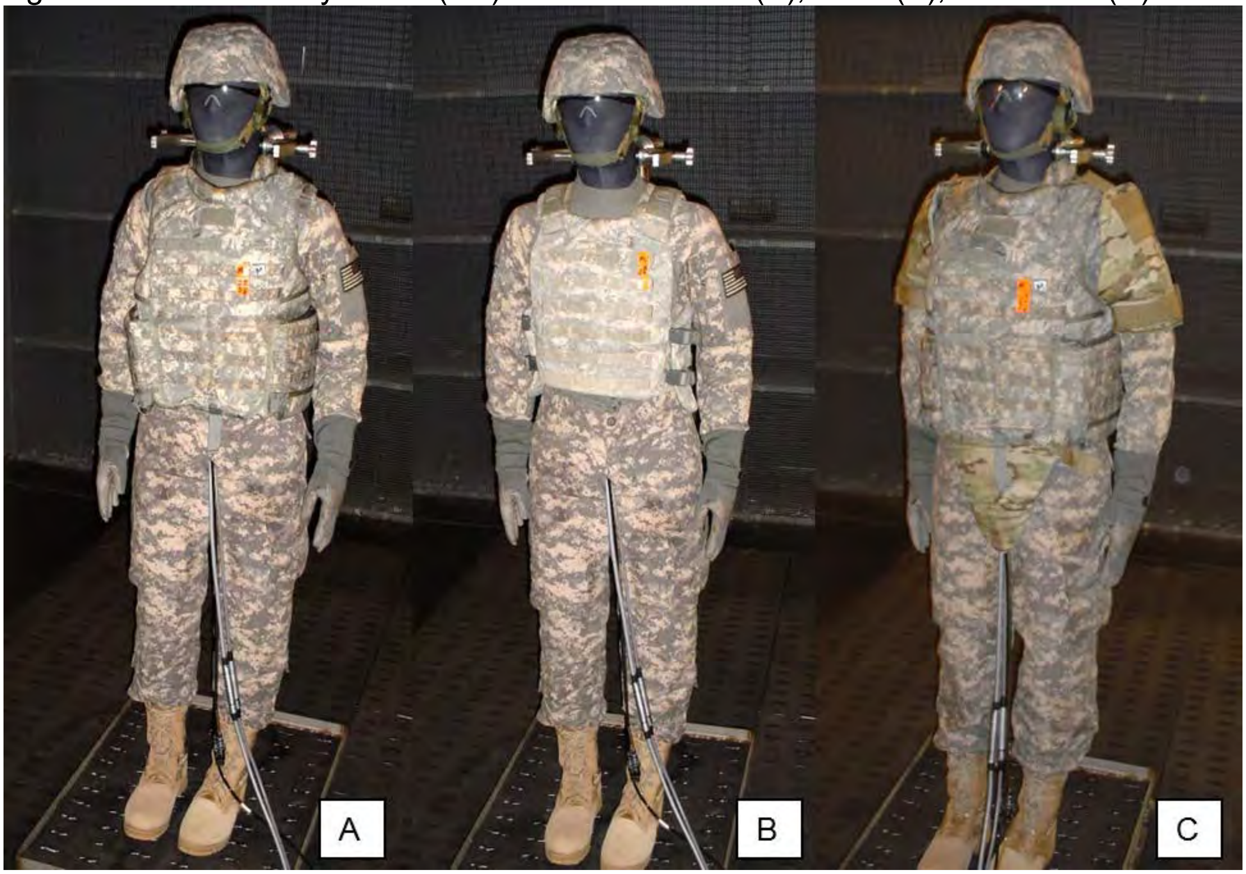
Three different body armor (BA) plus clothing ensembles were tested: Tiers 1, 3, and 4 (Figure 1). Tier 1 clothing consisted of a cotton t-shirt, underwear, and green cotton socks, Flame Resistant Army Combat Uniform (FRACU) shirt and pants, Army issued canvas belt, and desert hot weather suede combat boots. Tier 1 ballistic protection included a soft armor concealable vest, and Army combat helmet. Tier 3 clothing ensemble included Army Combat Shirt (ACS), underwear, green cotton socks, FRACU pants, Army issued canvas belt, gloves, and desert hot weather suede combat boots. Tier 3 ballistic protection included a prototype tactical body armor vest with ceramic front, back, and side plates, and Army combat helmet. Tier 4 clothing included underwear, green cotton socks, FRACU pants, Army issued canvas belt, gloves, and desert hot weather suede combat boots. Tier 4 ballistic protection included a Full Spectrum, ballistic combat shirt (includes integrated neck and deltoid protection), prototype tactical body armor vest with ceramic front, back, and side plates, and Army combat helmet.

Figure 1. Prototype body armor (BA) configurations, Tier 1 (A), Tier 3 (B), and Tier 4 (C)

(see text for detailed description)

Data from analogous configurations U.S. Army BA systems [1] were used for comparison purposes. Existing US Army ensembles currently in use that provide comparable ballistic protection to prototype Tiers 1, 3, and 4 ensembles being tested are baseline BA systems BA-1, BA-3, and BA-5+. Each BA configuration tested included ACS, FRACU pants, brown polypropylene boxer briefs, green cotton socks, Max Grip combat gloves, Oakley M frame eye protection, and desert hot weather suede combat boots. Ballistic protection for BA-1 included Improved Outer Tactical Vest (IOTV) and Army combat helmet. BA-3 ballistic protection included Plate Carrier Vest (PC) with ceramic front, back, and side plates, and Army combat helmet. BA-5+ ballistic protection included IOTV, with ceramic front, back, and side plates, groin protection, and Army combat helmet. BA-1, BA-3, and BA-5+ are shown below in Figure 2.

Figure 2. Baseline body armor (BA) ensembles BA-1 (A), BA-3 (B), and BA-5+(C)



(see text for detailed description)

Biophysical Assessments

Biophysical testing was conducted using a twenty zone sweating thermal manikin (Newton, 20 zone, Measurement Technologies Northwest, Seattle, WA; http://www.mtnw-usa.com/) within a climate-controlled wind tunnel. Tests were conducted for thermal and evaporative resistance according to American Society for Testing and Materials (ASTM) standards F1291-10 and F2370-10 [2-3]. Data generated were converted to measures of total thermal insulation (I_T) in units of clo, a water vapor permeability index (i_m); the ratio of these two parameters describe the ensembles evaporative potential (i_m/clo) [4].

In accordance with ASTM standards, both thermal resistance (R_{ct}) and evaporative resistance (R_{et}) were tested under controlled isothermal conditions. For testing R_{ct}, chamber conditions were: air temperature (T_a) 20°C, 50% relative humidity (RH), wind velocity (V) 0.4 ms^{-1}, manikin surface / skin temperature (T_s) was set at 35°C. The temperature difference of 15°C between T_s and T_a provided a temperature gradient between manikin and local environment needed to assess sensible (dry) heat exchange. The power (W) used to maintain the T_s at 35°C was used to calculate the thermal resistance of each armor and clothing configuration. To measure R_{et}, both T_a and T_s are set to 35°C, RH 40%, V of 0.4 ms^{-1}. By having T_a and T_s set to the same temperature, all heat loss can be ascribed to evaporative (insensible / wet) heat exchange, therefore enabling a measure of evaporative resistance.

Measurements at three wind velocities (V) enabled the calculation of coefficient (gamma) values (^{g}) that describe the change in insulation and evaporative potential with increasing wind speeds [5]. Tests were replicated under the same environmental conditions but with increased V (1.2 and 2.0 ms^{-1}) to determine the effect of increased air flow and V on both R_{ct} and R_{et},.

Predictive Modeling

Modeling and simulation of human thermal responses were conducted using the USARIEM Heat Strain Decision Aid (HSDA) [6]. The simulated human was a healthy male, weighing 70 kg, 172 cm tall, normally hydrated, and heat acclimatized. Three simulated environments were used: hot-dry (desert) (49°C; 15% RH), hot-wet (jungle) (35°C; 75% RH), and temperate (35°C; 50% RH). Each simulated environment was assumed to be at sea level and V conditions of 1.0 ms^{-1}. For each simulation, work intensities simulating a walking speed of 1.34 ms^{-1} (3 mph) was used. Metabolic costs of walking were estimated using the equation from Pandolf et al [7], seen as:

$$M_W = 1.5 \cdot W + 2.0 \cdot (W + L) \cdot \left(\frac{L}{W}\right)^2 + \eta \cdot (W + L) \cdot (1.5 \cdot V^2 + 0.35 \cdot V \cdot G) \quad \text{(Eq. 1)}$$

where M_w = metabolic cost of walking (or standing) (in watts); W = body mass (kilograms); L = load mass (kilograms); ŋ = terrain factor (=1.0 for black top road); *V* = velocity (m/s); G = slope or grade (%).

Differences in the mass among the ensembles drive the corresponding metabolic cost of locomotion ($\dot{M}_{loco}$). This $\dot{M}_{loco}$ is the energy cost, in watts, that it takes for the simulated male to walk at a speed of 1.34 ms^{-1} while carrying the additional mass associated with each BA ensemble; with the understanding that there is a curvilinear relationship between increased mass or velocity and increased energy demands [8].

RESULTS

Biophysical Results

The total thermal (I_T, clo) (Figure 3) and evaporative (i_m) resistances, and evaporative potential (i_m/clo) (Figure 4) of each configuration were measured at three different wind velocities. Wind velocities used Tier 1 and 3 were: 0.4, 1.2, and 2.0 ms^{-1}; and for Tier 4 were: 0.58, 1.8, and 2.53 ms^{-1}. These measures obtained at three wind velocities enable calculations of wind effect coefficient values within the isothermal conditions (Table 1).

Figure 3. Thermal resistance (clo) for the three prototype body armor (BA) configurations

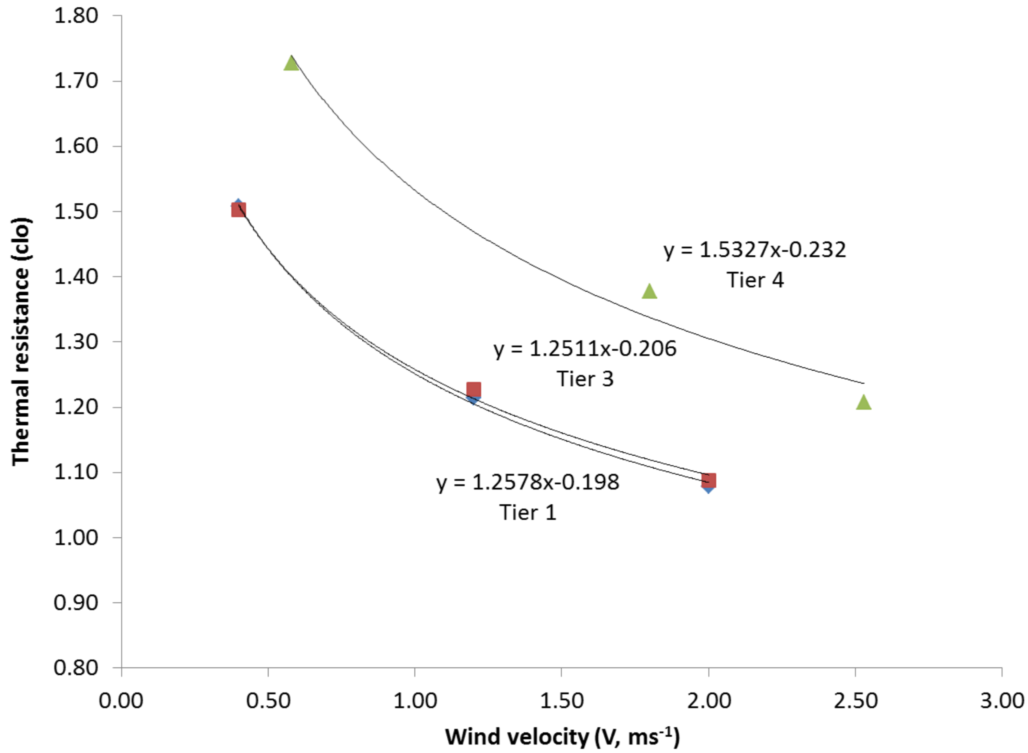


Figure 4. Evaporative potential (i_m/clo) for the three prototype body armor (BA) configurations

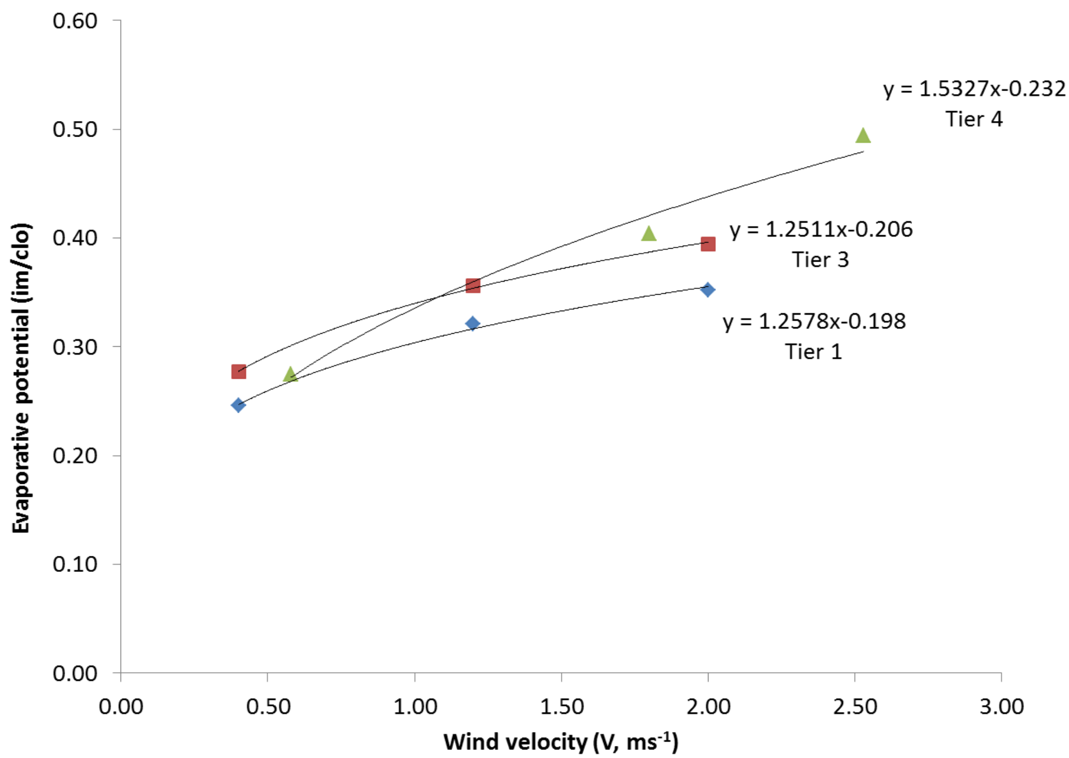


Table 1. Total thermal resistance (I_T, clo) and evaporative potential (i_m/clo) at wind velocities (V) of 0.4 and 1.0 ms^{-1} for three prototype and three comparable baseline body armor (BA) ensembles, and estimated metabolic cost of locomotion ($\dot{M}_{loco}$) at a walking rate of 1.34 ms^{-1} (3 mph)

	0.4 ms^{-1} *V*		**1.0 ms^{-1} *V***		**Weight**	**$\dot{M}_{loco}$ at 1.34 ms^{-1}**
	clo	**i_m /clo**	**clo**	**i_m /clo**	**kg**	**W**
Tier 1	1.51	0.25	1.25	0.30	5.8	310
Tier 3	1.51	0.28	1.26	0.34	14	338
Tier 4	1.90	0.24	1.53	0.34	16.9	349
BA-1	1.59	0.25	1.25	0.31	7.3	315
BA-3	1.57	0.24	1.25	0.31	12.9	334
BA-5+	1.63	0.22	1.28	0.27	17	350

Predictive Modeling Results

Predicted thermophysiological responses for each of the Tier 1, 3, and 4 systems and existing BA 1, 3, and 5+ systems were similar. These comparisons were similar for each configuration across environments (i.e., if a configuration performs better in one environmental condition it will likely perform better in another condition).

While minor differences can be observed between thermophysiological predictions for prototype Tier systems the pre-existing baseline BA systems, it should be noted that the majority of the differences between predicted increases in T_c between prototype Tier systems and baseline BA systems were observable near or after critical temperature levels (i.e., ≥38.5 °C) (Figures 5 – 7).

Figure 5. Predicted maximum work times (min) for Tier 1 and BA-1 in no sun, while under temperate, hot-humid (jungle), and hot-dry (desert) conditions

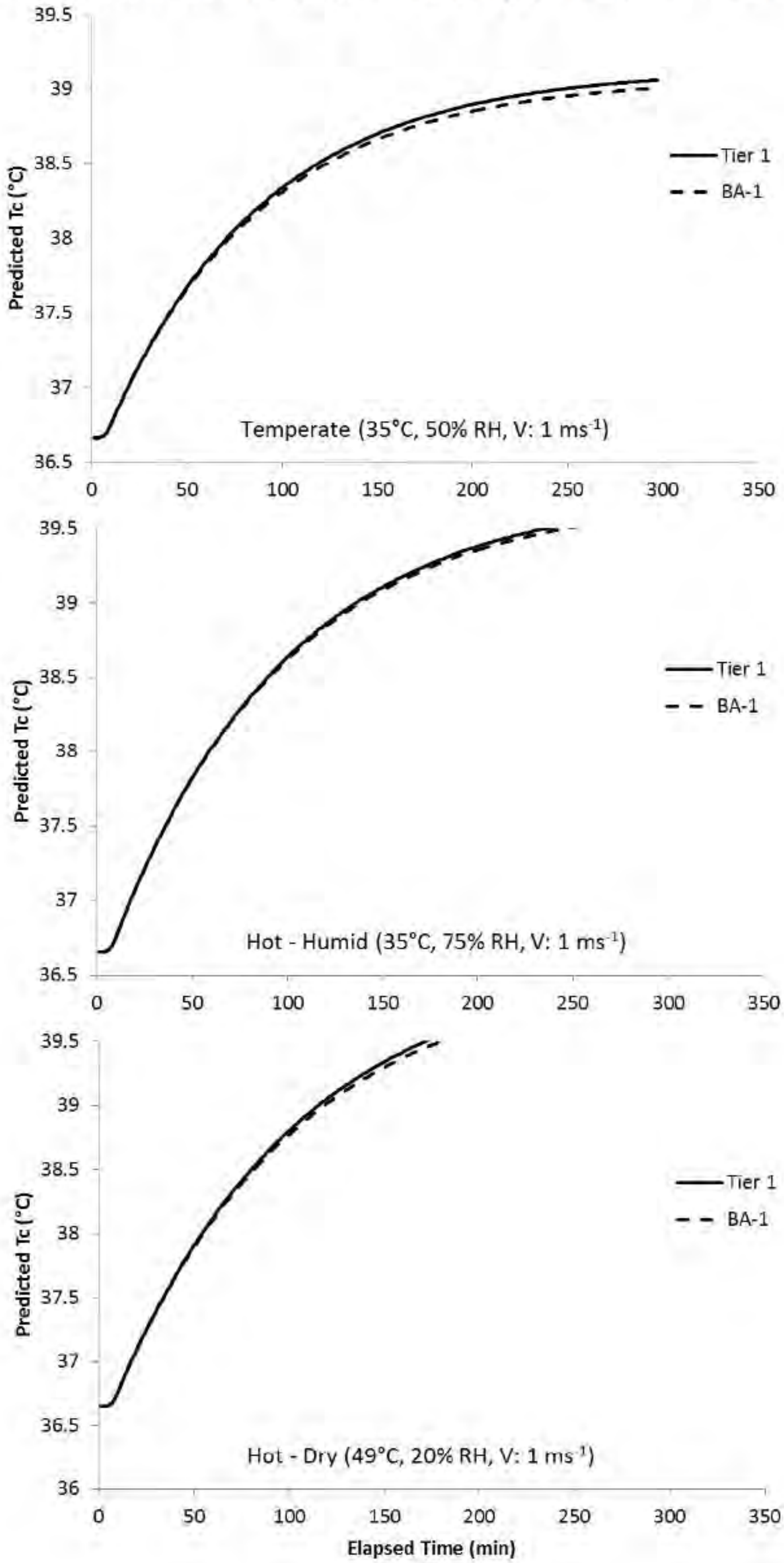


Figure 6. Predicted maximum work times (min) for Tier 3 and BA-3 in no sun, while under temperate, hot-humid (jungle), and hot-dry (desert) conditions

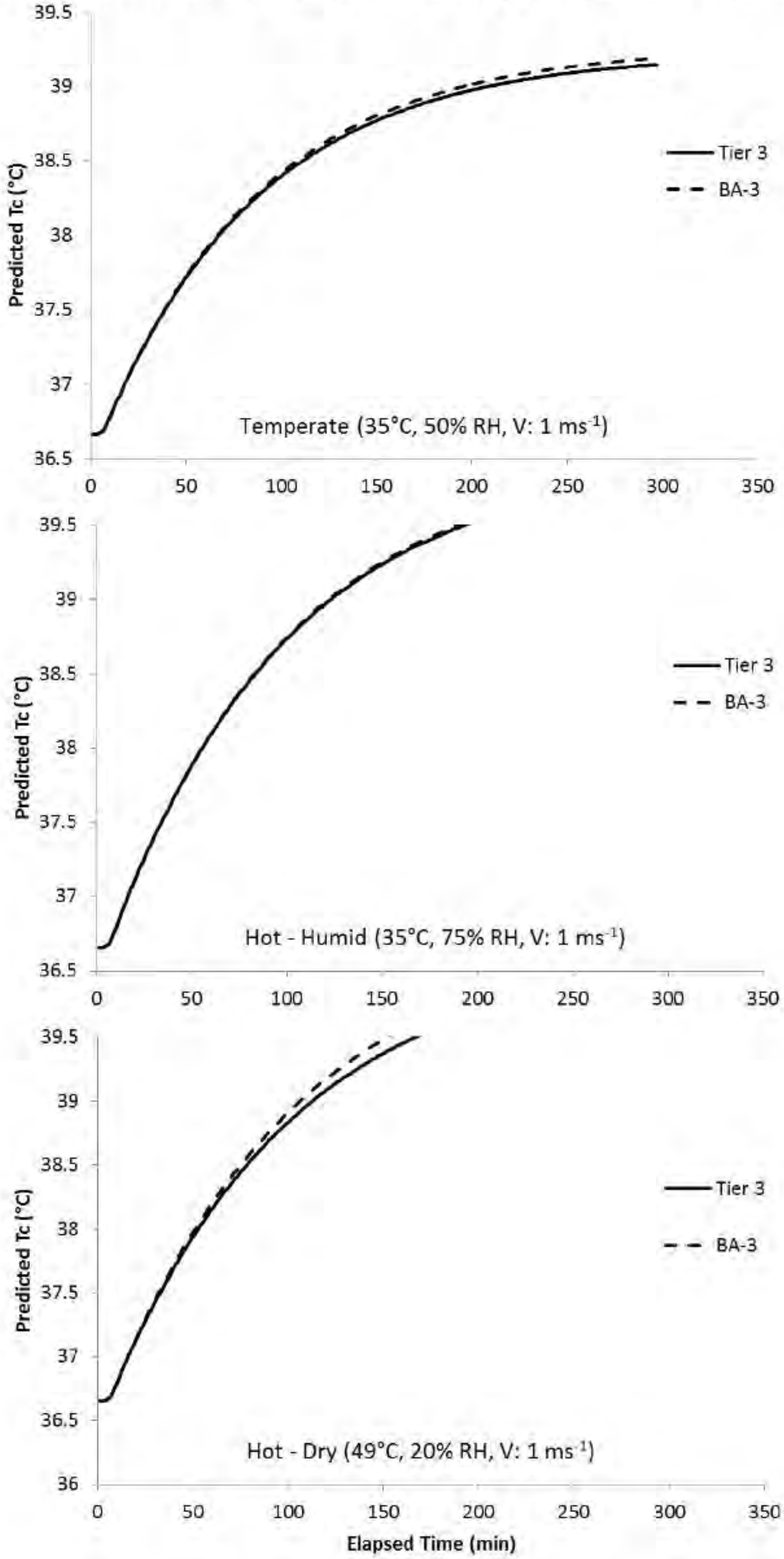
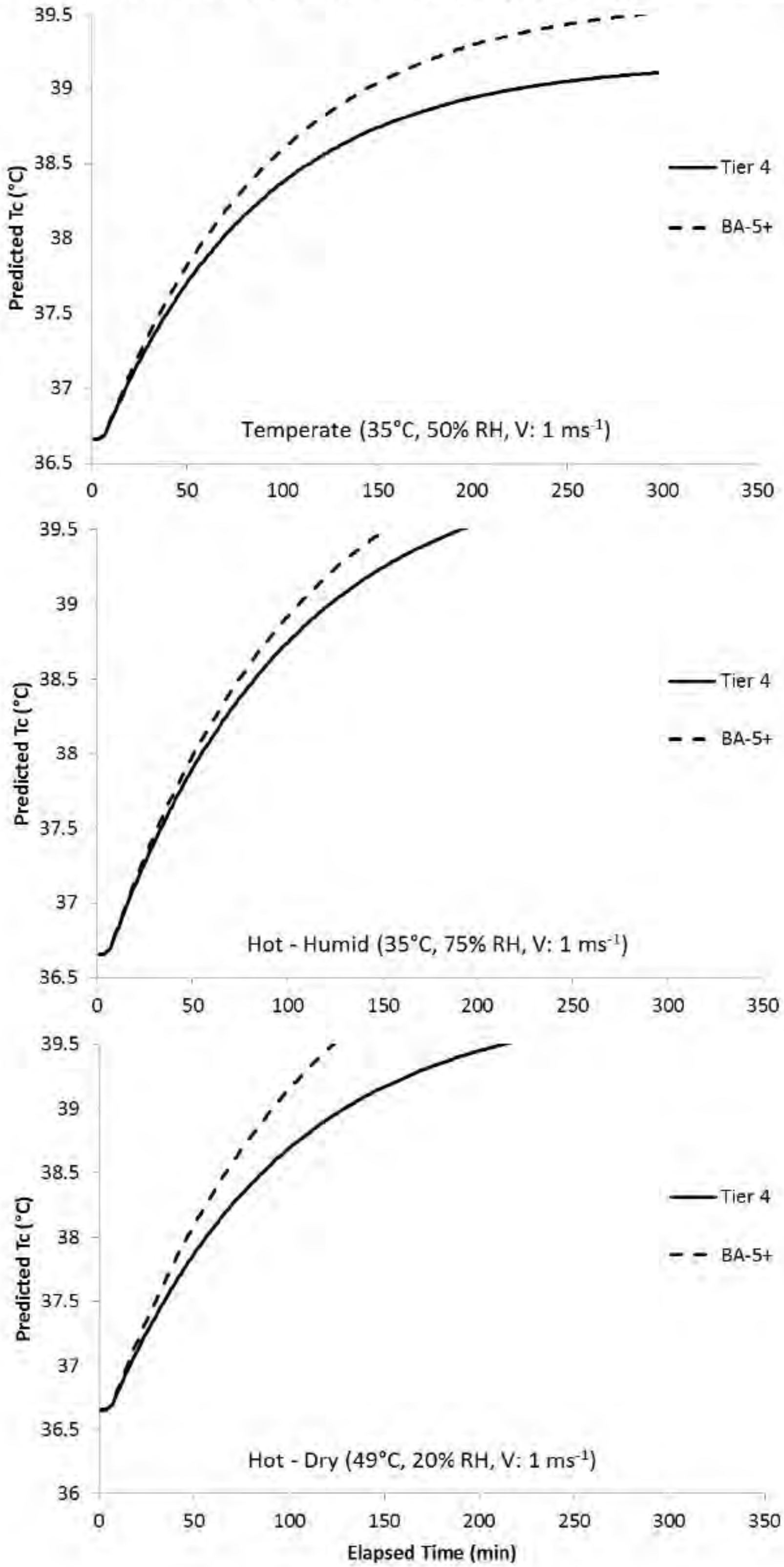


Figure 7. Predicted maximum work times (min) for Tier 4 and BA-5+ in no sun, while under temperate, hot-humid (jungle), and hot-dry (desert) conditions



DISCUSSION

This report provides a structured approach to evaluating new body armor systems. Specifically, a quantitative method is used to compare protective clothing and body armor configurations. This type of modeling provides a scientific method for assessing physiological effects of clothing ensembles prior to conducting human subject research. The study results show that under the modeled conditions there was very little difference between the prototype Tier systems and the baseline body armor systems with respect to the thermal burden imposed on the user. Additional work is needed to address other performance elements, such as mobility and range of movement constraints associated with wearing these ensembles [9-11]. Follow on work is also needed for human factors assessments related to comfort, acceptability and usability specific to military operations and other worn equipment.

Modular body armor systems often play a critical role in protective personnel from kinetic threats. However, body armor is encapsulating and heavy, compromising heat dissipation and increasing the metabolic costs of moving. Using simple analogies from nature, a stationary *testudines* (turtles) with its armored shell can be very effective at protecting against threats but are less mobile than most unarmored animals and have a limited ability to actively respond to threats. In contrast, *felis* (cat species) are very agile and capable of dynamic movements and offensive assaults, but are less protected. Furthermore, evolutionary adaptations such as natural armor can be seen in animals based on their potential role as predators or prey [12]. In contrast to most animals, modern dismounted military can readily tailor their BA protection levels based on expected threats and activities.

This study evaluated the relationship of the entire ensemble’s biophysical characteristics to human thermal responses to environment and physical activity. Future research topics include investigating effects of regional ensemble changes that may impact human thermoregulation, e.g., evaluating the use and positioning of body armor plates on thermal strain.

REFERENCES

1. Potter AW, Karis AJ, & Gonzalez JA. Biophysical characterization and predicted human thermal responses to US Army body armor protection levels (BAPL). U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T13-5, 2013, ADA#585406, accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a585406.pdf

2. ASTM International. F1291-10 Standard test method for measuring the thermal insulation of clothing using a heated manikin. 2010.

3. ASTM International. F2370-10 Standard test method for measuring the evaporative resistance of clothing using a sweating manikin. 2010.

4. Woodcock AH. Moisture permeability index - A new index for describing evaporative heat transfer through fabric systems. Quartermaster Research and Engineering Command, Natick, MA 01702 USA, Technical Report (TR-EP-149), 1961.

5. Potter AW, Gonzalez JA, Karis AJ, Rioux TP, Blanchard LA, & Xu X. Impact of estimating thermal manikin derived wind velocity coefficients on physiological modeling. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T14-7, 2014, ADA#607972 accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a607972.pdf

6. Blanchard LA, & Santee WR. Comparison of USARIEM heat strain decision aid to mobile decision aid and standard Army guidelines for warm weather training. U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760 USA, Technical Report, T08-7, 2008, ADA#483728 accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a483728.pdf

7. Pandolf KB, Givoni B, & Goldman RF. Predicting energy expenditure with loads while standing or walking very slowly. *Journal of Applied Physiology, 43*(4): 577-581, 1977.

8. Potter AW, Santee WR, Clements CM, Brooks KA, & Hoyt RW. Comparative Analysis of Metabolic Cost Equations: A Review. *Journal of Sport and Human Performance, 1*(3), 2013.

9. Mitchell KB. Range of Motion and Reaches of Warfighters in Body Armor. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 56, No. 1, pp. 1837-1841). Sage Publications. 2012.

10. Mitchell KB. *Standard Methodology for Assessment of Range of Motion While Wearing Body Armor*. U.S. Army Natick Soldier Research Development and Engineering Center, Natick, MA 01760 USA, Technical Report TR-13/033, 2013, ADA#593006 accessible at: www.dtic.mil/dtic/tr/fulltext/u2/a593006.pdf

11. Dorman LE, & Havenith G. The effects of protective clothing on energy consumption during different activities. *European Journal of Applied Physiology, 105*(3), 463-470, 2009.

12. Stankowich T. Armed and dangerous: predicting the presence and function of defensive weaponry in mammals. *Adaptive Behavior*, *20*(1), 32-43, 2012.