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EXPLOSIVE ORDNANCE DISPOSAL (EOD) ENSEMBLES: BIOPHYSICAL CHARACTERISTICS AND PREDICTED WORK TIMES WITH AND WITHOUT CHEMICAL PROTECTION AND ACTIVE COOLING SYSTEMS

United States Army
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EXPLOSIVE ORDNANCE DISPOSAL (EOD) ENSEMBLES: BIOPHYSICAL CHARACTERISTICS AND PREDICTED WORK TIMES WITH AND WITHOUT CHEMICAL PROTECTION AND ACTIVE COOLING SYSTEMS

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14. ABSTRACT

Explosive ordnance disposal (EOD) technicians play a critical response role within law enforcement and the military. These technicians wear fully encapsulating EOD suits designed to protect the individual wearer from immediate area blast threats. While the ultimate goal of these suits is to protect EOD technicians from fragmentation and blast, the encapsulating design and significant mass of the EOD protective ensemble put significant thermal and metabolic strain on the wearer. e weight, impermeability, and highly insulated nature of these ensembles, puts individual wearers at significant risk of thermal strain and decreased work capacity. The increased weight of the ensembles (e.g., >35 kg) add significant metabolic demands on the individual; while their capability to dissipate heat and maintain thermal homeostasis is virtually eliminated. Purposes of this report: 1) document biophysical characteristics of 4 EOD configurations, 2) model thermophysiological responses as a function of each configuration, environment, and work intensity, and 3) make comparisons of modeling results to previously published human research data.

15. SUBJECT TERMS

predictive modeling; EOD; thermoregulation; thermal limits; active cooling; EOD9

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EXECUTIVE SUMMARY

In response to global terrorism and asymmetric warfare, explosive ordnance disposal (EOD) technicians play a critical response role within law enforcement and the military. These technicians wear fully encapsulating EOD suits designed to protect the individual wearer from immediate area blast threats. While the ultimate goal of these suits is to protect EOD technicians from fragmentation and blast, the encapsulating design and significant mass of the EOD protective ensemble put significant thermal and metabolic strain on the wearer.

The weight, impermeability, and highly insulated nature of these ensembles, puts individual wearers at significant risk of thermal strain and decreased work capacity. The increased weight of the ensembles (e.g., >35 kg) add significant metabolic demands on the individual; while their capability to dissipate heat and maintain thermal homeostasis is virtually eliminated.

The purposes of this report are 1) to document the biophysical characteristics of four different EOD configurations, 2) model the thermophysiological responses of EOD technicians as a function of each ensemble configuration, environment, and work intensity, and 3) to make comparisons of modeling results to previously published human research data.

INTRODUCTION

In response to global terrorism and asymmetric warfare, explosive ordnance disposal (EOD) technicians play a critical response role within law enforcement and the military. Technicians wear fully encapsulating EOD suits designed to protect the individual wearer from immediate area blast threats. While the ultimate goal of these suits is to protect EOD technicians from fragmentation and blast, their encapsulating design and significant mass put significant thermal and metabolic strain on the wearer [1-6].

There are essentially three broad elements that interact to influence heat stress: 1) environmental conditions (i.e., air temperature (T_a), relative humidity (RH), wind velocity (V), solar radiation), 2) metabolic heat production ($\dot{M}$), and 3) biophysical characteristics (thermal (clo) and evaporative (i_m) resistance) of clothing [7].

As homeotherms, humans naturally produce heat and the body's internal thermoregulatory system typically attempts to maintain thermal homeostasis by dissipating heat. This balance is maintained via four main pathways of heat exchange: radiation (R), convection (C), conduction (K), and evaporation (E), as seen below:

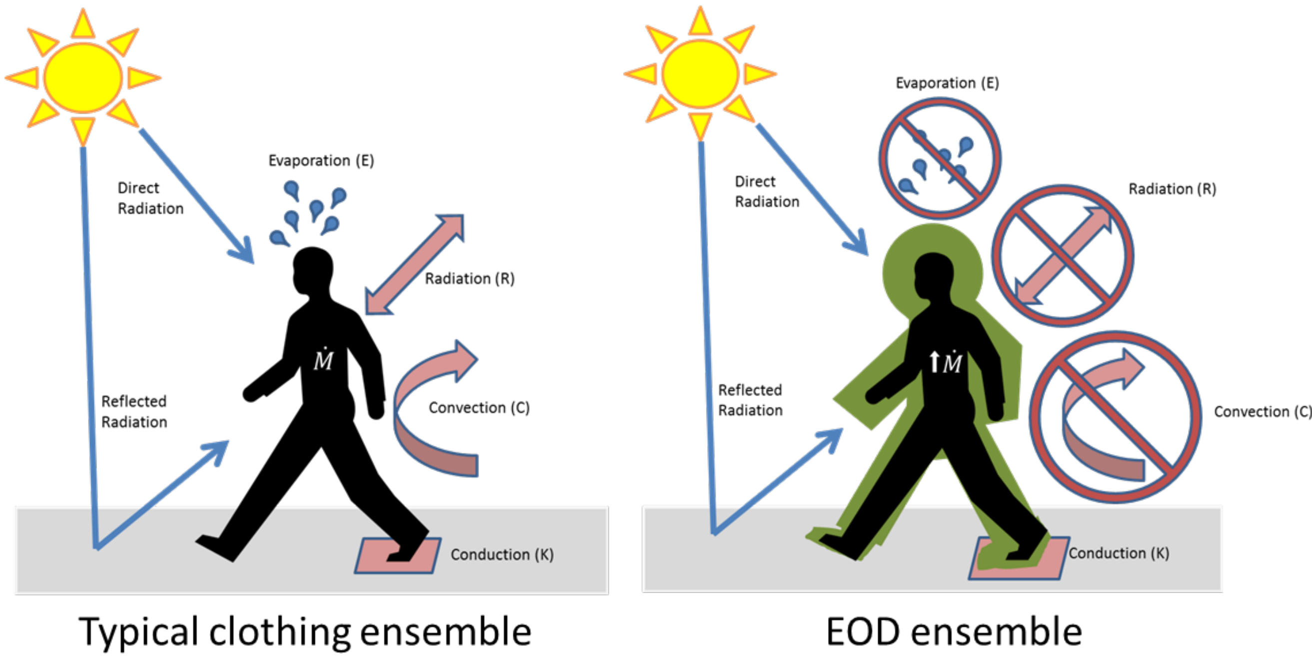
$$S = M \pm W \pm R \pm C \pm K - E \ [\mathrm{W/m^2}]$$

where *S* is heat storage; *M* is metabolic rate; and *W* is work rate. Radiation (R) refers to heat transferred at the speed of light via electromagnetic waves (e.g., solar or infrared radiation). Convection (C) is heat transfer with fluid contact (e.g., air or water). Conduction (K) is heat transfer via contact with a solid object (e.g., touching a cold surface). Evaporation (E) is heat loss to the environment involving phase changes of liquid to vapor, typically associated to evaporation of sweat or respiratory water loss. However, evaporative heat is only lost to the environment, thus this is always a negative in this equation.

From a heat balance perspective, for individuals wearing EOD ensembles, *R, C*, and *E* are virtually eliminated, thus severely restricting the ability to dissipate metabolic heat and maintain thermal homeostasis; while the weight of the ensembles (e.g., >35 kg) significantly increases metabolic rate ($\dot{M}$) and heat production (Figure 1). That is, increased metabolic heat production and a reduction in the ability to dissipate heat results in rapid increase in thermal strain, reduced work capacity, and increased risk of heat illness..

The purposes of this report are 1) to document the biophysical characteristics of four different EOD configurations, 2) model the thermophysiological responses of EOD technicians as a function of each ensemble configuration, environment, and work intensity, and 3) to make comparisons of modeling results to previously published human research data.

Figure 1. Heat exchange in typical ensembles versus Explosive Ordnance Disposal (EOD) ensembles



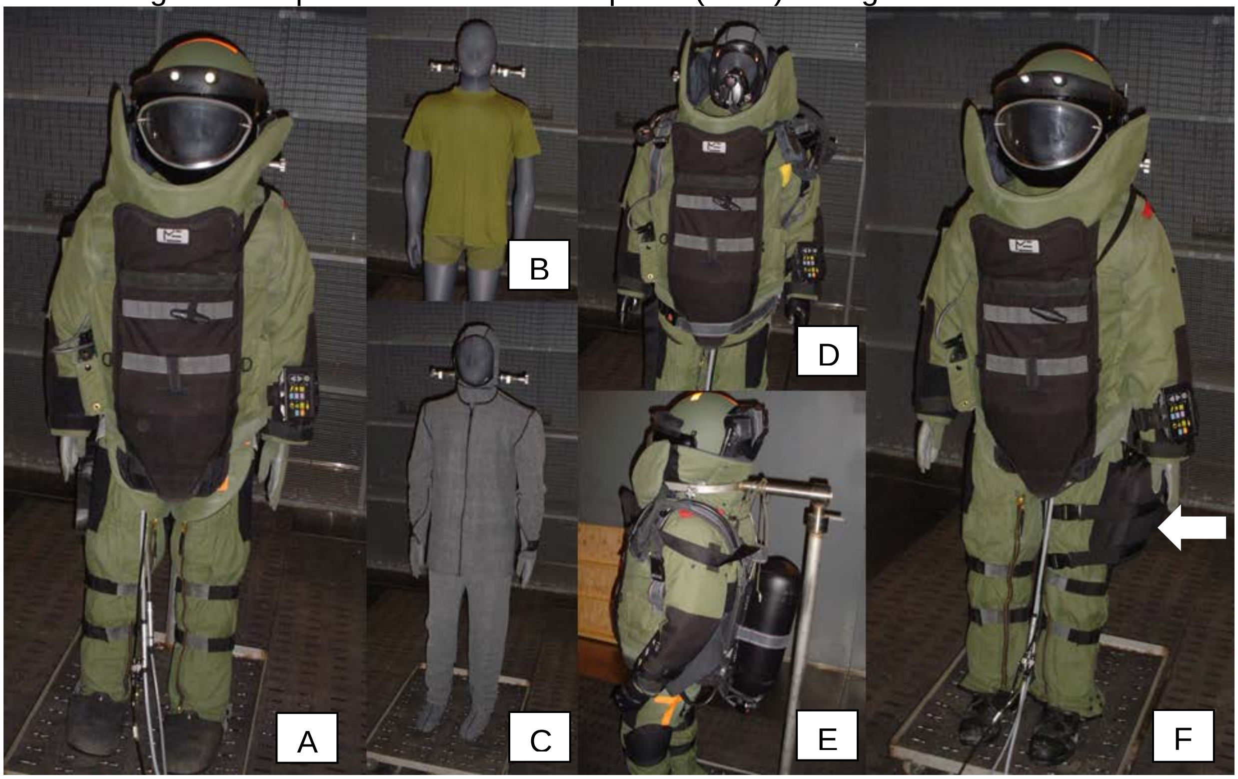
METHODS

Ensembles

The biophysical characteristics of four variations of the EOD Suit (Med-Eng EOD 9 suit, Allen Vanguard; Ottawa, Canada) were assessed.

Figure 2 shows the entire EOD ensemble and various key pieces that differentiate each configuration. All configurations included: cotton undergarments t-shirt, boxer briefs, and socks); the EOD ballistic suit (EOD9: Jacket, Trousers, Integrated groin protector (IGP), and Boot Protector); GORE lined leather combat boots; and NOMEX® gloves with Velcro; and EOD9 full face helmet. Configuration specific items included: **Configuration 1:** The baseline (Ba-EOD) configuration consisted of all of the above listed items. **Configuration 2:** The chemical protective (EOD CB) configuration included the baseline items, chemical protective undergarments (hood, shirt, gloves, pants, and socks), white cotton glove liners, butyl rubber overboots, and self-contained breathing apparatus (SCBA) with air tank. **Configuration 3:** EOD suit with cooling undergarment (EOD cooling) included the baseline items, a three-piece liquid circulating personal cooling suit (shirt, pants, hood) and ice-based 100V cooling unit (BCS4; Allen Vanguard; Ottawa, Canada) (Figure 3). **Configuration 4:** EOD suit chemical protection and cooling undergarment (EOD CB + cooling) included the baseline items, as well as each of additional items in configurations 2 and 3 (EOD CB and EOD cooling) (See Appendix A for item descriptions and National Stock Numbers (NSN)).

Figure 2. Explosive Ordnance Disposal (EOD) configuration elements



A = Ba-EOD; B = cotton t-shirt and boxer briefs; C = chemical protective undergarments (hood, shirt, gloves, pants, and socks); D = EOD CB minus helmet; E = SCBA and air tank; F = EOD with cooling pack ⇦

Figure 3. Three-piece liquid circulating personal cooling suit and ice-based 100V cooling unit; (BCS4 Med-Eng; Allen Vanguard; Ottawa, Canada)

The thermal manikin has 20 zones including zones for the head that allowed for swapping out of values specific to the manikin head, enabling calculation of total insulation with and without the EOD helmet for each configuration.

Each individual piece of equipment from the whole ensemble was weighed (Table 1). These measures of weight were used for the estimated metabolic demands associated to carrying of each specific configuration mass.

Table 1. Total ensemble and individual equipment weights shown as kilograms with approximate weights in pounds

Item / Ensemble	kg	lbs	Ensemble used in
Ba-EOD (1)	34.94	77	
EOD CB (2)	36.17	79.7	
EOD Cooling (3)	51.27	113	
EOD CB + Cooling (4)	52.5	115.7	
Ba-EOD (1) no helmet	29.04	64	
EOD CB (2) no helmet	30.27	66.7	
EOD Cooling (3) no helmet	45.37	100	
EOD CB + Cooling (4) no helmet	46.6	102.7	
Diaper (ballistic)	1.36	3	1, 2, 3, 4
Torso (ballistic)	17.24	38	1, 2, 3, 4
Pants (ballistic)	7.17	15.8	1, 2, 3, 4
Full face helmet	5.90	13	1, 2, 3, 4
CB pants	0.64	1.4	2, 4
CB shirt	0.82	1.8	2, 4
CB hood	0.27	0.6	2, 4
CB gloves	0.09	0.2	2, 4
CB booties	0.23	0.5	2, 4
toe protector	0.91	2	1, 3
boots	2.36	5.2	1, 3
CB boots	2.45	5.4	2, 4
socks	0.09	0.2	3, 4
Cooling pump	1.27	2.8	3, 4
Cooling shirt	0.73	1.6	3, 4
Cooling pants	0.54	1.2	3, 4
Cooling water bottle	2.36	5.2	3, 4
SCBA	11.43	25.2	3, 4

Biophysical Assessments

The biophysical characteristics were assessed on each of the four variations of the Med-Eng EOD 9 suit. Testing was conducted using a twenty zone sweating thermal manikin (Newton, 20 zone, Measurement Technologies Northwest, Seattle, WA) operated within a climate-controlled wind tunnel. Thermal (R_{ct}) and evaporative (R_{et}) resistance were assessed according to American Society for Testing and Materials (ASTM) standards F1291-10 and F2370-10 [8-9]. These measures were then converted to measures of total thermal insulation (I_T) in units of clo and a water vapor permeability index (i_m). The ratio of the two (i_m/clo) describes the evaporative potential.

Measurements at three wind velocities (V) enabled the calculation of coefficient (gamma) values (^{g}), describing changes in the biophysical characteristics based on potential air flow within any given environment [10]. Tests were replicated at three different wind velocities of approximately: 0.55, 1.63, and 2.33 ms^{-1}. A regression was fitted to each of the specific measures at each level of V.

Typically testing of the heat removal or cooling capacity of body-worn cooling systems would be done according to ASTM standard F2371-10 [11]. However, this test requires a saturated steady-state condition that was unreachable due to the fully impermeably of the EOD suit. Therefore, values used in this report are from those reported by the company and author estimates [12].

Predictive Modeling

Modeling of the human thermal responses to exercise while wearing the EOD ensembles were conducted using the USARIEM Heat Strain Decision Aid (HSDA) [13-14]. The simulated conditions of environment, activity, and human characteristics used were based on those used by Stewart et al [2]. Simulated human characteristics include a population of healthy males, body mass 79 kg, height 180 cm, normally hydrated and heat acclimatized. Three environmental conditions were simulated: temperate (24°C; 50% RH), hot-dry (desert) (48°C; 20% RH), and hot-wet (jungle) (32°C; 60% RH). Each environment was assumed to be at sea level with average V of 1.0 ms^{-1} adjusted for simulated walking velocities. Four conditions were simulated for each environment, representing standing still, and moving at 0.7, 1.1, and 1.52 ms^{-1}.

Metabolic costs of standing and locomotion ($\dot{M}_{loco}$) were estimated using the equation from Pandolf et al., [15]. The differences in weight for each configuration drive changes in the $\dot{M}_{loco}$ specific to each ensemble.

RESULTS

Biophysical Results

The measured total thermal resistance (R_{ct}) converted to I_T (clo) for each V was used to determine estimates of standard and modeled measures at 0.4 and 1.0 ms^{-1} respectively (Table 2, Figure 4). Values for each configuration without helmet were calcuated by replacing regional measures from the head and face (Table 3, Figure 5).

Table 2. Total thermal resistance (I_T, clo) at three wind velocities (V) and estimated measures of 0.4 and 1.0 ms^{-1}

	Measured clo			**estimated clo**	
	0.55 ms^{-1}	**1.63 ms^{-1}**	**2.33 ms^{-1}**	**0.4 ms^{-1}**	**1.0 ms^{-1}**
Ba-EOD	2.743	2.135	1.830	3.031	2.360
EOD CB	3.034	2.634	2.359	3.209	2.766
EOD Cooling	2.853	2.288	2.073	3.039	2.502
EOD CB + Cooling	3.324	2.881	2.688	3.501	3.063

Figure 4. Total thermal insulation (I_T, clo) at three different wind velocities (V, ms^{-1}) for four EOD configurations

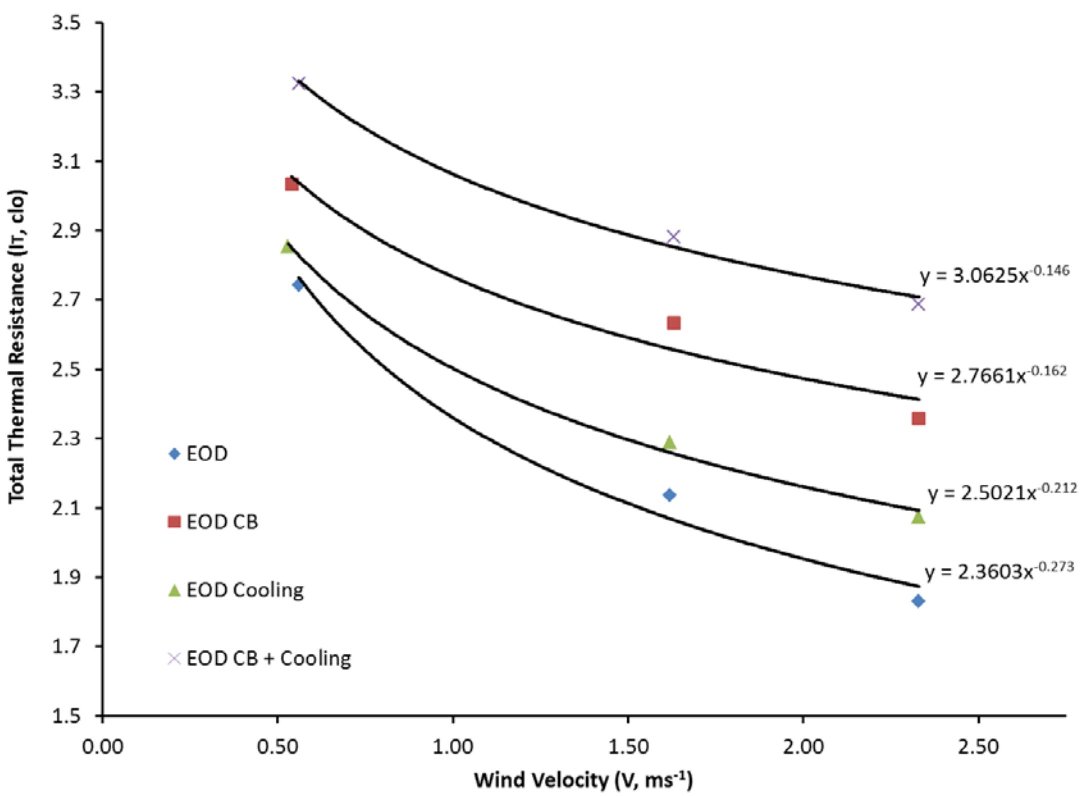
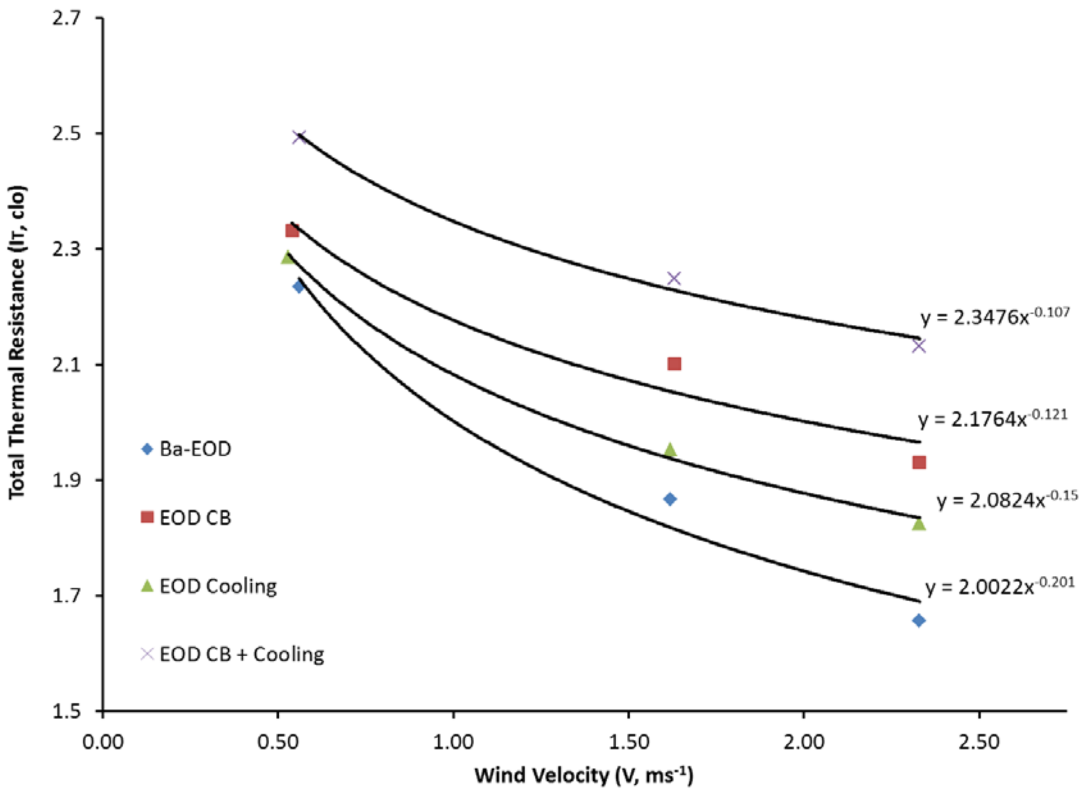


Table 3. Total thermal resistance (I_T, clo) at three wind velocities (V) without full face helmet and estimated measures of 0.4 and 1.0 ms^{-1}

	Measured clo			estimated clo	
	0.55 ms^{-1}	**1.63 ms^{-1}**	**2.33 ms^{-1}**	**0.4 ms^{-1}**	**1.0 ms^{-1}**
Ba-EOD	2.234	1.866	1.657	2.407	2.002
EOD CB	2.331	2.101	1.930	2.432	2.176
EOD Cooling	2.286	1.952	1.824	2.389	2.082
EOD CB + Cooling	2.492	2.248	2.131	2.590	2.348

Figure 5. Total thermal insulation (I_T, clo) at three different wind velocities (V, ms^{-1}) for four EOD configurations without full face helmet



Measures of evaporative resistance (R_{et}) could not be obtained from any of the configurations on the manikin, as a steady-state condition of evaporative heat flux could not be reached due to the highly occlusive nature of the EOD ensemble. The inability to obtain a steady-state evaporative heat flux is definable as impermeable. The theoretical range of i_m is from 0 (completely impermeable) to 1 (completely permeable). While it is typically understood that a value of 1 will not be found, it should also be assumed that an absolute value of 0 is also unlikely. However, values of i_m = 0 were assumed for each of these ensembles as the level of permeability are negligible (<0.005).

Predictive Modeling Results

Predicted thermophysiological responses for each configuration within three different environmental conditions were modeled based on four work rates. These estimated work rates were associated to each ensemble using the equation from Pandolf et al [15], mass specific to each ensemble, the simulated human mass, walking speeds, and a level terrain condition (Table 3).

Table 4. Configuration weights and estimated metabolic cost of standing and locomotion ($\dot{M}_{loco}$) at three speeds

	Weight	$\dot{M}_{loco}$ (W)			
	kg	Standing	0.7 ms^{-1}	1.1 ms^{-1}	1.52 ms^{-1}
Ba-EOD	34.94	163	247	370	558
EOD CB	36.17	167	251	376	566
EOD Cooling	51.27	228	324	465	680
EOD CB + Cooling	52.5	235	331	473	690

Figure 6. Modeled rise in core temperature wearing Ba-EOD at three work intensities based on locomotion at speeds: 0.7, 1.1, and 1.52 ms^{-1}; compared to collected human data in temperate conditions (24°C, 50% RH)

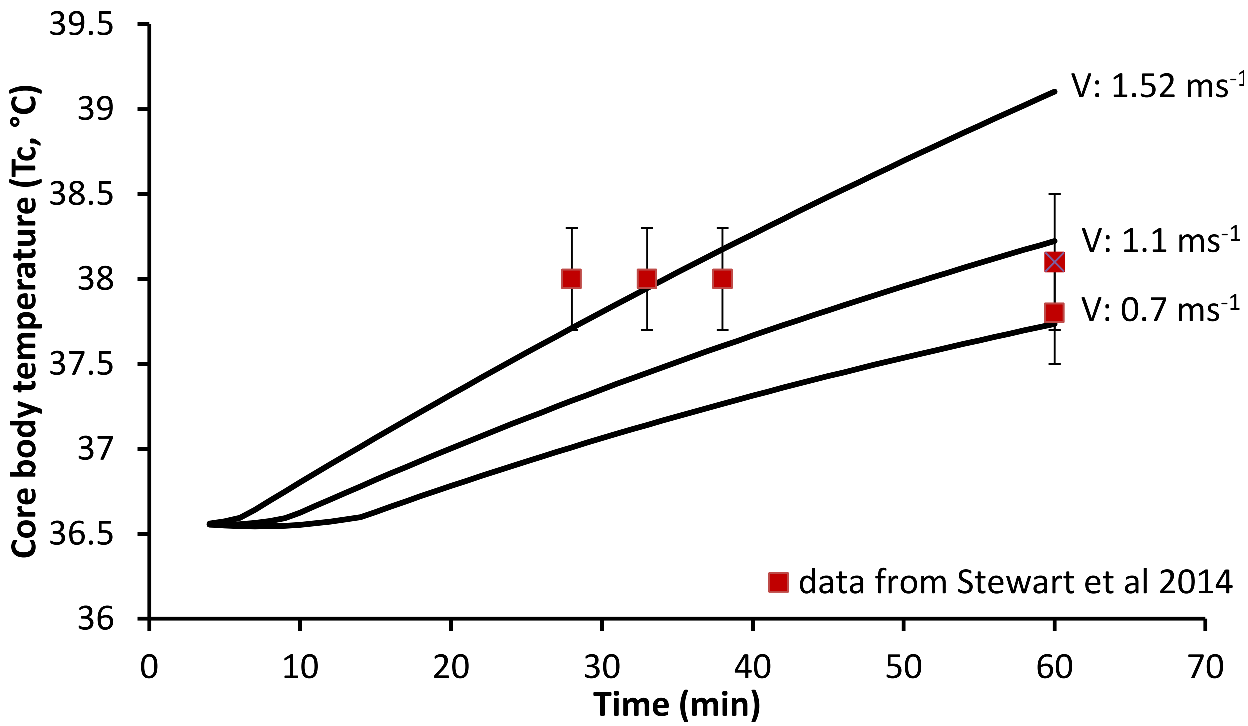


Figure 7. Modeled rise in core temperature wearing Ba-EOD at three work intensities based on locomotion at speeds: 0.7, 1.1, and 1.52 ms^{-1}; compared to collected human data in hot/dry conditions (48°C, 20% RH)

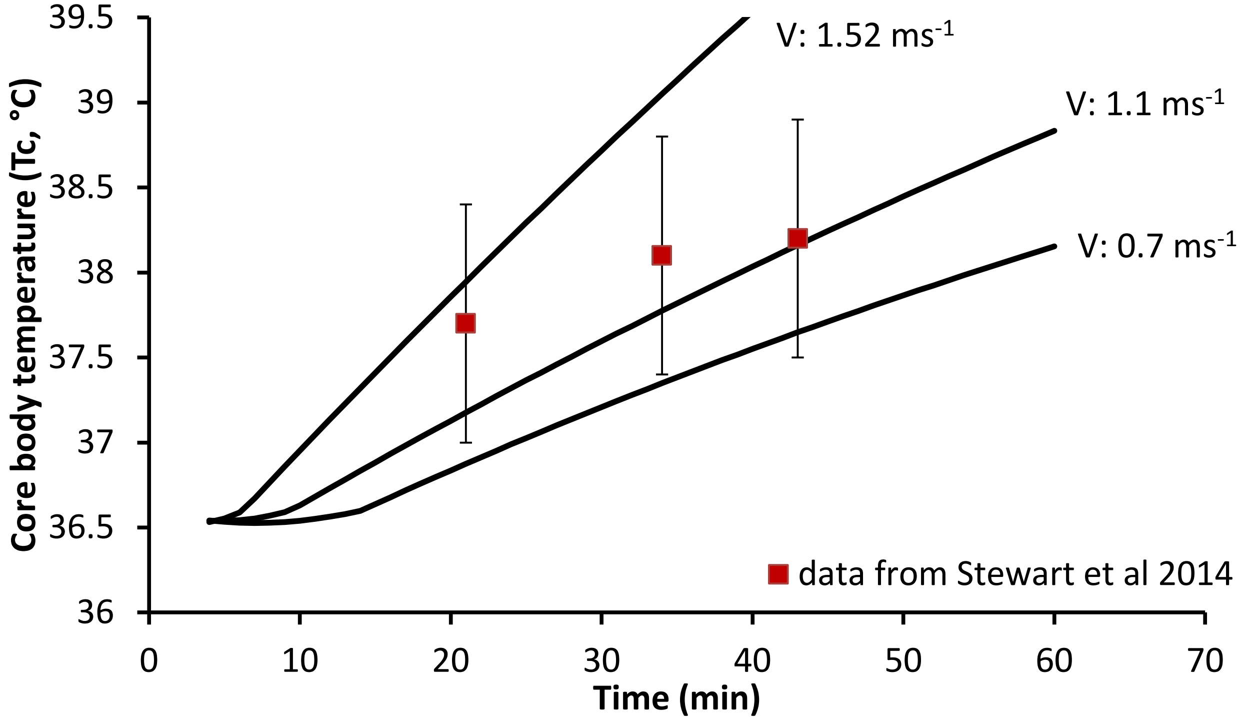
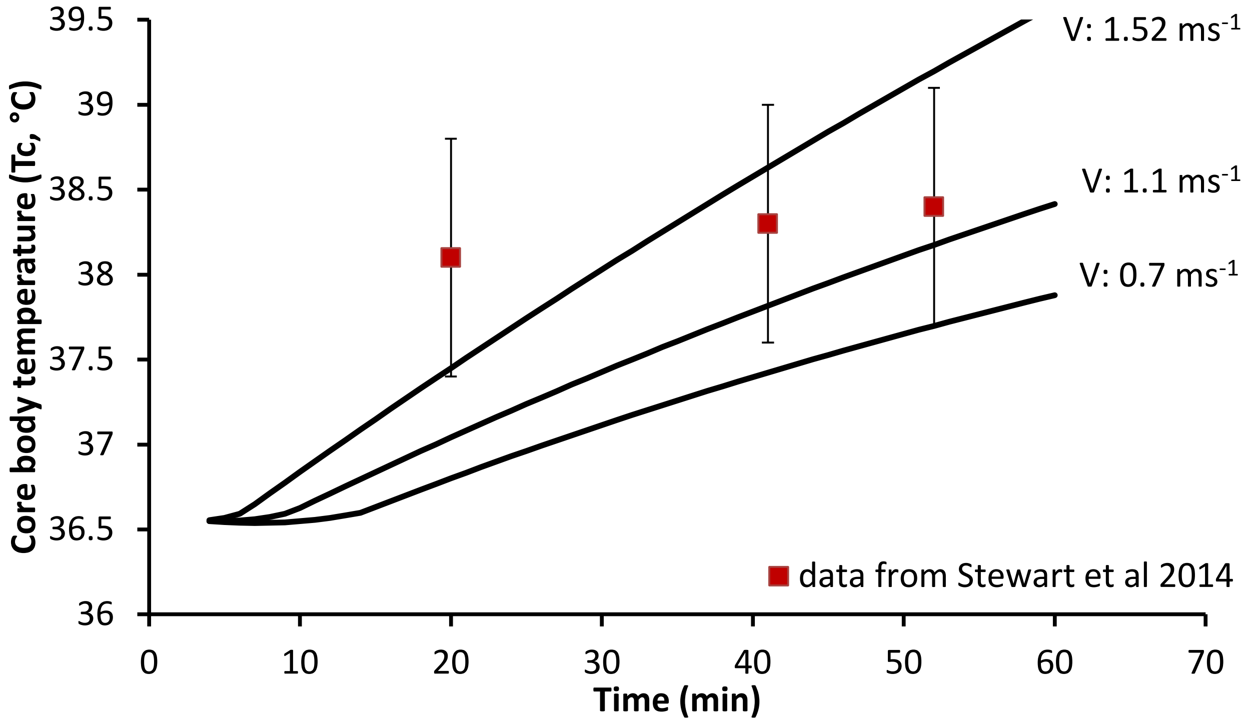


Figure 8. Modeled rise in core temperature wearing Ba-EOD at three work intensities based on locomotion at speeds: 0.7, 1.1, and 1.52 ms^{-1}; compared to collected human data in hot/humid conditions (32°C, 60% RH)



Predictions were made based on the biophysical properties and increased metabolic demand from added mass, to estimate core body temperature rise for each configuration within the three environments at a movement speed of 1.1 ms^{-1} (Figures 9-11).

Figure 9. Modeled rise in core temperature wearing four configurations of EOD suits at locomotion at speeds of 1.1 ms^{-1} in temperate conditions (24°C, 50% RH) without active cooling

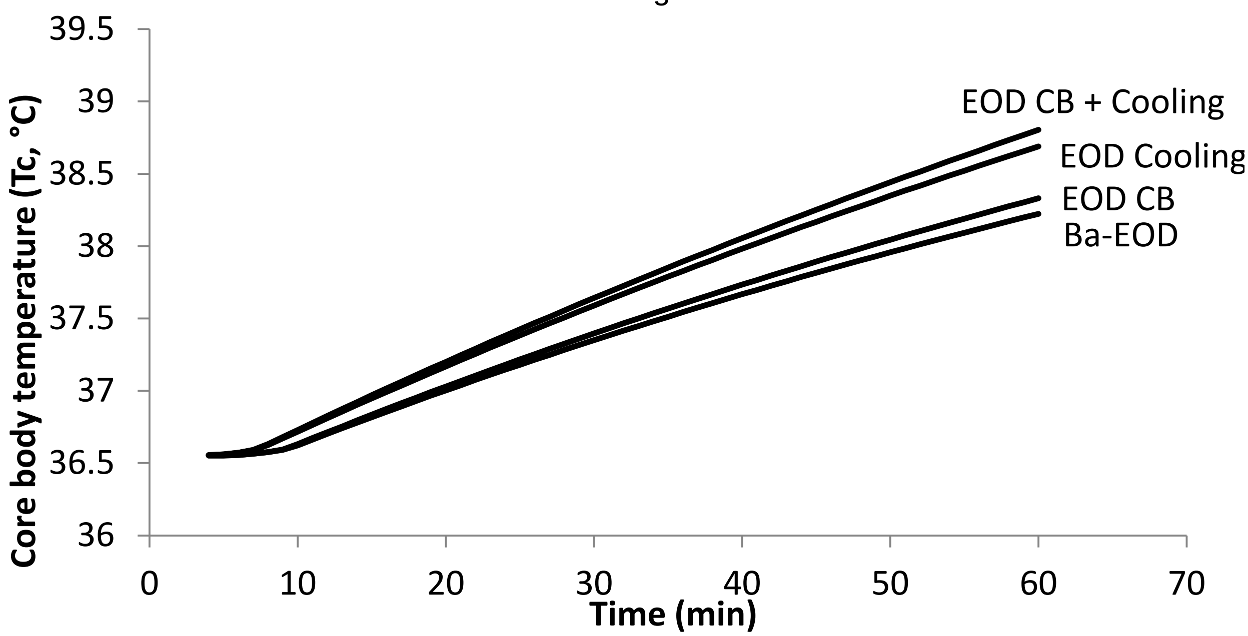


Figure 10. Modeled rise in core temperature wearing four configurations of EOD suits at locomotion at speeds of 1.1 ms^{-1} in hot/dry conditions (48°C, 20% RH) without active cooling

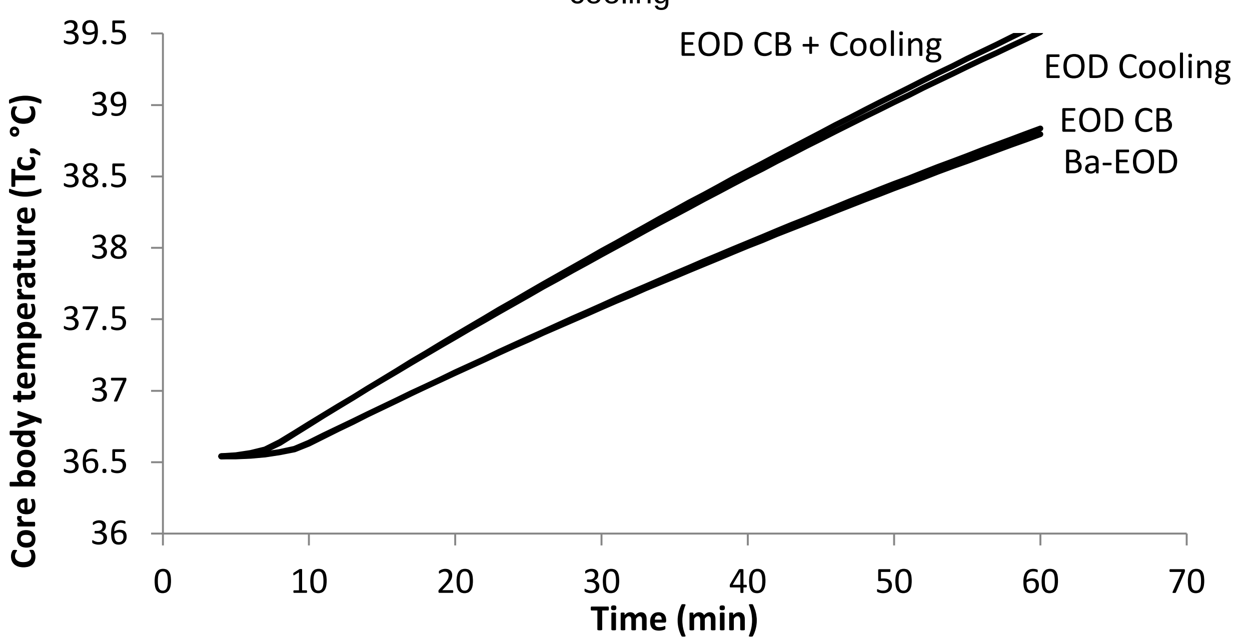
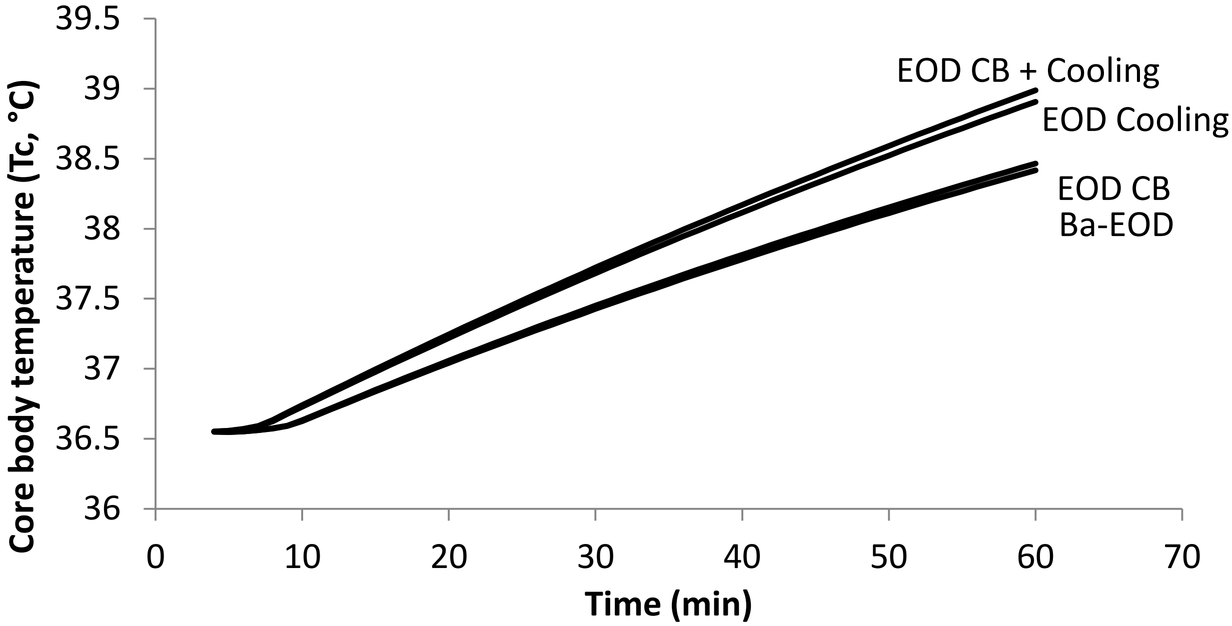


Figure 11. Modeled rise in core temperature wearing four configurations of EOD suits at locomotion at speeds of 1.1 ms^{-1} in hot/humid conditions (32°C, 60% RH) without active cooling



Based on the predicted increase in metabolic demand from standing associated to increased mass of each ensemble, modeling estimations were made for the three used environmental conditions (Figure 12-14). These modeled estimates assume the individual is standing still but has a consistent air movement of approximately 1.0 ms^{-1}.

Figure 12. Modeled rise in core temperature (T_c) at work intensities representative of standing in temperate conditions (24°C, 50% RH) without active cooling

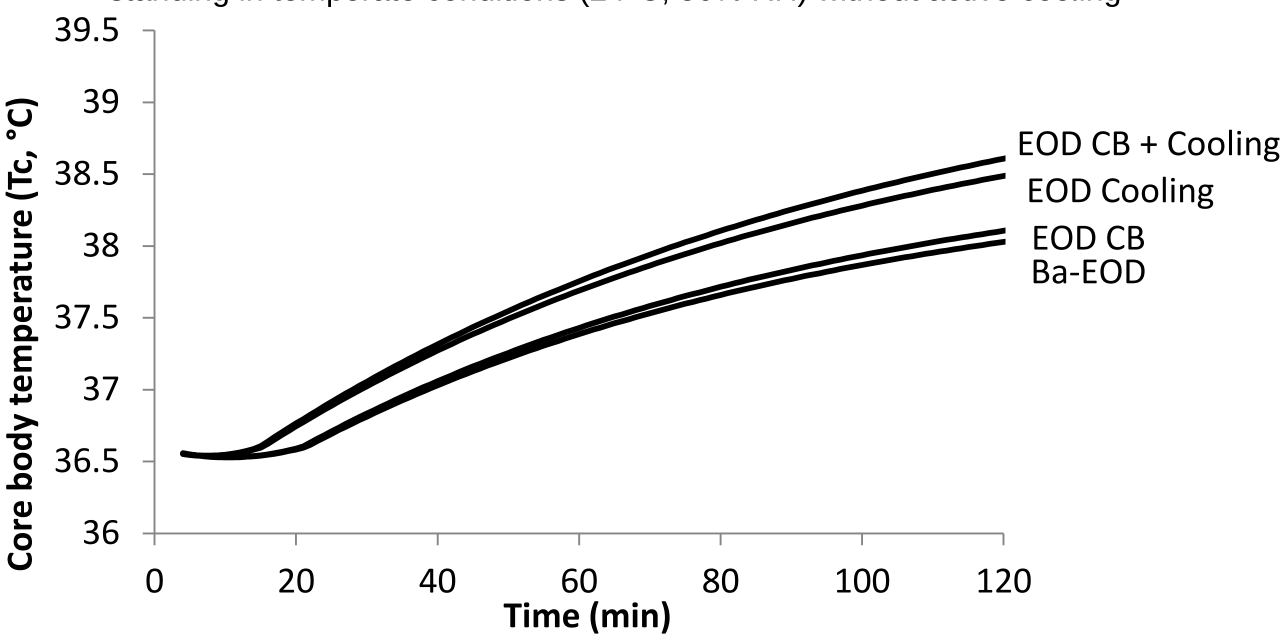


Figure 13. Modeled rise in core temperature (T_c) at work intensities representative of standing in hot/dry conditions (48°C, 20% RH) without active cooling

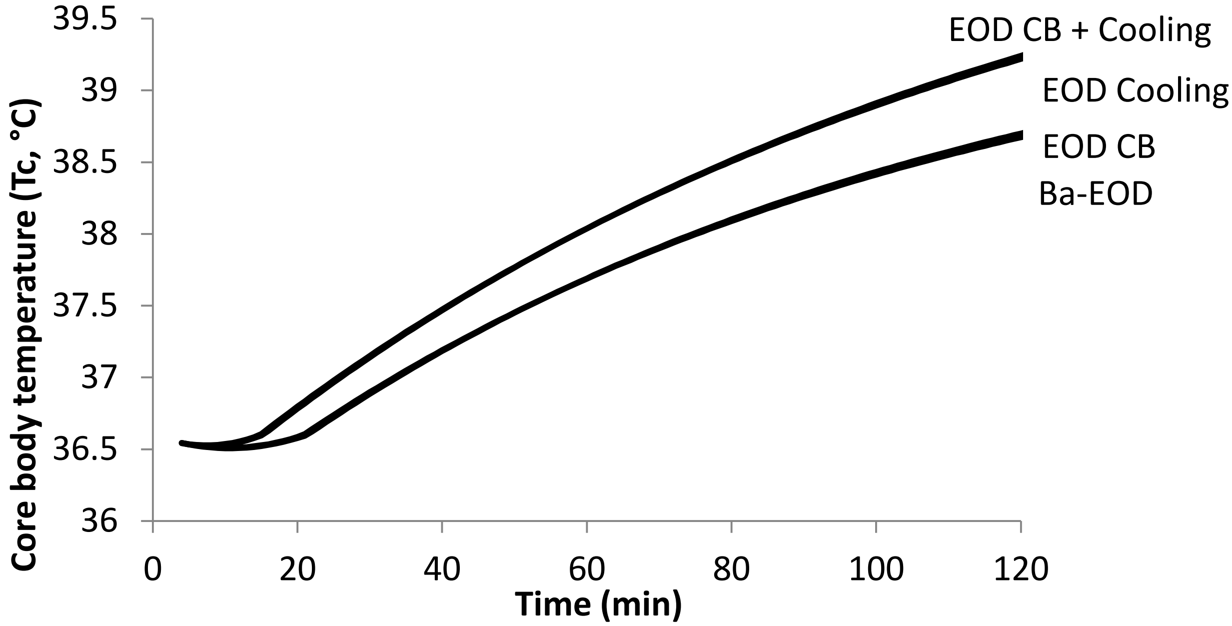
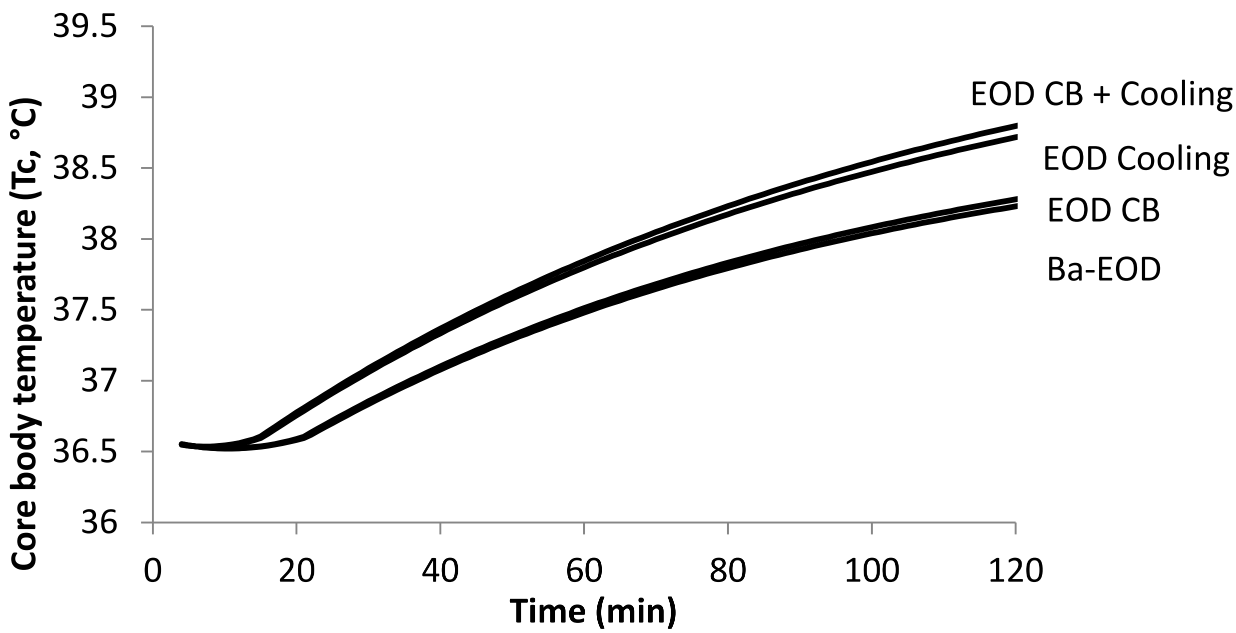


Figure 14. Modeled rise in core temperature (T_c) at work intensities representative of standing in hot/humid conditions (32°C, 60% RH) without active cooling



DISCUSSION

This report provides a biophysical assessment of four configurations of EOD suits with and without full face helmets. This work also provides modeling estimates of thermal endurance times that compare closely with human data previously published [2]. This report describes a scientifically valid method of making quantitative comparisons between different protective clothing configurations prior to conducting additional human subject research.

As observed by Stewart et al [2] there are a number physiological factors (e.g., heart rate, T_c, nausea, fatigue) that that limit tolerance times of individuals operating in these encapsulating and heavy suits. Along with these physiological limiting factors, there are a number of constraints that restrict or complicate operations longer than 60 minutes. For example, available air from SCBA units, or operational limits of personal cooling units. For these reasons, our modeling analyses were limited to 60 minutes. Similarly, while modeling of standing endurance was provided in this report based on increased metabolic demands of additional mass, it is not likely practical for individuals to stand for extended periods of time due to this added strain.

While measures of the effective heat removal or cooling capacity of the active cooling system could not be obtained on the manikin, reasonable estimates can be used to determine increased endurance levels. It has been reported that the system used can provide upwards of 250-270 W of cooling for approximately 45 minutes [16]. Typical cooling vests have shown much lower levels than this (~65 – 120 W) [12, 17]; however, as the BCS4 cooling system coverages nearly the entire body surface area (head, torso, legs, arms) this claim is reasonable. Estimated improvements to thermal endurance time has been modeled for moving at 1.1 ms^{-1} for the EOD Cooling and EOD CB + Cooling configurations with 150 and 250 W of active cooling (Figures 15-17).

Figure 15. Modeled rise in core temperature wearing two configurations of EOD suits at locomotion at speeds of 1.1 ms^{-1} without active cooling and with active cooling of 150 and 250 W in temperate conditions (24°C, 50% RH)

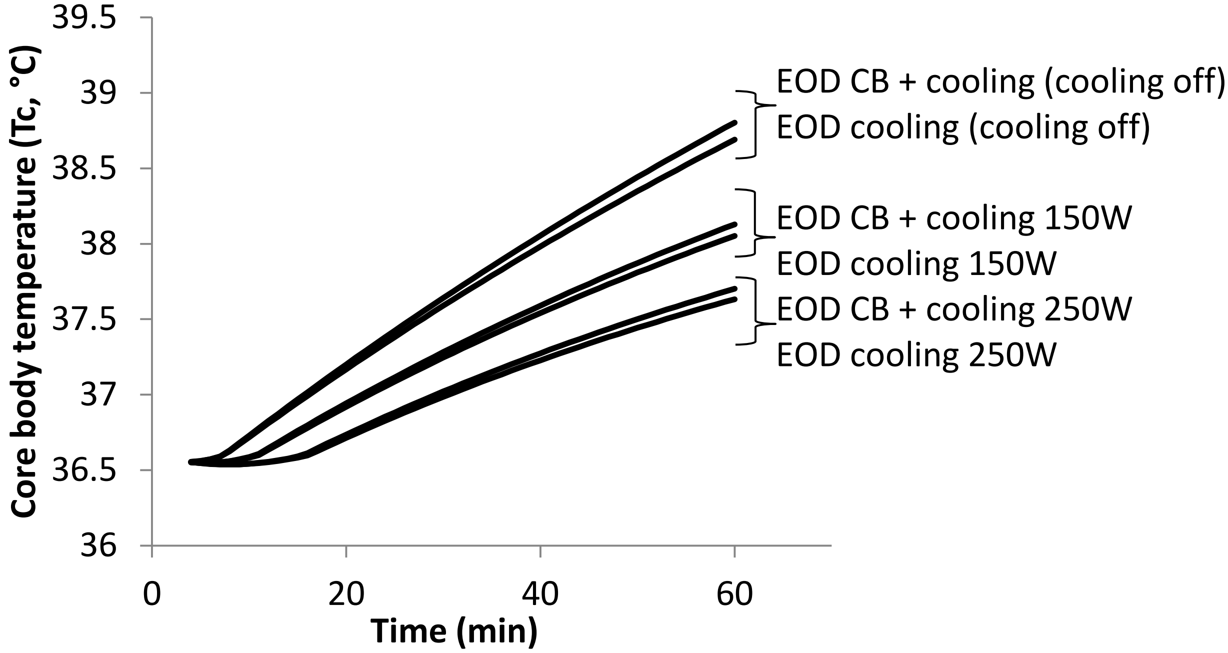


Figure 16. Modeled rise in core temperature wearing two configurations of EOD suits at locomotion at speeds of 1.1 ms^{-1} without active cooling and with active cooling of 150 and 250 W in hot/dry conditions (48°C, 20% RH)

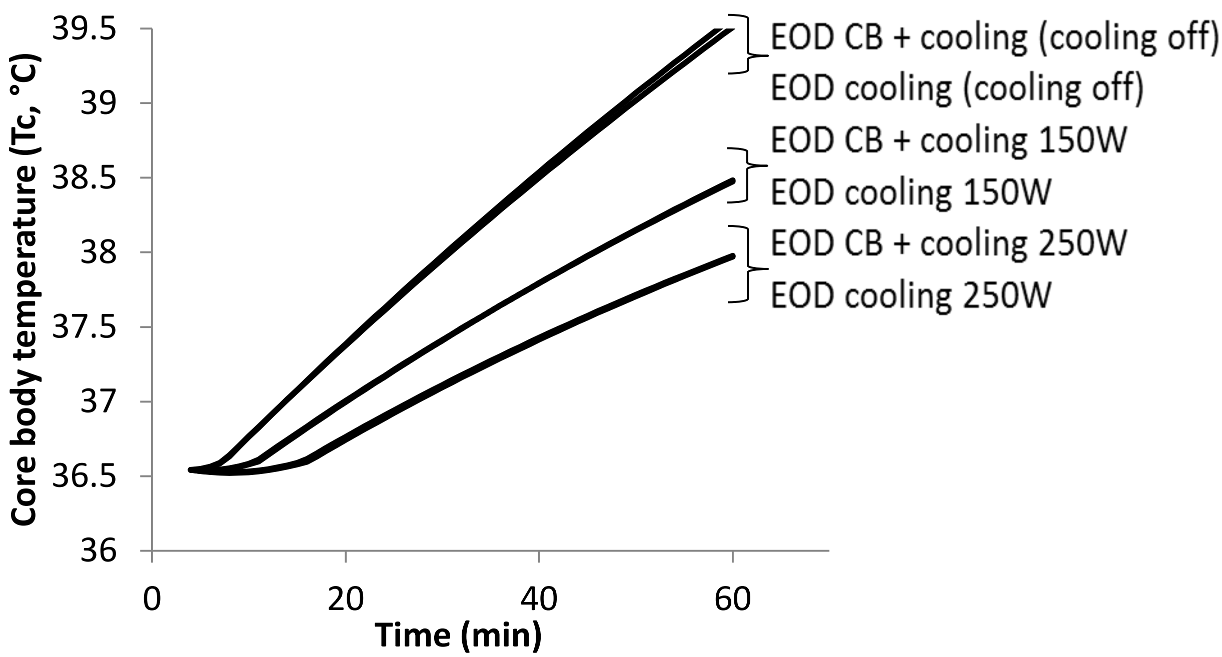
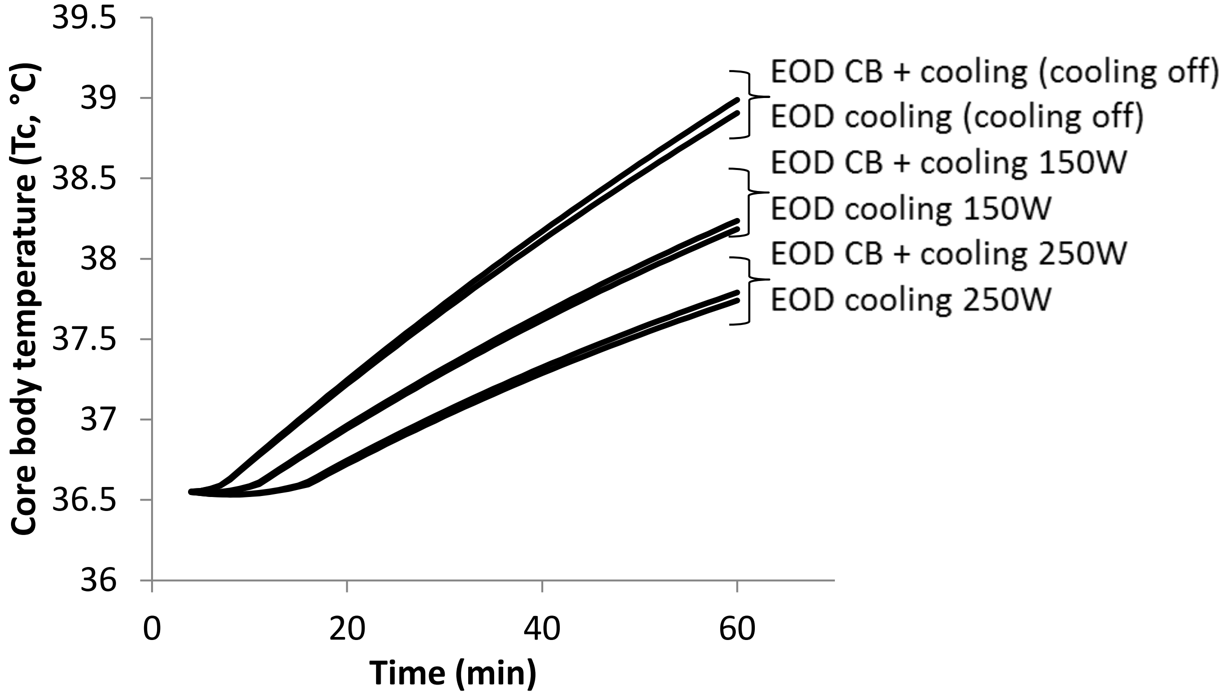


Figure 17. Modeled rise in core temperature wearing two configurations of EOD suits at locomotion at speeds of 1.1 ms^{-1} without active cooling and with active cooling of 150 and 250 W in hot/humid conditions (32°C, 60% RH)



CONCLUSIONS

This work provides a quantitative assessment of the biophysical properties and predicted maximal work times for these different EOD configurations while operating in different environments while standing or walking at three different velocities.

The biophysical characteristics and predictive modeling results show a significant difference between each EOD configuration and their associated thermophysiological responses to environments and activities. This analysis provides mission planners and EOD technicians quantifiable insights into how to optimize configurations based on environments and expected activities.

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APPENDIX A.

Detailed Equipment listing

Item	Size	NSN
Suit EOD 9 Enhanced Mobility Olive Drab Medium - CF Consisting of:	M	8470-20-A0F-4888
EOD 9 Jacket	M	
EOD 9 Trousers	M	
EOD 9 Integrated Groin Protector	M	
EOD 9 Boot Protector	M	
Hand Protectors with Gloves Green - CF	10	8415-20-A0F-4889
EOD Jacket LG Olive Drab (if Medium jacket too small)	L	8415-20-A0F4885
EOD 9A Helmet Olive Drab (short chin cup)	N/A	8470-20-A0F4630
EOD 9BA Visor Kit (chin strap - CBRN)	N/A	8470-20-A0F4631
BCS4 Cooling Unit 100V	N/A	8415-20-A0F4894
Suit 3 pc Kermal MD - CF (Cooling Suit)	M	8415-20-A0F-4643
CDN ARMY Undergarment (Top)	M	
CDN ARMY Undergarment (Bottom)	M	
CDN ARMY Socks	M	
CDN ARMY Boots	M	
CPU Gloves MD - CF	M	8415-20-A0F-4897
CPU Socks LG - CF	L	8415-20-A0F4901
CPU Hood Modified (ISI) - CF	N/A	8415-20-A0F-4903
CPU Shirt MD - CF	M	8415-20-A0F-4905
CPU Trousers MD - CF	M	8415-20-A0F-4908
CBRN Overgloves	L	8415-21-921-2170
CBRN Overboots	10-11	8430-99-869-0397
CBRN Glove Inserts		8415-21-921-2546
Mask, CBRN, Double Curve Medium Viking ST with Vinyl Stowage Bag	M	4240-20-0073492
SCBA, CBRN, HP 60 Min Carbon DB, ZST, Case, VAS CON - CF Harness and Tank	N/A	4240-20-A0F4879
Cylinder, Air Carbon HP 60 Minute - CF	N/A	8120-20-007-3487