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Practical method for determining safe work while wearing explosive ordnance disposal suits

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A B S T R A C T

Explosive ordnance disposal (EOD) operators wear fully encapsulating suits to protect them from potential fragments and blast while disarming or destroying threats; however, these suits impose excess heat and cardiovascular strain. This work provides a practical method for planning safe working durations of these extremely hazardous and unique activities that previously did not exist. Biophysical measures were obtained for the EOD9 suit (Med-Eng EOD9 suit, Allen Vanguard; Ottawa, Canada) using a sweating thermal manikin. An EOD9-specific mathematical model of heat transfer was developed and compared to human data from eight healthy males (age, 25.3 ± 6.4 y; height, 180.4 ± 6.6 cm; weight, 79.4 ± 8.7 kg; VO2max, 57.0 ± 5.7 ml.kg.min -1). Activities included three walking speeds (0.69, 1.11, and 1.53 m/s), within three environmental conditions warm-humid (WH) (ambient temperature (T_a), 32 °C; relative humidity (RH), 60%; mean radiant temperature, 32 °C), and temperate (T) (24 °C; 50%; 24 °C). Comparisons were assessed using bias, limits of agreement (LoA), mean absolute error (MAE), and root mean square error (RMSE). Biophysical measures show EOD9 suit to be completely vapor impermeable, allowing for a simplified modeling method where evaporative cooling is completely restricted creating a strictly dry heat exchange. Averaged predicted core body temperatures possessed an acceptable bias (~0.05 °C), but possessed a MAE of 0.33 °C, RMSE of 0.42 °C, and LoA was ~0.88 to 0.79 compared to observed data. Observed endurance times were combined with thermal modeling to provide a simple method for estimating safe working times. Simplified method can be used as a guidance for determining EOD operation planning.

1. Introduction

Explosive ordnance disposal (EOD) operators serve a crucial role in both law enforcement and the military. These individuals wear heavy fully encapsulating armor suits to protect them from blast threats. However, the mass (35–53 kg) and impermeable nature of these suits greatly impacts human biophysical heat exchange (Stewart et al., 2011, 2014). The significant mass of EOD suits increases the energy demands and ultimately metabolic heat production (Bach et al., 2017; Looney et al., 2019a, 2019b). By restricting the ability of threats to enter the suit (e.g., fragments, shrapnel), these impermeable suits also restrict evaporative heat loss, the primary means of environmental and metabolic heat dissipation, further exacerbating thermal strain (Potter et al., 2015a, 2015b).

With the complexities related to balancing both safety and security (Boustras and Waring, 2020) it becomes critical to ensure the real-time health of those first responders (Costello et al., 2015; Tharion et al., 2013). Several studies have measured the physiological and cognitive strains imposed during EOD activities (Stewart et al., 2011, 2014); while others have shown the physical strains and mobility constraints of EOD activities (Wu et al., 2021). Ultimately, these risks of injury are inherent in the nature of the tasks and are intuitively higher when individuals operate beyond safe working durations (e.g., fatigued, thermally stressed). Currently, there are no standards, formal guidance, or decision aids that help EOD operators plan the duration of their activities based on the environmental conditions and anticipated metabolic demands.

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The present work seeks to provide a simple and practical solution to fill this gap.

Human biophysical heat exchange is typically referred to as heat or thermal energy balance, and can be described as:

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

where \(S\) is heat storage; \(M\) is metabolic rate; \(W\) is work rate. Conduction \((K)\) is heat transfer due to the body’s direct contact with a solid object (e.g., touching a cold surface). Convection \((C)\) is heat transfer between the body and a fluid such as air or water. Radiation \((R)\) is heat that is transferred via electromagnetic waves (e.g., solar radiation). Evaporation \((E)\) is heat loss to the environment due to the phase change from liquid to vapor, typically associated with evaporation from sweat or respiratory water loss. From this equation it is clear that EOD gear increases \(S\) by augmenting \(M\) via increased body mass, distorting \(K\), \(C\), and \(R\), and essentially abolishing \(E\) (Potter et al., 2015b) (Fig. 1).

The completely impermeable nature of the EOD9 ensemble allows for simplification of the human heat balance equation (Eq. (1)), as evaporative heat loss is essentially non-existent. This simplified method becomes a strictly dry \((K, C, R)\) heat exchange model; where:

$$S_{EOD} = M \pm K \pm C \pm R \ [W/m^2]$$

While EOD gear effectively protects operators from blast injury, the compromised \(E\) impairs heat loss and increases the risk of individuals becoming heat exhausted or even suffering from exertional heat stroke. Similar to activities wearing nearly impermeable chemical protective ensembles, uncompensable conditions increase the rate of core body temperature \((T_c)\) rise and reduces the amount of time to heat exhaustion (Bouchama and Knochel, 2002; Goldman, 1970; Goldman and Breckenridge, 1976; Sawka et al., 2001) and possible heat stroke (Casa et al., 2015). These risks make the ability to model \(T_c\) responses and safe work times to given work rates, environments, and durations in an EOD suit a crucial first step in preventing heat related injuries and improve operator performance.

To better understand the impact of EOD clothing on the physiological responses to activity, Stewart et al. (2011, 2014) recently conducted experiments in which participants wore EOD clothing while varying the work rate and environmental conditions. In this paper, the acceptability of thermal model predictions of \(T_c\) responses is examined as the first step towards defining work practices to optimize work productivity, while minimizing likelihood of heat exhaustion or other environmental heat injuries (EHI). Initially measures of the biophysical properties of the EOD9 suit were conducted, followed by the development of a novel simplified method to predict \(T_c\) responses. This simplified model was compared to human data, and then analyzed whether predicted \(T_c\) could accurately predict observed work times.

## 2. Methods

Biophysical assessments were conducted to obtain thermal \((R_t)\) and evaporative \((R_e)\) resistance measures for the EOD9 suit using a sweating thermal manikin. These biophysical values were used as inputs for a thermoregulatory model (Potter et al., 2017) and used to create a simplified model that accounts for the EOD9 suit’s extremely high evaporative resistance. Comparisons of this simplified model were made to those published (Stewart et al., 2011, 2014) to establish criterion validity.

### 2.1. Biophysical properties of the EOD9 ensemble

The EOD9 Suit (Med-Eng EOD9 suit, Allen Vanguard; Ottawa, Canada) was assessed using a twenty-zone sweating thermal manikin (Newton, 20 zone, Thermetrics, Seattle, WA) operated within a climate-controlled chamber, according to American Society for Testing and Materials (ASTM) standards (ASTM, 2016a, 2016b). Thermal resistance \((m^2\ C/W)\) characterizes the heat transfer from the body, mostly due to convection, described:

$$R_t = \frac{(T_s - T_a)}{Q/A} \ [m^2\ C/W]$$

where \(T_s\) is the temperature of the measurement surface and \(T_a\) is the ambient temperature, both are in °C. \(Q\) is the power input in Watts required to maintain the surface of the measurement instrument at \(T_s\) and \(A\) is the area of the measurement surface in \(m^2\). Evaporative resistance \((m^2 Pa/W)\) characterizes the heat lost from the body due to evaporation (sweat) and in isothermal conditions \((T_s = T_a)\) is described:

$$R_e = \frac{(P_{sat} - P_{v})}{Q/A} \ [m^2 Pa/W]$$

where \(P_{sat}\) is the vapor pressure in Pascal units at the surface of the measurement instrument which is assumed to be at full saturation, and \(P_v\) is the vapor pressure in Pascal, of the ambient environment.

Biophysical assessments were conducted at three wind velocities \((V_w)\) (0.55, 1.63, and 2.33 m/s) and a regression (power function) was

![Typical clothing ensemble](image1)

![EOD ensemble](image2)

Fig. 1. Heat exchange in typical clothing ensembles (left) versus Explosive Ordnance Disposal (EOD) (right) ensembles.
fitted to each measure to enable the calculation of wind coefficient, describing changes in the biophysical characteristics based on potential air flow within any given environment (Potter, 2016; Potter et al., 2014).

### 2.2. Thermal modeling of the EOD9 suit

Select elements from the Heat Strain Decision Aid (HSDA) (Potter et al., 2017) were used as the starting point for assessing the EOD9 suit. HSDA is one of the US Army’s widely used empirically-based human thermal models (Givoni and Goldman, 1972; Gonzalez et al., 1997; Potter et al., 2017, 2019). This method uses inputs of the human and their activity, the environment, and clothing properties to make predictions of T

The model used relies on an empirical equation for estimating an equilibrium point of T

where T

where T

where T

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### 2.3. Human data for comparison

Participants were briefed on the purpose of the study and potential risks before voluntarily giving their informed written consent. The study conformed to the current Declaration of Helsinki guidelines and was approved by Queensland University of Technology Human Research Ethics Committee (#1000001160).

Modeling predictions were compared to data from eight healthy males (age, 25.3 ± 6.4 y; height, 180.4 ± 6.6 cm; weight, 79.4 ± 8.7 kg; VOC

### 3. Results

#### 3.1. Biophysical assessment of EOD9

Thermal resistance (R

#### 3.2. Modeling thermoregulatory response

While the E

#### 3.3. Statistical analysis

Statistical analyses were performed using a combination of MATLAB (The MathWorks, Inc., Natick, MA) and Excel (Microsoft Corporation, Redmond, WA). Descriptive statistics are presented as means ± SD. Bias, limits of agreement (LoA), mean absolute error (MAE), and root mean square error (RMSE) were used to compare predictions to observations of T

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### Table 1

| Visit | Human study controlled crossover design. |
|-------|------------------------------------------|
| 1     | Minimum seven days rest                  |
| 2     | One environmental condition, based on randomized order: Warm-Humid (WH) (T

#### Fig. 2. Thermal resistance (R

#### Table 1

| Visit | Human study controlled crossover design. |
|-------|------------------------------------------|
| Rest  | Minimum seven days rest                  |
| 2     | One environmental condition, based on randomized order: Warm-Humid (WH) (T

#### Rest  | Minimum seven days rest                  |
| 3     | One randomized environment, (WH, HD, or T) |
| 4     | One randomized environment, (WH, HD, or T) |

#### Rest  | Minimum seven days rest                  |
| 3     | One randomized environment, (WH, HD, or T) |
| 4     | One randomized environment, (WH, HD, or T) |

#### Rest  | Minimum seven days rest                  |
| 3     | One randomized environment, (WH, HD, or T) |
| 4     | One randomized environment, (WH, HD, or T) |
responses to the nine different conditions (3 walking speeds in 3 environments). Inputs to the model used were based on individual data points for height and weight, initial $T_c$, estimated metabolic rates, and the final $T_c$ of observed and modeled values were compared and are illustrated in Fig. 3. This illustration (Fig. 3) shows there is a correlation between the estimated and observed data, with an upper and lower LoA between 0.79 and −0.88.

Table 2 provides descriptive data (mean ± SD) from measured individual observations and modeled predictions, model bias, MAE, and RMSE for each environmental condition and for the total collective set of data. Table 2 shows a close agreement with the aggregate data observed and modeled as well as very low bias for the total (−0.05 °C) as well as for each environmental group (T, 0.15; WH, −0.19; HD, −0.09). These low bias values are within acceptable error for previous direct measure criteria (±0.27 °C) (Casa et al., 2007). Additionally, the MAE for each condition was within the observed SD; while RMSE was within the observed SD for all conditions except WH (±0.43 vs. 0.50 °C).

Additionally, this approach was used to model the activities based on an average male (180 cm; 79 kg) wearing the 33.4 kg EOD9 suit and baseline layers (1.34 ± 0.65 kg) and walking at the three walking velocities (V) (0.69 m/s, 247 W; 1.11 m/s, 370 W; 1.53 m/s, 558 W) in each of the three environmental conditions (T, WH, HD) (Fig. 4). Fig. 4 illustrates the accelerated rate of fatigue or need to halt exercise when wearing EOD clothing in comparison to wearing less compromising clothing or working just in hot weather. Activities in the EOD suit increase the rate of reaching clinical limits for heat exhaustion (>38 °C) as well as the military limits for heat exhaustion in uncompensable (38.6 °C) and compensable conditions (39.5 °C) (Bouchama and Knochel, 2002; Sawka et al., 2001). From a military safety perspective, the impermeable nature of the EOD9 suit puts the wearer in an uncompensable condition making their risk threshold much lower. Fig. 4 shows the observed versus modeled times a worker is at significant risk of heat injuries at any work intensity (low-high) in HD conditions.

### 3.3. Simple guidance for estimation of tolerance times

Restriction of heat loss by E reduces variability in response to high humidity within the environment, effectively reducing environmental conditions of interest to only air temperature ($T_a$) and solar radiation. Using the simplified modeling method, estimates of rise in $T_c$ can be done on a minute-by-minute scale. However, given the relatively short periods of time an individual can maintain a safe working $T_c$, these EOD9 ensembles, it is important to consider other reasons for ending activities such as exhaustion. Given this shorter period of safe working times, an even simpler practical calculation of safe work times can be estimated. Observed data of times to exhaustion or point of thermal limits are shown in Fig. 5 based on changes in environmental conditions (left) and walking velocity (right).

Using the simplified thermal model and effect calculations of decrements shown in Fig. 5, a simple equation and table for estimating endurance time ($E_t$) in minutes can be represented as:

$$E_t = Wt - Dt - Ds$$  \(8\)

where $Wt$ is maximum work time (minutes); $Dt$ is decrement in work time due to $T_a$; and $Ds$ is decrement in work time due to solar radiation (Table 3). These decrements are based on modeling conditions for each environmental condition, metabolic rate, and solar exposure. The $E_t$ is based on estimated time to exhaustion and time to reach a $T_c$ of 38.5 °C, as the EOD suit creates uncompensable conditions (Montain et al., 1994; Sawka et al., 2001).

Fig. 6 shows a comparison of endurance times from the observed data to the simplified method outlined in Eq. (8) and Table 3. As observed $T_a$ was slightly different that the rounded temperatures in Table 3, weighted adjustments were made for comparisons. Weighting in Table 3 was made to be more conservative in conditions where heat stress is higher risk and to allow for longer working times in less stressful conditions (e.g., temperature at low activity). This conservative approach to setting the simple model parameters has an impact on the statistical comparability between the data and simple model. This can be

### Table 2

| Environmental Condition | Observed | Modeled | Bias | MAE | RMSE |
|-------------------------|----------|---------|------|-----|------|
| Collective Data         | 38.08 ± 0.45 | 38.03 ± 0.34 | −0.05 | 0.33 | 0.42 |
| Temperate (T) (24 °C; 50% HC) | 37.96 ± 0.43 | 38.11 ± 0.36 | 0.15 | 0.31 | 0.42 |
| Warm-Humid (WH) (32 °C; 60%) | 38.26 ± 0.43 | 38.06 ± 0.33 | −0.19 | 0.40 | 0.50 |
| Hot-Dry (HD) (48 °C; 20%) | 38.01 ± 0.44 | 37.93 ± 0.31 | −0.09 | 0.27 | 0.33 |

![Fig. 3](image-url). Observed and modeled final $T_c$ (°C) (left panel) and modeled error (right panel) while wearing EOD9 suit in temperate (T) (24 °C; 50%), warm-humid (WH) (32 °C; 60%), and hot-dry (HD) (48 °C; 20%) conditions, walking at three speeds (0.69, 1.11, and 1.53 m/s).
specifically seen in the hot-dry high work rate (1.53 m/s) plot in Fig. 6; where due to the large range of endurance times observed (10–30.5 min) and setting of conservative values reduces the agreement to the mean values. This conservative approach provided relatively low predictions in comparison to the observed endurance time mean ± SD (Table 4).

4. Discussion

This work shows the development of a method to predict $T_c$ response when wearing EOD suits and derive safe operating times in order to prevent EHI. After confirming that the EOD9 suit was vapor impermeable, a simplified $T_c$ estimation method was created and compared the predicted values to observed data to confirm criterion validity. After success of these tasks, a model that accurately predicted work times was created.

Fig. 3 shows a comparison of modeled predictions to observed $T_c$ values at termination of exercise; while Fig. 4 shows modeled increases in $T_c$ for continued operations within each condition. This comparison demonstrates close agreement between the observed $T_c$ elevation with the modeled $T_c$ at the same time points and agreement with endurance times; thereby supporting use of the simplified modeling to predict $T_c$ elevation during EOD operations. However, the error plot from Fig. 3 also shows skewing of the predictions indicating some potential issues within the model that are not completely understood from the current
It is well recognized that EOD operators do not typically move fast due to the heavy mass of the suit. Typically, EOD operations involve periods of walking (up to several hundred meters) at a self-selected pace (~1.2–1.5 m/s) while carrying or pushing (in a wheelbarrow) equipment (up to 75 kg) to and from the site of ordnance (unpublished observations). While working, ordnance operators will adopt a variety of postures whilst manipulating tools and equipment, including standing, crouching, stooping, and lying prone; the heavy weight of the ensemble adds considerably to the metabolic cost, and consequently the thermal strain, of these activities.

While the basis of this modeling is focused on \( T_e \) as the foundational element of interest, other physiological factors (heart rate, nausea, etc.) as well as subjective elements (comfort) can be the cause for reduced tolerance when working in EOD suits (Borg et al., 2015; Stewart et al., 2014). The simplified method of predicting \( T_e \) was compared to data from Stewart et al., (Stewart et al., 2014) who observed the majority of limiting factors of endurance time during each of the 72 data-points were due to HR > 90% of HR max (n = 50), followed by fatigue or nausea (n = 6); while only one was due to a measured \( T_e \) over 39 °C (Stewart et al., 2014). From a real-world physiological perspective, high HR alone would not cause injuries and would be self-regulated (i.e., working beyond max heart rate is generally not probable); while working beyond thermal inertia (i.e., \( T_e \) limits) is very possible, resulting in potential EHI.

Modeling results suggest that the ambient RH has negligible impact when encapsulated in the EOD suit. Therefore, the significant differences in responses between the WH and HD conditions is most likely driven by the differences in \( T_e \) between conditions. It is also important to note that Stewart et al., 2014 included limitations to endurance time based on safety limits of maximal heart rates. For the current modeling effort, these limits for endurance times are helpful as they can translate to more realistic responses of real-world settings; where there are often more complex and inclusive of reasons for ending work, rather than simply using \( T_e \) as a measure of thermal stress alone.

Monitoring of individuals’ statuses in real-time is ideal for EOD operations; however, the EOD suits and work conditions often pose both technical and tactical challenges (e.g., wearable sensors can have difficulty in transmitting on-body data, wireless communications can pose threats to detonation of explosives). However, recent work has been conducted using wearable devices to measure heart rate to make non-invasive estimates of \( T_e \) (Looney et al., 2018) and specifically in EOD operations (Hunt et al., 2019). This ability for real-time monitoring of heart rate and potential estimates of \( T_e \) can provide significant context to an individual’s status (Friedl et al., 2016; Hunt et al., 2019; Tharion et al., 2013) and could be used in conjunction with initial planning methods, such as those proposed within this manuscript.

The modeling and analyses within this paper provides low-tech and usable solutions for initial planning of EOD operations. The modeling approach used predicted close agreement to both the measure of \( T_e \) as well as a reasonable estimate of endurance times. While the data shows there is relatively high variability in the endurance times observed by the research volunteers (Table 4); the initial use of a conservative estimate of endurance time as provided in the simplified method (Eq. (8) and Table 3), allows for a reasonable solution to risk mitigation planning. These planning solutions can be used in alone or in conjunction with real-time wearable monitoring to better mitigate heat stress and safe work times for EOD operations.

5. Conclusion
This work quantitatively confirms the EOD9 suit is completely water vapor impermeable, preventing any heat loss via evaporation. The thermoregulatory modeling outlined, provides practical insights into both core body temperature predictions as well as estimates of safe working durations while wearing the EOD9 suit. The simplified method proposed in this manuscript provides a practical solution for estimating safe work durations while conducting EOD activities. Future research should be conducted to compare the real-world outcomes to these predictions to ensure an acceptable level of accuracy can be provided for different activities, individuals, and environmental conditions.

### Table 3
Endurance time (E<sub>t</sub>) calculation factors.

| Factor | Minutes | Description |
|--------|---------|-------------|
| Wt     | 100     | Activity level |
|        | 78      | Standing |
|        | 70      | Light work: walking 0.69 m/s (~247 W) |
|        | 48      | Moderate work: walking 1.11 m/s (~370 W) |
|        |         | Heavy work: walking 1.53 m/s (~558 W) |
| Dt     | 0       | Air temperature (T<sub>T</sub>) |
|        | 5       | 0 °C |
|        | 10      | 10 °C |
|        | 20      | 20 °C |
|        | 30      | 30 °C |
|        | 35      | 40 °C |
|        |         | 50 °C |
| Ds     | 0       | Solar radiation (sun exposure) |
|        | 3       | No sun |
|        | 6       | Full sun |

### Table 4
Modeled accuracy for endurance time (minutes) from simplified method (Eq. (8)) for each environmental condition and activity rate.

| Environmental Condition          | Observed Mean ± SD | Observed Range | Bias | MAE | RMSE |
|----------------------------------|--------------------|----------------|------|-----|------|
| Collective Data                  | 37.61 ± 15.91      | 10–60          | −1.61| 7.94| 9.90 |
| Temperate (T)                    | 44.94 ± 16.03      | 10–60          | 0.40 | 7.81| 9.75 |
| (24 °C; 50%)                     |                    |                |      |     |      |
| Warm-Humid (WH)                  | 37.10 ± 15.42      | 10–60          | 0.23 | 6.81| 8.35 |
| (32 °C; 60%)                     |                    |                |      |     |      |
| Hot-Dry (HD)                     | 30.79 ± 12.80      | 10–60          | −5.46| 9.21| 11.36|
| (48 °C; 20%)                     |                    |                |      |     |      |
| 0.69 m/s (~247 W)                | 50.44 ± 10.77      | 27–60          | −1.77| 6.56| 8.52 |
| 1.11 m/s (~370 W)                | 40.06 ± 12.73      | 16–60          | 0.60 | 8.77| 10.81|
| 1.53 ms (~558 W)                 | 22.33 ± 8.77       | 10–45.5        | −3.67| 8.50| 10.22|
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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