

The Pandolf load carriage equation is a poor predictor of metabolic rate while wearing explosive ordnance disposal protective clothing

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Conflict of interest

The authors have declared that no competing interests exist.

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ABSTRACT (150 words)

This investigation aimed to quantify metabolic rate when wearing an explosive ordnance disposal (EOD) ensemble (~33kg) during standing and locomotion; and determine whether the Pandolf load carriage equation accurately predicts metabolic rate when wearing an EOD ensemble during standing and locomotion. Ten males completed eight trials with metabolic rate measured through indirect calorimetry. Walking in EOD at 2.5, 4.0 and 5.5km·h⁻¹ was significantly ($p<0.05$) greater than matched trials without the EOD ensemble by 49% (127W), 65% (213W); 78% (345W), respectively. Mean bias (95% limits of agreement) between predicted and measured metabolism during standing, 2.5, 4 and 5.5km·h⁻¹ were 47W (19 to 75W); -111W (-172 to -49W); -122W (-189 to -54W); -158W (-245 to -72W), respectively. The Pandolf equation significantly underestimated measured metabolic rate during locomotion. These findings have practical implications for EOD technicians during training and operation and should be considered when developing maximum workload duration models and work-rest schedules.

PRACTITIONER SUMMARY (50 words)

Using a rigorous methodological design we quantified metabolic rate of wearing EOD clothing during locomotion. For the first time we demonstrated that metabolic rate when wearing this ensemble is greater than that predicted by the Pandolf equation. These original findings have significant implications for EOD training and operation.

KEYWORDS

Metabolism, Military Ergonomics, Occupational, Personal Protective Equipment, Predictive equation.

INTRODUCTION

Personal protective clothing (PPC) is frequently employed in military (Cadarette et al. 2006, Borg, Stewart, and Costello 2015), occupational (Dorman and Havenith 2009, Taylor et al. 2012) and sporting (Armstrong et al. 2010, Harmer 2008) settings to provide physical protection for the operative in order to aid in the prevention of injury. Typically, protective garments provoke ergonomic decrements in the user as a consequence of attempting to maintain both safety and functionality. The majority of occupational research into the metabolic (or energy) cost of PPC has focused primarily on chemical and fire ensembles (Dorman and Havenith 2009, Elsner and Kolkhorst 2008, Taylor et al. 2012), military personnel (Drain et al. 2016) or other labour intensive occupations (DiVencenzo et al. 2014, Dorman and Havenith 2009, Jorgensen 1985, Saha et al. 1979). PPC and personal protective equipment (PPE) increase metabolic rate during walking or running and simulated work tasks (Dorman and Havenith 2009, Elsner and Kolkhorst 2008, Taylor et al. 2012). These increases are primarily a function of ensemble mass, associated movement restriction, friction and altered gait mechanics imposed by the garment (Duggan 1988, Qu and Yeo 2011, Teitlebaum and Goldman 1972); therefore increasing metabolic and thermal loads and consequently reducing time to exhaustion (Costello, Stewart, and Stewart 2015a, Stewart et al. 2014).

The quantification of the metabolic rate associated with PPC and PPE aids operational planning in occupational settings through the development of maximum workload duration models and work-rest schedules for load carriage under various circumstances alongside the implementation of safe training for operatives. Currently, laboratory developed guidelines for maximal work duration are based from relative work intensities ($\% \dot{V}O_{2max}$) in the absence of any load carriage components (Saha et al. 1979, Wu and Wang 2001). In military training or deployment a variety of tools are utilised in order to estimate metabolic rates during prolonged load carriage such as metabolic equivalent (MET) values (Ainsworth et al. 2011) or field manuals such as Technical Bulletin Medicine (Blanchard and Santee 2008), Heat Strain Decision Aid (Sawka et al. 2003), Foot Marches Field Manual (FM21-18 1990) or SCENARIO (Kraning and Gonzalez 1997). These tools are derived from predictive equations that require input of individual characteristics (e.g. age, height, mass) and extrinsic factors (e.g. terrain, gradient, load) (American College Of Sports Medicine 2014, Epstein, Stroschein, and Pandolf 1987, Givoni and Goldman 1971, Pandolf, Givoni, and Goldman 1977,

Santee et al. 2001, Santee, Small, and Blanchard 2003). The most commonly applied metabolic prediction equation for load carriage during standing and locomotion was originally developed by Givoni and Goldman (1971) and was subsequently updated by Pandolf, Givoni, and Goldman (1977). This formula uses an individual's body mass, velocity, and the load carried, in conjunction with the terrain traversed and the gradient of the surface, to derive a predicted metabolic rate (see *Methods*). Since its development, the Pandolf, Givoni, and Goldman (1977) prediction equation has been validated for load carriage up to 40 kg, locomotive speeds up to 6.0 km·hr⁻¹ as well as grades between 0 and 10% (Duggan and Haisman 1992, Pimental and Pandolf 1979).

Recently, metabolic rate of various PPC has been reported, ranging from relatively light chemical suits (Dorman and Havenith 2009) through to considerably heavier firefighting clothing (11 kg) and associated PPE in the form of a self-contained breathing apparatus (15 kg; ~27 kg total) (Elsner and Kolkhorst 2008). Due to the inherent risk of the task, explosive ordnance disposal (EOD) technicians are required to don very heavy PPC (>35 kg) to provide ballistic and thermal protection (Costello, Stewart, and Stewart 2015a, Costello, Stewart, and Stewart 2015b, Stewart et al. 2014). This ensemble is presented in Figure 1 and is comprised of three main components; helmet, jacket and trousers (and groin protection). Typically, EOD technicians are required to physically locate and identify the explosive device before attempting to disarm or enforce controlled detonation. Accordingly, the length of a given task can vary considerably depending on the ambient environment, geographical location and operational intelligence. For example, based upon a threat, an EOD technician may be required to manually locate a concealed device over a large area (e.g. skyscraper). Despite the frequent use of EOD PPC in the military, domestic police forces, counter-terrorism agencies and even commercial mining and demolition firms, to our knowledge the metabolic rate of wearing an the ensemble has not been presented in the literature. Although, preliminary data presented by Thake et al. (2009) suggest that a significant reduction in oxygen consumption while wearing the EOD ensemble can be achieved with heat acclimation. Nevertheless, it is not clear if the commonly used Pandolf equation can accurately estimate the metabolic rate of wearing the EOD ensemble during different workloads. Therefore the purpose of this investigation was to quantify the metabolic rate when wearing an EOD ensemble during standing and steady state locomotion at various speeds and determine the ability the Pandolf load carriage equation to accurately

predict metabolic rate of the EOD ensemble across a range of workloads. We hypothesized that (1) the metabolic rate of wearing an EOD would be significantly greater than other PPC (e.g. firefighting) reported in the literature, and (2) the Pandolf equation would accurately predict the metabolic rate of locomotion in the ensemble.



Figure 1. Explosive ordnance disposal (EOD) ensemble: a) Helmet (5.9 kg); b) Jacket (17.8 kg); c) Trousers (with Groin Protection) (9.7 kg); Total ensemble mass = 33.4 kg.

METHODS

Participants

Ten healthy, recreationally active males volunteered to participate in this study; participant characteristics are presented in Table 1. Prior to commencing the study all participants were provided with written information detailing the purpose of the study and associated risks, completed a health screen questionnaire and gave verbal and written informed consent in accordance with the Declaration of Helsinki. Ethical approval was granted from the Queensland University of Technology's Human Research Ethics Committee.

Table 1. Participant Characteristics

ID	Age (y)	Mass (kg)	Height (m)	$\dot{V}O_{2PEAK}$ (mL·kg ⁻¹ ·min ⁻¹)
1	26.2	81.24	1.80	56
2	25.9	73.40	1.75	50
3	23.7	86.53	1.87	52
4	23.5	92.42	1.83	46
5	26.5	93.62	1.82	47
6	24.4	90.93	1.89	55
7	36.4	86.63	1.87	47
8	21.4	65.21	1.74	59
9	25.5	68.65	1.76	54
10	23.4	80.90	1.78	56
Mean	25.7	82.0	1.81	52
SD	4.1	10	0.05	4

Experimental Design

Participants were required to attend the laboratory on three occasions, separated by 48 hours. The first visit involved aerobic capacity testing ($\dot{V}O_{2PEAK}$) and an extensive familiarisation with the EOD protective clothing and testing procedures. During the familiarisation the participants were allowed to walk around the laboratory and on the treadmill at the speeds to be utilised for the trials as detailed previously (Costello, Stewart, and Stewart 2015a, Costello, Stewart, and Stewart 2015b, Stewart et al. 2014). In the subsequent two visits participant's completed four trials (8 minutes each), including one upright standing and three treadmill-walking conditions of 2.5, 4 and 5.5 km·h⁻¹ with a 1% grade while wearing either athletic clothing (CON) or an EOD ensemble (EOD). Following pilot testing it was established that six minutes of treadmill walking was required to ensure steady state oxygen consumption ($\dot{V}O_2$) was achieved; defined as a change in $\dot{V}O_2 < 2$ ml·kg⁻¹·min⁻¹ (Baker et al. 2000). The second and third visits to the laboratory were identical except for the clothing ensembles (CON and EOD). Participants completed a total of four trials per visit. Trial order was randomised using a random number generator to ensure a within-participant controlled crossover design.

Participants were instructed to wear a standardised base clothing for each trial/day: shirt, shorts, underwear, socks, and shoes (clothing: 1.023 ± 0.220 kg; shoes: 0.646 ± 0.186 kg). These base ensemble requirements were standardised in accordance with American Society for Testing and Materials standard F2668-07 (ASTM Standard F2668–07 2011). For the EOD trials participants wore a Med-EngTM EOD9 suit (Allen Vanguard,

Ogdensburg, New York, USA) that consisted of jacket, trousers, groin protection and helmet (~33.4 kg) in addition to the base (i.e. control) ensemble (~1.6 kg).

Pre-experimental Testing

Ensemble familiarisation saw the participant don the EOD ensemble and walk around the laboratory and on a treadmill, set at 2.5, 4 and 5.5 km·h⁻¹ with a 1% grade, as previously described (Stewart et al. 2014). $\dot{V}O_{2PEAK}$ and maximum heart rate were determined via a standardised incremental aerobic test on a treadmill (Stewart et al. 2014).

Experimental Testing

In preparation for testing, participants were instructed to abstain from strenuous exercise, caffeine and alcohol 24 hours prior to attending the laboratory. On arrival to the temperature controlled laboratory (24 ± 1 °C; 67 ± 3 % relative humidity) height and nude body mass were measured. Participants were then equipped with a heart rate monitor and strap (Polar Team², Kempele, Finland). After 10 minutes seated rest, baseline heart rate was measured and the CON or EOD ensemble donned. $\dot{V}O_2$ (L·min⁻¹), via indirect calorimetry (TrueOne 2400, Parvo Medics, Utah, USA) were continuously recorded during all trials. Steady state $\dot{V}O_2$ data was averaged in the final two minutes of each trial (minute 6 to 8). Following each trial, and after removing the PPC in the EOD trials, the participants rested in the laboratory. Nude body mass was recorded after each rest period and if required participants were provided with identical dry clothes as well as a known quantity of water (average 0.120 ± 0.096 L) to compensate any sweat losses between trials in order to maintain a constant body mass. Following the return to their baseline heart rate value (± 5 b·min⁻¹) participants were allowed to commence the subsequent trial (average rest 14 ± 6 minutes).

Data Analysis

Measured metabolic rate was calculated from the averaged $\dot{V}O_2$ (minute 6 to 8) using equation one (American College Of Sports Medicine 2014); where M_M = measured metabolic rate (W) and $\dot{V}O_{2A}$ = absolute oxygen consumption (L·min⁻¹).

Equation One:
$$M_M = (\dot{V}O_{2A} \cdot 5)/0.0143$$

Predicted metabolic rate was calculated using the Pandolf load carriage equation (Pandolf, Givoni, and Goldman 1977); where M_p = predicted metabolic rate (W), W = participant mass (kg), L = external load (kg), V = walking speed ($m \cdot s^{-1}$), G = grade (%) and η = terrain coefficient ($\eta = 1$ for treadmill).

Equation Two:
$$M_p = 1.5W + 2.0(W + L)(L/W)^2 + \eta(W + L)(1.5V^2 + 0.35VG)$$

MET values for measured metabolic rate were calculated in equation three based of collected relative $\dot{V}O_2$. Before predicted MET values could be derived, predicted metabolic rate needed to be converted to absolute $\dot{V}O_2$ by transposing equation one (American College Of Sports Medicine 2014), then converted to a relative value to be used in equation three; where MET = metabolic equivalent of task and $\dot{V}O_{2R}$ = relative oxygen consumption expressed in $ml \cdot kg^{-1} \cdot min^{-1}$.

Equation Three:
$$MET = \dot{V}O_{2R}/3.5$$

Percentage error was calculated between the predicted (Pandolf, Givoni, and Goldman 1977) and measured metabolic rate while wearing the EOD suit; where M_p = predicted metabolic rate; M_M = measured metabolic rate.

Equation Four:
$$\% \text{ Error} = ([M_p/M_M] \cdot 100) - 100$$

Statistical Analysis

Normality was assessed using both descriptive methods (skewness, outliers, and distribution plots) and inferential statistics (Shapiro–Wilk test). $\dot{V}O_2$ steady state was statistically confirmed by a repeated measures analysis of variance (ANOVA) with pairwise comparisons for significance between 30 second averaged intervals between minute 6 and 8 (i.e. 6-6.5, 6.5-7, 7-7.5, and 7.5-8 min) for each ensemble and speed. Statistical significance for each of the primary outcome measures (predicted EOD metabolic rate, measured EOD metabolic rate, and prediction error [%]) was determined using a one-way (speed) repeated measures ANOVA. The percentage difference in metabolic rate from wearing the EOD ensemble relative to the paired

CON speed was tested for significance with a one-tailed single sample t-test. Main effects for MET values were analysed using a three-way (ensemble \times predicted/measured \times speed) repeated measures ANOVA. Post hoc analysis utilised the Bonferroni's correction for multiple pair-wise comparison tests. In addition, linear regression was used to determine the significance of correlations between predicted and measured metabolic rate across all trials for both CON and EOD (McDonald 2009). Finally, the absolute agreement between the predicted and measured metabolic rate (during all EOD conditions) were assessed by calculating the mean bias and 95% limits of agreement (LoA) in accordance with Bland and Altman (Bland and Altman 1999). All data were analysed using SPSS (SPSS version 21.0, SPSS Inc., Chicago, USA). Values of $p < 0.05$ were considered statistically significant. Data are displayed as mean \pm standard deviation unless otherwise stated.

RESULTS

All participants reached steady state $\dot{V}O_2$ no later than 6 minutes into each speed and ensemble; and once stable ($p > 0.05$) $\dot{V}O_2$ was maintained throughout the remainder of the trial. Predicted and measured metabolic rates and prediction errors in the EOD ensemble are presented in Table 2. Wearing the EOD ensemble significantly increased metabolic rate (2.5 km·h⁻¹, 49.4 \pm 8.7%; 4 km·h⁻¹, 64.7 \pm 10.9%; 5.5 km·h⁻¹, 78.3 \pm 13.9%; all $p < 0.05$; Figure 2) above the CON trials during the three walking speeds but not for standing (1.9 \pm 12.2%; $p = 0.64$; Figure 2). Statistical analysis of MET values identified significant ($p < 0.001$) main effects for ensemble, predicted/ measured, speed, and all combinations of interactions. Post-hoc analysis for the paired ensembles predicted and measured MET values are described in Figure 3. A strong correlation between the predicted and measured metabolic rate at all speeds for CON ($r^2 = 0.965$, $p < 0.01$, Figure 4a) and EOD ($r^2 = 0.976$, $p < 0.01$, Figure 4b) was observed. Finally, the mean bias (95% LoA) between predicted and measured during standing, 2.5, 4 and 5.5 km·h⁻¹ for the EOD ensemble were as follows: 47 W (19 to 75 W); -111 W (-172 to -49 W); -122 W (-189 to -54 W) and -158 W (-245 to -72W).

Table 2. Measured and predicted EOD metabolic rate (W), with associated prediction error (%) during tested speeds for each participant (n = 10).

ID	Predicted (W)				Measured (W)				Prediction Error (%)			
	Stand	Speed (km·h ⁻¹)			Stand	Speed (km·h ⁻¹)			Stand	Speed (km·h ⁻¹)		
		2.5	4.0	5.5		2.5	4.0	5.5		2.5	4.0	5.5
1	164	276	421	635	101	346	472	748	62	-20	-11	-15
2	156	262	399	596	80	343	503	689	95	-24	-21	-13
3	168	284	444	656	129	420	559	797	30	-32	-21	-18
4	173	296	459	685	129	444	629	853	34	-33	-27	-20
5	177	300	462	694	129	434	598	881	37	-31	-23	-21
6	174	296	457	679	136	434	601	811	28	-32	-24	-16
7	172	288	444	665	143	399	559	794	20	-28	-21	-16
8	154	251	379	556	97	349	527	777	59	-28	-28	-28
9	154	255	385	570	106	315	475	745	45	-19	-19	-23
10	164	276	422	630	130	408	564	853	26	-32	-25	-26
Mean	166*	278*	427*	636*	118*	389*	549*	795*	44*	-28 [#]	-22	-20
SD	9	18	31	49	21	46	54	59	23	5	5	5

* = Significantly different to all conditions ($p < 0.001$); [#] = Significantly different to 4 km·h⁻¹ ($p = 0.004$) and 5.5 km·h⁻¹ ($p = 0.017$).

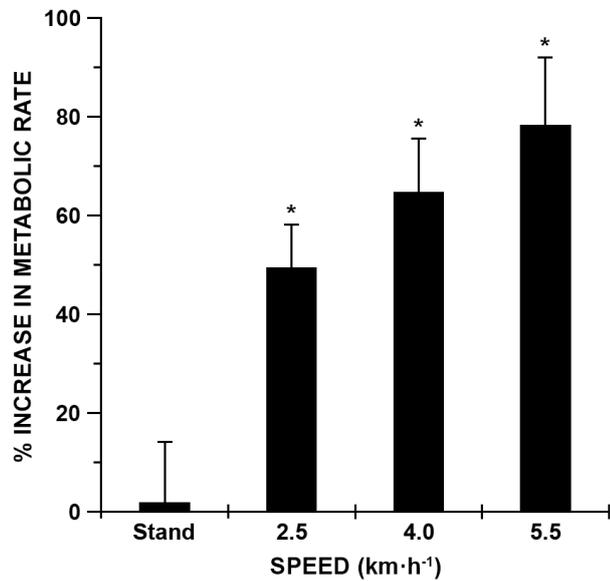


Figure 2. Mean percentage increase in metabolic rate from EOD ensemble relative to paired control trial at all tested speeds. * = Significant differences ($p < 0.05$) observed between EOD and paired CON trial.

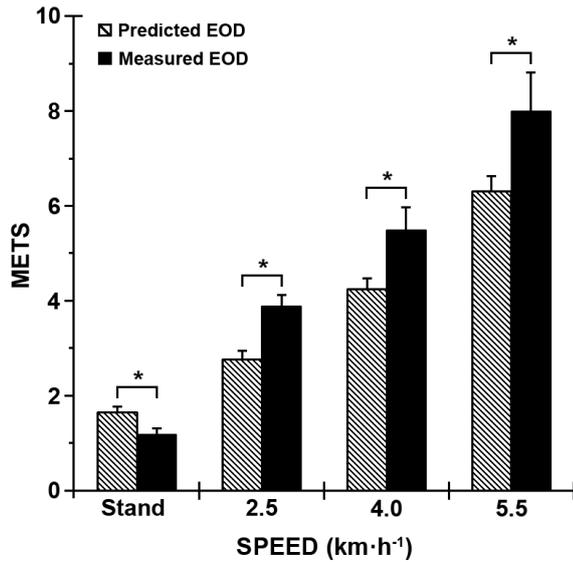


Figure 3. Predicted and measured MET values for EOD ensembles. * = Significant differences between predicted and measured ($p < 0.001$).

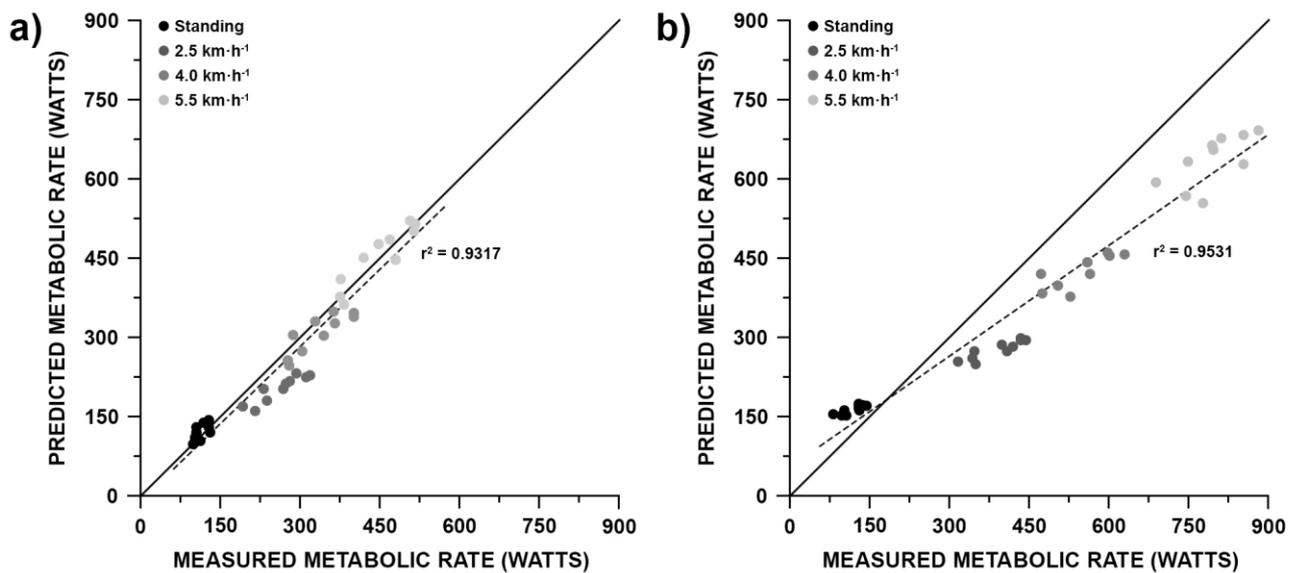


Figure 4. Linear regression of predicted vs. measured metabolic rate during a) CON ($p < 0.05$) and b) EOD trials ($p < 0.05$). Solid line is identity ($y = x$); dashed line is linear regression a) $y = 0.9736x - 11.451$; b) $y = 0.6975x + 54.159$.

DISCUSSION

To our knowledge this is the first study to quantify the metabolic rate when wearing explosives PPC during standing and locomotion; as well as evaluate a predictive load carriage equation with the EOD ensemble. The key findings from this study are 1) the EOD ensemble significantly increased the metabolic rate of work during locomotion (47-78%) but not during standing and 2) the Pandolf load carriage equation (Pandolf, Givoni, and Goldman 1977) significantly underestimated the metabolic rate while walking compared to the measured metabolic rate in the EOD ensemble.

Metabolic increases at walking speeds of 2.5, 4.0 and 5.5 km·h⁻¹ in EOD were greater than CON by 49%, 65% and 78%, respectively (Figure 2). The current investigation saw considerably higher increases in metabolic rate than those reported in previous studies (Dorman and Havenith 2009, Elsner and Kolkhorst 2008, Taylor et al. 2012); most likely attributed to the additional mass of the EOD ensemble. For example, Dorman and Havenith (2009) found significant increases in metabolic cost (ranging from 12 to 21%) in twelve protective ensembles (weighing 3.5 to 7.0 kg) relative to the control condition while walking at 5.0 km·h⁻¹. More recently, Taylor et al. (2012) observed a 47% increase in metabolic cost when wearing fire-fighting PPC (19.9 kg) compared to a control condition while walking at 4.8 km·h⁻¹ (0% grade). In the absence of dynamic muscular contraction (i.e. standing), the metabolic rate required by an individual should be less than that of locomotion. However, the development of isometric tension from supporting musculature means with the addition of load carriage while standing energy requirements increase and therefore so does metabolic rate (Pandolf, Givoni, and Goldman 1977). Conversely, in the current study, the addition of load in the form of the EOD ensemble saw no appreciable differences between the EOD and CON during standing ($1.9 \pm 12.2\%$, $p < 0.05$; Figure 2). Based upon the equation of Pandolf, Givoni, and Goldman (1977) this unexpected absence in increased metabolic rate is also illustrated in Figure 3; whereby MET values for predicted EOD were significantly greater than measured. These results could be explained by the findings of an earlier study by Pimental and Pandolf (1979) whereby the Pandolf equation slightly overestimated observed metabolic loads during traditional backpack load carriage (40 kg) while standing and underestimated during walking. Moreover, no significant differences in metabolic rate were shown during standing with either 20 or 40 kg loaded backpacks; suggesting that the mass (and/or load distribution) of the ensemble in the present study was

not heavy enough to elicit a significant rise in metabolic rate during standing. This premise is further supported by Griffin, Roberts, and Kram (2003) who found the metabolic rate while standing does not significantly increase when load carriage solely around the torso is less than 50% body mass. In the current investigation, the EOD ensemble was on average $42.2 \pm 5.5\%$ of participants' body mass, however only approximately half of the EOD ensemble mass was distributed around the torso (EOD jacket = 17.8 kg).

MET values for the intensity of physical activity have been classified as light (<3), moderate (3 to <6) and vigorous (≥ 6) (U.S. Department of Health and Human Services 2008). Significant differences ($p < 0.05$) in MET values were observed between all paired locomotive CON and EOD conditions. The greatest value (8.0 ± 0.8 METS) was measured during steady state EOD walking at $5.5 \text{ km}\cdot\text{h}^{-1}$. As part of the 2011 Compendium of Physical Activities (Ainsworth et al. 2011) running at $8.0 \text{ km}\cdot\text{h}^{-1}$ without any load carriage has been classified as 8.3 METs. Elsner and Kolkhorst (2008), measured MET values in 20 trained male fire-fighters wearing complete PPC ($\sim 27 \text{ kg}$) during a continuous series of 10 simulated fire-fighting tasks; such as climbing three flights of stairs, and advancing a fire hose 30 m, weighing 41 kg, through a cluttered area. The average time to complete the 10 simulated tasks was ~ 12 min and resulted in an average MET value of 8.3 ± 2.2 (Elsner and Kolkhorst 2008). Although the current investigation noted relatively high MET values for treadmill walking at $5.5 \text{ km}\cdot\text{h}^{-1}$ in the EOD ensemble, recent findings from our laboratory recommend slower speeds of $2.5 \text{ km}\cdot\text{h}^{-1}$ to ensure minimal physiological strain and therefore maximised tolerance time during operational activities in a range of ambient environments (Stewart et al. 2014). During this speed of locomotion the additional load from the EOD ensemble placed upon the user saw work intensity shift from light (2.6 METs) during CON to only moderate (3.9 METs) in the EOD trial.

Comparisons between the measured METs and those derived from the Pandolf load carriage equation are presented in Figure 3 with significant differences between each EOD predicted and EOD measured locomotive speeds. During walking, the greatest absolute difference between predicted and measured metabolic rate was at $5.5 \text{ km}\cdot\text{h}^{-1}$ (-158 W; -20%) and the greatest relative difference was seen at $2.5 \text{ km}\cdot\text{h}^{-1}$ (-111 W; -28%; Table 2). This underestimation of the Pandolf equation has previously been reported seen with significant underestimations of up to 20% in more modestly weighted PPC (trouser liners and heavy footwear:

3.4 kg) (Duggan and Ramsay 1986). The distribution of a load across the body plays an integral role in the extent of metabolic rate increase during locomotion. A given load placed upon the foot does not exert equal effect on metabolic rate as it would on the torso; in fact during walking the cost of an external load on the feet is two times greater than at the thighs and up to six times greater than at the torso (Jones et al. 1984). The variance in load distribution in the EOD ensemble could explain the underestimation of metabolic rate during all walking speeds by the Pandolf equation observed in the current study. Although currently used in the implementation of EOD training regimes Pandolf, Givoni, and Goldman (1977) developed the predictive formula for calculating the metabolic rate of load carriage around the torso, in the form of a backpack, only. Additional sources of error when applying this predictive equation to the EOD ensemble may be attributed to alterations in gait kinematics. Martin and Nelson (1986) identified an increase in walking speed results in greater flexion of the trunk and an increase in stride rate coupled with a simultaneous decrease in stride length and swing rate during backpack load carriage. As a result, alterations in an individual's preferential gait mechanics reduce the mechanical efficiency of motion (Cher, Stewart, and Worringham 2015, Donelan, Kram, and Kuo 2001). Greater metabolic rates observed when compared to the Pandolf equation at faster walking speeds (Figure 4b) may be a product of the relative thickness and cumbersome size of the PPC.

Although not recorded in the current study, the greater inefficiency (Dorman and Havenith 2005) may be related to an increased step width without corresponding lateral stabilisation of gait (Donelan et al. 2004). Whether or not these kinematic changes in load distribution, friction, drag and/or gait are augmented in the EOD ensemble and therefore responsible for the prediction error when applying the Pandolf equation is unclear and requires further biomechanical analysis. Additional research is also required to determine if the current findings are applicable to females, who in military occupations have identified poor fitting garments or body armour reducing comfort and restricting breathing (Harman et al. 1999, Knapik, Reynolds, and Harman 2004, Ling et al. 2004). Furthermore, the morphology of our recreationally trained sample may be more comparable to a military population rather than law enforcement (e.g. mining industry, police) as training standards and fitness status will differ between occupational settings utilising the EOD ensemble. There may be added value in measuring metabolic rate in EOD technicians working in different postures and ambient environments; and during tasks such as stair climbing, short distance running and carrying specialised

equipment (e.g. disruptor, x-ray machine). Quantifying the metabolic rate of upright standing in an EOD ensemble may have limited application as EOD technicians are more likely to be in a forward stooping posture or crouching position for the majority of their stationary work. Moreover, even though steady-state treadmill walking may not be a true reflection of all occupational tasks required of EOD technicians, it does provide a basis for metabolic rate of this unique protective ensemble. Therefore, the logical progression for any future research is in quantifying the metabolic rate of work during simulated occupational (EOD specific) tasks analogous to investigations of fire-fighters (Dreger and Petersen 2007, Elsner and Kolkhorst 2008, Holmer and Gavhed 2007). The failings in the original paper regarding the Pandolf equation to include the methodology used to develop their fitted equation and detail a range of error in the equation could explain the differences between our data and the prediction (Schertzer and Riemer 2014). However, it should be reiterated that the Pandolf equation evaluated in the current investigation, was used outside the modality of load carriage in which it was intended; specifically backpack loads.

CONCLUSION

This is the first study to quantify the metabolic rate of an EOD ensemble (>33 kg) across a range of workloads. The EOD ensemble increased metabolic rate by 49-78% (127 to 346 W) compared to the control condition during locomotion. This is considerably higher than that reported in other PPC ensembles at similar walking speeds, and is most likely related to the mass, friction and gait alterations when wearing the EOD garment. In addition, using a rigorous methodological design this study clearly demonstrates progressively erroneous estimations of metabolic rate, using the Pandolf equation, with increasing locomotive speeds while wearing EOD PPC. Consequently, predicting metabolic rate using the Pandolf equation for heavy, bulky PPC, such as the EOD ensemble, may not be accurate. Further development of this predictive equation, accounting for load distribution, movement restriction, friction, and altered gait mechanics when wearing EOD PPC is therefore warranted. These original findings have important practical implications for EOD technicians during training and operation scenarios and should be considered in the development of maximum workload duration models and work-rest schedules.

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