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**REVIEW**

# Protective clothing ensembles and physical employment standards[1]

Tom M. McLellan and George Havenith

**Abstract:** Physical employment standards (PESs) exist for certain occupational groups that also require the use of protective clothing ensembles (PCEs) during their normal work. This review addresses whether these current PESs appropriately incorporate the physiological burden associated with wearing PCEs during respective tasks. Metabolic heat production increases because of wearing PCE; this increase is greater than that because of simply the weight of the clothing and can vary 2-fold among individuals. This variation negates a simple adjustment to the PES for the effect of the clothing on metabolic rate. As a result, PES testing that only simulates the weight of the clothing and protective equipment does not adequately accommodate this effect. The physiological heat strain associated with the use of PCEs is also not addressed with current PESs. Typically the selection tests of a PES lasts less than 20 min, whereas the requirement for use of PCE in the workplace may approach 1 h before cooling strategies can be employed. One option that might be considered is to construct a heat stress test that requires new recruits and incumbents to work for a predetermined duration while exposed to a warm environmental temperature while wearing the PCE.

*Key words:* uncompensable heat stress, metabolic rate, aerobic fitness, body size, self-contained breathing apparatus, heat tolerance.

**Résumé :** Des normes physiques relatives à l'emploi (« PESs ») s'appliquent pour certains groupes professionnels qui doivent aussi porter un équipement de protection (« PCEs ») durant leur travail normal. Cette analyse documentaire vérifie si les PES prennent bien en compte le fardeau physiologique associé au port du PCE au cours des diverses tâches. La production de chaleur métabolique augmente à cause du port du PCE; cette augmentation est plus grande que celle attribuable au poids seul des vêtements et peut varier du double entre les individus. Cette variation annule la simple conformité aux PES en ce qui concerne les effets des vêtements sur l'activité métabolique. Par conséquent, l'évaluation des PES qui ne simulent que le poids des vêtements et de l'équipement de protection ne prend pas bien en compte cet effet. La contrainte physiologique associée au port des PCE n'est également pas prise en compte dans les PES actuelles. Typiquement, les tests de sélection en fonction des PES durent moins de 20 minutes alors que l'obligation du port du PCE dans le milieu de travail peut durer jusqu'à une heure avant qu'on utilise les stratégies de refroidissement. Une solution serait de développer un test de stress thermique durant lequel les recrues et les employés réguliers devraient travailler durant une période donnée tout en étant exposés à des conditions ambiantes chaudes et en portant le PCE. [Traduit par la Rédaction]

*Mots-clés :* stress thermique négligé, activité métabolique, capacité aérobie, gabarit, appareil respiratoire autonome, tolérance à la chaleur.

## Introduction

Physical employment standards (PESs) exist for certain public safety occupational groups, such as the military (Deakin et al. 1996, 2000; Todd Rogers et al. 2014), structural (Brandweer Nederland 2013; International Association of Fire Chiefs 1999; International Association of Firefighters 1999; Stevenson et al. 2009; Siddall et al. 2014) and wildland firefighters (Sharkey 1999; Petersen et al. 2010; Canadian Wildland Firefighter Fitness Testing 2012), nuclear security officers (Regulatory Document RD-363 2008), and police (Farenholtz and Rhodes 1990). These PESs typically require incumbents or new recruits to perform selection tests at least to the minimum acceptable performance level and/or perform a circuit of essential tasks of the job within a prescribed time. In some

countries the PESs were developed to accommodate the females and the older worker (Jamnik et al. 2013), whereas in others the PESs were established independent of age and sex (Tipton et al. 2013). For the military, wildland firefighters, and nuclear security officers the necessity to score at least to the minimum PES is a career requirement (Petersen et al. 2010; Canadian Wildland Firefighter Fitness Testing 2012; Deakin et al. 2000), whereas for other groups the PES is often used for new recruit selection only and is rarely used to reassess on an annual basis (Farenholtz and Rhodes 1990; International Association of Fire Chiefs 1999; International Association of Firefighters 1999).

For these occupational groups mentioned above, the use of a protective clothing ensemble (PCE) can be a daily requirement for the conduct of operations. For municipal fire services across North

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America, Australia, and several European countries, PESs either simulate the additional weight of the PCE (International Association of Fire Chiefs 1999; International Association of Firefighters 1999) or require the use of a PCE (Deakin et al. 1996; Dreger and Petersen 2007; vonHeimburg et al. 2013; Siddall et al. 2014) during testing. For military personnel not involved with fire suppression activity and for police services, PESs based on tests of fitness are deemed valid for selecting and retaining candidates that can handle the physical demands of the job safely and efficiently (Deakin et al. 2000; Anderson et al. 2001; Wilkinson et al. 2008). Small additional weights totaling approximately 5 kg are carried around the waist for Canadian wildland firefighters and police PES testing to simulate the burden of a utility belt for tools and equipment (Canadian Wildland Firefighter Fitness Testing 2012; Ministry of Community Safety and Correctional Services 2014).

Certainly it seems logical to include the need to wear the PCE during PES testing if the use of the clothing is a regular requirement in the work environment. It is far less clear, however, whether the physiological effects of using a PCE are entirely evident during circuit testing that might last only 8 min (Dreger and Petersen 2007; vonHeimburg et al. 2013) or whether simulating the additional load-bearing penalty of the PCE while completing a task-based circuit with a pass/fail threshold of 10 min and 20 s (International Association of Fire Chiefs 1999; International Association of Firefighters 1999) is a fair representation of the burden associated with wearing the PCE. Even less obvious is the apparent assumption that PES for other occupational groups, such as police, wildland firefighters, and the military (Deakin et al. 2000; Farenholtz and Rhodes 1990; Ministry of Community Safety and Correctional Services 2014), appropriately encompass the physiological burden and safety constraints associated with the use of a PCE during some work assignments.

The effects of protective clothing on heat transfer, as well as environmental, biophysical, and physiological factors that can affect heat storage and tolerance associated with the use of PCEs have been well characterized (Cheung et al. 2000; Havenith 1999; McLellan et al. 2013) and it is not the purpose of this review to restate these previous efforts. However, to overlay the use of PCE in the context of PESs it is necessary to briefly summarize the principal physiological constraints associated with wearing protective clothing. Once these issues are defined, an evaluation follows discussing current inclusion/exclusion criteria for use of a PCE during PES testing. This review then concludes with specific recommendations for additional evidence-based research that would improve the use of PES testing for various occupational groups that must wear a PCE.

## Protective clothing and metabolic rate

The characteristics of the PCE not only have a major impact on heat transfer between the individual wearing the clothing and the external environment but also have a large influence on the wearer's metabolic rate ($\dot{M}$). The clothing (and other protective equipment, such as respirators and a self-contained breathing apparatus (SCBA)) constitutes additional weight (from approximately 5 to 25 kg) that has to be carried and thus causes an increase in $\dot{M}$ and consequently in heat production (Goldman 1969; Smolander et al. 1984). However, more than half of the observed increase in $\dot{M}$ because of clothing can be attributed to other factors, such as increased friction of movement and hobbling effects of the clothing, rather than solely to the added weight of the PCE (Dorman and Havenith 2009; Duggan 1988; Patton et al. 1995; Teitlebaum and Goldman 1972). In addition, protective boots, for example, can have an impact on $\dot{M}$ that is greater than that because of simply their weight because of their effect on movement efficiency (see Taylor et al. 2016, in this special issue).

For example, Teitlebaum and Goldman (1972) observed an increase in $\dot{M}$ while wearing a 5-layer PCE that was 16% greater than

the energy cost associated with wearing a single-layer uniform while carrying the additional weight of the PCE around the waist in a weight belt. These differences were attributed to increased friction because of the interaction of the layers of clothing. Similarly, Duggan (1988) examined the effect of various combinations of the PCE on the energy cost of bench stepping. When corrected for the weight of the clothing, the oxygen uptake ($\dot{V}O_2$), as a measure of energy cost, was greater by an average of 9% in the 4-layer ensemble compared with the single-layer control condition, which equated to approximately 3% per additional layer above the base condition. Therefore, when estimating the energy cost of work in protective clothing, it is important to consider both the weight and the number of layers in the ensemble.

Dorman and Havenith (2007a, 2007b, 2007c, 2007d, 2007e, 2009) also demonstrated that the increase in $\dot{M}$ through the use of a PCE during stepping, walking, or throughout an obstacle course was attributed to more than just the additional weight of the clothing. As depicted in Fig. 1, some of the multilayer PCEs tested increased $\dot{M}$ by greater than 20% compared with the baseline single-layer uniform, despite only increasing the weight of the clothing by about 5 kg or 7% of body mass. Dorman and Havenith (2009) suggested an increase of 2.7% to 3% in metabolic rate and heat production per kilogram of clothing (Fig. 2), while the weight of the clothing alone would only result in a 1% increase per kilogram. This difference was attributed to the number of layers (Dorman and Havenith 2009), weight distribution across arms and limbs (Dorman and Havenith 2007a), friction between layers (Dorman and Havenith 2007b, 2007c), and to stiffness and bulk of the clothing (Dorman and Havenith 2007e). In addition, changes to the movement patterns when wearing PCEs were observed, with some workers consistently reducing their joint angle range of movement, while others exaggerated their movements and showed a larger joint angle in the movements tested (Dorman and Havenith 2007d), possibly explaining some of the inter-individual differences in metabolic rate increase because of PCE.

Another avenue through which PCE affects metabolic rate is through the faster and higher increase in body temperature it causes. Details of the mechanisms of this increase will be discussed later, but 1 impact of the higher body temperature is an extra increase in metabolic rate ($Q_{10}$ effect) of around 7% per degree Celsius body temperature increase (Kampmann and Bröde 2015). The $Q_{10}$ effect is independent to the numbers provided above by Dorman and Havenith (2009), where these latter values were obtained while ensuring body temperature showed only minimal increases.

Collectively, it is clear that the impact of the PCE on $\dot{M}$ is much greater than simply the load-carriage effect of the additional weight of the clothing. These data would argue strongly, therefore, that current PESs that only simulate the weight of the PCE during testing underestimate the impact of the clothing on metabolic demand by 15% or more. Interestingly, oxygen uptake ($\dot{V}O_2$) averaged 38 mL·kg$^{-1}$·min$^{-1}$ or approximately 75% maximal oxygen uptake ($\dot{V}O_{2max}$) for both men and women who completed and passed the task-based PES circuit used by many fire services in North America during recruit testing (Williams-Bell et al. 2009). If the true effect of wearing the clothing, rather than simply wearing a weighted vest, was actually 15% higher than these measured values, then the true metabolic demand of this task-based circuit would approach 45 mL·kg$^{-1}$·min$^{-1}$ or almost 90% $\dot{V}O_{2max}$ for the participants that were evaluated (Williams-Bell et al. 2009). Interestingly, this value of 45 mL·kg$^{-1}$·min$^{-1}$ was similar to the oxygen cost of carrying equipment up high-rise stairs while wearing full turnout gear with SCBA, which was the most physically demanding activity identified in the original task analysis and characterization of the physical demands of firefighting activities used to support early fitness screening protocols (Gledhill and Jamnik 1992).

Ultimately, the relevant question is whether the additional effect of clothing on the metabolic cost of movement necessitates

**Fig. 1.** The relative increase in metabolic rate for various protective clothing ensembles while walking (A), stepping (B), or completing an obstacle course (C). The asterisk indicates a significant increase above baseline control condition. (From Dorman and Havenith 2009, reproduced with permission of Eur. J. Appl. Physiol., Vol. 105, p. 469, © 2008 Springer.)
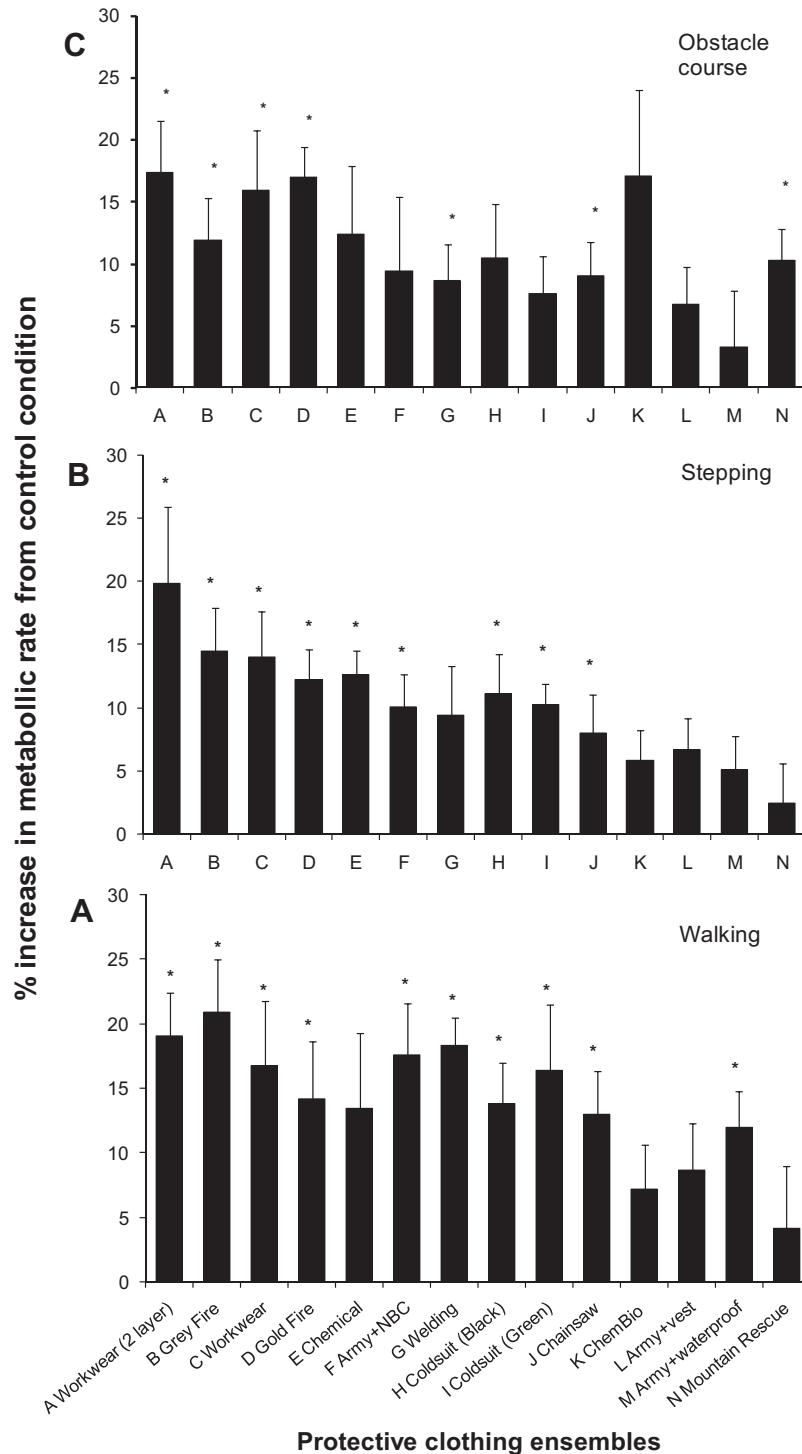


an adjustment to the use of this task-based PES for recruit selection. The answer should consider the individual variation associated with this increased metabolic cost of movement. For example, if the additional metabolic cost was constant for all individuals, then either the task-based pass/fail completion criterion could remain as it is without wearing the PCE or the completion criterion time could be adjusted proportionately to accommodate for the use of the clothing during testing. However, studies have shown that the additional metabolic cost of the clothing can vary among individuals by at least 2-fold (Dorman and Havenith 2009; Teitlebaum and Goldman 1972), possibly related to different movement strategies and efficiencies (Dorman and Havenith 2007d). Thus, failure to not recognize this additional, highly individual, effect of clothing during recruit testing or to simply apply the same adjustment to the pass/fail criterion for all participants would appear inappropriate. Additional research is needed to clarify those fac-

**Fig. 2.** Increase in metabolic rate during walking for a range of protective clothing ensemble in relation to participant weight without shoes. The theoretical and regression line for metabolic increase due to weight carried is reported for the presented data points. The letters A through N refer to various uniforms defined in Fig. 1. (From Dorman and Havenith 2009, reproduced with permission of Eur. J. Appl. Physiol., Vol. 105, p. 470, © 2008 Springer.)
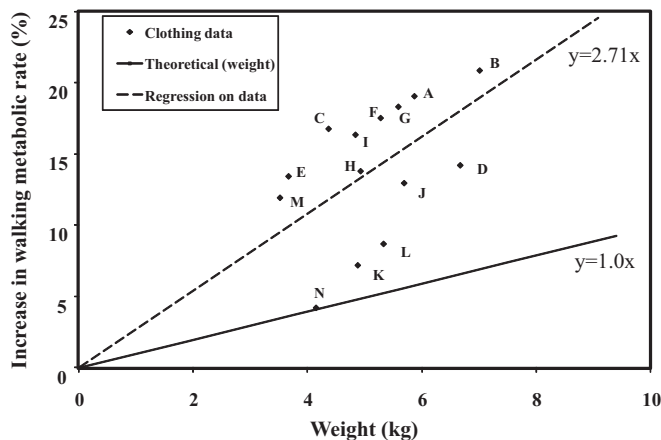


tors that create the variation among individuals in this additional metabolic penalty of wearing the PCE. Further, since some PESs were established to accommodate women and older incumbent personnel (Jamnik et al. 2013), research should focus on these subgroups. Even with sex- and age-free PESs, there is considerable individual variation with the performance of critical job tasks (Tipton et al. 2013). Certainly the impact of anthropometric factors on the fit of the clothing would seem relevant to consider as size and fit of clothing can have substantial effects on heat transfer through the PCE (Chen et al. 2004; Ueda et al. 2006; Wang et al. 2012). Havenith et al. (1990) observed for different work wear that tight clothing fit showed a 6%–31% lower insulation than loose fit. In addition, effects of fit on clothing friction and bulk can be expected, though no detailed research on this has taken place yet to our knowledge.

## Protective clothing and breathing apparatus

To confer protection from airborne hazards in the work environment, many occupations require the use of a breathing apparatus that either filters the inspired air to remove contaminants or require workers to breathe from a SCBA. Regardless of the type of respirator used there is an increase in both inspiratory and expiratory breathing resistance, which increases as flow rates increase to match metabolic demands (Butcher et al. 2006; Muza et al. 2002). At high flow rates, as required during heavy work, the increased breathing resistance could lead to respiratory muscle fatigue (Butcher et al. 2007). The use of the SCBA also decreases maximal exercise flow rates and $\dot{V}O_{2max}$ with 1 study reporting a 15% reduction in aerobic fitness solely because of the requirement to breathe through the regulator of the SCBA (Eves et al. 2005). The use of a multi-layered PCE together with the SCBA harness strapped around the chest further impedes the worker's ventilatory function accounting for approximately 20% of the total ventilatory impairment (Muza et al. 1996).

One might expect that occupational groups would include the requirement to breathe through a respirator during PES testing if their daily work environment requires the use of a respirator as part of their PCE. However, this does not appear to consistently be the case. Certainly in its present format the Candidate Physical Ability Test (International Association of Fire Chiefs 1999; International Association of Firefighters 1999) for firefighters only simulates the weight of the PCE, which includes the SCBA, but there is no re-

quirement to breathe from the respirator while performing the testing. In contrast, the PES developed for incumbent (but not recruit) Canadian military firefighters (Deakin et al. 1996; Todd Rogers et al. 2014) and testing used by many European countries (Brandweer Nederland 2013) require candidates to carry and breathe from the SCBA. If breathing from the SCBA reduces $\dot{V}O_{2max}$ by up to 15% (Eves et al. 2005), it would be logical to ask whether a candidate that barely meets the PES testing without the requirement to breathe from the SCBA would meet the PES determined while carrying and breathing from the SCBA. Certainly additional research that highlights this issue would be a valuable addition to PES testing for occupational groups that require the use of a breathing apparatus as part of their PCE.

## Protective clothing and heat storage

Protective clothing is designed to confer protection for individuals from the hazards of their workplace, which might include fire, smoke, chemical spills, biological agents, falling objects, explosives, and projectiles. To obtain the desired level of protection, therefore, the clothing may be relatively thick and/or have low air and water vapour permeability that limits the transfer of heat, liquid, and gas from the environment to the worker. At the same time, however, the clothing restricts the transfer of metabolic heat and water vapour produced by the evaporation of sweat from the body to the environment. As a consequence, the rate of body heat storage (*S*) will be greater when the PCE is used. The effect of wearing PCE on work performance can be substantial with reductions being 50% or greater compared with the wearing of normal work clothing (McLellan 1993; McLellan et al. 1993). Thickness and vapour permeability characteristics of specific PCEs are provided in detail by McLellan et al. (2013). Military biological and chemical protective clothing, for example, is almost twice as thick as the business attire established as the reference clothing and water vapour permeability is reduced by 35% (McLellan 2008).

The heat balance equation, shown below, represents the relationship between avenues for heat exchange between the body and the environment. The impact of clothing insulation ($I_T$) and clothing water vapour resistance ($R_{eT}$) on dry (radiation, convection, and conduction) and wet (evaporation from skin) heat transfer are also depicted in the heat balance equation:

$$\dot{S} = \dot{M} - \dot{W}_{ex} - (T_{sk} - T_a) \times I_T^{-1} - (P_{sk} - P_a) \times R_{eT}^{-1} - \dot{E}_{resp} - \dot{C}_{resp}$$

The rate of heat production ($\dot{M}$) will always represent a source of heat gain whereas wet heat transfer through evaporation at the skin (($P_{sk} - P_a$) × $R_{eT}^{-1}$) or through respiration ($\dot{E}_{resp}$) will generally represent an avenue of heat loss. Dry heat transfer depends on the temperature gradient between the ambient environment ($T_a$), the clothing, and the skin ($T_{sk}$) and can represent either an avenue of heat loss (if skin temperature exceeds the clothing and ambient temperatures) or heat gain (if ambient and clothing temperatures exceed skin temperature). In some special cases, e.g., of impermeable clothing, condensation of moisture may take place in the clothing and calculations become more complex. The reader is referred to specialist literature for this (Havenith et al. 2008, 2013). Convective heat transfer through respiration ($\dot{C}_{resp}$) is dependent on the temperature gradient between inspired and expired air and flow rates.

Under conditions where the requirement to dissipate metabolic heat from the body ($E_{req}$) exceeds the capacity of the environment to transfer this heat ($E_{max}$), uncompensable heat stress (UHS) is created where body heat storage and temperature continue to rise to individual limits of tolerance (Cheung et al. 2000; McLellan et al. 2013). The characteristics of the clothing and surrounding environment (temperature, vapour pressure, air speed, radiation) and the temperature and vapour pressure within the clothing determine $E_{max}$, whereas $\dot{M}$ and the temperature gradient between

**Fig. 3.** The relationship between tolerance time and metabolic rate when wearing a military nuclear, biological, and chemical protective clothing ensemble in different environmental conditions. The solid and dashed lines represent best-fit hyperbolic functions generated from individual tolerance times from a series of studies by McLellan and colleagues (McLellan et al. 1992, 1993, 1996) at temperatures from 30 °C–40 °C and ambient relative humidity (RH) from 15%–65%. (Reproduced with permission from © Her Majesty the Queen in Right of Canada, as represented by the Minister of National Defence, 2013, and Dr. T.M. McLellan of TM McLellan Research Inc.)
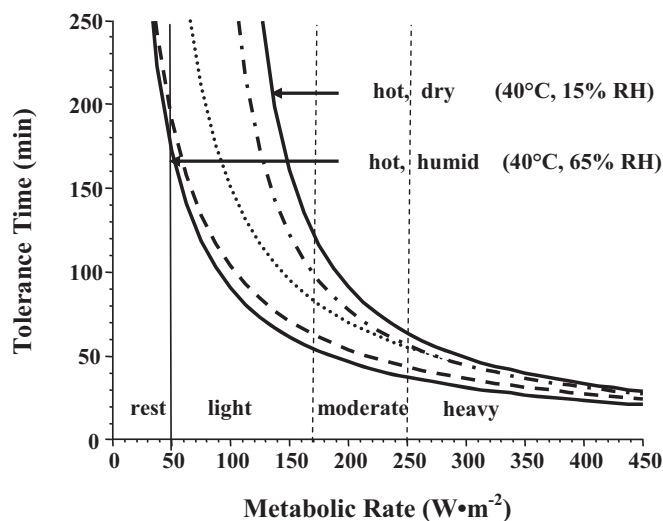


the skin and the environment are the primary determinants of $E_{req}$. The relationship between $\dot{M}$ and ambient temperature and vapour pressure on tolerance limits is shown in Fig. 3 for a military PCE. Ambient temperature and vapour pressure have far less impact on tolerance time as $\dot{M}$ increases since it takes time for the sweat that is secreted at the skin surface to be evaporated and move through the various clothing layers (McLellan et al. 1996). At metabolic rates above approximately 500 W (~ 250 W·m⁻²), the environmental temperature and vapour pressure have very little influence on the rate of heat storage when this military PCE is worn. In contrast, at lower rates of heat production the clothing barrier for evaporative heat transfer is eventually overcome and the resultant evaporative cooling (and tolerance time) becomes proportional to the vapour pressure gradient between the PCE and the environment allowing a balance to be achieved (McLellan et al. 1996).

The curves shown in Fig. 3 could also be used to explain the influence of changing thermal characteristics, or $R_{eT}$, of the PCE on tolerance. For example, if the clothing becomes thinner ($I_T$ decreases) or less resistant to water vapour transfer ($R_{eT}$ decreases), the curve would shift to the right. In contrast, with more layers or additional thickness of the PCE or an increased resistance to water vapour transfer, the curve would shift to the left. With totally impermeable clothing, such as used by hazmat workers (Beckett et al. 1986; Paull and Rosenthal 1987), the curve would be shifted far to the left, and the differentiation due to ambient relative humidity would be lost. Similarly, even within a given occupational group, such as firefighters, different countries may adopt different strategies for containing structural fires, which may increase (National Fire and Prevention Association 1500, 2013) or reduce (Australia/New Zealand Standard 4967, 2009) the thermal characteristics of the PCE that is worn.

In several occupational settings the requirement for protection from the hazards of the workplace has increased over recent years. For example, the need to provide protection from fragmen-

tation blast has necessitated the use of body armour that covers the torso, neck, arms, groin, and upper legs of soldiers (Larsen et al. 2011). Similarly, police routinely wear body armour over the torso (Dempsey et al. 2013) and may be required to don additional body armour to manage crowd control during periods of civil unrest or wear hazmat clothing during emergency response scenarios (Blacker et al. 2013). Although the armor confers additional protection, it creates an additional barrier to heat loss from the body (Caldwell et al. 2011). Another recent example is the fight against Ebola, which requires full body coverage of low permeable clothing. Used in warm, humid environments in West Africa, tolerance time for this type of protection while performing light intensity work is around 1 h only, requiring frequent personnel rotations and long recovery periods (Mèdecins Sans Frontieres, personal communication, Jan 2015).

Arguably, the risk of becoming a heat casualty because of the continued rise in body temperature during UHS is the greatest concern when individuals don the PCE, especially in hot environments or when $\dot{M}$ is high (Fig. 3). For structural firefighters this risk is evident in less than 60 min while conducting heavy work in their PCE and exposed to ambient temperatures at or above 25 °C (Selkirk and McLellan 2004). Yet the physical demand analyses that were used to generate the current PES for structural firefighters did not consider the impact of the heat strain of wearing PCE on the ability to conduct the job-related tasks in a safe and efficient manner (Jamnik et al. 2013). In the temperate Canadian climates environmental temperatures above 25 °C may only exist for a few months of the year. Yet for other regions of North America these ambient temperatures could occur anytime throughout the year. As a result, the added heat strain of wearing PCE could be a daily occurrence that would impact the manner that recruits or incumbents conduct job-related tasks. One option to manage this heat strain of wearing PCE is to develop specific work and rest guidelines, which has been done for firefighter (McLellan and Selkirk 2006) and military (Aoyagi et al. 1994) PCE. These guidelines, however, are based on mean responses generated from both sedentary and very active participants (Aoyagi et al. 1994; Selkirk and McLellan 2004) and may overestimate work times for the less aerobically fit individual. If the use of PCE is not a daily requirement of the workplace, such as with the military biological and chemical protective clothing, then the use of work and rest guidelines should suffice for managing the heat strain of wearing the clothing rather than constructing a unique PES that requires the use of PCE. In contrast, for occupational groups such as firefighters that require the use of PCE on a daily basis in warm or hot ambient temperatures, the PES could include an assessment of individual heat tolerance as discussed in more detail below.

## Protective clothing and aerobic fitness

Aerobic fitness is a key factor in understanding the individual variation to thermoregulation (Havenith and van Middendorp 1990; Havenith et al. 1995; Jay 2014). In addition, studies have shown that endurance-trained men and women, who are typically leaner than their untrained counterparts, can tolerate larger increases in body temperature during UHS (Cheung and McLellan 1998a; Selkirk and McLellan 2001; Selkirk et al. 2008). Even during passive heating at rest, endurance-trained individuals can tolerate greater increases in core temperature (Morrison et al. 2006). Regular aerobic exercise is accompanied by an expanded plasma volume, which confers greater protection from gut endotoxin leakage as thermal strain rises above 38.0 °C during UHS for endurance-trained individuals (Selkirk et al. 2008). In addition, a given absolute metabolic rate and thermal strain represent a lower relative strain for endurance-trained individuals, leading to lower heart rates and less redistribution of blood flow away from the gut (Selkirk et al. 2008), as well as lower neuroendocrine responses (Wright et al. 2010, 2012). Prolactin concentrations, a

**Table 1.** Aerobic capacity ($\dot{V}O_{2max}$) and core temperature ($T_c$) tolerated at exhaustion while wearing encapsulating clothing and exercising in a hot environment (40 °C and 30% relative humidity) for endurance-trained (engaged in regular aerobic training more than 3 times per week) or sedentary (not engaged in regular aerobic training) participants.

| $T_c$ ethical ceiling | Endurance trained | | | Sedentary | |
|---|---|---|---|---|---|
| | $\dot{V}O_{2max}$, mL·kg⁻¹·min⁻¹ | $T_c$, °C | | $\dot{V}O_{2max}$, mL·kg⁻¹·min⁻¹ | $T_c$, °C |
| 39.3 °C[a] | 60 (3); n = 8 | 39.2 (0.2)*,† | | 46 (3); n = 7 | 38.7 (0.3) |
| 39.5 °C[b] | 55 (5); n = 12 | 39.4 (0.2)*,† | | 44 (4); n = 12 | 38.7 (0.5) |
| 40.0 °C[c] | 62 (6); n = 12 | 39.7 (0.3)*,† | | 42 (3); n = 11 | 39.0 (0.3) |
| All studies | n = 32 | 39.4 (0.3)* | | n = 30 | 38.8 (0.4) |

**Note:** Values are means (SD).

*Significant difference between endurance trained and sedentary.

†Significant difference between other endurance trained $T_c$ values at exhaustion.

[a]Cheung and McLellan 1998a.

[b]Selkirk and McLellan 2001.

[c]Selkirk et al. 2008.

known marker of fatigue, are lower in endurance-trained individuals for a given level of thermal strain, yet similar at exhaustion despite the higher core temperature tolerated for endurance-trained individuals compared with sedentary individuals (Wright et al. 2012).

Current PESs for firefighters have established a minimum fitness level, which is deemed acceptable to meet the physical demands of the occupation (Deakin et al. 1996; International Association of Fire Chiefs 1999; International Association of Firefighters 1999; Siddall et al. 2014; Stevenson et al. 2009). The $\dot{V}O_2$ required to meet the 8–10-min pass criteria for these test circuits approximates 35–40 mL·kg⁻¹·min⁻¹ (Dreger and Petersen 2007; Williams-Bell et al. 2009), implying that an individual with a $\dot{V}O_{2max}$ of 45 mL·kg⁻¹·min⁻¹ should be able to meet this standard (McLellan and Skinner 1985). Although this level of aerobic fitness may be deemed acceptable to perform the physical tasks that represent firefighting, this may not be an acceptable level of fitness to reduce the risk of becoming a heat casualty while wearing PCE, especially if the requirement to remain encapsulated in the clothing exceeds 8–10 min. Core temperature limits are shown in Table 1 from a series of studies that compared the impact of aerobic fitness on thermotolerance while wearing a military PCE (Cheung and McLellan 1998a; Selkirk and McLellan 2001; Selkirk et al. 2008). Interestingly, the criteria for accepting a participant as "sedentary" was involvement in regular aerobic exercise not more than once per week and a $\dot{V}O_{2max}$ less than 50 mL·kg⁻¹·min⁻¹. This level of maximal aerobic fitness would appear adequate to meet the current PES for firefighters. However, it was clear from these studies that individuals who were not regularly active could not tolerate the same increase in core temperature as their more active counterpart and would be at an increased risk of succumbing to heat injury while wearing the PCE and performing their duties. As shown in Table 1, despite increases in the ethical ceiling for tolerable limits to the rise in core temperature during UHS, the maximal core temperature tolerated by sedentary participants did not change and averaged about 38.8 °C. In contrast, individual tolerable limits for those classified as endurance-trained continued to increase even as the ethical ceiling was raised to 40.0 °C. In fact in this latter study (Selkirk et al. 2008), 6 of 12 endurance trained volunteers reached the ethical ceiling and indicated they could have continued to perform in the PCE if this had been permitted and/or required.

Current work and rest schedules for the Toronto Fire Service (McLellan and Selkirk 2006) were established using 38.5 °C as the ceiling for the core temperature increase while wearing firefighting PCE. Higher limits of 39.0 °C were used to establish similar guidelines for personnel wearing military nuclear, biological, and chemical PCE (Aoyagi et al. 1994). In the latter case, the expecta-

tion was that these limits would be associated with a 5% heat casualty rate. For the data summarized in Table 1, only 2 of the 32 endurance trained participants, or 6%, ended their heat stress exposure while wearing the PCE at core temperatures below 39.0 °C. In contrast, the heat casualty rate would have increased to 60% for those classified as sedentary as 18 of 30 participants were unable to tolerate increases in core temperature to 39.0 °C. Yet all of these sedentary participants would have attained the military minimum PES for aerobic fitness of 32.6 mL·kg⁻¹·min⁻¹ (Deakin et al. 2000). Certainly with the more conservative limit used to establish guidelines for the Toronto Fire Service, heat casualty rates would be reduced. However, 30% of the sedentary participants were still unable to tolerate increases in core temperature to 38.5 °C. Approximately half of these individuals would also have been unable to meet the PES because of maximal fitness levels below 40 mL·kg⁻¹·min⁻¹. Therefore, it is conceivable that 15% of new firefighter recruits who meet the PES would be unable to perform their tasks while wearing the PCE for extended periods before succumbing to heat strain. Certainly the constraints of wearing PCE would not permit these recruits to perform their duties in a safe and efficient manner.

It would seem reasonable to expect that the fitness level of the new recruit should ensure not only their ability to conduct work-related tasks but also, just as importantly, their ability to tolerate the heat strain associated with wearing the PCE required by their employment. If the ability to tolerate a certain level of thermal strain in PCE became a requirement for the PES, then how would it be evaluated? Current PES task-based circuits that last 8–10 min (Deakin et al. 1996; International Association of Fire Chiefs 1999; International Association of Firefighters 1999) are not of sufficient duration to create this additional heat stress burden. Even longer ones, such as a 19-min test used in the Netherlands (Brandweer Nederland 2013) with various firefighting-specific components in PCE, are not considered to induce heat strain. One option might be to increase the minimum fitness level associated with the PES, since this should increase the core temperatures that could be tolerated before succumbing to heat injury (Cheung and McLellan 1998a; Selkirk and McLellan 2001; Selkirk et al. 2008). Alternatively, the duration of the PES testing could be increased to impose the additional heat stress burden of wearing the PCE on the candidates (though this would require a certain level of climate control during the test for standardization of conditions) or an additional component could be added to the PES testing specifically for the purpose of inducing this heat stress burden. This additional component to the current PES testing might be more reasonable to expect only for those jurisdictions where UHS conditions could occur more frequently throughout the year rather than in areas where such conditions might only exist during the summer months. However, firefighting doctrine (fighting fires mainly from outside buildings or having building entry as a regular component) may also affect exposure frequency and strain levels and should be considered in deciding on relevance of such an added heat stress test. If this option were considered then core temperature measurement should be included as part of the PES testing procedures to document that the candidate can endure the increase in heat strain that might be typical with the use of their PCE. The specific details of a heat stress test would require input from the firefighting community and scientists to determine the expected work intensity, exposure duration, and climatic conditions; the latter would require access to a climatic chamber and the costs associated with this requirement may be deemed too excessive to implement this additional heat tolerance component within the PES testing. Nevertheless, those occupational groups that require the use of PCE on a regular basis (i.e., firefighters) or during specialized operations (bomb-disposal or hazmat teams) need to realize that current PES testing does not adequately assess the associated heat strain of wearing PCE together with the increased risk of becoming a heat casualty. Further, many fire ser-

**Table 2.** The effect of load carriage on maximal aerobic capacity ($\dot{V}O_{2max}$) for a larger (100 kg) and smaller (65 kg) individual.

| Body mass, kg | $\dot{V}O_{2max}$, mL·kg$^{-1}_{bm}$·min$^{-1}$ | $\dot{V}O_{2max}$, mL·min$^{-1}$ | Clothing and equipment, kg | Total mass, kg | $\dot{V}O_{2max}$, mL·kg$^{-1}_{tot}$·min$^{-1}$ | $\dot{V}O_{2max}$, equivalent | $\dot{V}O_{2max}$, required, mL·kg$^{-1}_{bm}$·min$^{-1}$ |
|---|---|---|---|---|---|---|---|
| 100 | 45 | 4500 | 23 | 123 | 36.6 | — | 45 |
| 65 | 45 | 2925 | 23 | 88 | 33.2 | 36.6 | 49.6 |

**Note:** Body mass (bm), total mass carried (tot).

vices do not require incumbent PES testing and because of changing fitness levels during their careers these firefighters may be at increased risk of becoming a heat casualty during operations. This reluctance to continue an annual reassessment of PES needs to be reexamined.

If the option of a heat tolerance test is pursued, what might the requirements be? Currently, the Israeli Defence Force has implemented a heat tolerance test, which assists medical decisions regarding return-to-work for soldiers who previously succumbed to heat stroke during operations (Moran et al. 2004, 2007). The test requires that both heart rate and core temperature responses during 2 h of exercise in a hot environment do not exceed certain thresholds. However, there have been criticisms about the use of this test as a "heat tolerance" test. For example, there are no comparative records from those experiencing heat stroke prior to becoming a heat casualty and no indication that someone who fails the test may have also failed or even passed the test prior to experiencing heat stroke (O'Connor et al. 2010). Further, the test really does not assess "tolerance" as the cardiovascular and core temperature responses represent a compensable or plateau response to the exercise and heat stress. Those that are identified as "intolerant" have a lower level of aerobic fitness and higher body fatness (Lisman et al. 2014), and many would probably not be successful during the current PES testing. Instead, the heat tolerance test should create an uncompensable condition, which is more typically associated with wearing PCE, where core temperature and heart rate would continue to increase with continued exposure to the exercise and hot conditions. To be more applicable to the needs of structural firefighting, a heat tolerance test might last 50 min, or the equivalent air supply in a large SCBA or 2 smaller air cylinders, since typically firefighters then proceed to a rehabilitation station where active cooling options are available (for review see McLellan and Selkirk 2006).

Some of the public safety occupational groups offer "de facto" accommodation, such as familiarization to the PES testing and 6-week physical training programs, which have increased success rates during testing for recruits (Jamnik et al. 2013). Similar short-term aerobic training programs and/or acclimation to the hot/wet microenvironment of the PCE have not proven overly successful for improving heat tolerance while the clothing is worn (Cheung and McLellan 1998b, 1999; McLellan and Aoyagi 1996). Since there is a rapid plasma volume expansion during the first few days of an aerobic exercise program (Green et al. 1987), it is likely that other factors, which require longer periods of adaptation, are important to account for the differences in heat tolerance between endurance trained and untrained (Selkirk et al. 2008).

## Protective clothing equipment, load carriage, and aerobic fitness

An entire chapter within this series is devoted to the impact of load carriage for PESs and the reader is directed to this work for greater detail on this topic (Taylor et al. 2016). In addition, however, there are issues that are directly relevant when PCE is worn together with the requirement to carry additional loads. For example, although current PES testing for firefighters require candidates to carry the weight of the clothing and equipment routinely used in the workplace, it is important to realize that it is an absolute load of approximately 23 kg that is used for all candidates (Deakin et al. 1996; International Association of Fire Chiefs

1999; International Association of Firefighters 1999). This absolute load, however, represents a different relative weight-bearing penalty that is dependent on body mass. For example, this load represents an additional 23% penalty for a larger 100-kg candidate but a far greater penalty of 35% or more for smaller candidates that might weigh 65 kg or less. The smaller individual, therefore, must be more aerobically fit than their larger counterpart to meet the PES while wearing or carrying the equivalent weight of the PCE. This effect is outlined below in Table 2, where it shows that the smaller individual requires a maximal aerobic fitness closer to 50 mL·kg$^{-1}$·min$^{-1}$ rather than 45 mL·kg$^{-1}$·min$^{-1}$ to perform equally to the larger individual while carrying this additional weight of the clothing and equipment. It is important for the reader to understand that the oxygen cost of performing the circuit-based tasks used for PES testing of firefighters was normalized to the body mass of participants and reported as 35–40 mL·kg$^{-1}$·min$^{-1}$ (Dreger and Petersen 2007; Williams-Bell et al. 2009). These values were not expressed relative to the total weight that was carried, which includes the additional 23 kg of clothing and equipment. The absolute oxygen cost of weight-bearing activity is determined by the total weight carried, which should include the body mass together with any clothing worn and equipment carried.

Although the smaller individual must be more aerobically fit to accommodate the additional weight of the PCE and meet the PES, this increased fitness is associated with other advantages while performing their duties. As mentioned above, the higher aerobic fitness should reduce their risk of succumbing to heat injury while wearing the clothing because of higher core temperatures that can be tolerated (Cheung and McLellan 1998a; Selkirk and McLellan 2001; Selkirk et al. 2008). Further, higher levels of aerobic fitness are typically associated with reduced levels of body fatness, which will slow the rate of increase in core temperature for any given rate of heat production (Selkirk and McLellan 2001) because of the higher specific heat of lean versus adipose tissue (Gephart and Dubois 1915).

Air demand from the SCBA also will be reduced for the smaller individual, allowing them to perform their duties for longer periods of time before the requirement for air resupply. This was highlighted with actual measurement of air demand from the SCBA for incumbent firefighters during a simulated high-rise ascent to perform search and rescue (Williams-Bell et al. 2010a) as well as a search and rescue scenario in a smoke-filled subway (Williams-Bell et al. 2010b). In both of these studies air demand was positively correlated to body mass. Only 6 of 36 firefighters (33 men and 3 women) were able to ascend 23 floors without activating their low-air alarm on the SCBA (Williams-Bell et al. 2010a) and one of these was a 60-kg female (F.M. Williams-Bell, personal communication). Similarly, in the original testing completed for the Toronto Fire Service to establish work limits while wearing the PCE (Selkirk and McLellan 2004), 4 female incumbent firefighters were recruited since 10% of the Fire Service were women and 40 participants were tested. Two of these women had a body mass below 65 kg but maximal aerobic fitness levels exceeded 55 mL·kg$^{-1}$·min$^{-1}$, whereas the values varied from a low of 42 to over 65 mL·kg$^{-1}$·min$^{-1}$ for the male participants.

The reader should be convinced that the smaller individual, regardless of sex, must possess a higher aerobic fitness to meet the minimum requirement for any PES that imposes an absolute weight-bearing penalty to represent the PCE. We do not see this as

being biased or unfair but instead would argue that the smaller individual who passes the PES would actually fair better than their larger counterpart when PCE is worn. These differences would be evident with their greater thermotolerance with the heat strain of wearing the clothing, as well as a reduced air demand and work of breathing if job requirements include the use of SCBA.

## Recommendations for additional evidence-based research

The discussion above identified the following research topics that would assist in future development of PESs that involve wearing a PCE:

1. An assessment of the anthropometric factors that account for the individual variation in the load-bearing penalty of wearing different PCEs, while giving special attention to sex and age in this analysis.
2. Determine whether the burden of wearing PCE together with the requirement to breathe through a SCBA impacts the success and failure rates for PES testing that only simulates the weight of the PCE.
3. Consider developing an evidence-base to establish whether different PESs for a given occupational group, i.e., structural firefighting, produce similar distributions of failure and success.
4. Establishing a heat-tolerance test that encompasses wearing the PCE while conducting the physical demands of the occupation.
5. Identify the trade-off between body size and aerobic fitness as it pertains to the load-carriage penalty of using various PCEs. This is especially relevant for those occupational safety groups, such as explosive ordnance disposal personnel, where the PCE could weigh in excess of 50 kg. In other words, should there be a minimum absolute, rather than relative, maximal aerobic fitness to accommodate the load-bearing penalty.

## Recommendations for revised PES with the use of PCE

It should be apparent that donning a PCE creates unique physiological constraints that cannot be simulated simply by carrying the equivalent load during PES testing. As a result, we would argue that the PES testing used by many Fire Service in North America (International Association of Fire Chiefs 1999; International Association of Firefighters 1999) needs to change to accommodate the donning of the PCE similar to the way PCE is incorporated in the PES in several European countries (vonHeimburg et al. 2013) and Canadian military firefighters (Dreger and Petersen 2007; Todd Rogers et al. 2014). The use of the SCBA during PES testing should also be considered since this imposes limitations on aerobic power (Eves et al. 2005). It is also critical to identify those factors that influence the individual variation in the physiological penalty associated with wearing the PCE. Although the larger individual might tolerate the load-bearing penalty of the PCE more easily (Table 2), their heat tolerance may be reduced compared with their smaller counterparts who must have a higher aerobic fitness to accommodate the load. Thus, to continue to perform their duties during their careers, the smaller individuals might actually have to maintain a higher level of aerobic fitness. In contrast, the larger incumbent firefighter, although being able to accommodate the load-bearing penalty of the PCE, may actually be at greater risk of succumbing to heat injury while wearing the protective clothing.

We would also recommend that a unique heat-tolerance test be developed that could be used in certain jurisdictions where there is an ongoing risk of UHS when PCE is worn on a regular basis or during specialized operations as part of the job requirement. This heat-tolerance test would be assessed separately within the hybrid PES model, just as aerobic fitness is assessed independently from the applicant's ability to perform job-related tasks for some occupational groups (Jamnik et al. 2013).

There are also certain public safety occupational subgroups where PESs have not been developed, yet the physiological strain of wearing a PCE is very high, such as occurs with the use of a bomb-disposal suit or impermeable chemical protective clothing. Typically the individuals that wear these PCEs are selected from the incumbent ranks of the military, police, or firefighters. However, it could be argued that the additional physiological burden of wearing these specific PCEs require unique adjustments to the PESs for incumbent personnel chosen to perform the job-related tasks.

## Summary and conclusions

Many public safety occupational groups require the use of PCEs on a regular basis, yet some PES testing does not justly represent the physiological burden associated with the use of the clothing. Testing that only simulates the load-bearing penalty of the PCE (International Association of Fire Chiefs 1999; International Association of Firefighters 1999) underestimates the increase in metabolic demand. A single adjustment factor within the PES to accommodate this limitation would not seem appropriate given the large individual variation associated with this penalty (Dorman and Havenith 2009). In addition, job-related testing circuits that last about 10 min (Deakin et al. 1996; International Association of Fire Chiefs 1999; International Association of Firefighters 1999) are not of sufficient duration to create the heat-stress burden of donning the PCE. As a result, the development of a unique stand-alone heat-tolerance test should be considered and incorporated into existing hybrid model PESs, especially for those jurisdictions where UHS conditions could exist on a regular occurrence.

### Conflict of interest statement

The authors declare that they have no conflict of interest.

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