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Load carriage, human performance, and employment standards

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Abstract

The focus of this review is on the physiological considerations necessary for developing employment standards within occupations that have a heavy reliance on load carriage. Employees within military, fire fighting, law enforcement, and search and rescue occupations regularly work with heavy loads. For example, soldiers often carry loads >50 kg, whilst structural firefighters wear 20-25 kg of protective clothing and equipment, in addition to carrying external loads. It has long been known that heavy loads modify gait, mobility, metabolic rate, and efficiency, while concurrently elevating the risk of muscle fatigue and injury. In addition, load carriage often occurs within environmentally stressful conditions, with protective ensembles adding to the thermal burden of the workplace. Indeed, physiological strain relates not just to the mass and dimensions of carried objects, but to how those loads are positioned on and around the body. Yet heavy loads must be borne by men and women of varying body size, and with the expectation that operational capability will not be impinged. This presents a recruitment conundrum. How do employers identify capable and injury-resistant individuals while simultaneously avoiding discriminatory selection practices? In this communication, the relevant metabolic, cardiopulmonary, and thermoregulatory consequences of loaded work are reviewed, along with concomitant impediments to physical endurance and mobility. Also emphasised is the importance of including occupation-specific clothing, protective equipment, and loads during work-performance testing. Finally, recommendations are presented for how to address these issues when evaluating readiness for duty.

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Load carriage, human performance, and employment standards¹

Nigel A.S. Taylor, Gregory E. Peoples, and Stewart R. Petersen

Abstract: The focus of this review is on the physiological considerations necessary for developing employment standards within occupations that have a heavy reliance on load carriage. Employees within military, fire fighting, law enforcement, and search and rescue occupations regularly work with heavy loads. For example, soldiers often carry loads >50 kg, whilst structural firefighters wear 20–25 kg of protective clothing and equipment, in addition to carrying external loads. It has long been known that heavy loads modify gait, mobility, metabolic rate, and efficiency, while concurrently elevating the risk of muscle fatigue and injury. In addition, load carriage often occurs within environmentally stressful conditions, with protective ensembles adding to the thermal burden of the workplace. Indeed, physiological strain relates not just to the mass and dimensions of carried objects, but to how those loads are positioned on and around the body. Yet heavy loads must be borne by men and women of varying body size, and with the expectation that operational capability will not be impinged. This presents a recruitment conundrum. How do employers identify capable and injury-resistant individuals while simultaneously avoiding discriminatory selection practices? In this communication, the relevant metabolic, cardiopulmonary, and thermoregulatory consequences of loaded work are reviewed, along with concomitant impediments to physical endurance and mobility. Also emphasised is the importance of including occupation-specific clothing, protective equipment, and loads during work-performance testing. Finally, recommendations are presented for how to address these issues when evaluating readiness for duty.

Key words: backpacks, firefighter, load carriage, oxygen cost, military, employment standards, ventilation, work of breathing.

Résumé : Cette analyse documentaire traite principalement des aspects physiologiques essentiels à l'élaboration de normes d'emploi pour des postes dont la fonction majeure est le transport de charges. Les employés dans l'armée, les pompiers, la police, les membres de recherche et sauvetage travaillent régulièrement avec de lourdes charges. Par exemple, les soldats transportent souvent des charges de >50 kg et les pompiers de bâtiments portent un vêtement de protection pesant de 20 à 25 kg et déplacent aussi des charges externes. On sait depuis longtemps que le port de charges lourdes modifie la démarche, la mobilité, le taux métabolique et le rendement tout en augmentant le risque de fatigue musculaire et de blessure. De plus, le déplacement des charges est effectué fréquemment dans des conditions environnementales stressantes et les vêtements de protection accroissent la charge thermique dans cet endroit. En outre, la contrainte physiologique ne dépend pas seulement de la masse et des dimensions des objets à déplacer, mais aussi de leur positionnement sur et autour du corps. Pourtant, il faut que ces charges soient déplacées par des hommes et des femmes de gabarit divers dont les capacités opérationnelles ne seront pas dépassées. Le recrutement devient donc problématique. Comment est-ce que les employeurs identifient les individus aptes et à l'abri des blessures sans adopter des pratiques discriminatoires? Dans cette présentation, on analyse les conséquences métaboliques, cardiopulmonaires et thermorégulatrices pertinentes du travail avec des charges et on identifie les entraves à l'endurance physique et à la mobilité. On insiste aussi sur l'importance d'avoir des vêtements conçus pour la tâche, un équipement de protection et des charges pour l'évaluation du travail et de la performance. En dernier lieu, on présente des recommandations pour prendre en compte ces aspects au moment d'évaluer si l'individu possède les aptitudes pour la tâche. [Traduit par la Rédaction]

Mots-clés : sac à dos à armature, pompier, transport de charge, coût d'oxygène, militaire, normes de travail, ventilation, travail de la respiration.

Introduction

The identification and recruitment of a highly capable and injury-resistant workforce is a long-held expectation of both emergency-service (public safety) and defence organisations. However, those obligations must be balanced against the avoidance of inappropriately discriminatory selection practices (Shephard 1991; Jamnik et al. 2013; Tipton et al. 2013; Adams 2016), and with an understanding that the burden of accommodation should neither be unreason-

able nor impose undue hardships on employers (Hatfield 2005; Canadian Human Rights Commission 2007; Adams 2016). For occupations in which there is a requirement to routinely carry loads, these considerations take on another dimension, and so the emphasis of this communication is on the physiological challenges accompanying load carriage, and how these can influence work performance and the derivation of employment standards, screening (barrier) tests, and the necessary performance levels on those tests to

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Fig. 1. An historical summary of loads carried by soldiers from the ancient Assyrians through to those engaged in contemporary conflicts. Data are for dry masses only, and are modified from Orr (2010) with permission of Aust. Army J., vol. 7, © 2010 Commonwealth of Australia.

satisfactorily fulfil the requirements of various jobs. Nevertheless, regardless of how they are configured, carried loads may indefinitely remain a compromise between that which is operationally critical and that with the least adverse physiological impact (Renbourn 1954c).

In this paper, the terminology of Rogers et al. (2014) will be followed. That is, an *employment standard* is a conceptual understanding of the attributes that recruits or incumbents must possess to perform the essential work safely and effectively. In the current context, those attributes are primarily physiological in nature (e.g., aerobic fitness, muscle strength, and power). When screening tests are developed to assess those attributes, *cut-scores* are used to distinguish between acceptable and unacceptable test performance with respect to the employment standard.

Historical considerations

Perhaps the most detailed historical records of load carriage are those associated with the military, and whilst reviewing those records is best left to others (Lothian, 1921a, 1921b, 1921c; Carre 1952; Renbourn 1954a, 1954b, 1954c; Knapik et al. 1996, 2004; Orr 2010), there is a sound teleological basis for revisiting some key observations. Indeed, the problems that arise during geopolitical conflicts, such as the supply of essential support materials and equipment, often drive research.

The first, and most striking, issue is the size of the carried loads. Lothian (1921a, 1921b, 1921c, 1922), Knapik et al. (1996, 2004), and Orr (2010) have reviewed historical evidence on the size of loads carried by soldiers. Extracted from the last source is a selection of those loads (Fig. 1), which, prior to the 1980s, averaged about 30 kg. With greater levels of equipment sophistication and its mobilisation, came greater demands on the ability of soldiers to carry loads. Thus, over the last 30 years, those loads have increased by more than 50%, averaging almost 50 kg across the last three international conflicts (Fig. 1). Of course, the carried mass will always be mission-specific, increasing as soldiers move from assault dress through to combat, and eventually to marching order clothing and equipment configu-

rations (Haisman 1988). These all represent protracted load-carriage activities, the duration of which typically decreases as the load rises.

There are many examples of significant load carriage beyond the military context. A familiar public-safety occupation is fire fighting, which typically involves short-duration tasks, but often includes stair climbing. For example, the contemporary urban firefighter will, in addition to personal protective clothing (~4.5 kg), wear several items of protective equipment: boots (~2.5 kg), helmet (~1.4 kg), self-contained breathing apparatus (~12 kg), radio (~1 kg), and other incident-related equipment (Taylor et al. 2015b). Thus, even before commencing work, the firefighter is loaded with about 20 kg of protective equipment. For smaller individuals, this load may represent about 40% of their body mass. Since wildfire (Ruby et al. 2003) and some urban fire fighting incidents (Taylor et al. 2015a, 2015b) require significant physical endurance, firefighters are often forced to bear those loads for extended durations.

The second feature of Fig. 1 is that those data present median values taken from reported and estimated load ranges. As such, the more extreme loads (70 kg) carried by military personnel (Lothian 1922; Cathcart et al. 1923; Givoni and Goldman 1971; Orr 2010), not necessarily routinely, but certainly not rarely, remain hidden. Those loads can equal, and even exceed, the mass of some soldiers. Such loads are often related to the equipment used by specialised personnel within armed units, and they have obvious implications for recruitment and selection standards because, whilst the load itself remains constant, its physiological impact depends upon the size of the person bearing the load.

In fire fighting, additional loads are also incident related. For instance, when attending motor-vehicle accidents and rescuing trapped occupants, firefighters will use hydraulic cutting and spreading tools (~20 kg), and these must be operated and held stable across a range of planes from above shoulder height to below the knees. This work requires significant upper body strength and local muscle endurance (Taylor et al. 2015b).

Unfortunately, one often observes that, as technological advances reduce the mass of some carried items and render others obsolete, the overall carried load remains relatively constant. This truism has been applied across the centuries for soldiers (Fig. 1), and it may also be applied to the loads carried within civilian occupations. As Orr (2010) has suggested, this outcome seems to have resulted more from managerial decisions than it has from recommendations made by those who must endure the added burden. One might also assume that such decisions were not always made with an adequate recognition of the fact that protective equipment and loads often represent a compromise between sustaining operational integrity and minimising the physiological impact of, and the hazards associated with, load carriage (Taylor 2015). With the ever-increasing desire for employee diversification across many industries, managers must now also recognise, when seeking to give opportunities to a wider range of people, including those with lower capabilities, that they must not place those individuals under a significantly greater physiological encumbrance. Instead, the physiological demands of the critical tasks must determine selection. Therefore, these load-carriage decisions come with legal implications, and the physiological bases of those implications are defined in the next section.

Physiological impact of load carriage

A complete treatise covering the impingement of load carriage on physiological function goes beyond both the brief of, and the size restriction that applies to, this contribution. Readers are instead referred to the historical literature (e.g., Parkes 1866; Munson 1901; Cathcart et al. 1923), and to the more contemporary manuscripts of Haisman (1988), Knapik et al. (1996, 2004), Stevenson et al. (2004), and Epstein et al. (2013). Herein, attention is focussed upon those outcomes that are likely to influence whole-body metabolic rate, cardio-respiratory function, and thermal strain. These effects have a direct impact on the development of fair and equitable employment standards. Moreover, in physically demanding occupations, especially public-safety jobs (e.g., police and firefighters), load carriage is common and often essential. Nevertheless, pre-employment endurance testing is frequently evaluated in the absence of occupationally relevant load carriage. Consequently, there is some risk that inferences of readiness for duty drawn from such unloaded tests may be incorrect. Several topics not included here (e.g., muscle strain and ageing) are covered either in the accompanying communications or within the literature (e.g., Fallowfield et al. 2012; Hadid et al. 2012; Roy et al. 2012).

Metabolic cost

There is little doubt that load carriage increases physiological strain at any given intensity, and it diminishes the capacity for performing external work during near-maximal exercise. Simply put, some fraction of the available energy (or energy reserve) must be allocated to the support and movement of loads added to the body. Logically, the greater the mass of that load, the larger will be the fraction of the available energy pool assigned to load carriage. Consequently, less energy is available for locomotion.

Following that reasoning, the energy cost of locomotion will be higher when loaded, and the markers of physiological strain will be higher, although the utility of cardiorespiratory variables as predictive metabolic surrogates is limited within occupational settings (Notley et al. 2014a, 2015b). Conversely, an unloaded individual can accomplish substantially more external work. However, the impact of any load is not just a function of its mass, but its dimensions and distribution around the body. In this section, the ways that load carriage influences the metabolic requirements of work will be examined.

Intensity dependency of endurance standards

The metabolic cost of any task is linked to the intensity with which that task is performed, and this, in turn, will determine the tolerable work duration. Whilst these facts translate to all forms of work, they can often be overlooked. If that occurs within occu-

Fig. 2. The body-mass dependent nature of the oxygen cost of steady-state, treadmill walking (A; 4.8 km·h⁻¹) and bench stepping in an air-conditioned laboratory (B; 20 cm at 40 steps·min⁻¹). For each exercise mode, data are from 20 adults chosen to provide a wide range in body sizes (10 males, 10 females (body-mass range 53.7–91.7 kg)). Every person completed three trials, each with a different load: control (running shoes, shorts, t-shirt), control clothing plus self-contained breathing apparatus (11.3 kg), and wearing the complete personal protective clothing and equipment worn by firefighters (average added mass 19.8 kg). The stepping cadence was set to match the cardiovascular strain elicited during walking. For each condition, least-squares, best-fit linear regression lines ($r^2 = 0.800$ and 0.828 for A and B, respectively; 95% confidence intervals are represented as dashed lines) have been overlaid to describe the overall relationship. Data were extracted from the raw data of Taylor et al. (2012; with permission of Eur. J. Appl. Physiol., vol. 112, © 2011 Springer).

pational research upon which an endurance fitness cut-score will ultimately be set, then it will introduce an unacceptable bias (Tipton et al. 2013), paving the way for litigation (Jammik et al. 2013). Therefore, when defining the metabolic cost of occupational tasks, one must ensure that each task is performed by trained personnel wearing the full complement of contemporary personal protective clothing and equipment, and over operationally relevant distances, speeds, and terrains (Tipton et al. 2013; Taylor et al. 2015b). Moreover, it is critical that the work intensity investigated reflects the acceptable work rate necessary to complete work tasks to the satisfaction of the organisation in question (Tipton et al. 2013; Rogers et al. 2014).

Body-size dependency

The absolute oxygen consumption of constant-velocity walking and bench stepping increases as a linear function of body mass,

Fig. 3. The proportional impact of carried loads. Data are from steady-state walking (circles, $N = 20$) and bench-stepping trials (triangles, $N = 20$) conducted in each of two loaded states: control clothing (running shoes, shorts, t-shirt) plus self-contained breathing apparatus (11.3 kg; open symbols) and wearing the complete personal protective clothing and equipment worn by firefighters (average added mass 19.8 kg; filled symbols). Each point is a relationship coordinate (oxygen consumption versus overall mass) for the person-specific ratio of the value measured in each loaded state to that obtained from the same activity performed without a load (control clothing). These data were taken from Taylor et al. (2012; with permission of Eur. J. Appl. Physiol., vol. 112, © 2011 Springer) and the lines show the least-squares, best-fit linear regression with 95% confidence intervals (dashed; $r^2 = 0.722$). To help reveal the mass-dependent nature of this relationship, two individuals are identified (semi-nude body mass); the lightest person within the more heavily loaded trial (filled symbols), and heaviest subject within the lighter trial (open symbols).

including protective clothing, equipment, and added loads (Fig. 2). This first principle applies to all ambulatory activities for which this total mass is supported by the legs (Cathcart et al. 1923; Mahadeva et al. 1953; Goldman and Lampietro 1962; Workman and Armstrong 1963; Givoni and Goldman 1971; van der Walt and Wyndham 1973; Soule et al. 1978). The sensitivity (slope) of this relationship varies across studies, and is a function of movement velocity, stride length, gradient, and terrain (Pandolf et al. 1976, 1977; Soule et al. 1978; Pimental and Pandolf 1979; Koerhuis et al. 2009). For the ideal conditions illustrated in Fig. 2, however, the sensitivity was about 17 mL of additional oxygen consumed for each additional kilogram ($r^2 = 0.83$ (walking) and $r^2 = 0.80$ (bench stepping)), although these regression lines did not pass through zero (ordinate intercepts: Fig. 2A: -0.28 ; Fig. 2B: -0.13) and must therefore contain some, albeit very slight, mass bias (Packard and Boardman 1999). Thus, carrying a 50-kg pack, which is not an unusually heavy military load (Knapik et al. 2004; Orr 2010), elevates the average oxygen cost of route marching on a flat, hard surface by about 850 mL for every minute marched. However, this generalisation summarises the group response, and does not reflect the impact of loads on all individuals.

When carrying the same fixed mass at an equivalent velocity, smaller individuals work at a greater metabolic rate than their larger counterparts. This too is a first principle, perhaps first demonstrated by Taylor et al. (1980) across a range of species, including humans. Those investigators found that, when expressed as ratios between the loaded and unloaded states, the corresponding increase in the absolute oxygen cost of load carriage was proportional to the change in the load. This is illustrated in Fig. 3 using

data reported in Fig. 2, with the heaviest subjects clustered at the bottom left and the lightest towards the upper right within each loaded state. When analysed this way, the average quotient of these ratios was 1.04 across two different loaded states during both constant-velocity walking and bench stepping. Whilst this overall outcome is remarkably consistent with the observations of Taylor et al. (1980), it is evident from Fig. 3 that the regression line is steeper than the line of identity. That is, within both activities, the quotient of these ratios appeared to be systematically greater when more load was added: walking 0.97 (11.3 kg, standard deviation (SD) 0.04) versus 1.15 (19.8 kg, SD 0.08, $P < 0.05$), and bench stepping 0.97 (SD 0.05) versus 1.07 (SD 0.08, respectively; $P < 0.05$).

From these observations, it is clear that it is not just the absolute mass of the load that matters (Fig. 2), it is how that load influences each individual. It follows from Fig. 3 that the impact of any fixed load is a function of the relationship between its mass and each person's body mass, with the metabolic impact being greater for smaller people. Perhaps less obvious is the fact that even in an unloaded state, smaller people expend more energy per unit body mass than their larger counterparts during ambulatory activities completed at the same speed (Taylor et al. 1980). This is because muscles do not differentiate between loads of varying forms (adipose tissue versus weighted vest), providing such loads do not disturb the centre of gravity; this point will be revisited in subsequent sections. Therefore, smaller individuals consume more energy per unit mass carried, regardless of its form. In the military context, marching at a fixed speed forces those individuals to alter their gait to less efficient movement patterns, which exacerbates this difference. As a consequence, smaller personnel of either gender require greater physiological fitness.

Thus far, our focus has been upon the absolute oxygen (energy) cost, and variations between individuals and the mean group response. Another way to view this is obtained by analysing residuals, such as differences between the mean and each person's data (Fig. 4). When participants are arranged from lightest to heaviest, we see negative residuals predominantly occurring for those who were lighter than the sample average (Fig. 4A). However, when those data were expressed as mass-specific quotients (Royal Society 1975; relative oxygen consumption), positive and negative residuals became more evenly distributed (Fig. 4B), and the slope of the regression describing those values approached zero. Had the regression lines in Fig. 2 passed through the origin, the slope in Fig. 4B would have been zero. Therefore, if one's objective is to ensure loads have an equivalent metabolic impact on all people, then each individual's load should be the same fixed proportion of his or her body mass. To determine the metabolic demands of performing occupational tasks with fixed loads, then either an absolute or a mass-specific measurement approach is required. The size dependency of the latter is the focus of the next section, as one must consider the implications of, and correct for, situations in which mass normalisation fails to fully remove the effect of body size variations on the oxygen cost of work (Tanner 1949; Packard and Boardman 1999).

Body-size dependency of endurance standards

The matter of size dependency has a direct bearing on the development of employment screening tests and cut-scores, and a relevant example is found within the physiological aptitude testing of firefighters. It is appropriate to briefly reflect on endurance testing for occupations that routinely require load carriage. In many countries, the multi-stage, shuttle-run test (Léger and Lambert 1982) is used to evaluate the physiological endurance of candidates before entering various emergency services and the military. Whilst the prediction algorithms require modification for different applications (Stickland et al. 2003), the test provides a valid field prediction of peak aerobic power (Léger and Gadoury 1989; Wilkinson et al. 1999).

Until recently (Taylor 2012; Taylor et al. 2015b), however, the use of that test as a screening tool within fire fighting organisations appears not to have been challenged, as its use followed the seminal

Fig. 4. Oxygen consumption residuals during steady-state, treadmill walking ($4.8 \text{ km}\cdot\text{h}^{-1}$) whilst wearing running shoes, shorts, t-shirt, and self-contained breathing apparatus (11.3 kg). Data are for 20 adults (body-mass range 53.7–91.7 kg; 10 males, 10 females (subjects 1–3, 5–8, 10, 11, 14)) arranged in ascending order of body mass with a least-squares, best-fit linear regression line (95% confidence intervals: dashed lines). Panel A shows absolute oxygen consumption ($r^2 = 0.748$) while panel B contains the same data, but linearly normalised to the total load carried (mass-specific oxygen cost: $r^2 = 0.024$). Data were extracted from Taylor et al. (2012; with permission of Eur. J. Appl. Physiol., vol. 112, © 2011 Springer).

work of Gledhill and Jamnik (1992b) in which the physiological demands of firefighters were characterised. From that research arose a recommended required aerobic power for firefighters ($45 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), which was then widely, but not exclusively, adopted as an employment cut-score. Whilst the merits of aerobic power testing as a tool for predicting either endurance or performance are debated (Noakes and Ekblom 2008), we restrict ourselves here to three pragmatic issues.

Firstly, since employment readiness tests must provide a valid evaluation of occupationally relevant capabilities, one must ask whether or not physical endurance in an unloaded state represents a criterion physiological attribute of fire fighting. There is no doubt that the cardiorespiratory demands of urban fire fighting can be high (Davis et al. 1982; Gledhill and Jamnik 1992b; Sothmann et al. 1992; Budd et al. 1997), but recent evidence would not support the proposition that unloaded endurance is critical. Indeed, following rigorous procedures to identify the most physically demanding, urban fire fighting jobs, and to physiologically characterise the essential tasks, it became evident that not one activity was a whole-body, unloaded endurance task (Taylor et al. 2015b). Accordingly, for the

workforce upon which that research was based, the shuttle-run test was inappropriate.

Secondly, if endurance testing was justified, then one must evaluate the appropriateness of the fitness requirement recommended by Gledhill and Jamnik (1992a) for firefighters. The current authors do not seek to challenge the original observations or the logic behind deriving that recommendation. However, a methodological critique is tendered for consideration. That threshold is a mass-specific quotient (a linear normalisation to body mass), so its magnitude is body-size dependent. During the ambulatory activities in question, the body mass was unsupported and contributed significantly to the overall metabolic cost, so normalisation for mass appeared necessary (Fig. 4B). But which mass should be the denominator: body mass alone, or body mass plus that of the personal protective clothing and equipment? The original authors normalised for body mass only, since it was thought to most closely approximate that of the metabolically active tissues (Davis and Dotson 1987; Gledhill (personal communication)). The logic of that position is apparent, but with wide inter-individual variations in body composition and the lower metabolic rates of adipose and skel-

Table 1. A worked example for the possible impact of body mass, and protective clothing and equipment mass, on deriving the metabolic cost of occupational tasks.

Variable	Parameter	Hazmat task (N = 16)	Bushfire fighting (N = 16)	Stair climb dragging charged hose (N = 17)
Body mass (kg)	Mean	92.7	80.3	87.2
	Lightest five	80.1 (–14%)	67.1 (–16%)	71.2 (–18%)
	Heaviest five	103.9 (12%)	93.3 (16%)	101.6 (16%)
Absolute oxygen consumption (L·min ^{–1})	Mean	1.66	1.69	2.20
	Lightest five	1.50 (–10%)	1.30 (–23%)	1.75 (–20%)
	Heaviest five	1.73 (4%)	1.83 (8%)	2.39 (9%)
Specific oxygen consumption: body mass (mL·kg ^{–1} ·min ^{–1})	Mean	17.9	21.0	25.2
	Lightest five	18.7 (5%)	19.4 (–8%)	24.6 (–3%)
	Heaviest five	16.7 (–7%)	19.6 (–7%)	23.5 (–7%)
Specific oxygen consumption: total mass (mL·kg ^{–1} ·min ^{–1})	Mean	14.5	16.5	20.1
	Lightest five	14.7 (2%)	14.6 (–12%)	18.8 (–7%)
	Heaviest five	13.7 (–5%)	15.9 (–4%)	19.3 (–4%)

Note: Body mass and absolute oxygen consumption data (Metamax 3B, Cortex Biophysik, Leipzig, Germany) were extracted from [Taylor et al. \(2015b\)](#) for three fire fighting simulations performed by operational firefighters. For each variable, three parameters are presented: the overall sample mean and averages based on both the five lightest and five heaviest firefighters. Parenthetical percentages quantify the difference between each subsample average and the corresponding group mean. Mass-specific data were derived in two ways: firstly by using body mass alone and then by using the combined body, clothing, and equipment masses (an extra 22 kg for each simulation).

etal tissues, which contribute to the load but not to its carriage, then perhaps an approximation of skeletal muscle mass would have been a more relevant denominator. Nevertheless, the current authors propose another approach, which is our third pragmatic point.

From the preceding discussion, it is apparent that any additional anatomical or external mass increases the absolute oxygen cost of locomotion. The effect is illustrated in [Table 1](#) using three occupational simulations performed by individuals varying in body mass by >35 kg ([Taylor et al. 2015b](#)). If an occupational cut-score was based on the absolute oxygen cost of those activities, then it becomes clear that the characteristics of the sample may impose a significant and unacceptable (mass) bias on selection. For instance, if an absolute oxygen consumption was derived for dragging charged fire hoses, it would probably be based on the sample average (2.20 L·min^{–1}; [Table 1](#)). However, if that sample was unrepresentative of the workforce, and dominated by either light or heavy individuals, then the derived cut-score might shift from 20% below (lightest: 1.75 L·min^{–1}) to 9% above (2.39 L·min^{–1}) the group mean ([Table 1](#)). This mass bias can be modified, but not removed, by using mass-specific oxygen consumption data for the setting of cut-scores. Nevertheless, quotients cannot be considered as if they were only determined by the body mass, let alone that of the most metabolically active tissues ([Lyons et al. 2005](#)), and unless all of that size effect is removed through normalising, then a mass bias will remain ([Tanner 1949](#); [Poehlman and Toth, 1995](#); [Packard and Boardman 1999](#)), with the lightest and heaviest workers being held to different endurance requirements.

Moving down through [Table 1](#), specific oxygen consumption data are presented in two arithmetically (linearly) normalised forms; the first is standardised to the body mass alone, and the second to the combined mass of the body, protective clothing, and equipment (an additional 22 kg). One purpose of these derivations might be to determine the oxygen cost of tasks as performed in the field. For that purpose, one would include the external load, but then normalise for the body mass alone. Another objective might be to minimise the influence that clothing and equipment has on the oxygen cost of the task. In this situation, the task is not the load carriage itself, as it is always performed whilst wearing a protective ensemble, but the occupational task in isolation and disregarding either the body mass or that of the protective ensemble. This is somewhat analogous to taking these measurements on minimally clothed individuals before and after significant changes in body mass, since when workers be-

come heavier, for whatever reason, the oxygen cost of ambulation is higher. For reasons that will become apparent below, discussion about which of these approaches is better is merely a distraction, although such discussion is sometimes useful.

For each simulation in [Table 1](#), the mean specific oxygen consumption of the second derivation is approximately 20% smaller, and since the metabolic cost was load-dependent, then those values presumably suffered less, or perhaps a different, mass bias. Nevertheless, linear normalisation cannot be guaranteed to remove that bias ([Tanner 1949](#); [Poehlman and Toth 1995](#)), and while ever it remains (or is even suspected), employment standards and cut-scores based upon the mass-specific oxygen cost of occupational tasks may be subject to challenge. Accordingly, the 45 mL·kg^{–1}·min^{–1} standard recommended by [Gledhill and Jamnik \(1992a\)](#) could be as much as 20% lower (perhaps 35 mL·kg^{–1}·min^{–1}) if the original firefighters were 80 kg and wore 22 kg of personal protective clothing and equipment.

Across most applications, the relationship between body mass and oxygen consumption (metabolic rate) has typically been treated as if it were a linear function. Regardless of the ubiquity of that approach, a one-to-one relationship does not exist between oxygen consumption and body mass, either during basal or exercising states ([Kleiber 1932](#); [Tanner 1949](#); [Taylor et al. 1981](#); [Schmidt-Nielsen 1984](#); [Bowes et al. 2015](#)). Instead, those data can often best be described using power functions that pass through the origin ([White and Kearney 2014](#)). Additionally, linear normalisation cannot account for the inter-individual variability observed in steady-state oxygen consumption ([Kleiber 1947](#)), with its coefficient of variation frequently exceeding that for body mass ([Tanner 1949](#)). For instance, when maximal (unsupported) exercise is studied, one observes a positive relationship between the peak oxygen consumption (L·min^{–1}) and body mass, yet a negative relationship obtains when the mass-specific peaks (mL·kg^{–1}·min^{–1}) are plotted against body mass ([Åstrand and Rodahl 1986](#); [Nevill et al. 1992](#)). Even the fat-free mass normalisation of such data are fallacious ([Toth et al. 1993](#)). Finally, the impact of these artefacts appears greater for individuals at either end of the body-mass range ([Tanner 1949](#); [Schmidt-Nielsen 1984](#)). Therefore, the arithmetic normalisation of oxygen consumption is sometimes invalid. This is true whenever a regression line describing its relationship with mass does not pass through the origin ([Tanner 1949](#); [Atchley 1978](#); [Packard and Boardman 1999](#)), as this implies the impossible: beings without mass consuming oxygen.

Fig. 5. Mass-specific oxygen consumption during treadmill walking (A; 4.8 km·h⁻¹) and bench stepping (B; 20 cm at 40 steps·min⁻¹) with participants wearing the complete personal protective ensemble worn by firefighters (average mass 19.8 kg). Data were extracted from Fig. 2A and 2B (N = 20), with absolute oxygen consumption normalised to the body mass of each individual (grey symbols), and to the combined body and protective ensemble mass (black symbols). Lines are the least-squares, best-fit linear regressions.

To illustrate the impossible, reconsider Figs. 2A and 2B (full protective ensemble only), but now with those data normalised linearly (Figs. 5A and 5B) to both body mass (grey symbols) and the combined body and protective equipment masses (black symbols). In both exercise modes, several trends emerged. When normalised only to body mass, a predictable upward displacement of the apparent oxygen cost eventuated, with the regression slopes also becoming negative. In Fig. 2, the absolute oxygen costs were positively associated with the overall mass. Thus, normalisation overcompensated for the mass bias. More importantly, none of these relationships passed through the origin. Indeed, when only body-mass normalisation was used, the ordinate intercepts exceeded 22 mL·kg⁻¹·min⁻¹ (or 1.5 L·min⁻¹; mean body mass 67.7 kg), but when normalised to the complete protective ensemble, those intercepts approximated 15 mL·kg⁻¹·min⁻¹ (or 1.3 L·min⁻¹; mean combined mass 87.5 kg). Therefore, an unacceptable mass bias existed in both cases, and it varied across individuals when using the former method. Such bias, and its capacity to confound data interpretation, has long been known (Tanner 1949; Atchley 1978; Toth et al. 1993; Poehlman and Toth 1995; Packard and Boardman 1999).

These observations are important in two ways. Firstly, when characterising the physiological demands of occupational tasks, it is recommended that linear normalisation be discontinued, regardless of the mass used as the denominator, unless appropriate statistical correction is employed. Indeed, the preceding discussion might lead some to abandoning altogether the mass-specific reporting of oxygen consumption for occupational tasks involving load carriage (e.g., Taylor et al. 2015b; Groeller et al. 2015). This is the recommendation of the current authors, since a mass bias may have discriminatory consequences for individuals at either end of the body-mass distribution. Whilst a statistical solution exists for arithmetically normalised data (Packard and Boardman 1999), a definitive and empirically supported nonlinear solution does not currently exist for ambulatory tasks involving load carriage. Research of this nature is currently being undertaken by the authors.

Secondly, one must consider how best to test for physiological endurance in occupations that have a significant load-carriage expectation. With regard to endurance readiness thresholds based upon, or referenced to, peak aerobic power (maximal oxygen consumption), the current authors advise that extreme caution should be to be exercised when seeking to distill single predictive tests from an array of complex occupational tasks. However, if researchers are inclined to recommend an occupational endurance threshold that is based upon, or referenced to, peak aerobic power, then the impact of all protective equipment and other carried loads must be considered when deriving that measurement. This is because loads beyond a critical threshold may prevent the attainment of physiological maxima (see Impediments to physical endurance), depending upon how those loads are distributed. Moreover, there is evidence that unloaded endurance tests are unreliable predictors of loaded performance (Bilzon et al. 2001; Vanderburgh 2008), with heavier individuals often being significantly disadvantaged.

On this basis, and in combination with the preceding discussion, it was recommended that unloaded endurance tests be discontinued for Australian urban firefighters (Taylor et al. 2015b). It is further suggested that the 45 mL·kg⁻¹·min⁻¹ cut-score recommended for firefighters (or similarly derived targets), if evaluated from unloaded endurance tests, may be challenged on two fronts: the presence of a mass bias and the legitimacy of unloaded endurance testing for load-carriage occupations. It is not advocated that field-based endurance tests (e.g., Léger and Lambert 1982) be adapted by simply adding loads. Instead, it is suggested that physiological aptitude tests should, where possible, be occupational simulations completed carrying trade-specific loads (Groeller et al. 2015). If facilities are available, however, more traditional, unidirectional endurance tests could be performed in a loaded state (e.g., Dreger et al. 2006; von Heimburg and Medbø 2013).

Body-location dependency

As a first approximation, the generalisation that loads arranged close to the body's centre of gravity (or mass) exert the least physiological burden, is both reasonable and reliable (Parkes 1866; Munson 1901; Zuntz and Schumburg 1901). Nevertheless, efforts to quantify these location-dependent relationships have occurred somewhat more recently (Goldman and Iampietro 1962; Soule and Goldman 1969; Datta and Ramanathan 1971; Myers and Steudel 1985; Taylor et al. 2012), with some outcomes of that research summarised in Table 2.

The fractional contributions to the overall metabolic demand of equivalent loads added to different body segments, or even within the same segment (Griefahn et al. 2003), are markedly dissimilar (Table 2). Thus, the most inefficient location for load carriage is the foot, with its site-specific impact being 8.7 times greater than carrying an equivalent mass on the torso during walking; during stair climbing, foot loads are 6.4 times more costly (Taylor et al. 2012). Under different experimental conditions, Myers and Steudel (1985) and Legg and Mahanty (1986) reported similar observations,

Table 2. The location-dependent, mass-specific oxygen cost of load carriage ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$).

Load location	Walking		Bench stepping
	Soule and Goldman (1969)	Taylor et al. (2012)	Taylor et al. (2012)
Control clothing trial	12.80 (3.5kg)	12.94 (0.95kg)	14.90 (0.95kg)
Foot load (combined)	73.60 (12.0kg)	88.75 (2.44kg)	72.24 (2.44kg)
Head load	13.40 (14.0kg)	13.67 (1.40kg)	27.74 (1.40kg)
Torso load		10.21 (11.30kg)	11.36 (11.30kg)
Thermal clothing		32.63 (4.72kg)	36.45 (4.72kg)
Complete ensemble		22.02 (19.86kg)	19.62 (19.86kg)

Note: Data were extracted from Soule and Goldman (1969) and Taylor et al. (2012; with permission of Eur. J. Appl. Physiol., vol. 112, © 2011 Springer) for steady-state walking ($4.8\text{ km}\cdot\text{h}^{-1}$, 0% gradient; $N = 10$ and 20 , respectively), and from Taylor et al. (2012) for steady-state bench stepping (20 cm at $40\text{ steps}\cdot\text{min}^{-1}$; $N = 20$). For each condition, the absolute oxygen consumption ($\text{L}\cdot\text{min}^{-1}$) of the control trial was subtracted from that of each experimental trial, with the remainder normalised to the difference in the loads carried across those trials. The experimental ensembles were made up from either military combat dress or firefighter thermal protective clothing and separate torso, head, and foot loads. Parenthetical masses define the added loads within each condition.

and the hands are similarly inefficient sites (Lind and McNicol 1968; Soule and Goldman 1969).

Whilst the torso and head are involved in translational motion, the limbs perform both rotational and translation movements that occur somewhat independently of the torso. This, in addition to the inertial work required to initiate and terminate of each swing phase (Cavagna and Kaneko 1977), and the energy required to lift the foot during each step, explains why the limbs are less efficient sites for load carriage. Furthermore, the more distant such loads are from the centre of rotation of each limb, the greater is the movement arc and its oxygen cost.

The implications of these facts within occupational physiology are diverse. For example, when replicating boot mass using ankle loads (Gledhill and Jamnik 1992b), errors may be introduced if either the mass or its location modify the oxygen cost of the task. These errors are further magnified if, for example, a 2-kg boot mass is simply added to the torso during a screening test. To faithfully replicate the metabolic cost of that footwear, data from Table 2 indicate that 17.4 kg should be added to the torso. In addition, this knowledge provides an opportunity for targeting the redesign of protective equipment based upon its relative impact on workers. Reducing the mass of protective boots, for instance, will reduce locomotor energy costs by 6–8 times more than will an equivalent mass reduction from equipment loaded on the torso (Taylor et al. 2012). This dictates that engineers must work closely with physiologists and workers so that the next generation of equipment can be developed with a better appreciation of its likely physiological impact (Lee et al. 2015). It is also probable that these location dependencies will vary among people of different stature and body mass, and this may also have implications for employment standards and for worker health and safety. Whilst this is perhaps intuitive, the empirical evidence to support this thesis does not currently exist, so the authors are also investigating that possibility.

Impact of clothing on the energy cost of locomotion

Personal protective clothing is mandatory in many workplaces, and is frequently an essential subcomponent of protective ensembles. Clothing designed to protect workers from threats such as physical impacts, thermal extremes, and chemical or biological agents is often multi-layered, bulky, and heavy (Nunneley 1989; Goldman 1994; McLellan and Havenith 2016). These garments impose a significant oxygen cost on the wearer and contribute to the energy cost of locomotion. They also constitute an important part of the carried load. Therefore, the nature of the clothing itself may alter the energy requirements of work, and this must be considered within the development, and by extension, the implementation of workplace tests, employment standards and cut-scores.

Teitlebaum and Goldman (1972) evaluated the effects of multiple layers of heavy, cold-weather clothing on the energy cost of walking, as did Duggan (1988; stepping) and Dorman and Havenith (2009; walking, stepping, obstacle course). In each of those investigations, metabolic rate was elevated by 10%–15% when subjects wore the protective ensembles. In the most extensive investigation, Dorman and Havenith (2009) found that about half of the metabolic burden was associated with the clothing mass itself, whilst the balance could be ascribed to elevated frictional forces among the clothing layers. The latter effect has been described as locomotor hobbling (Teitlebaum and Goldman 1972), which increases the burden and modifies gait. While the magnitude of this effect will depend on the fabric properties of each garment layer, a simple estimate may lead to the conclusion that the energy requirements are increased by approximately 3% for each additional clothing layer placed over the base garment. Readers are directed to McLellan and Havenith (2016) for a more detailed treatment of this topic.

Load carriage and its impact upon gait

Load carriage can also alter the mechanics of locomotion and, consequently, the energy cost of work. For example, a common observation accompanying heavy load carriage on the back is a forward flexion of the trunk (Attwells et al. 2006), presumably to prevent a disadvantageous elevation and posterior displacement of the centre of gravity, and a loss of stability (Park et al. 2014). Logically, the heavier the load, the greater becomes the challenge to maintain the centre of gravity location, and more forward lean should be expected. Indeed, it appears that this torso rotation may occur in adults for carried masses of 30 kg and above (Martin and Nelson 1986). This phenomenon also occurs when walking up a gradient, but now at a lighter load. Consequently, during treadmill walking with a heavy pack, an exaggerated forward lean is observed as the gradient is increased (Phillips et al. 2016a).

Phillips et al. (2016a) observed that during loaded walking on gradients up to 4%, increments in absolute oxygen consumption could be explained on the basis of the overall mass elevation for each subject, as illustrated in Fig. 3. That is, when the absolute oxygen consumption was normalised to the total mass, minimising the influence of mass, the resulting specific oxygen consumption matched that observed within the unloaded condition. This first principle (Fig. 2) is often misremembered, yet it is quite predictable, even across genders (Taylor et al. 2012). In fact, some gender differences may be explained simply on the basis of body-size distributions. Nevertheless, when the treadmill gradient was elevated (6% and 8%) that outcome was altered, with the increase in oxygen consumption becoming disproportionately greater than the mass change (Fig. 6). It was concluded that, at some

Fig. 6. Oxygen consumption during treadmill walking ($91 \text{ m}\cdot\text{min}^{-1}$) in loaded (25-kg pack) and unloaded states across gradients from 0%–8%. Data were extracted from Phillips et al. (2016a) and used with permission of Eur. J. Appl. Physiol, vol. 116, © 2015 Springer. The symbols (*) identify sources of significant difference between the loaded and unloaded states ($P < 0.05$).

threshold beyond a gradient of 4%, loaded walking became less efficient, possibly because of a tendency for the centre of gravity to be displaced backwards, with this efficiency reduction explaining the oxygen-cost deviation.

Several groups have reported significant deviations from normal (unloaded) balance, posture, movement, and gait when carrying heavy loads (Martin and Nelson 1986; Quesada et al. 2000; Attwells et al. 2006; Qu and Yeo 2011; Park et al. 2014). In general, those changes have been shown to contribute to, or are at least suggestive of, an elevated energy cost of movement, an earlier onset of fatigue, and possibly an increased risk of injury (Epstein et al. 1988; Knapik et al. 2004). Moreover, during deliberate mass placements away from the midline, those outcomes also show a lateral dependency, with an even greater postural disturbance and more rapid fatigue development (Park et al. 2014).

Since these postural and locomotor perturbations are often related to stature and size (Martin and Nelson 1986; Haisman 1988), then smaller individuals, and in particular women, may experience significantly greater instability and fatigue. Not surprisingly, these changes can make such individuals more prone to workplace injuries (Bhambhani and Maikala 2000; Knapik et al. 2004; Park et al. 2014), and this raises two matters of relevance to employment selection: duty of care and discrimination. Less than adequate consideration of these, sometimes competing, responsibilities can lead to selection bias, with gender bias, perceived or otherwise, in employment standards and cut-scores providing a legitimate basis for contesting selection decisions (Supreme Court of Canada 1999; Eid 2001). This realisation has led the quest to establish gender-neutral cut-scores within traditionally male-oriented occupations (Jamnik et al. 2013; Friedl 2016), which are frequently dominated by load carriage and heavy physical demands.

With regard to walking mechanics and load carriage, two experiments are of occupational relevance, although they were only conducted over very short durations: Bhambhani and Maikala (2000) and Silder et al. (2013). Both groups employed level treadmill walking at self-selected speeds. Bhambhani and Maikala (2000) used loaded boxes (15 and 20 kg) carried in the hands at chest level. They observed greater physiological strain in the females, who bore less of the load with the hands. Instead, the women transferred some of the load to the body by resting the box on the chest. This strategy is consistent with the modest upper body strength typically observed in women

(Miller et al. 1993), but it is perhaps simply gender-related and not gender-dependent, as males with similar upper body strength may adopt an identical strategy. In contrast, Silder et al. (2013) used weighted vests representing 10%, 20%, and 30% of each subject's body mass (males 75 kg, females 63 kg). Since those loads imposed an equivalent relative burden on both groups, then it is perhaps not surprising that neither neuromuscular recruitment nor walking mechanics differed between the genders. Thus, the accommodation of these equivalent relative loads resulted in similar changes in gait, although this would not have been anticipated if the same fixed (absolute) and heavy loads were used (Haisman 1988; Knapik et al. 2004). Since many physically demanding occupations require the handling of fixed loads, sometimes asymmetrically distributed, and often when workers are wearing personal protective clothing and equipment, then a need exists for more focussed research on this area. Investigators also need to consider using men and women of matched, and workforce representative, physiological attributes. In the context of equitable employment standards, such research should be viewed as critical.

Cardiopulmonary effects

Loads carried away from the centre of gravity induce postural and mechanical accommodations, as well as a greater metabolic cost during locomotion (Soule and Goldman 1969; Balogun 1986; Abe et al. 2004), relative to loads distributed around the torso (Goldman and Iampietro 1962; Soule et al. 1978). Notwithstanding the benefit of the latter mode, thoracic load carriage alters cardiopulmonary function.

The primary responsibility of the respiratory system is to ensure that alveolar ventilation and gas exchange track variations in metabolic rate, thereby preserving blood-gas homeostasis. The brainstem controls the rate and depth of breathing, with the respiratory muscles overcoming three forces (Roussos and Campbell 2011): the static elastic forces of the lung parenchyma and chest wall, the dynamic resistive forces generated by the movement of air through airways and the non-elastic deformation of tissues, and inertial forces. Increases within any one of these forces can impair ventilation through fatigue-inducing elevations of inspiratory muscle work (Milic-Emili and Zin 2011; Tomczak et al. 2011; Brown and McConnell 2012). In the case of thoracic load carriage, increments in both the elastic (chest-wall restriction) and inertial (increased mass) contributions to the work of breathing will occur. This can be problematic during high-intensity work, during which ventilation increases disproportionately to changes in external work (Owles 1930).

There is no doubt that a significant thoracic load carriage reduces maximal exercise tolerance (Louhevaara et al. 1995; Eves et al. 2005; Taylor et al. 2012; Peoples et al. 2016; Phillips et al. 2016a), although some have reported that neither the peak cardiorespiratory responses nor peak (absolute) oxygen consumption were modified in well-motivated individuals when those loads were not excessive (Taylor et al. 2012; Peoples et al. 2016). One interpretation is that neither pulmonary nor central cardiac functions limited exercise, but the point of work intolerance was reached earlier and at lower external work rates. It is possible that two functional zones of loaded-work tolerance may exist: zone one includes loads from zero through to the point at which pulmonary or central cardiac functions are first compromised, while load-zone two extends from that load threshold to the point of zero work capability. As an example of work in the second zone, Eves et al. (2005) reported a small, although significant, reduction in absolute oxygen consumption during load carriage, but not peak heart rate or minute ventilation, at volitional exhaustion. When participants were loaded and breathed through the demand regulator of the self-contained breathing apparatus, this respiratory limitation became more pronounced (Eves et al. 2005; Dreger et al. 2006). Subsequently, Phillips et al. (2016a) observed significant reductions (~3%) in both peak minute ventilation and absolute oxygen consumption during heavy backpack carriage

(25 kg; $N = 50$). More recent evidence supports the possibility that this effect is perhaps related to how the load is mounted on the torso (Hingley and Peoples 2016, unpublished observations), with backpack, but not weighted-vest, loads being more likely to induce these reductions because of changes in the centre of gravity.

Thoracic load carriage imposes a unique combination of increased inertial and elastic loading, with the latter possibly inducing inspiratory muscle fatigue during prolonged and exhaustive exercise (Loke et al. 1982; Coast et al. 1990; Guenette et al. 2010). Not surprisingly, ventilatory impediments elicited during thoracic load carriage have been repeatedly demonstrated (Legg and Mahanty 1985; Muza et al. 1989; Walker et al. 2015; Phillips et al. 2016b), and can be induced by loads as little as 10 kg (Legg and Mahanty 1985). These perturbations are most evident within the dynamic maximal ventilatory manoeuvres, and appear to be progressively exacerbated as the load is elevated (Muza et al. 1989). Of those, reduced maximal voluntary ventilation has ramifications for the breathing reserve during near-maximal exercise, with chest-wall restriction independently increasing the work of breathing and inducing sensations of dyspnoea (Tomczak et al. 2011). Such dynamic volume alterations are consistent with respiratory limitations commonly seen in restrictive pulmonary diseases (Pride and Macklem 2011), highlighting the relevance of those changes to occupational and employment standards research.

These ventilatory adjustments may partly explain reductions in peak minute ventilation at volitional exhaustion (Walker et al. 2015). Indeed, Faghy and Brown (2014) reported a decrease in peak inspiratory and expiratory pressures generated following heavy exercise, with that change attributed to progressive respiratory muscle fatigue. Since the dynamic respiratory volumes are effort dependent, whilst maximal airflow is effort related, but with a significant effort-independent (flow-resistive) component, then the conditions are right for the respiratory system to limit maximal exercise (Stickland et al. 2008). In fact, electromyographic analysis of the sternocleidomastoid and external intercostals has revealed increased neuromuscular activity during loaded endurance exercise (Nadiv et al. 2012), and this supports the notion of a load carriage-induced respiratory muscle fatigue. In turn, this may elicit an autonomically mediated reduction in oxygen delivery to the working muscles through intramuscular vasoconstriction as the work of breathing increases (Harms et al. 1997; St Croix et al. 2000). Thus, blood flow to the legs is diminished during states of high metabolic demand when the work of breathing is simultaneously elevated. Given the possibility that an hierarchical and self-preserving sequence of staged homeostatic failures may exist (Bass 1963; Taylor and Patterson 2016), in which less critical functions appear to fail first, thereby preventing more catastrophic systemic failure, then this reduced leg blood flow and work tolerance might be viewed as a naturally acquired preventative strategy that terminates external work before pulmonary function is compromised. To date, these mechanisms have not been explored during more strenuous conditions involving thoracic load carriage, but deserve greater attention, given the significance of their mechanistic and occupational impact, reinforcing the need to use workplace-relevant thoracic loading during occupational screening tests.

During ambulatory tasks of relatively low metabolic demand, the addition of a load elevates the required minute ventilation when compared with the unloaded state (Majumdar et al. 1997; Bhambhani and Maikala 2000; Dreger et al. 2006; Peoples et al. 2016). Thus, ventilation tracks the load-induced change in metabolic demand, with the breathing pattern shifting towards that seen during chest-wall restriction (Caro et al. 1960; Harty et al. 1999) and in patients with restrictive disorders (Milic-Emili and Zin 2011; Pride and Macklem 2011). That is, the tidal volume is significantly reduced whilst the breathing frequency is raised (Louhevaara et al. 1985; Louhevaara et al. 1995; Walker et al. 2015), with those changes representing a ventilatory pattern for which, in the circumstances, the work of breathing is minimised. Significant thoracic loading is

also accompanied by a decrease in the end-expiratory lung volume owing to chest-wall compression (Brown and McConnell 2012), as is observed during upright water immersion (Taylor and Morrison 1991, 1999). In both circumstances, inspiratory muscle work will be elevated (Taylor and Morrison 1991, 1999; Harris 2005). This has not been thoroughly investigated during loaded work, although such research is currently being undertaken by the authors.

The significance of variations in load placement around the thorax is also only partially understood, with investigators primarily focussing upon respiratory volume and ventilatory outcomes. For example, Bygrave et al. (2004) reported that the tightness of fit of a loaded backpack (15 kg) was inversely related to ventilatory function. The same group observed that using a chest strap, instead of the conventional shoulder straps, which are a limitation when loads are heavy (Hadid et al. 2012), also impeded maximal ventilatory efforts. However, work of this nature, whilst identifying and describing the problem, does not provide a mechanistic explanation for those observations. For this to occur, more detailed mechanical research is required (Morrison and Taylor 1990; Taylor and Morrison 1990; Chaunchaiyakul et al. 2004), and this too is a current emphasis of the authors.

The physiological consequence of such breathing alterations is best exemplified in the capacity to control alveolar ventilation and to regulate blood-gas tensions. This area has not been adequately explored. For instance, whilst we know that arterial desaturation does not occur in most healthy individuals, even during maximal exercise (Stickland et al. 2008), we know little concerning hypoxaemia during loaded and occupationally relevant work. In studies where chest-wall restriction was artificially increased, arterial desaturation has indeed been observed during moderate-intensity exercise (Caro et al. 1960; Harty et al. 1999), although these examples elicited excessive vital capacity reductions (>30%), where torso loading is generally less severe. Nonetheless, chest-wall restriction influences work tolerance (Coast and Cline 2004), so further studies are needed across a range of loads and work intensities to more fully elucidate this interaction.

The heart is also subject to increased mechanical work during ambulatory load carriage, with the magnitude of the chronotropic contribution to the elevated cardiac output being inversely related to body mass during long-duration work (Fallowfield et al. 2012). This narrows the cardiac reserve and limits maximal work (Taylor et al. 2012), again emphasising the need for employee screening to replicate working conditions. Equally, mean arterial blood pressure is also elevated during heavy load carriage, and this translates into a significantly increased rate-pressure product (Sagiv et al. 1994). That index provides an indirect measurement of myocardial oxygen uptake and cardiac work.

The blood pressure rise observed during exercise is most pronounced during resistance work, with those changes necessary to overcome increased downstream vascular resistance and to ensure adequate oxygen delivery to the working muscles. Nevertheless, when thoracic load carriage is combined with an increased breathing resistance (e.g., self-contained breathing apparatus), left ventricular preloading and reduced end-diastolic filling have been observed (Nelson et al. 2009). Those changes were due to reductions in venous return that attended prolonged exercise, and that state would be further exacerbated by dehydration and hyperthermia. Clearly, load carriage places an increased demand on the heart to maintain cardiac output, and this depends upon the capacity of the coronary vasculature to meet the energy requirements of the heart when fulfilling its contractile obligations. To date, it appears that no research has been directed towards evaluating whether load carriage per se eventually contributes to heart wall remodelling of either a beneficial or pathological nature, and in particular that of the left ventricle, but some adaptations might be anticipated.

Thermoregulatory consequences

As a consequence of the independent impact of carried loads on metabolic rate, ambulatory efficiency, and the work of breathing,

the overall metabolic energy transformation (heat production) of an exercising person is elevated. That heat does not contribute usefully to either the external work or load carriage, but is stored within the body. However, more extreme temperature elevations become physiologically challenging and potentially life threatening (Sawka et al. 2011; Nybo et al. 2014). The thermodynamics of this problem are dictated by the available behavioural, physiological, and physical avenues for dissipating this thermal energy to the ambient environment, with those avenues being extensively modified in many workplaces.

Whenever the mean body temperature is disturbed from its normothermic (thermoneutral) state, homeostatic regulatory mechanisms are recruited to restore the body's thermal energy content (Werner et al. 2008). When a temperature elevation is detected, as it is during the performance of significant external work whilst carrying loads, the convective delivery of thermal energy to the skin is autonomically increased (Caldwell et al. 2014, 2016; Johnson et al. 2014). This is followed by the activation of sweating to elevate evaporative cooling (Taylor and Machado-Moreira 2013). Indeed, these compensatory mechanisms are activated regardless of factors that may modify their effectiveness, such as the presence of clothing, high environmental temperatures, or a high ambient water-vapour pressure.

The pathways for heat dissipation (conduction, convection, radiation, evaporation) are all gradient-dependent (Werner et al. 2008). That is, heat and water vapour inexorably move away from places possessing a higher thermal energy content (enthalpy) or water vapour pressure, towards cooler and less saturated locations. Those fluxes cease when physical barriers prevent such movements (McLellan and Havenith 2016) or when the thermal or vapour pressure gradients are removed. Indeed, flux reversal occurs whenever the gradients themselves are inverted, although our current interests centre upon flux barriers: clothing and personal protective equipment. Herein, the focus is upon the impact of these obligatory occupational ensembles and loads on heat production and dissipation, regardless of the ambient conditions.

Clothing adds a load to the body; sometimes insignificant, but sometimes burdensome (e.g., encapsulating chemical, biological, and radiological protective ensembles; McLellan et al. 2013; Taylor and Patterson 2016; McLellan and Havenith 2016). During ambulatory activities, the load itself increases oxygen consumption (Fig. 2). In addition, whole-body garments modify joint stiffness as a simple function of their thickness, with layered ensembles increasing internal frictional forces (Teitlebaum and Goldman 1972; Nunneley 1989; Dorman and Havenith 2009). These factors combine to reduce mechanical efficiency, with metabolic heat production being elevated via both mechanisms.

In a previous section, the impact of protective equipment (including body armour) on the oxygen cost of physical activity was explored, which comes with a corresponding elevation in endogenous heat production. Across different occupations, this imposition can range from minimal through to extreme (e.g., bomb-disposal ensembles). Some protective equipment is designed to place a barrier between the wearer and an external threat (ballistic, biological, chemical, radiological; Caldwell et al. 2011; McLellan and Havenith 2016). Whatever the objective or the nature of those barriers, they must also impede heat or water vapour fluxes. The more encapsulating the protection, the greater are those impediments. Indeed, some ensembles resemble a closed thermodynamic system with impermeable membranes permissive to energetic, but not material, exchanges with the environment. In this state, and depending upon the ambient conditions, heat storage can approximate heat production (Taylor et al. 2014), imposing a significant impediment to viable work durations (McLellan et al. 2013; Taylor 2015; Taylor and Patterson 2016). Moreover, continued physiological attempts to lose heat can actually exacerbate the problem, with excessive sweating leading to rapid dehydration, and the depletion of body fluids and electrolytes (Patterson et al. 2014), whilst cutaneous vascular en-

gorgement (Rowell et al. 1970; Fogarty et al. 2004) can challenge blood pressure regulation (Taylor and Patterson 2016).

How do these factors affect individuals, and what is their potential impact on physiological employment standards and cut-scores? At this time, there are perhaps more questions than answers. Nevertheless, some pieces of this puzzle are being assembled.

Firstly, let us consider whole-body encapsulation. That state includes most enclosed working environments for which air conditioning is not available (e.g., armoured vehicles). In those states, the microclimate becomes more humid because of continued transepidermal and, eventually, sudomotor water losses (Taylor and Machado-Moreira 2013). Whilst dry heat exchanges may continue, providing an adequate thermal gradient exists, evaporative cooling is progressively impaired, making sweat ineffectual. Since thermal exchanges with the environment occur through the skin, and since heat is stored within the body, then the relationship between the body surface area and its mass forms a decisive determinant of thermal balance. Accordingly, energy-efficient morphological configurations (large mass-specific surface areas) should favour heat tolerance (Taylor 2006).

This possibility was recently investigated in unclothed individuals by Notley et al. (2014b, 2015a, 2016) in compensable conditions (28 °C), during states of clamped heat production (cycling: 135 and 200 W·m⁻²). They observed that individuals with a lower specific surface area were forced to maintain greater sweat rates to achieve an equivalent heat loss (Notley et al. 2016). In addition, they found that up to 50% of the variation in whole-body sweat rate among individuals could be explained on the basis of differences in the specific surface area (Notley et al. 2015a, 2016). Therefore, within encapsulated and enclosed working conditions, where sweating is not just ineffective, but wasteful, smaller individuals, including women, may be more tolerant and experience less physiological strain (e.g., Shvartz et al. 1973; Notley et al. 2015c), as long as dry heat exchanges remain effective. This possibility has implications for recruitment, because if it can reliably be shown that tolerance has a significant morphological dependency, then it may provide a scientific justification for selection strategies that might otherwise appear discriminatory.

A second topic, and one for which we are currently lacking sufficient scientific evidence, involves the interaction between load carriage and uncompensable (endogenous) heat production among people of diverse morphological configurations. This is the other side of the specific surface area characteristic. While we dissipate heat more readily through large skin surfaces, we can store more heat within bigger bodies. Thus, the volume-specific heat capacity of any object is the product of its specific heat and mass. However, we have shown above that, during states of constant velocity locomotion with a fixed absolute load, smaller people face a greater metabolic cost. This translates into a proportionately greater endogenous heat production, with thermal energy now stored within a smaller volume. Can those individuals still dissipate this heat without a greater reliance upon evaporation? What happens when they are clothed? Do they have a greater propensity for hyperthermia than similarly stressed larger people? To support duty-of-care efforts directed at avoiding unacceptable thermal strain, we need to better understand how individuals of different body size tolerate the thermal impact of load carriage when working in fully clothed states.

Summary

The emphasis of this section was on the impact of load carriage on physiological function. We have seen that clothing, protective equipment, and load carriage not only elevate the metabolic demand, but can also reduce the physiological capacity of people at work. This impact deviates across individuals of varying size, and it has implications for recruitment policies and practices, as well as duty of care obligations. However, it is inappropriate to assume that the load-carriage implications from one occupation can be universally applied. Indeed, this impact will vary in several ways, perhaps most

evidently in how those loads are positioned and carried, with limb carriage representing the greatest metabolic impediment.

The impact of load carriage on job-related performance

Employment standards are normally translated into satisfying a cut-score or work-related performance, such as an acceptable task completion time or acceptable sustainable work rates. Logically, the conditions under which job-related tasks are typically completed should be carefully considered when determining readiness for duty. Since load carriage is often a key element, understanding the effects of occupationally relevant loads on performance is important. Therefore, the aim of this section is to review evidence concerning those effects, but with an emphasis on physical endurance and mobility.

Load carriage increases strain and reduces physical performance (Parkes 1866; Munson 1901; Goldman and Iampietro 1962; Taylor et al. 2012; Phillips et al. 2016a). This results from the re-assignment of some fraction of the available energy resources to support the load. In general, most aspects of work-related performance are diminished, sometimes, but not always, in proportion to the size or location of the load.

In many occupations, load carriage includes combinations of protective clothing and equipment. In addition, factors such as respiratory or thermal stress, secondary to load carriage, may have an adverse impact on locomotion and performance. For example, Orr et al. (2013) recently surveyed soldiers who reported perceptions of diminished task performance accompanying operational load carriage (up to 48 kg). Mobility was thought to be most affected; however, soldiers also perceived performance on tasks related to attention and marksmanship was reduced. In contrast, the same group (Carbone et al. 2014) reported that load carriage did not hinder but, in some cases, improved pistol marksmanship. They concluded that the tactical loads (22.8 kg) may provide a stabilising effect. Thus, these between-study differences may be explained by the size of the load(s), or the extent of the fatigue-inducing locomotion undertaken prior to shooting.

It is well established that thicker and more cumbersome protective clothing and ensembles will reduce joint ranges of motion (Huck 1991; Havenith and Heus 2004; Coca et al. 2008, 2010). Those changes translate into movement and ambulatory impediments, and the relative contributions of individual components of the complete protective ensemble worn by firefighters were evaluated by Taylor et al. (2012). Research of this nature provides insight into the importance of using relevant occupational clothing and loads when developing screening tests and cut-scores. Failure to do so may well lead to inaccuracies in replicating the essential physical demands of work. For example, tests such as the Canadian Forces Physical Fitness Maintenance Evaluation (Deakin et al. 1996; Dreger and Petersen 2007; Rogers et al. 2014) and the physiological aptitude test for Fire & Rescue New South Wales (Australia; Fullagar et al. 2015; Groeller et al. 2015) provide examples that require participants to wear complete protective ensembles when being evaluated for readiness for duty. However, other tests that purport to evaluate work readiness in firefighters do not necessarily require the wearing of actual protective clothing and equipment (Gledhill and Jamnik 1992b; International Association of Fire Fighters 1997; Williams-Bell et al. 2009). It is the authors' contention that unloaded testing and, to a lesser extent, testing with simulated loads, is unable to provide accurate assessments of work readiness. Indeed, the weight of evidence dictates that best practice requires the use of actual personal protective clothing and equipment.

When evaluating the impact of load carriage on job-related performance, the nature of that loading should be appropriately determined, and the following questions must be considered:

What is the mass of the carried load?

Is the load centralised, anterior, posterior, peripheral, or some combination?

Is the load absolute or normalised to the worker's size?

Is the load borne constantly, or is its impact intermittent?

How does the load interact with the worker and environment to modify strain?

Is the load real (actual equipment) or simulated (weighted vest)?

Which performance attributes need to be evaluated?

Impediments to physical endurance

The consequences of load carriage on graded maximal exercise performance have been evaluated by many groups over the last 30–40 years (Raven et al. 1977; Louhevaara et al. 1985, 1995; White and Hodous 1987; Polcyn et al. 2002; Eves et al. 2005; Dreger et al. 2006; Northington et al. 2007; Taylor et al. 2012; Peoples et al. 2016; Phillips et al. 2016a). From this research, the universal observation was a reduced work tolerance time, but without necessarily modifying the peak physiological responses. That is, light-moderate loads appeared not to impede the attainment of peak responses, unless they also imposed a thoracic restriction or markedly disturbed the centre of gravity, but they clearly reduced the performance of external work. If one imagines that at the point of maximal exercise, there is fixed pool of energy that can be used, then the fraction that can be assigned to useful external work must come from that which is not consumed to support other physiological obligations. Thus, the extent that carried loads modify any of those internal functions will be directly reflected in the capacity to perform external work. To illustrate this, we focus now on two recent projects (Peoples et al. 2016; Phillips et al. 2016a).

In the first investigation, Phillips et al. (2016a) studied changes in graded (maximal treadmill) exercise performance in loaded (25 kg backpack) and unloaded conditions. That load, or its positioning relative to the centre of gravity, was perhaps just beyond the threshold at which the burden of carriage prevented the attainment of physiological maxima. Indeed, peak exercise power was reduced by 11% when participants were loaded, and this was almost identical to reductions estimated from Louhevaara et al. (1995), while peak minute ventilation and absolute oxygen consumption were also lower. However, whilst body masses ranged from 70–118 kg, differences in peak power between the two conditions could not be explained on the basis of those variations. Thus, whilst Bilzon et al. (2001) suggested larger individuals were better suited to heavy load-carriage work, these observations appeared inconsistent with that hypothesis. Furthermore, the relationship between oxygen consumption and power output was the same in both conditions (16 mL·W⁻¹), implying that load carriage displaces that relationship vertically, but does not appear to modify its gain.

Given that load carriage elevates the metabolic cost of exercise (Fig. 2), then one would predict that the maximal acceptable duration for continuous work (Saha et al. 1979; Wu and Wang 2001) would decline as mass was added, or as workers were asked to work harder whilst carrying constant loads. However, previous estimations of maximal acceptable work durations were either theoretically derived (Bink 1962) or estimated from unloaded exercise, with sedentary subjects performing an exercise mode that was unrelated to most occupations (cycling: Wu and Wang 2001, 2002). Accordingly, the outcomes of such research are almost irrelevant to well-trained defence and emergency service personnel. Fortunately, others have tackled this topic using loaded running (Polcyn et al. 2002), loaded evacuation simulations (Ruby et al. 2003), and loaded marching (Koerhuis et al. 2009). Those investigators all reported performance decrements with load carriage, with that decrease varying systematically with increments in load (Polcyn et al. 2002).

Peoples et al. (2016) extended that work, exploring the concept of acceptable work duration in subjects performing submaximal exercise (treadmill) at five intensities (30%, 50%, 60%, 70%, and 80% of peak oxygen consumption) whilst wearing a weighted vest (22 kg). The task was to cover a 5-km distance before volitional fatigue. At the lightest intensity, all participants achieved that

target, but the frequency of premature terminations increased as the intensity was elevated. Thus, the tolerable ambulatory distance decreased from 4.3 km (SD 1.2) at the 50% exercise intensity to 2.4 km (SD 1.5) at 80% of the peak oxygen consumption. From this research, the authors derived methods for predicting the maximal acceptable work duration on the basis of the intensity-specific heart rate. To provide an acceptable work tolerance range between hard, but sustainable work, and working at the cusp of cardiovascular insufficiency (Taylor and Patterson 2016), two cardiac predictions were used. The lower end of that range corresponded with protracted steady-state work and a mean sustainable heart rate of 150 beats·min⁻¹ or lower ($r^2 = 0.80$), while the upper level was set at an absolute upper threshold of 180 beats·min⁻¹, and may represent emergency scenarios ($r^2 = 0.71$):

$$\begin{aligned}\text{Lower: acceptable duration} &= (1275 + 24.69) \\ &\times \exp^{(-4.494xx)} - 24.69 \\ \text{Upper: acceptable duration} &= (4392 + 4.760) \\ &\times \exp^{(-6.364xx)} - 4.76.\end{aligned}$$

where duration is in minutes, and x is the relative exercising heart rate (%): (exercising – resting heart rate)/(maximal – resting heart rate).

Compared with the observations of Wu and Wang (2001), bipedal load carriage resulted in halving the acceptable work times at intensities above 60% maximal oxygen consumption (Peoples et al. 2016). That outcome highlights the specific nature of different work and ambulatory tasks, both of which must be replicated within screening tests. Furthermore, the complexity of the interaction between load carriage and endurance, especially as it relates to cardiovascular strain, is highlighted when metabolic rate and environmental temperature are both elevated. For instance, Stewart et al. (2014) demonstrated that the endurance time for loaded walking, while wearing protective clothing, was dramatically reduced, not only by increasing work intensity, but through elevations in ambient temperature.

Impediments to mobility

A natural extension of the impact of clothing on joint ranges of motion (Havenith and Heus 2004; Coca et al. 2008, 2010) will be an interaction with mobility and the performance of occupation-specific activities and movement patterns. Overlaid onto these will be the further impingement of load carriage (Taylor et al. 2012, 2016; Carlton et al. 2014; Dempsey et al. 2013; Lewinski et al. 2015), which also modifies posture and balance (Punakallio et al. 2003; Dempsey et al. 2013; Shymon et al. 2014).

Three groups have investigated the impact of armoured loads on the operational mobility of police officers (Carlton et al. 2014 (22.8 kg: tactical movements, victim rescue); Dempsey et al. 2013 (7.7 kg: balance, acceleration, upper body strength, grappling, manoeuvrability); and Lewinski et al. 2015 (9.1 kg: sprint acceleration and velocity)). In each study, performance decrements accompanied the wearing of tactical loads, with decrements ranging from 7%–34%.

Most recently, the impact of load carriage on mobility was evaluated within the military context (Taylor et al. 2016). Soldiers performed a series of dismounted tactical movements that might be encountered on the battlefield (fire and movement simulation, obstacle-avoidance test, combat-rush simulation), plus two generic tests (vertical-jump test, forward-reach test). Five levels of passive, ballistic protection and body loading were evaluated, with loads varying from 19.1 kg (control) through to 29.2 kg. When those loads were regressed against fire and movement performance, each kilogram of added mass accounted for a 2.1% performance decrement ($r^2 = 0.93$), with the primary impediment being the time taken to rise from the prone position and commence forward movement. Obsta-

cle avoidance was also load-dependent, with a similar overall performance decrement (1.9%·kg⁻¹; $r^2 = 0.88$). However, unlike the observations of Lewinski et al. (2015), performance on the acceleration phases of the combat-rush simulation (5 and 10 m) was unrelated to loading, although the control trial was also a loaded state (19.1 kg). Nevertheless, the overall performance was affected, and the relative decrement was 1.58%·kg⁻¹ ($r^2 = 0.81$). Finally, both the vertical jump (–1.33%·kg⁻¹; $r^2 = 0.99$) and functional balance assessments (the forward reach test) were influenced by changes in load (–0.77%·kg⁻¹; $r^2 = 0.62$), although these were much less pronounced.

Summary

As one might predict, the impact of protective clothing, equipment, and load carriage translates into job-related performance decrements. Whilst we have only focussed here upon endurance and mobility, other changes will occur. There will also be significant environmental interactions in the field, and these need to be considered when evaluating occupational demands and testing. With regard to predictions of acceptable working times, there needs to be a continual refinement of all relevant aspects of strain, such that reasonable times for occupational task completion may be derived from the most relevant and applicable research.

Conclusions

In the context of employment standards and cut-scores, several important themes emerge to guide researchers in the processes of task and trade analysis, and in the development of valid and equitable evaluations of readiness for duty. Firstly, it is clear that load carriage has a negative impact across a wide range of physiological and performance attributes, although that reduction cannot wholly be explained on the basis of mass. Indeed, it is also related to the system of load carriage and how the load is distributed around the body. Secondly, fractional analysis of physiological strain due to load carriage is required to determine the source(s) of diminished performance, for it is only through that knowledge that effective intervention strategies can be implemented. Thirdly, the balance between increased protection and decreased performance must be considered. This double-edged sword requires careful consideration by managers, and it demands that researchers actively explore the possibility for different equipment, or equipment modifications, to improve work performance and to reduce physiological strain and workplace injuries. Should these alternatives not be viable, then researchers must closely replicate the actual load carriage conditions rather than simply simulating the mass of occupationally relevant load carriage. Finally, factors such as body size and gender may interact with the effects of absolute loads on performance, with some gender-related differences in performance being explained simply on the basis of variations in body size. These important themes should be applied to research that is focussed on the development of new screening tests and cut-scores, and they should also lead to a careful reflection on, and possibly a reevaluation of, the relevance of existing tests and standards for occupations in which load carriage is obligatory.

The weight of evidence leads inevitably to the conclusion that load carriage creates a unique set of physiological stresses during work, and these need to be reproduced during both the characterisation of those stresses in the workplace, and when evaluating the work-related capability of potential and incumbent employees. Depending upon the performance variables of interest, the first approach would be to faithfully reproduce the load conditions observed within the working environment. If that is not feasible, then gradual deviations away from the actual loaded conditions may be considered. However, such departures have the potential to erode the validity of those assessments, and researchers need to understand the impact of such outcomes on the defensibility of readiness-for-work assessments. Finally, it is highly unlikely that an accurate evaluation of one's loaded working capability is possible when evaluated in an unloaded state.

Conflict of interest statement

The authors report no conflicts of interest.

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