Influences of body composition upon the relative metabolic and cardiovascular demands of load-carryage

Jason Lyons, Adrian Allsopp and James Bilzon

Aim
To test the hypothesis that measures of aerobic fitness, body mass and indices of body composition will influence the metabolic and cardiovascular demands of simulated load-carryage tasks.

Method
Twenty-eight healthy male volunteers, following assessment of maximal oxygen uptake (\(\dot{V}O_2\max\)) and body composition, walked on a treadmill at 4 kph (1.11 m/s) for 60 min on gradients of 0, 3, 6 and 9% whilst carrying backpack loads of 0, 20 and 40 kg. During the final 3 min of each 5-min exercise bout, indirect respiratory calorimetry and heart rate data were collected and the ‘steady-state’ metabolic \(\dot{V}O_2\) and cardiovascular (heart rate) demands quantified.

Results
Absolute \(\dot{V}O_2\max\) (ml/min) produced the strongest correlation (\(r = -0.64, P < 0.01\)) with the metabolic demand of heavy load-carryage (40 kg). The body composition index lean body mass/(fat mass + external load) produced a moderate correlation (\(r = -0.52, P < 0.01\)) with the metabolic demand of heavy load-carryage. The increases in metabolic and cardiovascular demands were greater when the load carried increased from 20 to 40 kg compared with 0 to 20 kg at all four gradients. A model incorporating anthropometric and physiological characteristics with gradient and load explains 89% of the variability in the metabolic demands of load-carryage compared with 82% using gradient and load alone.

Conclusion
The results show that indices of body composition as well as absolute aerobic power influence the relative metabolic demands of load-carryage. Application of these measurements would ensure selection criteria for load-carryage occupations are based on lean muscle mass rather than running speed.

Key words
Absolute \(\dot{V}O_2\max\); body composition; cardiovascular demand; fitness tests; lean body mass/dead mass ratio; load-carryage; metabolic demand; occupational relevance.

Introduction
The ability to carry heavy loads for prolonged periods of time is a core functional competency for many occupations including fire fighters, construction workers, rescue workers and military personnel. The ability to predict accurately prolonged load-carryage capability using surrogate tests is essential, both for selection and annual fitness assessment of personnel. Many organizations currently use field tests of aerobic fitness (e.g. timed 2.4-km run, multistage fitness test) to predict occupational fitness. Whilst there is substantial evidence that load-carrying performance is closely associated with measures of aerobic fitness [1–4], these factors are often ignored in commonly used field tests [5–7]. Indeed, such tests are not sensitive enough to predict prolonged load-carryage capability on an individual basis.

A number of studies have clearly demonstrated that such non-load-carrying aerobic fitness tests impose a systematic bias against heavier personnel [8,9], some of whom may outperform lighter subjects during prolonged, heavy load-carryage tasks [10]. As such, measures of body mass and/or body composition may be important in improving the sensitivity of fitness test criteria.

Whilst body mass may be important in predicting prolonged load-carryage capability [11], it would seem logical that indices of body composition would be more sensitive predictors. Indeed, a high lean body mass is strongly correlated with absolute maximal oxygen uptake (\(\dot{V}O_2\max\)) and has previously been shown to predict load-carryage performance [12]. In addition, body fat is
‘dead weight’ when performing load-bearing activities and has previously been observed to impair performance during load-carrying tasks [13].

The aim of this study was to measure the metabolic and cardiovascular demands of simulated load-carrying tasks and test the hypothesis that measures of aerobic fitness and indices of body composition will be related to these demands.

**Methods**

Twenty-eight \( n = 28 \) healthy male volunteers acted as subjects for this study, which was carried out with ethical approval. All experimental measures were performed in an environmental chamber at a temperature of 20°C, relative humidity of 36% and an air velocity of 0.5 m/s.

Each subject walked at 4 kph for a total of 60 min (12 × 5-min stages) whilst wearing lightweight clothing. Heart rate was recorded at 5-s intervals throughout. Each subject performed 5 min of exercise on a 0, 3, 6 and 9% gradient (20 min) whilst carrying no load. After a 20-min recovery period subjects donned a 20-kg backpack and repeated the experimental procedure. After a further 20-min recovery period, the experiment was repeated whilst carrying 40 kg.

During the final 3 min of each 5-min exercise period, expired gases were collected and analysed at 20-s intervals and measures of expired gas volume \((\dot{V}E)\), oxygen uptake \((\dot{V}O_2)\) and carbon dioxide production \((\dot{V}CO_2)\) were calculated. Subjects were also asked to give their perceived rating of exertion at the end of each 5-min exercise period [16].

The ‘steady-state’ \( \dot{V}O_2 \) (ml/min) data were expressed relative to body mass (ml/kg/min) and \( \dot{V}O_2\text{max} \) (% \( \dot{V}O_2\text{max} \)). LBM: ‘dead mass’ (DM) ratio was calculated from the following formula: 

\[
\text{LBM/DM ratio} = \frac{\text{lean body mass}}{\text{fat mass} + \text{external load}}.
\]

This yielded a LBM/DM ratio of 2.1 (0.3) for 20 kg external load and was considered statistically significant if \( P < 0.05 \).

Relationships between the subjects’ physiological responses to the experimental conditions and their physical characteristics were assessed using the Pearson Product Moment correlation. Further multivariate analyses were performed using multiple linear regression techniques. Differences between group mean data were assessed by analysis of variance (ANOVA) for repeated measures techniques. Differences and correlations were considered statistically significant if \( P < 0.05 \).

**Results**

Mean (standard deviation; SD) physical characteristics of the subjects were as follows: age 30 (4) years; height 177 (6) cm; body mass 80.3 (9.2) kg. Skinfold measurements [14] allowed estimation of percentage body fat (15.4 (4.3)%). Nude body mass was then determined (Sartorius ISI 20, Göttingen, Germany) allowing lean body mass (LBM; 67.7 (6.7) kg), fat mass (FM; 12.6 (4.4) kg) and LBM/DM ratio (6.0 (2.2)) to be derived. The maximal oxygen uptake \((\dot{V}O_2\text{max})\) was 54.4 (5.1) ml/kg/min and heart rate (HRmax; 191 (8) b/min) of each subject was then determined during uphill treadmill running [15].

When marching at 4 kph with no load on the 0% gradient the mean (SD) metabolic demand was equivalent to 20% (±3%) \( \dot{V}O_2\text{max} \). Further increases were observed when the external load was increased to 40 kg, with the mean metabolic demand increasing to 51% (±5%) \( \dot{V}O_2\text{max} \) on the 9% gradient. Figure 1 shows the mean steady-state absolute metabolic demand \((\dot{V}O_2\text{ml/min})\) of all phases of the experiment. The mean increases in metabolic demand (ml/min) from carrying 0 kg to carrying 20 kg was equivalent to 135, 183, 214 and 274 on the 0, 3, 6 and 9% gradients, respectively. However, the mean increases in metabolic demand (ml/min) were markedly greater \((P < 0.01)\) from carrying 20 to 40 kg, and were equivalent to 217, 282, 365, 452 on the 0, 3, 6 and 9% gradients, respectively.

The variables producing the strongest correlations with the metabolic demands of the 40-kg load-carrying experiment on the 0% gradient were absolute \( \dot{V}O_2\text{max} \) \((r = -0.76, P < 0.01)\) and the LBM/DM ratio \((r = -0.60, P < 0.01)\). These variables also produced the strongest correlation when the gradient was increased to 9% (Table 1).

Using multiple linear regression techniques and the whole data set, the variables producing the strongest correlation with the metabolic demand (% \( \dot{V}O_2\text{max} \)) of load-carrying tasks were gradient, external load, absolute \( \dot{V}O_2\text{max} \), LBM, FM and LBM/FM ratio. The following

**Figure 1.** Mean (SD) absolute steady-state metabolic demand \((\dot{V}O_2\text{ml/min})\) of the 0 kg (○), 20 kg (●) and 40 kg (□) load-carrying experiments \((n = 28)\).
equation produced a strong correlation \( (r = 0.94, P < 0.01) \) with \( \%\dot{V}O_2\text{max} \) and a standard error of the estimate (SEE) of 3.15% \( \dot{V}O_2\text{max} \):

\[
\%\dot{V}O_2\text{max} = 26.99 + (2.01 \times \text{gradient}) + (0.36 \times \text{load}) - (0.007 \times AVO2) + (0.24 \times LBM) + (0.24 \times FM) + (0.44 \times LBDM) \tag{1}
\]

where \text{gradient} is the treadmill gradient (%), \text{load} is the external load carried (kg), \text{AVO2} is absolute maximal oxygen uptake (ml/min), \text{LBM} is lean body mass (kg), \text{FM} is fat mass (kg) and \text{LBDM} is lean body mass divided by dead mass. The overall variance accounted for by this equation (89%) was improved by 7% by the inclusion of the anthropometric and physiological characteristics compared with gradient and load alone (82%).

Figure 2 shows the mean (SD) heart rate responses of the subjects during all phases of the experiment. As with the metabolic demands of exercise, the mean increase in heart rate was greater \( (P < 0.01) \) from carrying 20 to 40 kg on the 0% (9.5 b/min), 3% (12.4 b/min), 6% (18.1 b/min) and 9% (22.5 b/min) gradients, compared with the mean increase from 0 to 20 kg on the 0% (5.5 b/min), 3% (6.8 b/min), 6% (9.6 b/min) and 9% (12.7 b/min) gradients. Corresponding ratings of perceived exertion (RPE) increased from a mean of 6 when carrying no load on the 0% gradient through to 15 when carrying 40 kg on the 9% gradient.

When carrying the 40 kg load on the 0% gradient, both absolute \( \dot{V}O_2\text{max} \) \( (r = -0.49, P < 0.01) \) and the LBM/DM ratio \( (r = -0.54, P < 0.01) \) produced strong correlations with steady-state heart rate (Table 2).

### Discussion

The main finding of this study was that absolute maximal oxygen uptake (\( \dot{V}O_2\text{max} \)) and the LBM/DM ratio were the two variables most closely associated with the \( \%\dot{V}O_2\text{max} \) and cardiovascular demands of heavy (40 kg) load-carriage tasks. Together these variables produced a moderate correlation with the relative metabolic demands \( \%\dot{V}O_2\text{max} \) of the 40-kg load-carriage task \( (r = 0.64, P < 0.01) \). In comparison, relative \( \dot{V}O_2\text{max} \) (ml/kg/min), which is currently used by many organizations to predict the fitness of personnel for load-carriage tasks, produced a weaker correlation with the metabolic demands \( \%\dot{V}O_2\text{max} \) of the 40-kg load-carriage task \( (r = -0.50, P < 0.01) \).

The ability of personnel to carry heavy loads has been the subject of interest for many years [17,18]. It is now well established that the energy expenditure per kg of load carried is equal to the energy expenditure per kg of body weight up to approximately 30 kg [19,20]. The present data are supportive of this notion, which explains why the metabolic demands \( \%\dot{V}O_2\text{max} \) of the 0- and 20-kg load-carriage tasks were closely associated with relative \( \dot{V}O_2\text{max} \) (ml/kg/min). However, it has also been suggested that, when carrying increasingly heavier loads, humans become less efficient and the energy expenditure per kg of load increases sharply [21]. The present data are consistent with this view. This may explain why, during the present study, the correlation between the metabolic demand \( \%\dot{V}O_2\text{max} \) of exercise
and absolute $\dot{V}O_2\text{max}$ (ml/min) became progressively stronger as the load increased. As the load increases and subjects become less efficient, a high absolute $\dot{V}O_2$ (ml/min) reserve is essential for heavy load-carryage tasks.

Whilst increases in body mass may be disadvantageous when performing non-load-carrying activities (e.g. running), they may be advantageous for heavy load-carryage activities. However, the current data clearly demonstrate that body composition, rather than total body mass, is more closely associated with the metabolic demands ($\%\dot{V}O_2\text{max}$) of heavy load-carryage tasks. By expressing the body composition data as a ratio of LBM to ‘dead mass’ (DM = fat mass + external load), strong correlations with the metabolic demands ($\%\dot{V}O_2\text{max}$) of the 40-kg load-carryage tasks were observed. This novel body composition index has not, to our knowledge, previously been published. Physiologically, it follows that the more LBM an individual has available to carry the DM, the relative demands of the task will be the lower.

From the results of this study, it is concluded that measures of body composition (LBM/DM ratio) and absolute $\dot{V}O_2\text{max}$ (ml/min) are important factors, as opposed to measures of relative $\dot{V}O_2\text{max}$ (ml/kg/min), when assessing the physical capacity of personnel for heavy load-carryage tasks. These factors influence the metabolic need of load-carryage in addition to the effects from gradient and load.

Whilst we acknowledge that the study population was relatively fit and lean (mean BMI 25.5 kg/m$^2$), our conclusions are more likely to apply to other diverse groups. This work should be extended to investigate whether there are similar relationships between the metabolic cost of load-carryage and body composition for females. Application of these measurements would ensure the selection of personnel on the basis of lean muscle mass rather running speed for occupations which utilize a high oxygen consumption during load-carryage.

### Acknowledgements

The authors are grateful to the Royal Marine and British Army personnel who volunteered as subjects for this study. The authors would also like to acknowledge the advice and support of Dr R. J. Pethybridge and Professor M. J. Tipton. This work was sponsored by the Ministry of Defence (Navy).

### Table 2. Correlations between the steady-state heart rate responses to exercise (b/min) and various physical characteristics and measures of maximal oxygen uptake ($n = 28$)

<table>
<thead>
<tr>
<th></th>
<th>0 kg</th>
<th>0%</th>
<th>20 kg</th>
<th>0%</th>
<th>40 kg</th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body fat (%)</td>
<td>0.29</td>
<td>0.35</td>
<td>0.35</td>
<td>0.48*</td>
<td>0.42*</td>
<td>0.39*</td>
</tr>
<tr>
<td>$\dot{V}O_2\text{max}$ (ml/kg/min)</td>
<td>$-$0.33</td>
<td>$-$0.38*</td>
<td>$-$0.38*</td>
<td>$-$0.58**</td>
<td>$-$0.48**</td>
<td>$-$0.55**</td>
</tr>
<tr>
<td>$\dot{V}O_2\text{max}$ (ml/min)</td>
<td>$-$0.18</td>
<td>$-$0.10</td>
<td>$-$0.28</td>
<td>$-$0.37</td>
<td>$-$0.49**</td>
<td>$-$0.52**</td>
</tr>
<tr>
<td>LBM (kg)</td>
<td>$-$0.04</td>
<td>0.06</td>
<td>$-$0.13</td>
<td>$-$0.12</td>
<td>$-$0.32</td>
<td>$-$0.29</td>
</tr>
<tr>
<td>LBM/DM</td>
<td>$-$0.14</td>
<td>$-$0.20</td>
<td>$-$0.33</td>
<td>$-$0.45*</td>
<td>$-$0.54**</td>
<td>$-$0.52**</td>
</tr>
</tbody>
</table>

Data are included for the 0 and 9% gradient phases of exercise whilst carrying 0, 20 and 40 kg. Symbols denote a significant relationship: *$p < 0.05$; **$p < 0.01$.

### References