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ORIGINAL ARTICLE

The impact of thoracic load carriage up to 45 kg on the cardiopulmonary response to exercise

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Abstract

Purpose The purposes of this experiment were to, first, document the effect of 45-kg thoracic loading on peak exercise responses and, second, the effects of systematic increases in thoracic load on physiological responses to submaximal treadmill walking at a standardized speed and grade.

Methods On separate days, 19 males (age 27 ± 5 years, height 180.0 ± 7.4 cm, mass 86.9 ± 15.1 kg) completed randomly ordered graded exercise tests to exhaustion in loaded (45 kg) and unloaded conditions. On a third day, each subject completed four randomly ordered, 10-min bouts of treadmill walking at 1.34 m s^{-1} and 4 % grade in the following conditions: unloaded, and with backpacks weighted to 15, 30, and 45 kg.

Results With 45-kg thoracic loading, absolute oxygen consumption ($\dot{V}O_2$), minute ventilation, power output, and test duration were significantly decreased at peak exercise. End-inspiratory lung volume and tidal volume were significantly reduced with no changes in end-expiratory lung volume, breathing frequency, and the respiratory exchange ratio. Peak end-tidal carbon dioxide and the ratio of alveolar ventilation to carbon dioxide production were similar between conditions. The reductions in peak physiological responses were greater than expected based on previous research with lighter loads. During submaximal treadmill exercise, $\dot{V}O_2$ increased ($P < 0.05$) by 11.0 (unloaded to 15 kg), 14.5 (15–30 kg), and 18.0 % (30–45 kg) showing that the increase in exercise $\dot{V}O_2$ was not proportional to load mass.

Conclusion These results provide further insight into the specificity of physiological responses to different types of load carriage.

Keywords Thoracic load carriage · Oxygen demand · Ventilation · Breathing pattern · Occupational physiology · Performance

Abbreviations

f_B	Breathing frequency
EELV	End-expiratory lung volume
EILV	End-inspiratory lung volume
FEV_1	Forced expired volume in 1 second
FPE	Fire protective ensemble
FVC	Forced vital capacity
IC	Inspiratory capacity
P_aCO_2	Partial pressure of arterial carbon dioxide
$P_{ET}CO_2$	Partial pressure of end-tidal carbon dioxide
RER	Respiratory exchange ratio
$\dot{V}_A$	Alveolar ventilation
$\dot{V}CO_2$	Carbon dioxide production
$\dot{V}O_2$	Oxygen consumption
V_T	Tidal volume

Introduction

Many physically demanding occupations, such as infantry and search and rescue and some recreational activities (e.g., mountaineering), involve very heavy load carriage.

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Loads may consist of protective clothing, weapons, tools, medical supplies or other mission-essential equipment, and are commonly carried with a fitted backpack. Although the backpack is one of the most practical forms of load carriage, there are physiological and performance consequences to thoracic load carriage. Metabolic rate must increase to support the additional weight, and others have developed predictive equations to estimate the effect of load on metabolic rate during exercise (Givoni and Goldman 1971; Taylor et al. 2012). For example, Taylor et al. (2012) suggested that the oxygen cost of exercise with moderate to heavy loads (~20 kg) will be increased by approximately 17 mL per kg of added mass during level walking or bench stepping. It is unknown whether this prediction can be confidently applied to other exercise conditions or loads of different mass.

Load carriage increases physiological strain and reduces work capacity (Ruby et al. 2003; Taylor et al. 2012). Phillips et al. (2016b) reported a reduction in graded exercise test duration of nearly 30 % with a 25-kg pack, while peak minute ventilation and oxygen uptake were only reduced by 2.2 and 2.5 %, respectively. Louhevaara et al. (1995) reported similar findings during graded exercise with fire protective ensemble weighing 26 kg. Both concluded that the weight of the external load carriage reduced treadmill performance, however, the cardiopulmonary system was not severely impacted, and the physiological reserve for exercise was well maintained. These results suggest that with loads of similar mass, exercise performance will be reduced by approximately 1 % for every added 1 kg of load despite minimal (<5 %) reduction of peak physiological responses (e.g., peak ventilation and oxygen consumption).

It is very common for infantry to carry very heavy loads up to 45 kg or more during ground operations (Knapik et al. 2004; Epstein et al. 2013). There is no universally accepted classification of load carriage mass; however, we suggest that loads of this mass should be described as *very* heavy. Although there is a developing body of the literature investigating the physiological responses to external load carriage, there is limited research reporting the effects of very heavy load carriage on physiological responses to treadmill exercise. The first purpose of this study was to compare physiological responses during graded treadmill tests to exhaustion with and without 45-kg thoracic load carriage. The second purpose was to document the effects of progressive increases in thoracic load (unloaded, 15, 30 and 45 kg), using properly fitted and loaded backpacks, on physiological responses to treadmill walking at a standardized speed and grade.

Methods

Subjects

Nineteen healthy, non-smoking active males (mean ± SD, age 27 ± 5 years, height 180.0 ± 7.4 cm, mass 86.9 ± 15.1 kg) provided written informed consent to participate in the study, which was approved by the University of Alberta Health Research Ethics Board.

Experimental design

This within-subject, repeated measures study was completed in two parts. Part I included two randomly ordered graded exercise tests to exhaustion in unloaded and 45-kg conditions on separate days. For Part II, subjects completed four randomly ordered exercise bouts in the following conditions: unloaded; and while wearing the same correctly sized and fitted 80-L backpacks (Arc'teryx Bora 80, North Vancouver, BC, Canada) weighted to 15, 30, and 45 kg. All 19 subjects completed Part I; however, one subject was not available to complete Part II; therefore, results for Part II were reported for 18 participants. Each subject was carefully sized and fitted for the correct pack before the experiment. Pack sizing (e.g., strap tightness and frame size) was documented to ensure consistent fitting during all loaded test conditions. The control condition involved unloaded exercise without a pack. Subjects were dressed in the same exercise clothing (shorts, t-shirt and running shoes) in all conditions throughout the experiment. All tests were carried out in an air-conditioned laboratory (21–23 °C) with low humidity (1–5 %).

Resting spirometry

Each subject completed randomly ordered resting pulmonary function testing (TrueOne, ParvoMedics, Salt Lake City, UT, USA) in the unloaded and 45-kg conditions, respectively, to determine forced vital capacity (FVC), forced expired volume in 1 s (FEV_1), FEV_1/FVC, and peak expiratory flow rate. Spirometry testing was performed according to the guidelines of the American Thoracic Society (Miller et al. 2005). Maneuvers were completed while standing upright with minimal forward lean.

Spirometry was also completed after the unloaded graded exercise test to screen for exercise-induced bronchoconstriction following the protocol described by Miller et al. (2005). This screening revealed no evidence of exercise-induced bronchoconstriction.

Graded exercise tests

On separate days, each subject completed, in random order, a graded exercise test in the unloaded and 45-kg conditions to measure peak oxygen uptake ($\dot{V}O_{2peak}$). The graded exercise test consisted of a constant speed (1.34 m s^{-1}) walking protocol on a motorized treadmill (Standard Industries, Fargo, ND, USA). The test began at 0 % grade with step increases of 2 % grade applied every 2 min until volitional exhaustion. A two-way breathing valve and mixing chamber was used to collect expired gases (Hans Rudolph, Kansas City, MO, USA). Expired gases and ventilatory parameters were analyzed for each breath, and data were averaged over 30-s periods with a metabolic measurement system (TrueOne, ParvoMedics, Salt Lake City, UT, USA). The highest $\dot{V}O_2$ reading averaged over 30 s was accepted as $\dot{V}O_{2peak}$. For each submaximal stage, expired gas and ventilatory parameters were averaged during the second minute to determine submaximal physiological responses. The system was calibrated according to manufacturer's guidelines prior to each test. Calibration of the gas analyzers was verified immediately following each test. Heart rate was monitored continuously using telemetry and was recorded during the last 10 s of each minute (Polar Beat, Electro, Lachine, QC, Canada). After at least 48 h of recovery, the subject completed the second graded exercise test in the alternate condition.

Power output during treadmill exercise was calculated using the equation (mass × speed × grade). The mass used included the mass of the subject and, in the loaded condition, also the mass of the pack (Phillips et al. 2016b).

Submaximal exercise protocol

On a separate day, within a single session, subjects completed separate bouts of exercise in four conditions: unloaded and while wearing a properly sized and fitted 80-L backpack weighted to 15, 30, and 45 kg. The exercise bouts consisted of 10 min of treadmill walking at 1.34 m s^{-1} and 4 % treadmill grade. Extensive pilot work revealed that walking speeds greater than 1.34 m s^{-1} were not tolerable for some subjects with the 45-kg pack during either the graded exercise test or the submaximal protocol. Exercise bouts were bracketed by standardized a warm-up (3 min) and cool-down (3 min) and were separated by 10 min of rest. For each exercise bout, expired gas and heart rate data were collected as previously mentioned. The $\dot{V}O_2$ in the final 5 min of each exercise bout was averaged and reported. It is important to note that a steady-state $\dot{V}O_2$ was achieved, and there was no significant different between the 6th and 10th minute readings in any of the conditions. During the rest periods, subjects were permitted to consume up to 125 mL of cool water.

Ventilation and lung volumes

For Part I, deadspace ventilation was determined from the difference between minute ventilation and alveolar ventilation ($\dot{V}_A$) as described by West (2008). Alveolar ventilation was estimated using:

$$P_aCO_2 = \left(\dot{V}CO_2/\dot{V}_A\right) \cdot K$$

In this equation, K is a conversion factor used to adjust carbon dioxide production ($\dot{V}CO_2$) to body temperature and pressure. Due to the difficulty of determining arterial carbon dioxide partial pressure (P_aCO_2), pressure of end-tidal carbon dioxide ($P_{ET}CO_2$) was assumed to be equal to P_aCO_2 (Stickland et al. 2013).

End-tidal CO_2 was measured (R-1 pump, P-61B sensor and CD-3A CO_2 analyzer, AEI Technologies Naperville, IL, USA) from a small port off of the mouthpiece collected through a drying line. End-tidal CO_2 data were recorded with a data acquisition system (Powerlab 8/35, AD Instruments, New South Wales, Australia) and stored for subsequent analysis.

Operating lung volumes were determined from measurements of inspiratory capacity taken at rest and during the last 30 s of each 2-min stage on the graded exercise test. An inspiratory pneumotach (ParvoMedics, Sandy, UT, USA) attached to the two-way breathing valve was used to measure inspired volume. End-expiratory lung volume (EELV) was calculated by subtracting inspiratory capacity from FVC obtained at rest. End-inspiratory lung volume (EILV) was then estimated by adding tidal volume (V_T) and EELV. Tidal volume was recorded during the 30 s leading up to the inspiratory capacity maneuver and then averaged. Changes in EELV and EILV were expressed as a percentage of FVC. The determination of operating lung volume is dependent on the correct performance and analysis of the inspiratory capacity maneuver. Although esophageal pressures were not measured to help confirm a complete inspiratory capacity (Guenette et al. 2007), each subject completed extensive practice of the maneuver during exercise prior to the experimental protocols to improve validity and reliability of the IC measurements. During analysis, volume was corrected for any pneumotachometer drift that may have occurred by selecting six breaths prior to the maneuver and "zeroing" expiratory volume (Johnson et al. 1999; Phillips et al. 2016a).

Perceived exercise stress

Perceived exercise stress was recorded at the end of every 2-min stage during the graded exercise test (Part I) and at 5- and 10-min during each constant speed and grade exercise bout (Part II) using the modified Borg perceived exertion scale (Borg 1982). This scale is anchored such that 0 represents "no exercise stress" and 10 represents "maximal exercise stress." (Borg 1982; O'Donnell et al. 2000).

Data analysis

Data are presented as mean ± standard error (SE) unless otherwise indicated. Two-way, repeated-measures analysis of variance was used to compare the effect of load carriage to the unloaded control on key dependent variables at rest and during exercise. If a significant change or interaction effect was found, Tukey's post hoc test was used to locate each difference. Paired Student's *t* tests were used to detect any differences in pulmonary function test results and the difference in selected variables of interest during graded exercise tests in Part I. For Part II, measured $\dot{V}O_2$ data were compared to the previously published prediction equations of Taylor et al. (2012) and Givoni and Goldman (1971) using paired Student's *t* tests. Pearson product-moment correlation was used to examine relationships between variables of interest. All statistical analyses were performed using Sigma Plot Software version 13.0 (Systat Software Inc., Chicago, USA). Significance was set a priori at $P < 0.05$.

Results

Part I

Pulmonary function

Results of resting pulmonary function are shown in Table 1. In the unloaded condition, all subjects had normal spirometry values (>80 % predicted). With 45-kg thoracic loading, FVC and FEV_1 were reduced by 5.0 and 5.8 %, respectively, compared to the unloaded condition. Peak expiratory flow rates and FEV_1/FVC were not different between conditions.

Graded exercise

Figure 1 shows the oxygen cost during graded exercise in both conditions. At rest and throughout exercise at matched treadmill speed and grades, oxygen uptake was significantly higher in the loaded condition with the differences becoming progressively greater at steeper grades. At comparable submaximal oxygen uptakes, minute ventilation was always higher under load. The increase in minute ventilation was secondary to altered breathing pattern (shallow and frequent) and increased deadspace ventilation (Figs. 2, 3). As expected, alveolar ventilation was the same between conditions at similar oxygen demands throughout graded exercise (Fig. 3). At comparable oxygen uptakes (2.0, 2.5 and 3.0 L min^{-1}) during graded exercise, perceived exercise stress was significantly higher (3.6 ± 0.4 vs. 3.0 ± 0.4, 5.1 ± 0.4 vs. 4.2 ± 0.3 and 6.7 ± 0.5 vs. 5.5 ± 0.4 Borg units, respectively) in the loaded condition.

Table 1 Mean (±SE) resting pulmonary function ($n = 19$)

Variable	Unloaded	45 kg
FVC (L)	6.00 (0.22)	5.70 (0.21)^a
FEV_1 (L)	4.80 (0.16)	4.52 (0.15)^a
FEV_1/FVC	0.80 (0.02)	0.80 (0.02)
PEFR (L s^{-1})	10.30 (0.38)	10.23 (0.36)

FVC forced vital capacity, *FEV_1* forced expired volume in 1 s, *PEFR* peak expiratory flow rate

[a] $P < 0.05$ between conditions

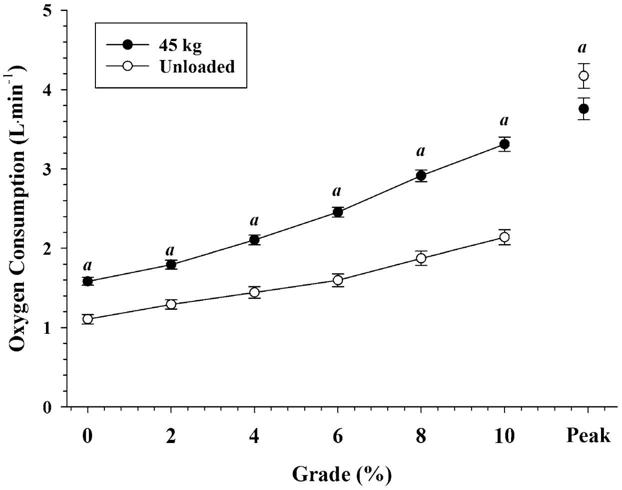

Fig. 1 Mean ± SE oxygen consumption during graded exercise in loaded (*closed symbols*) and unloaded (*open symbols*) conditions. $^a P < 0.05$ between conditions. $n = 19$

Figure 4 shows operating lung volume during graded exercise at similar ventilation rates. While standing at rest, EELV was reduced under load with no difference in EILV when compared to the control. From standing rest to exercise and thereafter to exhaustion, EELV did not change in the loaded condition. During exercise, EILV was significantly lower in the loaded condition at any given minute ventilation.

Peak physiological responses

The physiological responses to peak exercise are shown in Table 2. With 45-kg thoracic loading, $\dot{V}O_{2peak}$, alveolar and minute ventilation were significantly decreased. End-inspiratory lung volume and tidal volume were also significantly reduced with no change in end-expiratory lung volume, breathing frequency (f_B), and the respiratory exchange ratio. Peak end-tidal carbon dioxide and the ratio of alveolar ventilation to carbon dioxide production were similar between conditions. The rating of perceived exertion was the same between conditions at peak exercise. Test duration was substantially reduced by 45 ± 1 % in the loaded condition. There was no association between the change in $\dot{V}O_{2peak}$ between conditions and body size (height or mass) or aerobic fitness ($\dot{V}O_{2peak}$); however, there was a strong negative correlation ($r = -0.80$) between body mass and the change in test duration between load and unloaded conditions.

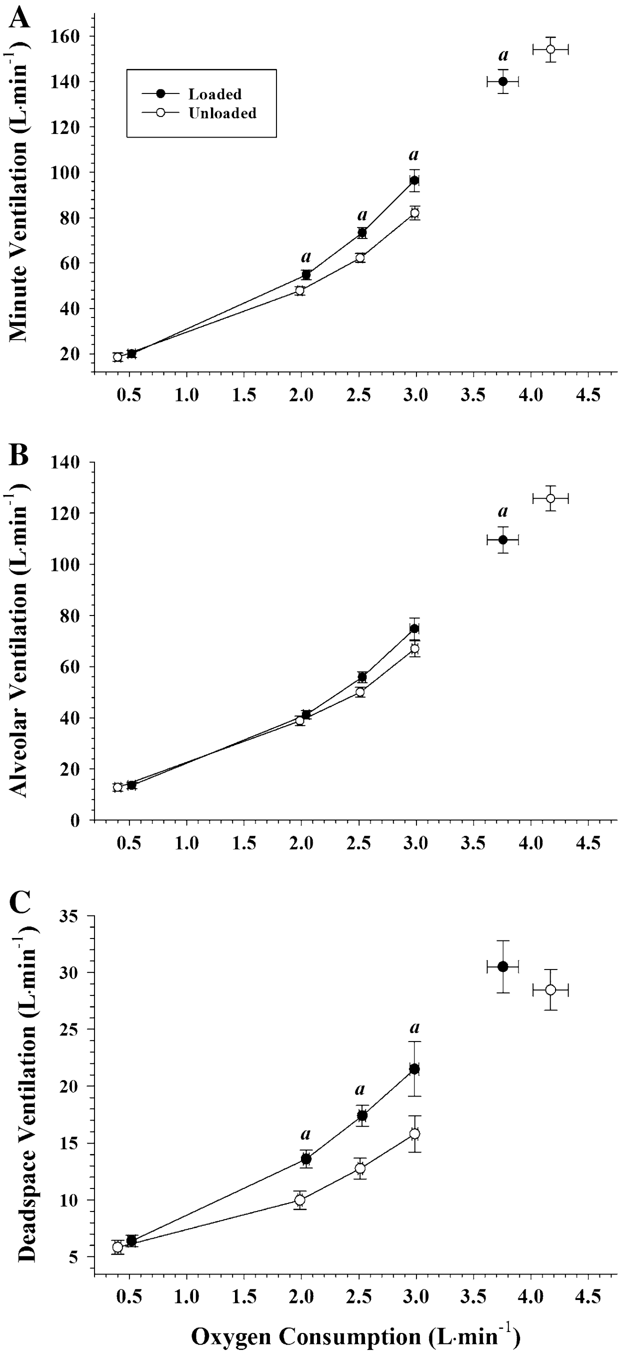

Fig. 2 Mean ± SE **a** minute ventilation, **b** alveolar ventilation, and **c** deadspace ventilation during graded exercise in loaded (*closed symbols*) and unloaded (*open symbols*) conditions. $^{a}P < 0.05$ between conditions. $n = 19$

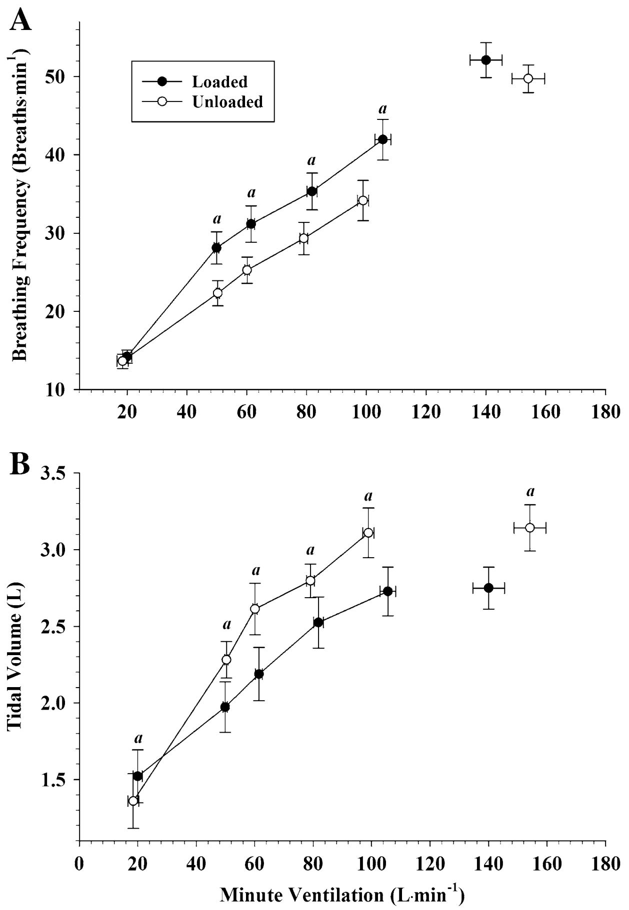

Fig. 3 Mean ± SE (**a**) breathing frequency and (**b**) tidal volume during graded exercise in loaded (*closed symbols*) and unloaded (*open symbols*) conditions. $^{a}P < 0.05$ between conditions. $n = 19$

Part II

Progressive thoracic loading during submaximal exercise

During submaximal treadmill exercise at a constant speed and grade, $\dot{V}O_2$ increased ($P < 0.05$) by 11.0 (unloaded to 15 kg), 14.5 (15–30 kg) and 18.0 % (30–45 kg) (Table 3). When normalized to total mass (body mass + backpack), $\dot{V}O_2$ was reduced ($P < 0.05$) by 4.4 % with the 15-kg pack and increased ($P < 0.05$) by 5.6 % with the 45-kg pack, when compared to unloaded (Table 3). The oxygen cost of carrying the pack was 10.1 ± 1.2, 14.0 ± 1.0 and 18.0 ± 1.0 mL $kg^{-1}_{pack\ mass}$ in the 15-, 30-, and 45-kg test conditions, respectively. When comparing our results to

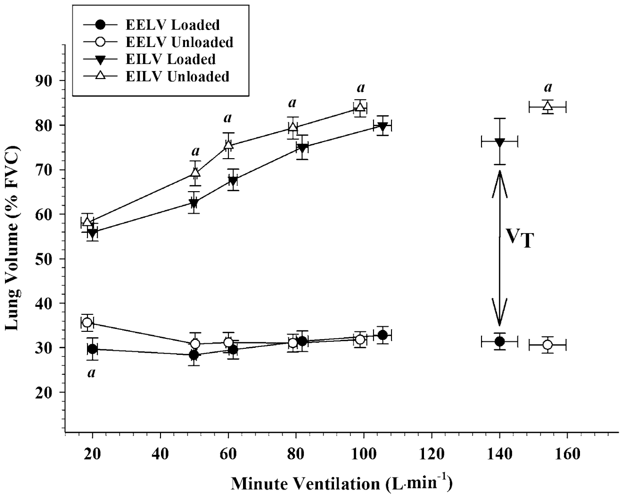

Fig. 4 Mean ± SE operating lung volumes during graded exercise to exhaustion. *EELV* end-expiratory lung volume, *EILV* end-inspiratory lung volume, V_T tidal volume. $^aP < 0.05$ between conditions. $n = 19$

Table 2 Mean (±SE) peak physiological and performance responses from graded exercise test to exhaustion ($n = 19$)

Variable	Unloaded	45 kg
$\dot{V}O_{2peak}$ (L min^{-1})	4.17 (0.14)	3.76 (0.13)^a
$\dot{V}O_{2baseline}$ (L min^{-1})	0.42 (0.10)	0.52 (0.12)^a
$\dot{V}O_{2reserve}$ (L min^{-1})	3.75 (0.13)	3.24 (0.11)^a
$\dot{V}CO_{2peak}$ (L min^{-1})	4.73 (0.15)	4.32 (0.14)^a
$\dot{V}_E$ (L min^{-1})	154.1 (5.0)	140.0 (5.0)^a
$\dot{V}_A$ (L min^{-1})	125.3 (4.6)	109.6 (4.8)^a
$\dot{V}_D$ (L min^{-1})	28.9 (1.6)	30.5 (2.2)
$\dot{V}_E/\dot{V}O_2$	37 (1)	38 (1)
$\dot{V}_E/\dot{V}CO_2$	41 (1)	44 (1)^a
$\dot{V}_A/\dot{V}CO_2$	26 (1)	25 (1)
$P_{ET}CO_2$ (mmHg)	32.6 (0.8)	33.7 (0.9)
f_B (breaths·min^{-1})	50 (2)	52 (2)
V_T (L)	3.14 (0.15)	2.75 (0.13)^a
RER	1.14 (0.02)	1.15 (0.02)
Heart rate (beats min^{-1})	183 (3)	179 (3)^a
Perceived exertion (0–10)	8.5 (0.2)	8.8 (0.2)
Power output (W)	290 (13)	240 (12)^a
Test duration (s)	1485 (56)	792 (25)^a

$\dot{V}O_2$ oxygen consumption, $\dot{V}O_{2reserve}$ $\dot{V}O_{2peak} - \dot{V}O_{2baseline}$, $\dot{V}CO_2$ carbon dioxide production, $\dot{V}_E$ minute ventilation, $\dot{V}_A$ alveolar ventilation, $\dot{V}_D$ deadspace ventilation, $P_{ET}CO_2$ pressure of end-tidal carbon dioxide, f_B breathing frequency, V_T tidal volume, *RER* respiratory exchange ratio

[a] $P < 0.05$ between conditions

the prediction equations of Taylor et al. (2012) and Givoni and Goldman (1971), $\dot{V}O_2$ was significantly lower than predicted by both equations in the 15 kg (95 ± 1 and 90 ± 1 % predicted, respectively) and 30 kg (96 ± 2 and 92 ± 2 % predicted, respectively) conditions (Fig. 5). With the 45-kg pack, measured $\dot{V}O_2$ was similar to the estimated values from both prediction equations (103 ± 2 and 99 ± 3 % predicted, respectively).

Discussion

The major findings from this study are threefold. First, with 45-kg thoracic load carriage, $\dot{V}O_{2peak}$ was substantially reduced when compared to an unloaded control. This is a novel outcome, because previous investigations with lighter loads (20–26 kg) have reported only minor reductions in $\dot{V}O_{2peak}$ when compared to the unloaded control. In the present experiment, the reductions in peak physiological responses were larger than expected based on previous work (Louhevaara et al. 1995; Taylor et al. 2012; Phillips et al. 2016b; Phillips et al. 2016c). Second, 45-kg thoracic load carriage reduced the physiological reserve and increased the exercise ventilatory requirement for oxygen, secondary to an alteration in breathing pattern and operating lung volume during graded submaximal exercise. Third, with systematic increases in pack weight, there was a disproportional increase in the oxygen cost of load carriage. These results are not in complete agreement with predicted values of the oxygen cost of load carriage from previous research and suggest that load configuration and load mass must be considered when estimating metabolic demand during exercise with load carriage. These findings have important implications for occupations where very heavy load carriage is required, and suggest that physiological responses may be quite specific to the nature of load.

Peak exercise

With 45-kg thoracic load carriage, $\dot{V}O_{2peak}$ was decreased by 10 ± 1 % when compared to the unloaded control. At peak exercise, f_B was similar in both conditions; however, V_T was significantly lower with the pack. Previous reports using lighter forms of thoracic load carriage have suggested that the small reduction in $\dot{V}O_{2peak}$ may be secondary to a reduction in peak minute ventilation (Phillips et al. 2016b). In the present study, peak end-tidal carbon dioxide and the ratio of alveolar ventilation to carbon dioxide production were similar between conditions in the current study, which implies that ventilation was appropriate for metabolic demand, sufficient to maintain blood gas homeostasis and avoid alveolar hypoventilation with the very heavy pack. Although peak alveolar and minute ventilation were reduced with 45-kg thoracic loading, the reason for decreased $\dot{V}O_{2peak}$ is unclear.

Table 3 Mean (±SE) oxygen consumption during exercise at a fixed external treadmill speed (1.34 m s^{-1}) and grade (4 %) ($n = 18$)

Variable	Unloaded	15 kg	30 kg	45 kg
Oxygen consumption (mL $kg^{-1}_{totalmass}$ min^{-1})	15.8 (0.2)	15.1 (0.2)^{a}	15.4 (0.3)	16.7 (0.4)^{a,b,c}
Oxygen consumption (mL min^{-1})	1371 (62)	1533 (55)	1791 (51)^{a,b}	2183 (61)^{a,b,c}
Total change in oxygen consumption (mL min^{-1})	NA	162 (17)	420 (31)	812 (46)

[a] $P < 0.05$ compared to unloaded

[b] $P < 0.05$ compared to 15 kg

[c] $P < 0.05$ compared to 30 kg

At rest, EELV was reduced in the loaded condition, however, EELV did not change further at the onset of exercise. End-expiratory lung volume remained more or less constant throughout the graded exercise protocol and was the same between conditions up to peak exercise. The large reduction in V_T in the loaded test was the result of a reduction in EILV that became evident at light exercise and remained consistently lower until peak exercise. The results suggest that very heavy thoracic load carriage creates a substantial mechanical disadvantage and that the respiratory muscles may be heavily burdened at moderate to heavy exercise intensities. Harms et al. (2000) showed that during high-intensity cycling exercise increased respiratory muscle work causes redirection of blood flow from locomotor muscles to the respiratory muscles, through sympathetically mediated vasoconstriction. The reduced blood flow to locomotor muscles could increase perceived exertion and impair exercise performance (Sheel et al. 2001; Legrand et al. 2007; Borghi-Silva et al. 2008; Sheel and Romer 2012). In our study, perceived exertion at peak exercise was similar, despite reduced $\dot{V}O_{2peak}$ and power output under load. It is possible the heavy thoracic load burdened the respiratory muscles and reduced blood flow to locomotor muscles at near-maximal exercise intensities, resulting in increased perceived exertion and early termination of exercise. Although our submaximal and maximal exercise perceived exertion data are in agreement with this hypothesis, we suggest that further research, including measurements of esophageal pressure, phrenic nerve activity, and limb blood flow, is required to begin to understand the mechanism(s) behind reduced peak oxygen uptake with very heavy thoracic load carriage.

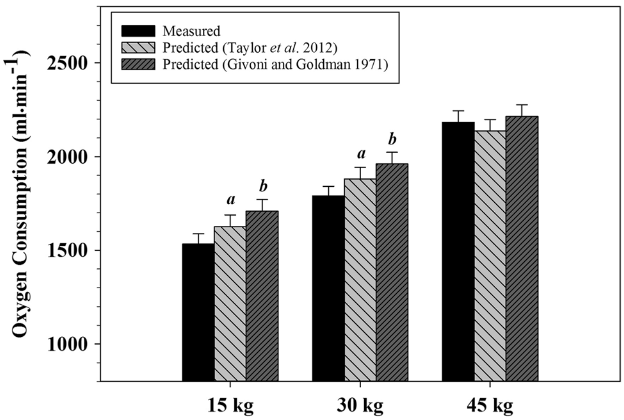

Fig. 5 Mean ± SE measured and predicted (Taylor et al. 2012; Givoni and Goldman 1971) oxygen consumption during 10 min of treadmill exercise. $n = 18$. $^{a}P < 0.05$ measured value vs. predicted value from Taylor et al. (2012). $^{b}P < 0.05$ measured value vs. predicted value from Givoni and Goldman (1971)

Ventilatory response to submaximal graded exercise

During incremental exercise, the progressive rise in minute ventilation is accomplished by increased V_T and f_B. Furthermore, increased V_T is a combination of reduced EELV and increased EILV (Sheel and Romer 2012). The exercise-induced changes in lung volume and breathing pattern are accomplished to minimize deadspace ventilation and reduce the flow-resistive work of breathing. In our study, normal breathing pattern and ventilatory responses to graded exercise were observed in the unloaded condition. Under load, these responses were altered. At rest with load, EELV was significantly lower than unloaded. During graded exercise, EELV did not change during mild, moderate, and maximal exercise intensities. The increase in V_T was accomplished entirely by increasing EILV. The reduction in V_T under load may partially be explained by the pack restricting the chest-wall and limiting EILV (Figs. 3, 4). However, we suggest that the lower V_T results from an attempt to reduce the loading-related increased inspiratory work of breathing. Logically, f_B was increased to match alveolar ventilation to metabolic demand and maintain arterial blood gas homeostasis; however, these adjustments in breathing pattern led to increased deadspace and minute ventilation under load at submaximal exercises intensities (Fig. 2). The adjustment in breathing pattern may be an effective strategy to overcome the mechanical disadvantage acutely; however, prolonged bouts of load carriage may result in significantly increased ventilatory requirement to oxygen uptake and perceived exertion. We have recently demonstrated increased minute ventilation during sustained exercise (45 min at 68 % $\dot{V}O_{2peak}$) with

25-kg thoracic load carriage (Phillips et al. 2016a, c). In that study, subjects exercising under load were able to maintain similar minute ventilation to unloaded control condition, for approximately 20 min. However, thereafter subjects developed a rapid and shallow breathing pattern that significantly increased deadspace, minute ventilation, and perceived exertion and breathing discomfort. In the infantry, carrying loads up to and exceeding 45 kg for prolonged durations up to and exceeding 60 min is common (Patton et al. 1991; Knapik et al. 2004; Faghy and Brown 2014). Our findings suggest that very heavy thoracic load carriage (45 kg) may result in a larger reduction in occupational performance then would be expected from the weight of the pack alone. We further suggest that the ventilatory responses from very heavy thoracic load carriage may have serious consequences on submaximal exercise performance and need to be considered in future research.

Physiological reserve

Heavy load carriage increases metabolic demand and lowers the energy available for locomotion (Wang and Cerny 2004; Taylor et al. 2012, 2016). With the 45-kg pack, standing baseline $\dot{V}O_2$ was elevated and $\dot{V}O_{2\text{peak}}$ was greatly reduced, which logically reduced the physiological reserve (peak − baseline) (Table 2). These results have serious implications for occupations where very heavy load carriage is required. Increased thoracic loading reduced the energy available for vertical and horizontal displacement; however, the reduced physiological reserve (decreased $\dot{V}O_{2\text{peak}}$) also decreased the total energy available for whole-body exercise. With 45-kg load carriage, the large reduction in $\dot{V}O_{2\text{peak}}$ further compounds the reduction in energy availability and may reduce exercise performance more than expected. The decrease in ambulatory reserve under load could have serious implications for occupational safety and effectiveness, and future research is required to further understand the physiological and performance consequences for very heavy (45 kg) load carriage.

The effect of body size on load carriage treadmill performance

The reduction in $\dot{V}O_{2\text{peak}}$ with thoracic loading was similar in all subjects and was not associated with height, body mass or unloaded $\dot{V}O_{2\text{peak}}$. There was, however, a strong negative association ($r = -0.80$) between the change in treadmill test duration and body mass. Interestingly, these results are somewhat different than our previous work investigating the effect of 25-kg thoracic load carriage on exercise performance (Phillips et al. 2016b). In the current study, we suggest that body mass may account for approximately 64 % of the variance in performance. Previous research suggests that heavier males and females may be only slightly advantaged during load carriage with absolute loads of 25 kg (Phillips et al. 2016b, c); however, the present results are more pronounced. These novel data demonstrate the need for testing specificity when selecting capable employees in physically demanding occupations that require very heavy load carriage.

The effect of pack weight on oxygen uptake during exercise

During constant treadmill exercise at a standardized speed and grade, we observed a disproportional increase between $\dot{V}O_2$ and pack weight. During exercise in each of the experimental conditions, the oxygen cost of load carriage varied between 15-, 30-, and 45-kg load conditions (approximately 11, 14 and 18 mL of O_2 per kg of load carried), and this observation is not consistent with the previous research (Givoni and Goldman 1971; Taylor et al. 2012).

Givoni and Goldman (1971) developed an equation to predict metabolic demand of load carriage during various forms of exercise using the following equation:

$$M = n(W + L)[2.3 + 0.32\,(V - 2.5)^{1.65} + G(0.2 + 0.07(V - 2.5))].$$

The variables included in this equation are metabolic rate (M), terrain factor (n), body mass (W), external load (L), walking speed (V), and gradient (G). Taylor et al. (2012) developed a predictive model for the oxygen cost of load carriage to be 17 mL of O_2 for every kg of extra weight carried. Although these models have been previously validated, it is unclear if they can be confidently applied to various forms of load carriage. In the experiment by Taylor et al. (2012), load carriage was in the form of fire protective ensemble (FPE). The weight distribution with FPE is different than with thoracic loading (backpack only). Other factors that affect metabolic demand during exercise, such as the hobbling effect and uncompensable heat storage with FPE (Teitlebaum and Goldman 1979; Nunneley 1989; Dorman and Havenith 2009; McLellan et al. 2013), may also contribute to that prediction model when evaluating the oxygen demand of load carriage.

There were significant differences between our measured results and the predicted values in the 15- and 30-kg conditions. In the 45-kg condition, our measured results were similar to the predicted values. As expected, in both prediction equations, the relationship between pack mass and $\dot{V}O_2$ was linear. Our measured data showed a disproportional increase in oxygen demand with systematic increases in pack weight at a constant speed and grade, and we suggest the increased metabolic demand with load carriage appears to be non-linear and specific to pack mass.

The cause for the disproportional increase is not clear, but it seems plausible that subjects altered their walking mechanics and body position with progressive increases in thoracic loading. The alteration in body position to maintain center of gravity likely potentiated a biomechanical disadvantage and a compensatory postural strategy (increased muscle activation in abdominals, lower back, hip, knee, and ankle) was adopted. The increase muscle activity in the torso may help explain the increased $\dot{V}O_2$; however, further biomechanical analysis during treadmill walking with a wide range of external load carriage is required.

Limitations

This investigation was completed with young, healthy males and as such, attempts to generalize to other demographics should be undertaken with appropriate caution. There is an emerging body of knowledge supporting a substantial degree of specificity in the physiological responses to load carriage countering the more traditional view that such responses were primarily explained by load mass (Petersen et al. 2016; Taylor et al. 2016). In occupational settings, the most contentious grounds for discrimination are age, sex, and health (Petersen et al. 2016). Our previous work has shown very similar effects on peak physiological responses and performance with thoracic loading of 25 kg in size-matched males and females (Phillips et al. 2016c). Also with 25-kg packs, there was only a moderate association between body mass and the change in test duration under load (Phillips et al. 2016b). In the current project, body mass was more strongly associated with 45-kg load carriage performance. The reference female is smaller in mass and stature and has lower peak aerobic power than the reference male (Epstein et al. 2013; Roberts et al. 2016), so based on our current observations, females may show even greater reductions in performance with very heavy load carriage than their male counterparts. To fully investigate how very heavy load carriage affects other groups (e.g., females, older individuals), more research will be required. We caution readers to not overgeneralize the current findings to different groups, such as females and older individuals.

Conclusion

The results from this investigation demonstrate the impact of thoracic load carriage up to 45 kg on the cardiopulmonary response to exercise. Results from the graded exercise test with 45-kg loads showed a larger reduction in peak physiological values than would be expected based on previous reports with lighter loads. During exercise with progressive loading (15–45 kg), increases in metabolic rate were not proportional to the changes in backpack weight. These results provide further support for the notion that physiological responses to load carriage are specific to the nature of the load. Importantly, the greater than expected erosion of the physiological reserve with very heavy load carriage should be of interest to scientists developing physical employment standards. Understanding the effects of load carriage on physiological responses to exercise can improve methods for assessment of physiological readiness for work and ultimately, improve effectiveness and safety in physically demanding occupations and recreational activities.

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Compliance with ethical standards

Conflict of interest There are no conflicts of interest.

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