



Ventilatory responses in males and females during graded exercise with and without thoracic load carriage

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Abstract

Purpose and methods To compare the effects of thoracic load carriage on the ventilatory and perceptual responses to graded exercise, 14 pairs of height-matched, physically active males and females completed randomly ordered modified Balke treadmill exercise tests with and without a correctly sized and fitted 20.4 kg backpack and work clothing. Subjects walked at 1.56 m.s⁻¹ while grade was increased by 2% every 2 min until exhaustion. Ventilatory responses were measured with open circuit spirometry and perceptual responses were evaluated using the modified Borg scale. Inspiratory capacity maneuvers were performed to calculate operating lung volumes.

Results Despite height matching, males had significantly greater lung volumes and peak oxygen uptake ($\dot{V}O_{2\text{peak}}$). Peak $\dot{V}O_2$ and ventilation (\dot{V}_E) were lower ($p < 0.05$) for all subjects under load. Throughout exercise, the ventilatory equivalents for $\dot{V}O_2$ and carbon dioxide production were significantly higher in females, independent of condition. At similar relative submaximal intensities ($\% \dot{V}O_{2\text{peak}}$), there was no difference in \dot{V}_E between conditions in either group, however, all subjects adopted a rapid and shallow breathing pattern under load with decreased tidal volume secondary to lower end-inspiratory lung volume. The relative changes in breathing pattern and operating lung volume between unloaded and loaded conditions were similar between males and females. Females reported significantly higher dyspnea ratings for a given \dot{V}_E compared to males; however, the relationship between dyspnea and \dot{V}_E was unaffected by load carriage.

Conclusion The relative response patterns for ventilatory and perceptual responses to graded exercise with thoracic loading were similar in males and females.

Keywords Thoracic load carriage · Occupational physiology · Sex differences · Ventilation · Operating lung volume · Oxygen uptake

Abbreviations

ANOVA Analysis of variance
 f_B Breathing frequency
EELV End-expiratory lung volume
EILV End-inspiratory lung volume
FEV₁ Forced expired volume in 1 s

FVC Forced vital capacity
IC Inspiratory capacity
METS Metabolic equivalent
 $P_a\text{CO}_2$ Partial pressure of arterial carbon dioxide
PEFR Peak expiratory flow rate
 $P_{\text{ET}}\text{CO}_2$ Partial pressure of end-tidal carbon dioxide
RER Respiratory exchange ratio
 $\dot{V}\text{CO}_2$ Carbon dioxide production
 \dot{V}_E Minute ventilation
 $\dot{V}O_2$ Oxygen consumption
 V_T Tidal volume

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Introduction

During incremental exercise, minute ventilation increases to raise alveolar ventilation in proportion to oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}\text{CO}_2$) to

regulate arterial blood gases. The progressive rise in minute ventilation is accomplished by increased tidal volume and breathing frequency. During mild exercise ($<50\% \dot{V}O_{2\text{peak}}$), increased minute ventilation is predominantly a result of increased tidal volume. In healthy humans, increased tidal volume is a combination of reduced end-expiratory lung volume and increased end-inspiratory lung volume. At higher exercise intensities, there is a plateau in tidal volume and minute ventilation is further increased by breathing frequency (MacParland et al. 1992). This change in operating lung volume and breathing pattern helps minimize dead space ventilation as well as both resistive and elastic work of breathing (Sheel and Romer 2012; Henke et al. 1988).

Heavy load carriage, including fitted backpacks and work clothing ensembles, has previously been shown to increase metabolic demand and reduce tolerance during weight-bearing exercise (e.g., level or uphill walking) in young healthy individuals (Phillips et al. 2016b, c; Dominelli et al. 2012; Patton 1991). Despite a large reduction in weight-bearing exercise tolerance (30%), thoracic loading up to 25 kg had only small effects on the ventilatory responses to incremental exercise and peak minute ventilation and $\dot{V}O_2$ (Phillips et al. 2016b, c, 2018; Peoples et al. 2016).

Current guidelines for best practice in the development of physical employment standards suggest that experimental results from one group of workers (e.g., males) should not be assumed to generalize to other groups (e.g., females), and this is especially true in sensitive areas such as age and sex (Petersen et al. 2016; Roberts et al. 2016; Kenny et al. 2016). Despite a growing body of work investigating ventilatory responses to exercise with thoracic load carriage, almost all of the published research has been completed in young healthy males. The results should not be generalized to females or older adults without appropriate caution, especially in physically demanding public safety occupations that require thoracic load carriage during time-sensitive responses to emergency situations. In some jurisdictions (e.g., Canada), the courts have required employers to proactively explore the potential differences between groups (e.g., age and sex) when developing physical employment standards related to physiological readiness for work (Eid 2000). As such, it is important to understand any physiological sex differences and the resulting consequences on exercise performance and occupational safety.

It has been well documented that females, on average, are smaller in mass, stature and functional capacity (Epstein 2013; Roberts et al. 2016). When compared to height-matched males, females have smaller lungs, smaller airways, increased work of breathing during exercise and decreased aerobic power (Bouwsema et al. 2017; Dominelli et al. 2015b, 2018; Tan et al. 2011). We have previously suggested that sized-matched males and females have similar reductions in graded treadmill test performance and $\dot{V}O_{2\text{peak}}$

with 25 kg load carriage (Phillips et al. 2016c). However, submaximal responses, operating lung volume and detailed gas exchange measurements were not recorded (Phillips et al. 2016c). It is possible the smaller lung size and greater respiratory muscle oxygen cost of exercise hyperpnea in females, may result in: a compensatory change in breathing pattern and operating lung volume at submaximal exercise intensities; elevated perceived dyspnea intensity; early termination of exercise; and, a larger than expected reduction in peak minute ventilation and $\dot{V}O_2$, when compared to height-matched males during exercise with thoracic load carriage.

Therefore, the purpose of this study was to compare the effects of thoracic load carriage on ventilatory responses to graded exercise in height-matched males and females. We hypothesized that the relative ventilatory responses to graded exercise with thoracic load carriage, when compared to an unloaded control, would be similar between the sexes.

Methods

Subjects

Fourteen pairs of height-matched males and females, with no known history of asthma, smoking, or cardiopulmonary disease provided informed consent to participate in the study, which had been previously approved by the appropriate institutional research ethics board. Mean \pm SD age, stature, and mass for males and females, respectively, were: 26 ± 7 vs 30 ± 6 years, $p=0.17$; 177.0 ± 4.0 vs 176.1 ± 6.6 cm, $p=0.52$; and, 79.4 ± 8.7 and 72.7 ± 11.2 kg, $p=0.04$. This study was part of a larger project examining physiological and performance consequences of thoracic load carriage in young, healthy individuals (Phillips et al. 2018). Data from 14 males and 10 females previously examined were included in the current paper. In an attempt to reduce the variance between men and women, participants were matched by height, which is consistent with previous work examining sex differences in ventilatory mechanics and pulmonary gas exchange at rest and during exercise (Dominelli et al. 2018; Bouwsema et al. 2017).

Participants were screened for vigorous exercise with the Physical Activity Readiness Questionnaire (PAR-Q+). The complex actions of hormonal fluctuations during the menstrual cycle are known to influence resting body temperature and ventilation (Hessemer and Brück 1985; England and Farhi 1976). To minimize the possible effects of hormones such as progesterone and estrogen on $\dot{V}O_{2\text{peak}}$, experimental trials (see Days 2 and 3 below) were limited to the early follicular phase for female participants, as indicated by a self-identified menstrual history (Guenette et al. 2007; Lebrun et al. 1995).

Experimental design

The study employed a within-subject, repeated-measures design and was completed on three separate days within a 2-week period. On Day 1, subjects enrolled in the study and completed a thorough familiarization of the graded exercise test protocols including proper pack, coverall and boot fitting, familiarization with modified Borg perceptual scales and practicing inspiratory capacity maneuvers during treadmill exercise. In the unloaded condition, subjects wore typical exercise clothing including shorts, t-shirt and training shoes. For the loaded condition, participants added a properly sized and fitted backpack (Arc' Teryx Bora 75, North Vancouver, BC) filled to a consistent weight (20.4 kg) and volume. Pack sizing (e.g., strap tightness and frame size) was documented to ensure consistent fitting during all loaded test conditions. The 20.4 kg mass is a standard load in fitness for duty assessments in wildland firefighters (Petersen et al. 2010; Phillips et al. 2018). Additionally, participants wore light-weight work boots (Original Swat, Georgetown, ON) and semi-permeable cotton coveralls (Condor, Edmonton, AB). On Days 2 and 3, subjects completed spirometry and graded exercise tests to exhaustion in unloaded and loaded conditions (randomly ordered). All tests were carried out in an air-conditioned laboratory (21–23 °C) with low humidity (1–15%).

Resting spirometry

Prior to the graded exercises tests, each subject completed resting spirometry (TrueOne, ParvoMedics, Salt Lake City, UT, USA) in the test condition for that day, to determine forced vital capacity (FVC), forced expired volume in 1 s (FEV₁), FEV₁/FVC and peak expiratory flow rate, as previously described (Phillips et al. 2016d).

Graded exercise tests

The modified Balke exercise test consisted of a constant speed (1.56 m·s⁻¹) walking protocol on a motorized treadmill (Standard Industries, Fargo, ND). Following 4-min of quiet standing while baseline measurements were recorded, the subject began walking at 0% grade. Step increases of 2% grade were 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). Each test began with a dry breathing valve and gas collection hose, moisture trap and mixing chamber. Expired gases and ventilatory parameters were analyzed and then averaged over 30 s periods with a metabolic measurement system (TrueOne, ParvoMedics, Salt Lake City, UT, USA). End-tidal CO₂ was measured (R-1 pump, P-61B sensor and CD-3A CO₂ analyzer, AEI Technologies Naperville, IL,

USA) from a small port off of the mouthpiece collected through a drying line. End-tidal CO₂ ($P_{ET}CO_2$) data were recorded with a data acquisition system (Powerlab 8/35, AD Instruments, New South Wales, Australia) and stored for subsequent analysis. The highest $\dot{V}O_2$ reading averaged over a 30-s period was accepted as $\dot{V}O_{2peak}$. For each submaximal stage, expired gas and ventilatory parameters were averaged during the second minute to estimate 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. The metabolic measurement system was acceptably stable throughout all tests and no correction was required. 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 spirometry and the second graded exercise test in the alternate condition.

Operating lung volumes

Operating lung volumes were determined from measurements of inspiratory capacity taken at rest and during the last 30 s of each 2-min stage of the graded exercise test. A pneumotach (Hans Rudolph, Kansas City, MO, USA) attached to the inspiratory side of the two-way breathing valve was used to measure flow and determine inspired volume. End-expiratory lung volume was calculated by subtracting inspiratory capacity from forced vital capacity obtained at rest. End-inspiratory lung volume was then estimated by adding tidal volume and end-expiratory lung volume. Tidal volume was recorded during the 30 s leading up to the inspiratory capacity maneuver and then averaged. Changes in end-inspiratory and end-expiratory lung volume were expressed as a percentage of forced vital capacity. 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, on Day 1 of the study, in an effort to improve quality of the inspiratory capacity 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 (Phillips et al. 2016a; Johnson et al. 1999).

Perceptual responses

Perceived exertion and dyspnea were recorded during baseline and at the end of every 2-min stage during the graded exercise test using the modified Borg 0–10 category ratio scale (Borg 1982). Within this study, dyspnea was defined, for our subjects, as the intensity of breathing stress. The 0–10 category ratio scale is anchored such that 0 represented

“no exercise or breathing stress” and 10 represented “maximal exercise or breathing stress” (Borg 1982). Perceived exertion and dyspnea were compared within conditions and between groups at similar submaximal ventilation rates and at peak exercise.

Data analysis

Data are presented as mean \pm standard error (SE) unless otherwise indicated. For all inferential analyses, the probability of a type 1 error was set a priori at 0.05. Unpaired *t* tests were used to evaluate between-group comparisons of baseline subject characteristics and relative changes from unloaded to loaded submaximal and peak physiological parameters. A three-way repeated-measures ANOVA was used to evaluate the effect of unloaded vs loaded (Factor A) during graded exercise (repeated factor) in males and females (fixed factor). To interpret the condition by time interaction within each group, a two-way repeated-measures ANOVA was used. Bonferroni's post hoc test was used to locate each difference. The slope of the relationship between dyspnea and ventilation was determined, using linear regression, to give an index of each individual's dyspnea response to graded exercise. All statistical analyses were performed using Sigma Plot Software version 13.0 (Systat Software., Chicago, USA).

Results

Subject characteristics and resting pulmonary function

Resting spirometry values are displayed in Table 1. Although the subjects were height-matched, the males had larger forced vital capacity, forced expiratory volume in 1 s and higher peak expiratory flow. All subjects had normal lung function (forced expiratory volume in 1 s > 80% predicted) in the unloaded condition with no evidence of obstructive or restrictive patterns. In both groups, forced vital capacity and forced expiratory volume in 1 s were significantly reduced under load when compared to the unloaded condition. Peak expiratory flow and the FEV₁/FVC ratio were not different between unloaded and loaded conditions in either group.

Submaximal graded exercise responses

Oxygen uptake and ventilatory responses to unloaded graded exercise are shown in Fig. 1. As expected because of the difference in mass, $\dot{V}O_2$ and \dot{V}_E were higher in males at a given treadmill grade, compared to females. The ventilatory equivalents for $\dot{V}O_2$ and $\dot{V}CO_2$ ($\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$) were higher at all levels of exercise in females (Fig. 1).

Table 1 Mean (\pm SE) resting pulmonary function in unloaded and loaded conditions

Variable	Male (n = 14)	Female (n = 14)
Unloaded FVC (L)	5.89 (0.21)	4.74 (0.18) [#]
Unloaded FVC (% predicted)	108 (3)	105 (3)
Loaded FVC (L)	5.65 (0.20)*	4.49 (0.72)* [#]
Loaded FVC (% predicted)	104 (3)*	101 (3)*
Δ FVC (%)	4.4 (0.9)	5.3 (1.6)
Unloaded FEV ₁ (L)	4.54 (0.13)	3.94 (0.15) [#]
Loaded FEV ₁ (L)	4.37 (0.12)*	3.73 (0.19)* [#]
Δ FEV ₁ (%)	3.8 (1.4)	5.2 (1.8)
Unloaded FEV ₁ /FVC	0.77 (0.02)	0.84 (0.02)
Loaded FEV ₁ /FVC	0.79 (0.02)	0.84 (0.02)
Δ FEV ₁ /FVC (%)	1.2 (1.1)	0.4 (1.7)
Unloaded PEFR (L·s ⁻¹)	9.8 (0.3)	8.2 (0.3) [#]
Loaded PEFR (L·s ⁻¹)	9.7 (0.2)	8.0 (0.3) [#]
Δ PEFR (%)	0.7 (3.3)	1.1 (4.7)

FVC forced vital capacity, FEV₁ forced expired volume in 1 s, PEFR peak expiratory flow rate

[#]*p* < 0.05 between male and female

**p* < 0.05 between conditions within each group

At similar relative oxygen uptakes ($\% \dot{V}O_{2\text{peak}}$), there was a main effect for group (*p* < 0.001), however, no difference in \dot{V}_E between conditions, in either group, was observed (Fig. 2). Females had a more rapid (increased breathing frequency) and shallow (reduced tidal volume) breathing pattern when compared to males, independent of condition. Under load, both males and females demonstrated a similar increase in breathing frequency and decrease in tidal volume at comparable relative oxygen uptakes throughout exercise, when compared to the unloaded condition (Fig. 3). The reduced tidal volume under load was secondary to a reduction in end-inspiratory lung volume (Fig. 4). Despite a mild alteration in breathing pattern, $\dot{V}_E/\dot{V}CO_2$ and $P_{ET}CO_2$ data were not consistently different between conditions, indicating no substantial evidence of increased deadspace ventilation at submaximal exercise intensities with 20.4 kg thoracic load carriage.

The change in breathing pattern, operating lung volume and ventilation at specific absolute and relative submaximal exercise intensities are displayed in Fig. 5. The relative change from unloaded to loaded was similar in all key variables of interest, in males and females, at a $\dot{V}O_2$ of 2.0 L·min⁻¹ and 70% of $\dot{V}O_{2\text{peak}}$ (Fig. 5).

Peak exercise

Peak physiological responses to graded exercise are displayed in Table 2. In the unloaded condition, females

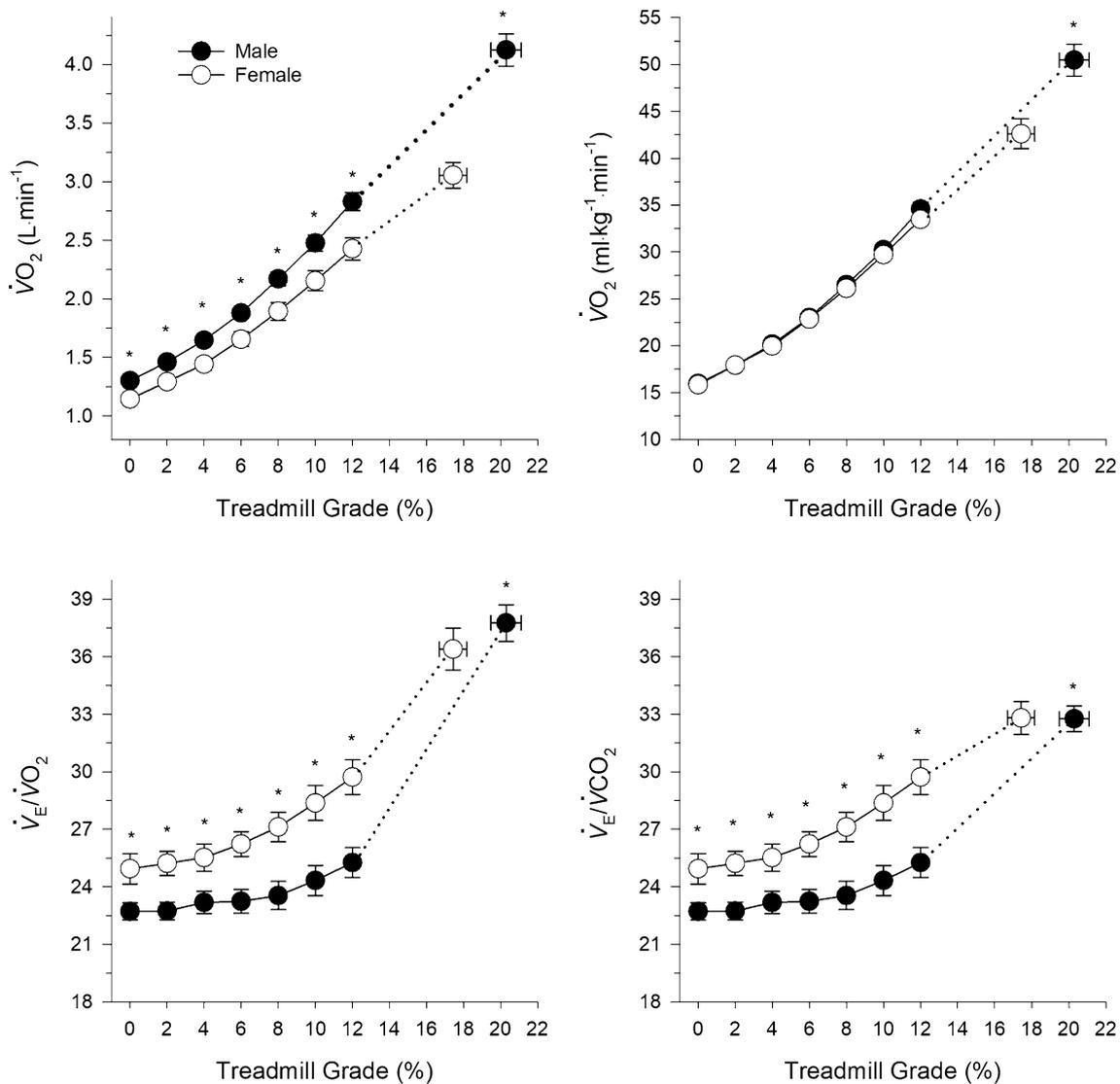


Fig. 1 Mean \pm SE absolute and relative oxygen consumption ($\dot{V}O_2$), and ventilatory equivalents to both oxygen consumption ($\dot{V}_E/\dot{V}O_2$) and carbon dioxide production ($\dot{V}_E/\dot{V}CO_2$) during graded exercise in males and females in the unloaded condition. * $P < 0.05$ between groups

had lower peak treadmill grade, and decreased $\dot{V}O_{2\text{peak}}$ and $\dot{V}_{E\text{peak}}$ ($p < 0.05$), when compared to the male group. In the loaded condition, $\dot{V}O_{2\text{peak}}$ and $\dot{V}_{E\text{peak}}$ were significantly decreased in both groups, when compared to the unloaded condition. In both groups, the decreased peak \dot{V}_E , under load, was the result of a reduction in tidal volume, secondary to lower end-inspiratory lung volume (both $p < 0.05$). In females, $P_{ET}CO_2$ was higher ($p < 0.05$) at peak exercise under load, compared to the unloaded condition. The relative reductions in peak physiological responses (e.g., $\dot{V}O_{2\text{peak}}$ and $\dot{V}_{E\text{peak}}$) under load were similar between males and females.

Perceived dyspnea

Females had higher perceived dyspnea ratings for a given ventilatory rate compared to males throughout exercise (Table 3). Peak dyspnea and the relationship between dyspnea and ventilatory rate were not affected in the loaded condition in males or females (Table 2; Fig. 6, respectively).

Fig. 2 Mean \pm SE ventilation (\dot{V}_E), ventilatory equivalents to carbon dioxide production (\dot{V}_E/\dot{V}_{CO_2}) and the partial pressure of carbon dioxide ($P_{ET}CO_2$) during graded exercise in males (circles) and females (triangles) in both unloaded (closed symbols) and loaded (open symbols) conditions. A main group effect was observed in all three variables (\dot{V}_E $p < 0.001$, \dot{V}_E/\dot{V}_{CO_2} $p < 0.001$, $P_{ET}CO_2$ $p < 0.001$). * $p < 0.05$ between conditions in males. # $p < 0.05$ between conditions in females

Sex differences in ventilatory and perceptual responses at selected submaximal intensities

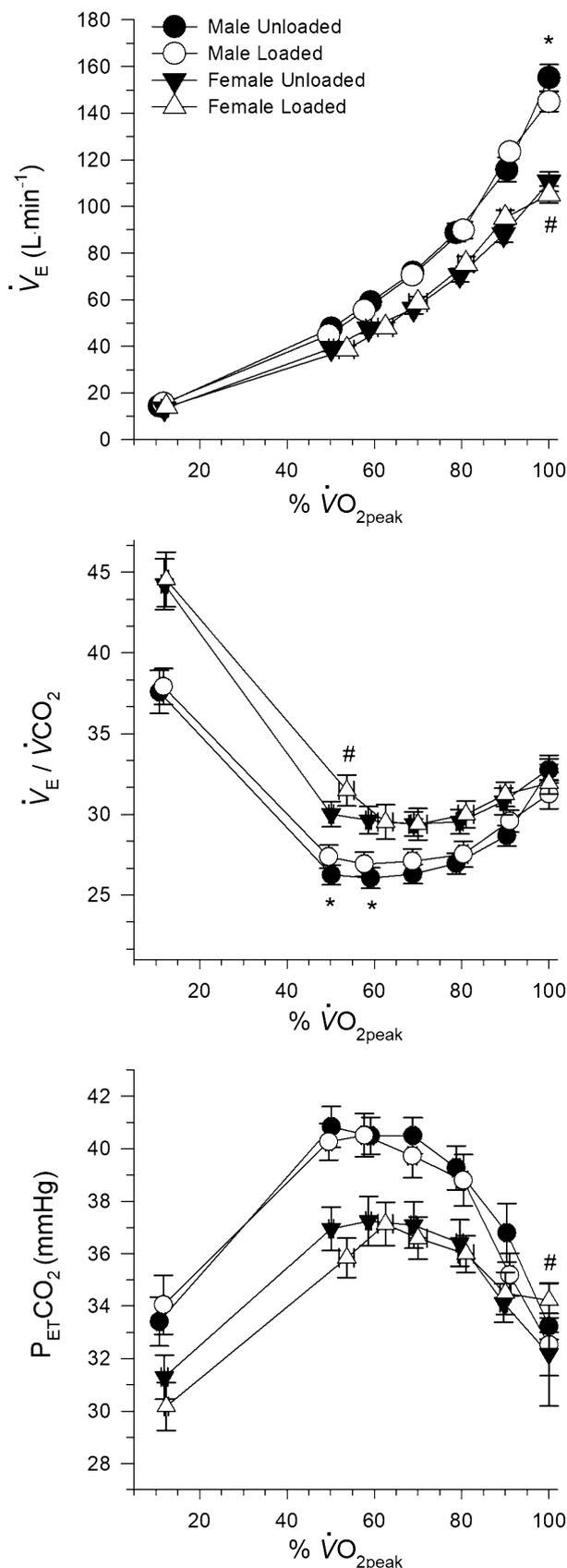
In the loaded condition, at an absolute submaximal oxygen uptake of $2.0 \text{ L}\cdot\text{min}^{-1}$, minute ventilation, perceived exertion and dyspnea were significantly higher in females (Table 3). At a relative intensity of $70\% \dot{V}O_{2\text{peak}}$, the absolute values for minute \dot{V}_E and $\dot{V}O_2$ were significantly lower for females, but the values for perceived exertion and dyspnea were the same as males (Table 3). At a comparable relative $\dot{V}O_2$ ($22 \text{ mL}\cdot\text{kg}^{-1}_{\text{TOTALMASS}}\cdot\text{min}^{-1}$), $\dot{V}_E/\dot{V}O_2$, perceived exertion and dyspnea were higher in females (Table 3).

Discussion

This is the first study to investigate sex differences in the ventilatory and perceptual responses to graded treadmill exercise, with and without thoracic loading, and the major findings are threefold. First, the effect of thoracic load carriage on submaximal ventilatory responses to graded exercise was similar in height-matched males and females. With thoracic load carriage, both males and females adopted a similar rapid and shallow breathing pattern under load. The lack of change in exercise ventilation, end-tidal CO_2 and \dot{V}_E/\dot{V}_{CO_2} , when compared to the unloaded condition at a similar submaximal $\dot{V}O_2$, suggests there was no significant increase in deadspace ventilation with load, in males or females. Second, there were no changes in perceived dyspnea under load when expressed relative to minute ventilation in either group. These data suggest the small adjustment in breathing pattern and operating lung volume did not alter the perceptual responses to graded exercise with thoracic load carriage in males or females. Third, at comparable metabolic demands during exercise ($\sim 2.0 \text{ L}\cdot\text{min}^{-1}$ and approximately $22 \text{ mL}\cdot\text{kg}^{-1}_{\text{TOTALMASS}}\cdot\text{min}^{-1}$), \dot{V}_E , perceived exertion and dyspnea were higher in females. These data suggest that, at standardized, occupationally relevant workloads, females are more heavily burdened with a thoracic load of comparable mass than height-matched males.

Sex differences in submaximal ventilatory responses to graded exercise

Our current results show that females had a more rapid and shallow breathing pattern and higher \dot{V}_E/\dot{V}_{CO_2} during



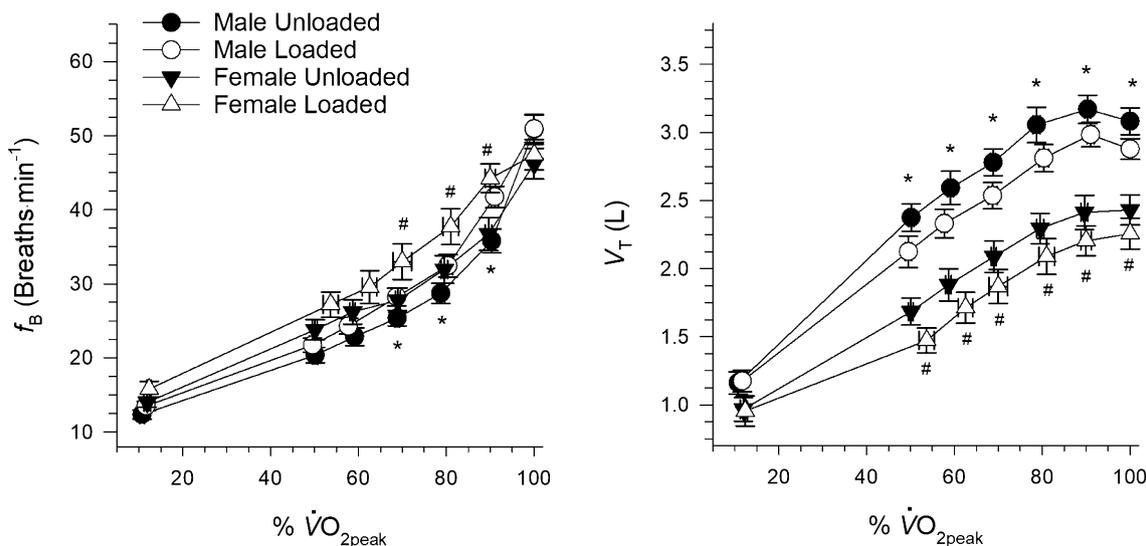


Fig. 3 Mean \pm SE breathing frequency (f_B) and tidal volume (V_T) during graded exercise in males (circles) and females (triangles) in both unloaded (closed symbols) and loaded (open symbols) conditions. A

main group effect was observed in both variables (f_B $p < 0.001$, V_T $p < 0.001$). * $p < 0.05$ between conditions in males. # $p < 0.05$ between conditions in females

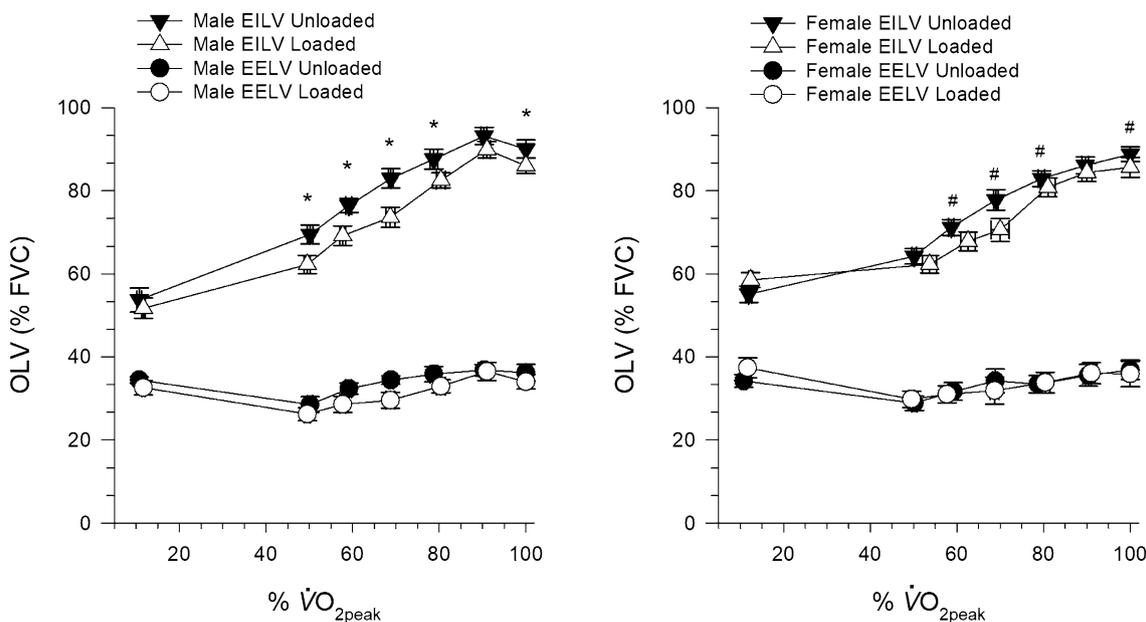
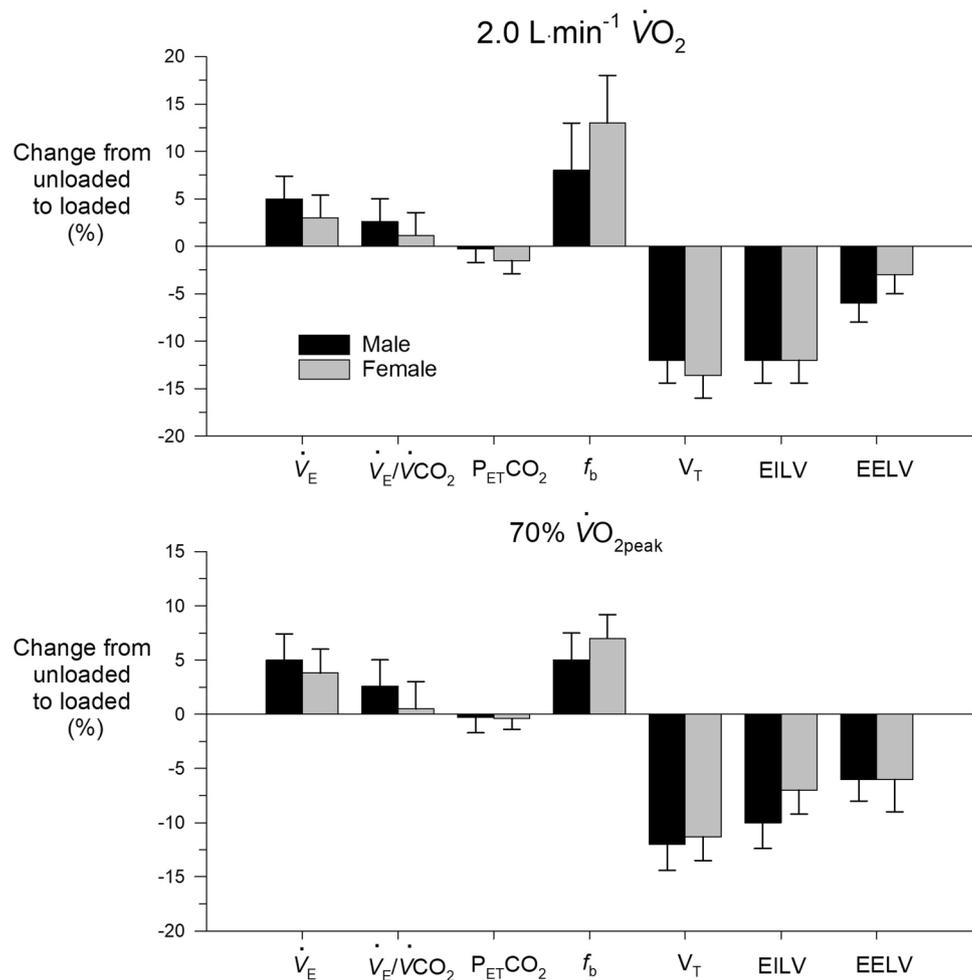


Fig. 4 Mean \pm SE operating lung volume (OLV) during graded exercise in males (left column) and females (right column) in both unloaded (closed symbols) and loaded (open symbols) conditions. * $p < 0.05$ between conditions in males. # $p < 0.05$ between conditions in females

graded exercise, when compared to males, independent of the experimental condition. Although the females had smaller lungs (Table 1), operating lung volumes normalized to lung size were similar between the sexes throughout exercise. These findings are in agreement with previous reports on sex differences in the ventilatory responses to exercise (Schaeffer et al. 2014; Kilbride et al. 2003). Kilbride et al. (2003) demonstrated an increase in the dead

space to tidal volume ratio (\dot{V}_D/V_T), secondary to a reduction in tidal volume and increased breathing frequency, when compared to males during graded exercise. Those authors suggested that the increase in $\dot{V}_E/\dot{V}CO_2$ was secondary to increased deadspace. It seems that females, in unloaded conditions, likely demonstrate increased dead space ventilation during graded exercise, when compared

Fig. 5 Mean \pm SE relative changes from unloaded to loaded in \dot{V}_E , minute ventilation; ventilatory equivalent to carbon dioxide production, $\dot{V}_E/\dot{V}CO_2$; partial pressure of end-tidal carbon dioxide, $P_{ET}CO_2$; breathing frequency, f_b ; tidal volume, V_T ; end-inspiratory lung volume, EILV; and end-expiratory lung volume, EELV at an absolute $\dot{V}O_2$ of $2.0 \text{ L}\cdot\text{min}^{-1}$ and a relative $\dot{V}O_2$ of $70\% \dot{V}O_{2peak}$ in males and females. There was no difference in relative changes in males or females



to height-matched males, which is the expected result of a rapid and shallow breathing pattern adopted to compensate for smaller lungs and to minimize the elastic work of breathing.

Submaximal ventilatory responses to graded exercise with thoracic load carriage

In keeping with findings from previous studies in males (Phillips et al. 2016a, d; Wang and Cerny 2004), thoracic load carriage resulted in a compensatory change in breathing pattern and operating lung volume at submaximal exercise intensities in our male group. Despite a small change in breathing pattern and operating lung volume under load, \dot{V}_E was not different at similar oxygen uptakes compared to the unloaded condition (Fig. 2).

At similar submaximal oxygen uptakes, there was no change in \dot{V}_E between conditions in females despite a change in breathing pattern (rapid and shallow). Figure 5 shows that the effect of thoracic load carriage on ventilatory responses is similar, between the sexes at both relative and absolute

oxygen uptakes. Although our groups were matched for height, the females had smaller lung size, lower body mass and $\dot{V}O_{2peak}$ than the male group. It could be assumed that graded exercise with 20.4 kg thoracic loading may have a larger effect on females than males, as the absolute mass of the pack represents a greater relative burden in lighter individuals with smaller lung size; however, none of our data support this hypothesis.

Peak exercise

In the present study, females had lower peak $\dot{V}O_2$ and \dot{V}_E , when compared to their height-matched male counterparts, regardless of the experimental condition. Although the females had lower aerobic power, there was no apparent sex difference in the relative reduction in peak $\dot{V}O_2$ or \dot{V}_E . A recent publication from our laboratory reported exercise performance and peak physiological responses with and without 25 kg load carriage in seven size (mass and stature) matched pairs of males and females and reported no difference between the sexes in the relative reduction in test

Table 2 Mean (\pm SE) performance and physiological responses at peak exercise

Variable	Male		Female	
	Unloaded	Loaded	Unloaded	Loaded
Treadmill grade (%)	20.3 (0.8)	13.0 (0.6)*	17.4 (0.7) [‡]	10.1 (0.6)*
$\dot{V}O_2$ (L·min ⁻¹)	4.12 (0.14)	3.98 (0.12)*	3.06 (0.11) [‡]	2.96 (0.10)*
$\dot{V}CO_2$ (L·min ⁻¹)	4.75 (0.16)	4.65 (0.13)	3.38 (0.12) [‡]	3.31 (0.12)
\dot{V}_E (L·min ⁻¹)	155.3 (5.6)	146.7 (4.3)*	110.6 (4.2) [‡]	105.2 (3.7)*
$\dot{V}_E/\dot{V}O_2$	38 (1)	37 (1)	36 (1)	36 (1)
$\dot{V}_E/\dot{V}CO_2$	33 (1)	32 (1)	33 (1)	32 (1)
$P_{ET}CO_2$ (mmHg)	33.2 (0.5)	32.6 (2.4)	32.1 (0.8)	34.2 (0.7)*
RER	1.16 (0.01)	1.18 (0.01)	1.13 (0.01)	1.12 (0.02)
f_B (breaths·min ⁻¹)	51 (2)	51 (2)	46 (2) [‡]	47 (2)
V_T (L)	3.08 (0.10)	2.88 (0.08)*	2.43 (0.11) [‡]	2.23 (0.11)*
EELV (% FVC)	36 (2)	34 (2)	37 (2)	36 (3)
EILV (% FVC)	90 (2)	86 (2)*	89 (2)	86 (2)*
T_i/T_{tot}	0.39 (0.01)	0.40 (0.01)	0.41 (0.01)	0.43 (0.01)
T_e/T_{tot}	0.61 (0.01)	0.60 (0.01)	0.59 (0.01)	0.57 (0.01)
HR (beats·min ⁻¹)	188 (2)	185 (2)	184 (2)	182 (2)
RPE (0–10)	8.9 (0.4)	8.5 (0.4)	8.9 (0.3)	8.6 (0.3)
Dyspnea (0–10)	9.0 (0.4)	8.4 (0.4)	8.1 (0.4) [‡]	8.1 (0.3)
Dyspnea/ \dot{V}_E slope	0.06 (0.01)	0.06 (0.01)	0.09 (0.01) [‡]	0.10 (0.01)

$\dot{V}O_2$ oxygen consumption, $\dot{V}CO_2$ carbon dioxide production, \dot{V}_E minute ventilation, $P_{ET}CO_2$ pressure of end-tidal carbon dioxide, RER respiratory exchange ratio, f_B breathing frequency, V_T tidal volume, EELV end-expiratory lung volume, EILV end-inspiratory lung volume, T_i time of inspiration, T_e time of expiration, T_{tot} time of respiratory cycle, HR heart rate, RPE rating of perceived exertion

[‡] $p < 0.05$ between male and female in unloaded condition

* $p < 0.05$ between conditions within each group

duration or $\dot{V}O_{2peak}$ under load (Phillips et al. 2016c). In that communication, the sex comparison was a secondary analysis, however, the findings in our current study are in agreement and support the preliminary conclusions of our previous work.

In the present study, at peak exercise in both males and females, the small reduction in \dot{V}_E under load was secondary to lower tidal volume and end-inspiratory lung volume, while no change was observed in breathing frequency or end-expiratory lung volume. Despite a similar reduction in \dot{V}_E and no change in $\dot{V}_E/\dot{V}CO_2$, there was a slight increase in $P_{ET}CO_2$, in the female group under load, when compared to unloaded. These data suggest that females may have increased relative dead space and impaired alveolar ventilation at peak exercise under load. Work of breathing has been reported to be higher in females, compared to males, at given absolute ventilation rates above 60 L·min⁻¹ during incremental exercise (Guenette et al. 2007), probably secondary to smaller lung size and reduced airway diameter (Guenette et al. 2007; Dominelli et al. 2015a, b). The combination of reduced airway diameter and increased chest-wall loading may have significantly burdened the respiratory muscles at peak exercise and prevented a compensatory increase in force generation, which logically could impair alveolar

ventilation and increase CO₂ retention. However, without measurements of esophageal pressure to quantify work of breathing, these comments are speculative. Our primary goal was to understand possible sex differences during maximal exercise with thoracic load carriage, and the small but significant reduction in $\dot{V}O_{2peak}$ in young males and females cannot be explained by the present data.

Perceptual responses to graded exercise

The results from the current study show that perceived dyspnea was consistently higher at any given \dot{V}_E during submaximal exercise in females, independent of condition. When comparing absolute \dot{V}_E between the sexes, it is important to note that females were required to operate at a greater fraction of their maximal ventilatory capacity relative to males. However, when dyspnea was displayed relative to peak minute ventilation, there were no apparent sex differences (Fig. 6). Despite an alteration in breathing pattern and operating lung volume under load at a given \dot{V}_E , there appeared to be no change in the perceived dyspnea responses to exercise in either group when compared to the unloaded condition. These findings would suggest that the neuro-mechanical relationship between perceived dyspnea and \dot{V}_E

Table 3 Mean (\pm SE) physiological and perceptual responses during submaximal exercise at selected absolute (2.0 L \cdot min $^{-1}$) and relative (70% $\dot{V}O_{2peak}$ and 6 METS) oxygen uptakes in the loaded condition

	Male	Female
Absolute $\dot{V}O_2$		
$\dot{V}O_2$ (L \cdot min $^{-1}$)	1.98 (0.04)	2.03 (0.03)
\dot{V}_E (L \cdot min $^{-1}$)	47.8 (1.5)	58.8 (1.6)*
$\dot{V}_E/\dot{V}O_2$	24 (1)	29 (1)*
Perceived exertion (0–10)	2.3 (0.3)	3.9 (0.3)*
Dyspnea (0–10)	2.8 (0.3)	4.0 (0.3)*
70% $\dot{V}O_{2peak}$		
$\dot{V}O_2$ (L \cdot min $^{-1}$)	2.73 (0.08)	2.14 (0.10)*
\dot{V}_E (L \cdot min $^{-1}$)	71.7 (2.4)	58.9 (2.4)*
$\dot{V}_E/\dot{V}O_2$	26 (1)	27 (2)
Perceived exertion (0–10)	4.7 (0.3)	4.1 (0.3)
Dyspnea (0–10)	4.2 (0.3)	3.9 (0.3)
~6 METS		
$\dot{V}O_2$ (mL \cdot kg $^{-1}$ _{TOTALMASS} \cdot min $^{-1}$)	21.6 (0.2)	21.5 (0.4)
\dot{V}_E (L \cdot min $^{-1}$)	54.0 (1.9)	56.0 (1.9)
$\dot{V}_E/\dot{V}O_2$	25 (1)	28 (1)*
Perceived exertion (0–10)	2.9 (0.2)	4.4 (0.4)*
Dyspnea (0–10)	2.6 (0.2)	3.7 (0.4)*

$\dot{V}O_2$ oxygen consumption, \dot{V}_E minute ventilation, $\dot{V}_E/\dot{V}O_2$ ventilatory equivalent to oxygen consumption

* $p < 0.05$ between male and female

during graded exercise was not influenced by thoracic load carriage in males or females.

Practical implications for occupational physiology and physical employment standards

The demands of many public safety occupations are frequently considered to be absolute (e.g., standardized tools, protective clothing, or equipment used by all workers), with the parameters of time and work intensity determined by the necessities of a time-sensitive response to an emergency situation. In occupations such as law enforcement, military, structural firefighting, search and rescue, and wildland firefighting, factors such as load carriage and protective clothing ensembles are common and make the work more difficult. Standards for physiological readiness for work are often based on a single point of reference that may be grounded in physiological (e.g., $\dot{V}O_{2max}$) or performance (e.g., time to complete a task) contexts.

The data shown in Table 3 provide some interesting insights into similarities and differences in the ventilatory responses of males and females during graded exercise and may be helpful to identify areas for future research to identify how sex differences must be considered when determining fitness for work. We have selected three approaches for comparison of ventilatory responses between males and females, in the loaded condition only, at what may be considered relevant intensities for emergency responders. These comparisons were made first, at a submaximal absolute oxygen uptake, second, at a fraction of $\dot{V}O_{2peak}$ typically

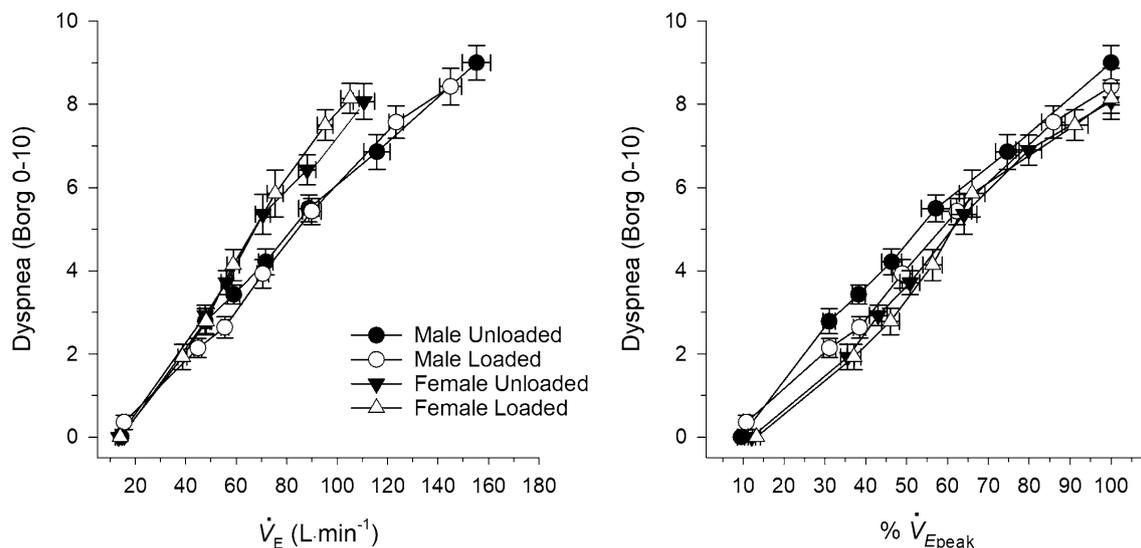


Fig. 6 Mean \pm SE dyspnea at comparable absolute (left column) and relative (right column) ventilation rates (\dot{V}_E) during graded exercise in males (circles) and females (triangles) in both unloaded (closed

symbols) and loaded (open symbols) conditions. A main effect for group was observed for dyspnea vs absolute ventilation ($p < 0.01$) but not relative ventilation

associated with the ventilatory and lactate thresholds, and third, at a similar relative $\dot{V}O_2$ (~6 METS), normalized to total mass.

Approach 1: absolute oxygen uptake

At an absolute oxygen uptake of $2.0 \text{ L}\cdot\text{min}^{-1}$, which is classified as very heavy work (Åstrand and Rodahl 1986), our female subjects had significantly higher \dot{V}_E (approximately 23%) than their height-matched male counterparts. Logically, this difference was also evident in the $\dot{V}_E/\dot{V}O_2$ ratio. Ratings of perceived exertion and dyspnea were substantially higher as well. These data infer that under work conditions with an absolute energy requirement, female workers would exhibit significantly higher ventilatory responses and perceive the work to be more challenging than their male counterparts.

Approach 2: fraction of peak oxygen uptake

In the second example, we have compared the same variables at 70% $\dot{V}O_{2\text{peak}}$, an intensity approximately equivalent to the ventilatory threshold (Phillips et al. 2016b, c, d) in the belief that this would be close to the intensity that workers would self-select to complete a prolonged work task as part of an emergency response (e.g., hiking at a brisk, self-selected pace). Our male subjects had higher $\dot{V}O_{2\text{peak}}$ (Table 3) and hence the $\dot{V}O_2$ at 70% of peak was substantially higher (approximately 22%) than the females. Our female subjects, despite lower oxygen uptake and minute ventilation, and similar ventilatory equivalent for oxygen, reported the same ratings of exertion and dyspnea as the male subjects. These data suggest that while the females would, using the hiking example, move at a slower pace, they would experience the same perceptions of exertion and dyspnea as the males, who would be moving faster.

Approach 3: total mass-specific oxygen uptake

The third approach evaluated responses at a similar oxygen uptake, normalized to total mass (body mass plus mass of work clothing and pack). This rate of work, approximately six METS, would be classified as heavy work (Åstrand and Rodahl 1986) and is very similar to the sub-threshold, prolonged exercise with heavy load carriage with males and females (Phillips et al. 2016c, d). This approach would logically have subjects of both sexes working at the same rate (e.g., marching as a group). In this example, mean $\dot{V}O_2$, normalized to total mass was $21\text{--}22 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$, was consistent with purposeful walking under load. Under these conditions, the ventilatory equivalent for oxygen, as well as perceived exertion and dyspnea were significantly higher in females. We have previously reported (Phillips et al. 2016c,

d) significant increases in minute ventilation during prolonged exercise in both males and females, and we suggest that the differences shown in the present data may be exacerbated during sustained exercise under load.

Although the relative changes in ventilatory responses from unloaded to loaded conditions were similar between the sexes, the examples mentioned above illustrate that, in height-matched males and females, there are significant differences in either physiological responses or perceptions of strain during similar exercise challenges. These differences may be of interest and even importance to scientists developing fair and equitable physical employment standards that involve both male and female workers. At the very least, this information should be considered as direction for future research in this field.

Methodological considerations

Pressure of end-tidal carbon dioxide ($P_{\text{ET}}\text{CO}_2$) was assumed to be equal to $P_a\text{CO}_2$ (Stickland et al. 2013). Although there may be concerns over using $P_{\text{ET}}\text{CO}_2$ as a surrogate for $P_a\text{CO}_2$, we are confident this is not a confounding factor for the current study. $P_{\text{ET}}\text{CO}_2$ may be lower than $P_a\text{CO}_2$ when individuals have increased alveolar deadspace, however, alveolar deadspace occurs primarily in patients with lung disease (e.g., chronic obstructive pulmonary disease) and all of our participants were young and healthy with normal lung function (Elbehairy et al. 2015). Each subject acted as their own controls, so any potential alveolar deadspace due to intrinsic ventilation–perfusion mismatch would likely be consistent across conditions in both males and females.

While our male and female groups consisted of purposefully matched pairs based on stature, we caution readers not to overgeneralize our findings to other key demographics (e.g., age, lung size, body mass, aerobic fitness) or conditions (e.g., heavier packs). If our groups were matched for both stature and mass, it is possible that the between-group differences observed in our study might be smaller. Alternatively, larger physiological differences should be expected if a convenience sample (e.g., larger differences in mass, stature and lung size) of men and women was recruited.

It is well known that heat stress can affect ventilation. Although core temperature was not measured, based on previous work with the same clothing and load carriage during prolonged exercise (Phillips et al. 2018), we are confident there was no difference in thermal stress between conditions during the graded exercise protocols. The duration of exercise in the current study was much shorter than in the previous experiment (Phillips et al. 2018), and it is unlikely that the change in core temperature would be different between conditions in males or females.

We adopted a conservative approach to the possibility that menstrual cycle phase might affect the ventilatory response

to exercise and consequently made the decision to account for menstrual cycle within the female group. It has been shown that menstrual cycle phase has little or no effect on exercise ventilation (MacNutt et al. 2012). However, Lebrun et al. (1995) demonstrated that fluctuation in endogenous female steroid hormones significantly affected $\dot{V}O_{2\text{peak}}$ in aerobically trained female athletes. While controlling for menstrual cycle phase may limit the generalizability of the results to the workplace, it seemed prudent to seek strong internal validity for the experiment.

Because the experimental condition consisted of an absolute load (20.4 kg), matching our groups on an index of body size (e.g., height) was critical to better control the study and minimize the between-subject variability in relative burden (e.g., pack mass relative to body mass). We believe that recruiting a homogenous group of participants is one approach to clarifying sex differences during treadmill exercise with and without an absolute external load (20.4 kg pack). Future work is required to expand our findings to better understand potential sex differences in more heterogeneous samples.

Summary

The results from the current study demonstrated that although females had lower peak minute ventilation and $\dot{V}O_{2\text{peak}}$, the relative ventilatory and dyspnea responses to exercise with thoracic loading were similar in males and females. The current study is one of few investigations examining detailed sex comparisons during exercise with load carriage. Understanding any sex differences and the effects on the physiological responses under load can improve performance and safety in physically demanding occupations and recreational settings requiring load carriage.

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Author contributions DBP, MKS and SRP conceived and designed the experiment. DBP, CME and SRP conducted experiments. DBP, CME, MKS and SRP analyzed and interpreted data. DBP and SRP wrote the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest.

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