Ventilatory Responses to Prolonged Exercise with Heavy Load Carriage

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

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Abstract

The purpose of this experiment was to study breathing pattern, operational lung volume and respiratory muscle strength during 45 minutes of exercise with a heavy backpack (25 kg). Fifteen males completed randomly ordered graded exercise tests on a treadmill with (L) and without (U) a correctly sized and fitted 80 L pack weighing 25 kg. Subsequently, each subject completed two exercise challenges (L and U conditions, in random order) that consisted of 45 minutes of treadmill walking at 67 ± 4% VO_{2peak}. Maximal inspiratory and expiratory pressures (MIP and MEP) were measured before and immediately following exercise. During exercise, ventilatory and gas-exchange data were recorded every five minutes. Perceptual responses were recorded in the first five-minute measurement cycle and were repeated every ten minutes during exercise. Between-condition comparisons were made during exercise every five minutes, while within-condition comparisons were made between the 15 and 45 min time points only. During loaded exercise, breathing frequency (B_F) and ventilation (V_E) increased by 21.7 and 15.1% ($P<0.05$), respectively, while tidal volume (V_T) and end-inspiratory lung volume (EILV) were reduced by 6.3 and 6.4% ($P<0.05$), respectively. Following exercise in the loaded condition, maximal inspiratory pressure decreased by 6.7% ($P<0.05$) with no change in maximal expiratory pressure. No changes in maximal inspiratory or expiratory pressures were observed following exercise in the unloaded condition. Although aerobic demand was matched between conditions, exercise stress, leg fatigue and breathing stress were always perceived to be higher ($P<0.05$) in the loaded condition. In summary, the mechanical disadvantage placed on the respiratory system during prolonged exercise with a heavy pack suggests that work of breathing (WOB) was increased and this resulted in a progressive alteration in ventilatory mechanics. The decrease in maximal inspiratory pressure and compensatory changes in breathing pattern and EILV is suggestive of respiratory muscle fatigue. We suggest that in an attempt to minimize the WOB, subjects adopted a shallow and frequent breathing pattern; however, this breathing pattern increased dead space and minute ventilation, increasing perceived exercise stress and breathing discomfort.

Preface

This thesis is an original work by Devin Brent Phillips. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Health Research Ethics Board, Project Name "Ventilatory Mechanics during Prolonged Exercise with Heavy Load Carriage", ID. Pro00042068, September 2013.

Acknowledgments

I would like to thank my lab mates Michael Scarlett, Liam Boyd, Vince Tedjasaputra and Jonathon Mayne for helping me throughout my graduate studies. Thank you to Dr. Stewart Petersen for his mentorship throughout my time in the Work Physiology lab at the University of Alberta. I could not have asked for a better graduate supervisor. Thank you to Dr. Michael Stickland for his expertise in cardiopulmonary physiology. Thank you to all the research participants who volunteered their time to take part in my study.

I would like to give a special thanks to my family for the continuous support throughout my life. Thank you to Lara Sreibers for helping motivate me throughout my graduate studies program.

Table of contents

List of Tables

List of Figures

Chapter 1 – Introduction

1.1 Background

Exercising while carrying a heavy load is common to many occupations such as infantry, firefighting and search and rescue technicians (SAR TECH). A SAR TECH commonly carries a heavy pack during a mountain rescue, when vehicles are unable to reach the rescue scene. A standard mountain rescue pack weighs approximately 25 kg (Petersen et al., 2011). While carrying the pack, a SAR TECH may engage in high intensity exercise, with a typical rescue mission consisting of approximately 45 minutes of continuous effort (75% VO_{2peak}) (Petersen et al., 2011).

There is a relationship between load carried and the oxygen cost (VO_2) during exercise (Beekley et al., 2007; Dominelli et al., 2011). According to Dominelli et al. (2010) trained participants marching at a fixed speed ($1.1\ m \cdot s^{-1}$) and grade (10%) with various loads (5-35 kg) resulted in a progressive increase in VO_2 as the load carried increased. Epstein et al (1988) suggested that carrying a 40 kg load at a sub-threshold intensity will result in a constant increase in VO_2 over time and may become too difficult to maintain for prolonged periods of exercise. This increase in VO_2 was attributed to biomechanical factors, which progressively decreased efficiency. While a heavy load carried on the back increases VO_2 and negatively effects efficiency, exercise efficiency under heavy load is further impaired when carrying loads in the hands or on the legs (Abe et al., 2004). Based on the oxygen cost and the biomechanics of load placement, walking with a backpack is the most efficient form of load carriage transportation. Abe et al. (2004) examined the ideal walking speed with load carriage and found that speeds between 1.33 and $1.50\ m \cdot s^{-1}$ required a significantly lower oxygen cost of walking compared to faster or slower speeds. Due to the time sensitive nature of emergency occupations, 1.50 $m \cdot s^{-1}$ is representative of a purposeful marching pace.

Load carriage may place additional strain on the respiratory system. Dominelli et al. (2011) demonstrated that a 25 kg hiking pack strapped tightly to the body led to a small decrease in resting Forced Vital Capacity (FVC) and Forced Expiratory Volume in one second (FEV_1). These authors suggested that the small decrease in maximal expired flow-volume values is due to the load on the posterior chest wall and not the chest strap restriction. Lesser et al. (2010) reported a 3.3% and 3.4% decrease in FVC and FEV_1 respectively, with no change in FEV_1/FVC ratio at rest wearing a 25 kg pack. Despite a small effect on FVC and FEV_1 at rest, there is limited evidence demonstrating an alteration in lung volume and work of breathing at rest and during exercise with heavy load carriage (Brown and McConnell, 2012).

Previous research has shown that, during acute exercise (5 min) carrying a 25 kg pack, alveolar ventilation (V_A) is maintained by an alteration in breathing pattern and operational lung volume. Lesser et al. (2010) observed a 9% decrease in tidal volume (V_T) and 14% increase in breathing frequency (B_F) during 5 minutes of exercise (75% VO_{2peak}) with a 25 kg pack. Further, end-inspiratory lung volume (EILV) was decreased by 6% with no change in end-expiratory lung volume (EELV). These results suggest that acute loaded exercise causes subjects to maintain V_A and attempt to minimize work of breathing (WOB) by breathing more rapid and shallow. If exercise time is increased, the compensatory changes in breathing pattern may not be enough to minimize WOB and overcome the ventilatory disadvantage placed on the respiratory system by the pack. A longer work bout may fatigue the respiratory muscles, furthering a rapid and shallow breathing pattern, which would increase dead space ventilation (V_D), V_E and WOB. The presence of respiratory muscle fatigue may result in a sympathetic-mediated "metaboreflex" consequently decreasing leg blood flow, increasing perceived exertion and potentially decreasing occupational effectiveness (Dempsey et al., 2008; Romer et al., 2005).

Stickland et al. (2004) found that during prolonged cycling (3 h) there was a 23% increase in V_E secondary to increased V_D. In order to maintain V_A, V_E must increase to match the increase in V_D. Tympanic temperature increased by 1.1°C, which might also influence increases in V_E (White, 2006). If prolonged exercise without heavy load carriage results in rapid and shallow breathing and increased V_D, these ventilatory parameters may be further exacerbated when carrying a heavy load. However, changes in breathing pattern, V_D and V_E during prolonged exercise with heavy load carriage are currently unknown. The respiratory consequences of prolonged exercise with heavy load carriage could have important implications for real world occupations such as military and search and rescue (Brown and McConnell, 2012).

1.2 Purpose and Hypothesis

The purpose of this investigation was to study components of ventilatory mechanics, specifically: breathing pattern and operational lung volume during 45 minutes of exercise with heavy load carriage (25 kg). The study also aimed to examine the effect of 45 minutes of exercise with heavy load carriage on respiratory muscle strength.

It was hypothesized that prolonged exercise with heavy load carriage would overload the respiratory muscles and result in a compensatory change in breathing pattern in order to minimize the WOB. Specifically, V_T and EILV would decrease and B_F would increase, with the differences becoming greater over time, compared to the unloaded condition. The progressive alteration in breathing pattern would increase V_D requiring V_E to increase in order to maintain V_A. It was also hypothesized that inspiratory muscle strength would decrease after exercise, which is suggestive of respiratory muscle fatigue.

1.3 Significance

It is known that during brief bouts of exercise with heavy load carriage (25 kg), V_A is maintained by a 9% decrease in V_T and a 14% increase in B_F (Lesser et al., 2010). The increase in B_F coupled with a possible increased work of breathing (WOB) could overload and fatigue the respiratory muscles over a prolonged period of vigorous exercise. A sympathetic-mediated competition for blood, via the metaboreflex, may then occur, limiting blood flow to the limbs during submaximal exercise (Harms et al., 1998; Dempsey et al., 2008). This could result in an increased perceived exertion or further, a decreased exercise performance. There is previous research studying effects of load carriage on metabolic demand, gait dynamics and perceptual responses to load positioning (Keren et al., 1981; Qu et al., 2011; Stuempfle et al., 2004). However, the effect of prolonged exercise with heavy load carriage on ventilatory parameters, specifically: breathing patterns, operational lung volume and respiratory muscle strength has not been reported.

1.4 Delimitations

The sample in this study was taken from a population of young, healthy and fit males. A backpack fitting session was completed in order to ensure proper fitting and familiarity with the backpack prior to the exercise sessions. The results of this experiment can be generalized for young, healthy males with normal lung function. Subjects with exercise-induced bronchospasm were excluded from the study.

This study simulated a high-intensity prolonged work bout that a search and rescue worker may experience. An example could be a mountain rescue, where providing medical attention may require SAR TECHs to hike over rough terrain to the scene of the incident quickly and with urgency.

The treadmill was set at a constant speed and grade, where on a mountain or foothill, the grade and walking surface is variable.

The study measured ventilatory parameters, specifically: breathing pattern, operational lung volume, respiratory muscle strength, end-tidal CO_2 ($ETCO_2$) and exercise flow volume (EFLV). Modified visual analogue scales (VAS) were used to evaluate exercise stress, breathing discomfort and leg fatigue. Work of breathing and chest wall compliance was not measured in this study.

The independent variables were the loaded and unloaded conditions. The dependent variables were selected responses in ventilatory parameters, specifically: breathing pattern, lung volume and respiratory muscle strength.

This study used a specific 25 kg backpack with a pre-set treadmill speed ($1.5\ m{\cdot}s^{-1}$), which may not relate to other packs or load carriage protocols. A 25 kg load carriage can be classified as a heavy load. Petersen et al. (2011) created a physical fitness standard for SAR TECH applicants and observed that standard packs used in mountain rescues were approximately 25 kg.

Specific submaximal work intensities were determined by performing maximal exercise tests for each participant in both loaded and unloaded conditions to determine ventilatory threshold (T_V). Using linear regression, oxygen cost was matched between conditions.

Room temperature was kept at approximately 22˚C for every test, with minor fluctuations in temperature, barometric pressure and humidity occurring day-to-day.

Exercise trials were separated by at least 24 hours in order to minimize cumulative fatigue. Subjects were asked to refrain from alcohol consumption at least 24 hours before each trial. Urine specific gravity (U_{sg}) was recorded before each experimental trial to ensure proper hydration.

1.5 Limitations

Backpack fitting and tightness are somewhat subjective measures and could vary between subjects or trials. A specific order was used to standardize backpack fit. The tightening order was: waist, shoulder and chest. Subjects then pulled on straps until appropriate tightness was achieved. Strap tightness was measured by recording the length of the excess strap hanging from the buckle. Each strap was tightened to within ± 1 cm for the remainder of the experiment.

The protocol required 5 separate trials of maximal and/or vigorous exercise lasting up to 45 minutes. A full effort was required from subjects in order to achieve VO_{2peak}. This limitation was addressed by selecting subjects that were fit and highly motivated to be involved in the study.

Inspiratory capacity (IC), maximal inspiratory/expiratory pressure (MIP/MEP) and forced vital capacity maneuvers require a concentrated effort. Practice trials for all maneuvers and outlining criteria for completing the specific test dissolved this limitation (ATS Guidelines, 2005).

1.6 Ethical considerations

- Subjects were recruited through word of mouth.
- Subjects were screened using a health questionnaire (PAR-Q +) and provided written informed consent prior to enrollment in this study. Subjects also required additional screening by a physician for ingestion of the temperature capsule.
- Subjects were given the opportunity to ask questions at any time during the experiment.
- Subjects had the right to withdraw at any time during the study.
- Data from the experiment were confidential and was not disclosed to other subjects or third party individuals at any time. Data were shared and discussed with co-researchers involved in the investigation.

- Subjects were given the opportunity to gain knowledge about their resting and exercise lung function, T_V and VO_{2peak}.
- Subjects were informed of the risks that are involved with exercise to exhaustion in order to measure VO_{2peak}. Exercise to exhaustion may result in temporary muscle aches and joint pain. The chance of irregular heartbeat, heart attack, stroke, or death is extremely rare in a normal healthy male (Gibbons et al., 1989)
- Subjects were required to carry a 25 kg pack for prolonged bouts of high intensity exercise. The extra load on the back may have increased the risk of injuries such as foot blisters, ankle swelling, back and knee pain.
- In case of an emergency during the experiment, workers would refer to laboratory emergency action plan.
- All raw data will be retained for five years in a locked filing cabinet at the Van Vliet center at the University of Alberta after publication of the results.

1.7 Definitions

1.7.1 Load carriage

Load carriage is defined as a load that is carried on the back and uses waist and chest straps to keep the load close to the body (Dominelli et al., 2011; Lesser, 2010). Light load carriage ranges from 1-10 kg. Moderate load carriage ranges from 11-20 kg. Heavy load carriage ranges from 21- 40 kg, and very heavy load carriage is anything over 40 kg.

1.7.2 Ventilatory threshold

Anaerobic threshold is defined as the level of oxygen consumption (VO_2) above which aerobic energy production is supplemented, during exercise, by anaerobic mechanisms (Wasserman, 1987; Svedahl and MacIntosh, 2003). Anaerobic threshold can be determined by either direct measurements of lactate (lactate threshold) or gas exchange (ventilatory threshold). For this study, ventilatory threshold was identified by a systematic increase in V_E/VO_2, while V_E/VCO_2 remained constant or decreased (Stage 2, Wasserman, 1987).

1.7.3 Operational lung volume

Operational lung volume consists of EELV and EILV. Measuring V_T and inspiratory capacity (IC) are required to estimate operational lung volume during exercise. Subtracting IC from a resting total lung capacity (TLC) calculates EELV. EILV is calculating by adding V_T volume to EELV (Butcher et al., 2007; Mayne et al., 2009; Guenette et al., 2007;).

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Chapter 2 – Ventilatory responses to prolonged exercise with heavy load carriage

2.1 Introduction

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It was hypothesized that prolonged exercise with heavy load carriage would overload the respiratory muscles and result in a compensatory change in breathing pattern in order to minimize the WOB. Specifically, V_T and EILV would decrease and B_F would increase, with the differences becoming greater over time, compared to the unloaded condition. The progressive alteration in breathing pattern would increase V_D requiring V_E to increase in order to maintain V_A. It was also hypothesized that inspiratory muscle strength would decrease after exercise, which is suggestive of respiratory muscle fatigue.

2.2 Methods

2.2.1 Subjects

A convenience sample of fifteen male volunteers was recruited to participate in the study, which had received approval from the University of Alberta Health Research Ethics Board. The physical characteristics of the participants were (mean ±SD): age 28.6 ± 3.3 years, stature 182.3 ± 5.4 cm, mass 83.5 ± 9.5 kg. All subjects passed a physical activity readiness questionnaire (PAR-Q +) and were screened by a physician for ingestion of the temperature capsule. Each volunteer provided written consent after completing necessary screening procedures. Due to the demanding nature of the experiment, all subjects had no known history of cardiopulmonary disease. All subjects had normal lung function with no airway obstruction or exercise-induced bronchoconstriction.

2.2.2 Design

A within-subject repeated-measures design was used. The experimental condition involved exercise with heavy load carriage and was referred to as loaded (L). The control condition involved unloaded exercise and was referred to as unloaded (UL). The order of the conditions was randomly assigned. The dependent variables were minute ventilation, operational lung volume, breathing pattern and respiratory muscle strength.

Subjects were dressed in personal exercise clothing throughout the experiment. Subjects were asked to wear the same clothing (short and t-shirt) and shoe ensemble throughout the trials. In the loaded condition, the subjects wore a properly sized and fitted backpack (Arc Tery'x Bora 80, North Vancouver, BC).

2.2.3 Experimental protocol

2.2.3.1 Screening and backpack fitting session

Subjects were introduced to the laboratory and went through appropriate screening and consent procedures. Subjects were then fitted with the proper sized backpack. All packs were filled with a consistent weight (25 kg) and volume for every loaded trial throughout the experiment. Sizes were determined by measuring the length of the torso from the C7 vertebrae to the iliac crest. Subjects were instructed to tighten the pack in the following order; hip belt, shoulder straps and chest strap. Subjects were then familiarized with the backpack by completing a short bout of exercise on the treadmill. Upon completion of exercise, strap tightness was measured by recording the length of the excess strap hanging from the buckle. Each strap was tightened to within ±1 cm for the remainder of the experiment.

2.2.3.2 Graded exercise tests

Subjects were randomly assigned to a loaded or unloaded condition. Resting forced expiratory maneuvers were performed using a spirometer (TrueOne, ParvoMedics, Salt Lake City, Utah, USA). The best of at least three FVC trials was used in the data analysis. Spirometry was performed according to ATS (2005) guidelines. Resting spirometry was performed in an upright standing position with minimal forward lean.

The subject completed a GXT to exhaustion to determine T_V and measure VO_{2peak}. The GXT consisted of a constant speed (1.5 $m{\cdot}s^{-1}$) walking protocol on a motorized treadmill (Standard Industries, Fargo, ND). The protocol began at 0% grade and increased by 2% every 2 minutes until T_V was detected. Once T_V was confirmed, the grade was then increased 2% every minute until volitional exhaustion. Ventilatory threshold was determined by an increase in V_E/VO_2 ratio, while V_E/VCO_2 remained steady or increased slightly (Wasserman, 1987). Post exercise spirometry was performed to rule out exercise-induced bronchoconstriction (EIB). After at least 24-hours of recovery, the subject completed the second GXT in the alternate condition.

2.2.3.3 Pulmonary function tests

Each subject was randomly assigned to complete resting pulmonary function testing (Vmax Encore, Carefusion, Yorba Linda, California, USA) in both conditions. Total lung capacity (TLC) was calculated by nitrogen washout. Pulmonary function testing was performed according to the guidelines of the American Thoracic Society (2005). Maneuvers were completed while standing upright with minimal forward lean. Spirometry was performed in order to obtain vital capacity (VC). Nitrogen washout was used to determine functional residual capacity (FRC) and residual volume (RV). Total lung capacity was then determined by adding VC and RV.

2.2.3.4 Practice session

Subjects completed a practice session to ensure the workloads were appropriate for the experimental protocol (EP). The practice session consisted of two separate bouts (20 min) of sub threshold exercise. For the loaded condition, the treadmill grade selected was 2% below the grade that elicited T_V during the loaded GXT. Using linear regression, oxygen demand was matched, solving for treadmill grade, between conditions. Subjects completed the two exercise bouts to ensure that the aerobic demands derived from the GXT were matched between conditions (± 0.1 L/min). This session also was an opportunity to practice MIP/MEP and IC maneuvers.

2.2.3.5 Experimental sessions

Subjects completed the first EP randomly assigned to the loaded or unloaded condition. During the experimental protocol, subjects performed 45 minutes of exercise at a constant speed ($1.5\ m \cdot s^{-1}$) and grade. The treadmill grade for both conditions was pre-determined, as mentioned above. Baseline measurements were recorded 5 minutes prior to exercise. Inspiratory capacity maneuvers were completed at baseline and at 5-minute intervals during exercise. Perceptual responses (exercise stress, breathing discomfort and leg fatigue) were recorded in the first 5-minute measurement cycle and were repeated every 10 minutes throughout the experimental trial.

Before and after exercise, each subject completed forced expiratory maneuvers on a spirometer to obtain flow volume loops. Subjects also completed MIP/MEP maneuvers before and within 5 minutes of exercise completion.

2.2.4 Procedures

2.2.4.1 Cardio-Respiratory measurements

A two-way breathing valve was used to collect expired gases (Hans Rudolph, Kansas City, MO, USA). Expired gases and ventilatory parameters were analyzed and calculated using a metabolic measurement system (TrueOne, ParvoMedics, Salt Lake City, UT, USA). The system was calibrated according to manufacturer's specific guidelines prior to each test. Heart rate (HR) was monitored continuously using telemetry and was recorded at the end of each minute (Polar Beat, Electro, Lachine, QC). Blood pressure was taken by auscultation at rest and at 5, 25 and 45 minutes of exercise during the EP.

Alveolar ventilation was calculated from VCO_2 and PCO_2, while V_D was determined from the difference between V_E and V_A (West, 2000). Arterial PCO_2 (P_aCO_2) was estimated from end-tidal CO_2 measurements (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, AIDInstruments, New South Wales, Australia) and displayed in real-time on a laptop computer. Gas analyzer calibration was performed immediately prior to each test. Calibration of the gas analyzers was checked immediately following each test to verify that calibration had been maintained during the data collection period.

2.2.4.2 Lung Volume

Inspiratory capacity maneuvers were completed during baseline to obtain resting lung volumes. For baseline measurements, the treadmill was set to the predetermined exercise grade during the baseline measurements. Subjects stood in a walking position. Changes in lung volumes were estimated by completing IC maneuvers at 5-minute intervals during the EPs.

An inspiratory pneumotach (ParvoMedics, Sandy, UT, USA) attached to the same two-way breathing valve was used to measure inspiratory pressure changes. Calibration of the system was performed according to manufacturer’s specific guidelines prior to each exercise trial.

End-expiratory lung volume and end-inspiratory lung volume were then estimated from IC measurements taken at rest and during exercise. Subtracting IC from TLC will estimate EELV. End-inspiratory lung volume was then estimated by adding V_T and EELV (Butcher et al., 2006; O’Donnell et al., 2001). Tidal volume was recorded in the minute leading up to the IC maneuver and then averaged. Changes in EELV and EILV were expressed as a percentage of TLC obtained from the pulmonary function testing on day 4 of the experiment. It was assumed that TLC does not change with exercise (O'Donnell et al., 2001).

2.2.4.3 Respiratory muscle strength

Maximal inspiratory pressure and maximal expiratory pressure were measured as indices of respiratory muscle strength. Maximal inspiratory/expiratory pressure was measured by having the subject produce a maximal inspiration or expiration through a mouthpiece into an occluded rigid tube. The tube was attached to a positive/negative pressure gauge (Cole Parmer Co, Stratford, USA) and a small leak (1mm diameter) prevented accessory muscle contribution. Measuring MIP commenced at RV and MEP began at TLC. Respiratory muscle strength measurements were recorded before exercise and within 5 minutes of exercise completion. Each trial was repeated until there were two maximal values within 5 cm H_2O.

2.2.4.4 Core temperature

Core temperature was monitored continuously using telemetry and was recorded at 5-minute intervals (VitalSense™, Mini Mitter, Bend, OR). The temperature capsule was ingested 5 hours prior to the start of the experimental trial.

2.2.4.5 Analysis

Data are presented as mean ± standard error (SE) unless indicated otherwise. Two-way, repeated-measures analysis of variance (ANOVA) was used to detect any differences in HR, VO_2, VCO_2, $ETCO_2$, PCO_2, V_E, V_A, V_D, V_T, B_F, IC, EELV, EILV and core temperature between conditions at rest and 5-minute intervals during exercise. During exercise, perceptual scales were analyzed between conditions at 5 min and repeated at 10-minute intervals. Within condition analysis was limited to 15 and 45-minute data in order to ensure comparisons were made after steady exercise was achieved. The physiological responses observed in the first 10 minutes occur in order to achieve physiological steady state. If a significant change or interaction effect was found, Tukey's post hoc test was used to locate each difference. Student's t-test was used to detect any differences in pulmonary function, MIP/MEP, perceptual scales compared to ventilation slopes, and maximal exercise data between conditions. Pearson Product-Moment correlation coefficients were used to examine the relationships between variables of interest. All statistical analyses was performed using Sigma Plot Software version 12.0 (Systat Software Inc., Chicago, USA). Significance was set *a priori* at $P < 0.05$.

2.3 Results

2.3.1 Resting pulmonary function

In the loaded condition there were a small but significant decreases in FVC (6.00 L ± 0.17 vs. 6.23 ± 0.18) and FEV1 (4.66 L ± 0.14 vs. 4.87 ± 0.14). There was no change in the FEV_1/FVC ratio (0.78 ± 0.01 vs. 0.78 ± 0.01) compared to the unloaded condition (Table 2-1).

2.3.2 Maximal oxygen uptake

The physiological responses to maximal exercise are shown in Table 2-2. In the loaded condition, VO_{2peak} significantly reduced (4.50 L·min^{-1} ± 0.50 vs. 4.62 L·min^{-1} ± 0.50) while there were no significant changes in V_E (164.4 L·min^{-1} ± 20.4 vs. 165.1 L·min^{-1} ± 23.1), B_F (54 breaths·min^{-1} ± 10 vs. 53 breaths·min^{-1} ± 10) and V_T (3.09 L ± 0.39 vs. 3.17 ± 0.31) at peak exercise compared to the unloaded condition. Peak treadmill grade (%) and power output (W) were significantly reduced in the loaded condition (18.0 % ± 2.4 vs. 26.7% ± 2.9 and 292 W ± 48 vs. 332 W ± 44) compared to the unloaded condition. There was no relationship between body mass and the change in maximal oxygen uptake (ΔVO_{2peak}) between conditions (Figure 2.1).

2.3.3 Body mass and urine specific gravity

Body mass (mean ±SD) was the same between conditions (UL 83.9 ± 10.1 kg, L 84.0 ± 10.0 kg) prior to exercise. Body mass decreased by 1.2 kg (± 0.06) and 1.4 kg (± 0.06) in the unloaded and loaded conditions, respectively. Urine specific gravity, measured at the start of each day met the criterion for normal hydration. The USG was not significantly different between conditions prior to exercise (UL 1.014 ± 0.007, L 1.011 ± 0.006). These results suggest that subjects were properly hydrated prior to exercise.

2.3.4 Temperature responses during 45 min of exercise with heavy load carriage

Core temperature was not significantly different between conditions at any point during the experimental trials (Figure 2.2). Core temperature increased by 1.51°C (± 0.08) and 1.69 °C (± 0.08) (n=10) in the unloaded and loaded conditions, respectively, throughout the exercise trials. These results suggest that any changes in ventilatory responses between conditions were not due to a difference in core temperature. Core temperature measurements were not done for the final 5 subjects.

2.3.5 Effect of heavy load carriage on cardiorespiratory responses during 45 minutes of submaximal exercise

Oxygen demand was the same between conditions through the experimental trial with the exception of small differences occurring at 30 and 45 min (Figure 2.3). In the loaded condition, V_E gradually increased and was significantly higher than the unloaded condition after 25 min. As expected the difference became greater over time throughout the exercise trial (Figure 2.4). Breathing frequency gradually increased within both conditions throughout the experimental trials. In the loaded condition, B_F was significantly higher than the unloaded condition after 10 min and the difference became great over time (Figure 2.5). In the loaded condition, V_T gradually decreased throughout the exercise trial with a significant decrease between conditions occurring at 40 min. In the unloaded condition, V_T did not change throughout the exercise trial (Figure 2.6). Calculated V_D was the same between conditions in the first 25 min of exercise; however, V_D was significantly higher at 30 min with the difference becoming greater over time throughout the exercise trial (Figure 2.8). Heart rate gradually increased throughout the exercise trial in both conditions and was significantly higher in the loaded condition throughout the exercise bout (Figure 2.12). Blood pressure was the same between conditions at rest and during exercise throughout the EP.

2.3.6 Effect of heavy load carriage on operating lung volume during 45 minutes of submaximal exercise

End expiratory lung volume was not different between conditions throughout the exercise bout and did not change within each condition during the exercise trials (Figure 2.7). End inspiratory lung volume did not change significantly within either condition but was significantly lower in the loaded condition at 15 min and again at 35 min until the end of exercise, compared to the unloaded condition. Inspiratory capacity was not different between conditions throughout the exercise bout and did not change within each condition throughout the exercise trials. Therefore, the decrease in V_T during loaded exercise was the result of decreased EILV while EELV remained constant.

2.3.7 Respiratory muscle strength

Prior to exercise, MIP/MEP values were the same in both conditions. Table 2-3 illustrates that, after 45 minutes of exercise, MIP significantly decreased in the loaded condition compared to the pre-exercise value. There was no change in MEP values between pre and post exercise in the loaded condition. There was no change in MIP/MEP values between pre and post exercise in the unloaded condition.

2.3.8 Visual analogue scales

Exercise stress, breathing discomfort and leg fatigue perceptual responses all increased within conditions throughout the exercise trial. Between conditions, exercise stress, breathing discomfort and leg fatigue were significantly higher in the loaded condition at 25, 35 and 45 min respectively, compared to the unloaded condition, with the differences becoming greater over time (Figures G.10, G.11 and G.12). Breathing discomfort increased proportionally to increased V_E in both conditions (Figure 2.13).

2.4 Discussion

2.4.1 Major findings

One of the main results of this experiment was the difference in ventilatory responses between acute and prolonged exercise with heavy load carriage. The mechanical disadvantage placed on the respiratory system during acute exercise under load does not increase minute ventilation, although breathing pattern is slightly altered (Lesser, 2010). It is likely that the extra load placed on the thorax increased WOB, however, the respiratory muscles were able to temporarily overcome the increased breathing resistance and avoid ventilatory impairment during acute exercise. This is further supported by our sub-maximal and maximal exercise results showing no difference in V_E, between conditions, during short-term exercise (5 – 20 min) at similar oxygen demands. Consistent with our hypothesis, the results demonstrate that prolonged exercise (45 min) with heavy load carriage further potentiated the mechanical disadvantage placed on the respiratory system and resulted in a progressive alteration in ventilatory mechanics. The decrease in maximal inspiratory pressure, compensatory changes in breathing pattern, decreased EILV and increased perceived breathing discomfort is suggestive of respiratory muscle fatigue. In an attempt to minimize the load placed on the fatiguing respiratory muscles, subjects adopted a shallow and frequent breathing pattern, however, over a prolonged bout of exercise this progressively increased dead space and minute ventilation furthering the increase in WOB and perceived breathing discomfort.

2.4.2 Ventilatory mechanics during exercise with heavy load carriage

Oxygen consumption, core temperature and blood pressure responses were the same between conditions throughout the experimental trials. The matching of these variables ensured that any physiological changes in ventilatory responses to exercise between conditions were due to the weight of the backpack on the thorax and not an alteration in thermoregulation.

At rest with load carriage, EELV and EILV were 15.1 and 8.5% lower compared to the unloaded condition. There was no difference in resting V_T between conditions, which suggests that subjects breathed at a lower lung volume at rest with load carriage.

During exercise with heavy load carriage, EELV was the same between conditions while EILV decreased, starting at 35 min. End-inspiratory lung volume was 5.9, 7.7 and 6.4% lower at 35, 40, and 45 minutes, respectively, compared to the unloaded condition. Inspiratory capacity did not change within condition or between conditions, suggesting that loaded V_T decreased only through a decrease in EILV.

Minute ventilation increased by 12.6 ± 4% during the unloaded exercise trial. This was consistent with previous studies demonstrating increased V_E with prolonged exercise. Hopkins et al. (1998) observed a 10.5% increase in V_E during 60 min of cycling at 65% $VO_{2peak.}$ Stickland et al. (2004) reported a similar increase in V_E during a longer bout (2.51 ±0.86 h) of cycling at 70% VO_{2peak}. Both authors suggested the increase in V_E was a result of an increase in V_D. The increase in V_D during a constant workload is partially due to ventilation-perfusion (V_A/Q) mismatch. Hopkins et al. (1998) found a progressive V_A/Q mismatch during 1 hr of cycling. The development of interstitial edema is thought to be the reason why V_A/Q mismatch increases over time. However Hopkins et al. (1998) also found that pulmonary artery pressure decreases progressively during prolonged exercise (1 h). A decline in pulmonary vascular pressure during exercise would have the effect of decreasing capillary recruitment and increasing physiological dead space, resulting in an increased V_D (Stickland et al, 2004).

Core temperature increased 1.51°C ± 0.36 (n=10) from baseline to 45 min during the unloaded exercise trial. Increased core temperature (1°C) is responsible for significant increases in V_E at rest; however, it is more difficult to demonstrate an independent influence of core temperature on V_E during exercise (White, 2006). There was no difference in core temperature change between conditions at any point during the exercise trials. These results suggest that the differences in V_E cannot be attributed to core temperature changes during exercise.

The rationale that breathing is increased in order to serve a heat loss role and/or as a result of increased V_D makes it difficult to determine the precise mechanisms that leads to increases in V_E, disproportional to VO_2, during prolonged exercise. It is likely that an increased V_A/Q, decreased pulmonary arterial pressure and increased core temperature all contribute to increased V_E during prolonged exercise, however, future investigation will be required to determine the precise contribution of each mechanism on V_E during exercise. Minute ventilation increased by 23.7 ± 14.4% during the loaded condition exercise trial. Part of the increase in V_E can be attributed to the mechanisms mentioned above, however, there was clearly an interaction effect on V_E as result of the backpack. These results suggest that the progressive increase in V_E, compared to the unloaded condition, is due to an alteration in ventilatory mechanics; specifically breathing pattern and operational lung volume during 45 min of exercise.

In this study, there were no differences in V_E between conditions up to 20 min (Figure 2.4), however, the mean differences became greater over time with a significant increase in the loaded V_E occurring at 25 min. Ventilation was 9.7, 10.9 and 15.1% higher at 25, 35 and 45 min respectively compared to the unloaded condition. There was no change in breathing pattern at 5 min but small changes in B_F and V_T occurred at 10 and 15 min, respectively. Breathing frequency was 11.7, 11.0, 16.3 and 21.7% higher at 15, 25, 35 and 45 min, respectively, compared to the unloaded condition. Although V_T progressively decreased throughout the exercise trial, there were no differences between conditions from 20 to 35 min. Tidal volume significantly decreased in the last 10 min of exercise. Tidal volume was 6.8 and 6.3% lower at 40 and 45 min respectively compared to the unloaded condition.

The increase in V_E, compared to the unloaded condition, appears to be driven mainly by a progressive increase in B_F and decrease in V_T and is characteristic of a rapid and shallow breathing pattern. The progressive increase in rapid, shallow breathing may have been adopted as a compensatory strategy to minimize the load placed on the respiratory muscles. However, this breathing pattern can become disadvantageous as V_E and O_2 cost of breathing increases with increased B_F and V_D (Wang et al., 2004). In the final 15 min of exercise, there was a significant increase in V_D in the loaded condition. The large increase in V_E in the final 10 min of exercise occurred to overcome the increase in V_D and maintain V_A. This may have placed an additional load on the inspiratory muscles and furthered increases in WOB (Sheel et al., 2001)

Inspiratory muscle strength (MIP) was significantly reduced after 45 min of exercise with heavy load carriage while expiratory muscle (MEP) strength did not change. Although respiratory muscle strength was not measured during exercise, the decrease in post-exercise MIP is suggestive of inspiratory muscle fatigue during 45 min of exercise under load. It is difficult to determine precisely when inspiratory muscle fatigue occurred; however, the progressive changes in breathing pattern, decreased EILV and increased V_E indicates a compensatory strategy to minimize WOB. As V_E progressively increased, WOB continued to increase and further burden the inspiratory muscles. If the exercise intensity did not change and the progressive increase in V_E continued, eventually the breathing pattern will impair the ability to maintain V_A, which would effectively decrease oxygen delivery to working muscle and decrease submaximal exercise performance. This is a novel finding, since, to our knowledge, the occupational impact of respiratory muscle fatigue from prolonged exercise with heavy load carriage has not been previously reported. Further investigation is needed to examine WOB and ventilatory mechanics during prolonged exercise to better understand the mechanical disadvantage and respiratory consequences of heavy load carriage.

2.4.3 Perceptual responses

Exercise with heavy load carriage increases the weight on the thorax and likely increases the oxygen cost of breathing during a prolonged exercise bout. As mentioned earlier, a rapid and shallow breathing pattern is adopted in order to minimize the weight lifted per breath with load carriage. However, the progressive alteration in breathing pattern increased V_E, which increased respiratory drive and breathing difficulty (O'Donnell et al., 2000). The slope between breathing discomfort compared to V_E was similar in both conditions (Figure 2.11). The results illustrate that increased perception of breathing discomfort was secondary to the increase in V_E. Due to a much larger increase in V_E during the loaded exercise bout, it makes it difficult to determine a precise ventilation rate that increased breathing discomfort between conditions. Measuring WOB at similar ventilation rates could aid our understanding of the relationship between ventilatory mechanics and perceptual breathing discomfort during constant intensity exercise with heavy load carriage.

According to Dempsey et al. (2008), respiratory muscle fatigue is largely due to the increased WOB of respiratory muscles. The increased inspiratory WOB may result in a decrease blood flow to the legs during prolonged exercise with a heavy pack. If B_F and V_E were to rise in order to maintain V_A during submaximal loaded exercise, the inspiratory WOB breathing could rise significantly and increase blood demand, resulting in a sympathetically mediated vasoconstrictor response in limbs known as the "inspiratory muscle metaboreflex" (Sheel et al., 2001). This decrease in leg blood flow could initially increase perceived exertion during exercise and eventually increase Q demand, resulting in metabolite accumulation and decreased exercise performance (Harms et al., 1997; Dempsey et al., 2008). It is possible that the increased perception of exercise stress in the loaded condition is the result of greater muscle recruitment throughout the body. Previous research suggests that rectus abdominis muscle activity increases when carrying heavy load carriage (Al-Khabbaz et al., 2008). The increase in muscle recruitment and change in posture during exercise with heavy load carriage could be contributing to the decreased leg blood flow and increased perceived exercise stress.

The results of our study support that perceived exercise stress and perceived leg fatigue are greater in exercise with load carriage at the same oxygen demand as the unloaded control. The decreased inspiratory muscle strength in the loaded condition post-exercise suggests that respiratory muscle fatigue likely occurred. Measuring leg blood flow in future research would give a better understanding of the relationship between the O_2 cost of breathing, peripheral blood distribution and perception of exercise stress, breathing discomfort and leg fatigue during prolonged exercise with heavy load carriage.

2.4.4 Pulmonary function

Consistent with previous findings (Dominelli et al., 2011), spirometric values decreased slightly with a properly fitted 25 kg backpack. Forced vital capacity and forced expiratory volume in one second decreased 3.7 and 3.3% respectively, compared to the unloaded condition. The ratio of FEV_1/FVC was not significantly different between conditions.

There are some similarities between wearing a heavy backpack and obesity, in that mass loading is evident by the extra weight placed on thorax. In obese populations, expired flow volumes are decreased as BMI increases (Jones et al. 2006). Previous research shows a decrease in FVC and FEV_1 by 5.5, and 6.6% respectively while chest-loaded to an equivalent BMI of 32 kg/m^2 (Wang et al., 2004). The extra weight carried on the chest and abdomen mass-loads the thorax and, as a consequence, nearly doubles the inspiratory WOB (Sharp et al., 1964). The mass of a heavy pack loads the thorax, however, it differs from obesity in that abdominal loading is not present in lean participants carrying a loaded backpack. The packs used in our study were properly fitted for each subject and distributed the added mass over a large area via, the waist strap, transferring a portion of the weight onto the hip. While the weight of pack increases the load placed on the chest wall, it does not restrict the thorax during inspiration. In our study, TLC did not change between conditions and RV, although not significant, increased slightly in the loaded condition. The increased transpulmonary pressure as a result of chest wall loading is known to increase closing volume and effectively increase closing capacity and RV (West, 2008). This may explain why expired flow volumes were decreased even though TLC did not change while wearing the pack.

2.4.5 Effects of carrying heavy load carriage on maximal exercise performance

This study confirmed that carrying heavy load carriage slightly decreased maximal oxygen uptake. Maximal oxygen uptake decreased by 2.6 ± 4%. There were no significant differences in V_E and breathing pattern at maximal exercise, which suggests that the heavy backpack did not result in ventilatory impairment. Although there was a large range of body mass in this study, there was no relationship between body mass and ΔVO_{2peak} between conditions. This suggests that size was not a determinant for changes in maximal oxygen uptake.

The slight decrease in the loaded VO_{2peak} may be the result of a biomechanical impairment while exercising at maximal treadmill grades. The inability to increase foot speed and/or stride length while carrying the heavy pack at steep treadmill grades may slightly decrease exercise capacity and maximal oxygen uptake. Previous research has demonstrated that running and/or jogging on a treadmill yields a higher VO_2peak, compared to walking (Keren et al. 1980). In this study, subjects were unable to break into a jog in the final stage of the loaded GXT although all subjects were able to jog in the final stage of the unloaded GXT.

As expected, VO_2 was always higher in the loaded condition at the same treadmill speed and grade during the GXT (Dominelli et al, 2011; Patton et al, 1991). The increased VO_2 at a given speed and grade under load was due to a greater energy demand needed to move the increased mass. The decreased efficiency as a result of carrying the heavy pack is thought to be the main reason for decreased peak power output and exercise performance, however, further investigation is required to determine the precise mechanisms that decrease maximal oxygen uptake with heavy load carriage.

2.4.6 Heart rate during exercise with heavy load carriage

Novel results of this experiment showed that, during loaded exercise, HR was always higher then the unloaded condition at matched oxygen uptake rates. During exercise, maintaining VO_2 is governed by the Fick equation. If VO_2 is the same and HR is higher in the loaded condition either stroke volume (SV) or peripheral arterial-venous difference ($A\text{-}VO_2$) is decreasing. According to De Cort et al. (1991), cardiac output is the major contributor to increases in VO_2 during exercise. It is likely that Q is maintained by an increase in HR and decreased SV during prolonged bouts of exercise with heavy load carriage. The load placed on the thorax may alter intra-thoracic pressure swings and cardiac function (Stark-Leyva, 2004). Further research investigating the effect of exercise with heavy load carriage on cardiac function is required.

2.5 Conclusion

The present investigation examined ventilatory responses to prolonged exercise with heavy load carriage. Ventilation was higher in the loaded condition, with the difference becoming greater over time. Breathing frequency progressively increased and V_T decreased, resulting in a rapid and shallow breathing pattern. End expiratory lung volume did not change, suggesting that V_T decreased only though a decrease in EILV in the loaded condition. Inspiratory muscle strength decreased after 45 min of exercise with heavy load carriage, which is suggestive of respiratory muscle fatigue. In conclusion, breathing pattern was altered in an attempt to minimize the WOB during prolonged exercising with heavy load carriage. However, the progressive decrease in V_T, increase in B_F and V_D increased the breathing intensity and perceived effort of steady submaximal exercise.

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Table 2-1. Mean (±SE) pulmonary function at rest in unloaded and loaded conditions

Variable	UL	L
FVC (L)	6.23 (0.18)	6.00 * (0.17)
FEV_1 (L)	4.87 (0.14)	4.66 * (0.14)
TLC (L)	7.77 (0.17)	7.59 (0.17)
VC (L)	6.32 (0.20)	6.11 * (0.20)
RV (L)	1.45 (0.10)	1.48 (0.11)

FVC, forced vital capacity; FEV_1, forced expired volume in 1 second; TLC, total lung capacity; VC, vital capacity; RV, residual volume. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions. n=15

Table 2-2. Mean (±SE) maximal exercise data in unloaded and loaded conditions

Variable	VO_{2peak} UL	VO_{2peak} L
VO_2 ($L \cdot min^{-1}$)	4.62 (0.53)	4.50* (0.49)
VO_2 ($ml \cdot min \cdot kg^{-1}$)	55.0 (5.5)	53.6* (4.8)
V_E ($L \cdot min^{-1}$)	165.1 (23.1)	164.4 (20.4)
V_T (L)	3.17 (0.31)	3.09 (0.39)
B_F ($breaths \cdot min^{-1}$)	53 (10)	54 (10)
HR ($beats \cdot min^{-1}$)	186 (11)	184* (11)
PO (W)	332 (44)	292* (48)

VO_2, volume of oxygen consumed; V_E, ventilation; V_T, tidal volume; B_F, breathing frequency; HR, heart rate; PO, power output. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions. n=15

Table 2-3. Mean (±SE) respiratory muscle strength in unloaded and loaded conditions

Variable	UL	L
MIP pre (cmH_2O)	134 (5)	135 (5)
MIP post (cmH_2O)	135 (5)	$126^{*\#}$ (4)
MEP pre (cmH_2O)	183 (6)	179 (6)
MEP post (cmH_2O)	181 (7)	178 (6)

MIP, maximal inspiratory pressure; MEP, maximal expiratory pressure. Asterisk (*) indicates significant difference ($P < 0.05$) from UL-MIP post; Number sign (#) indicates significant difference between MEP pre/post within the loaded condition. n=15

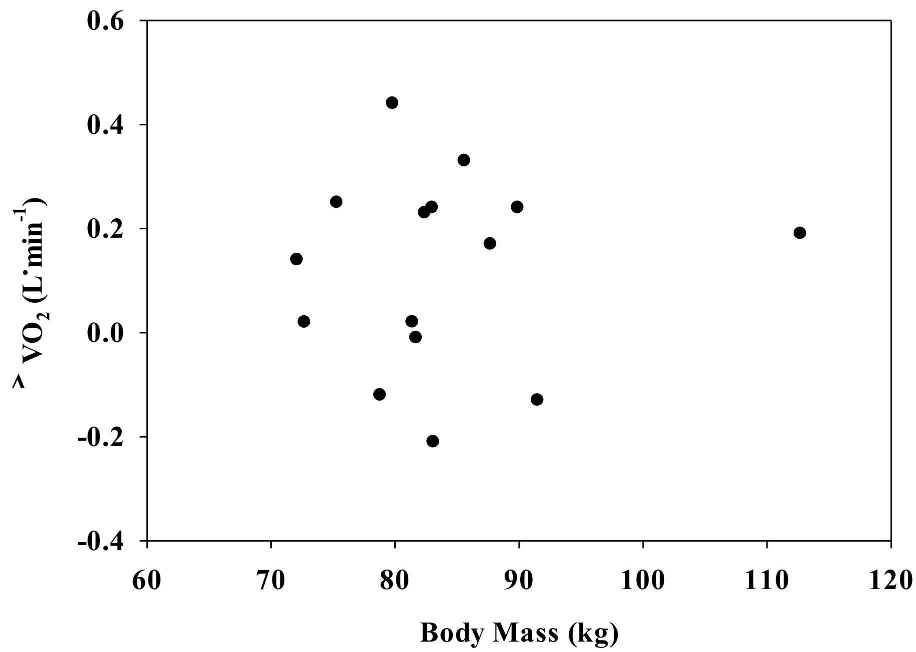

Figure 2.1. Relationship between the change in peak oxygen consumption (ΔVO_2) with and without load carriage and baseline body mass. Change in peak oxygen was determined by subtracting the loaded VO_{2peak} from the unloaded VO_{2peak}. y = 2.9498 + 83.366, r^2 = 0.055. n=15

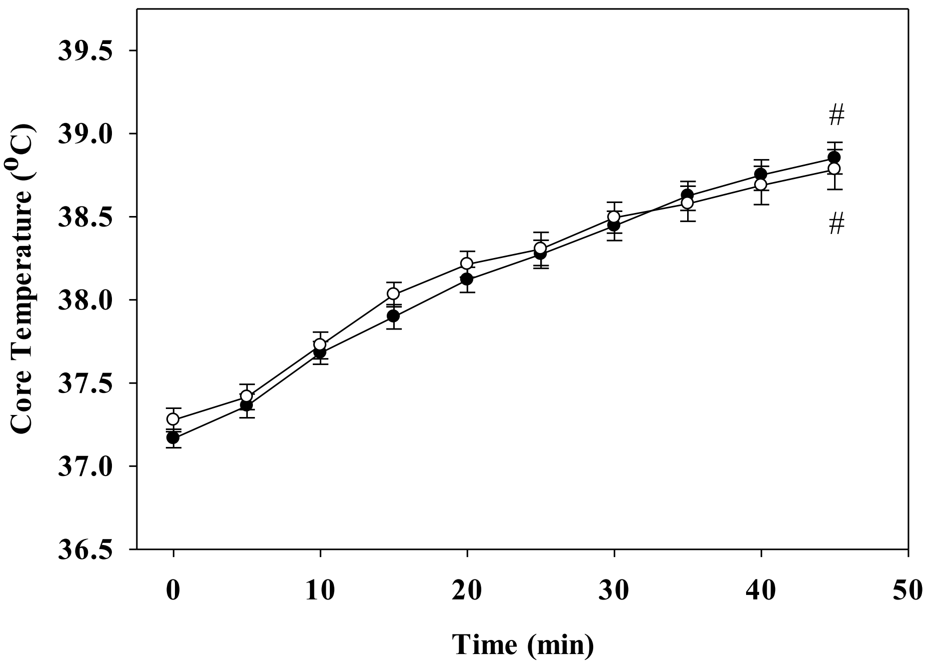

Figure 2.2. Mean (±SE) core temperature during exercise in loaded (closed circles) and unloaded (open circles) conditions. Number sign (#) indicates significant difference between 15 and 45 min within conditions ($P < 0.05$). n=10

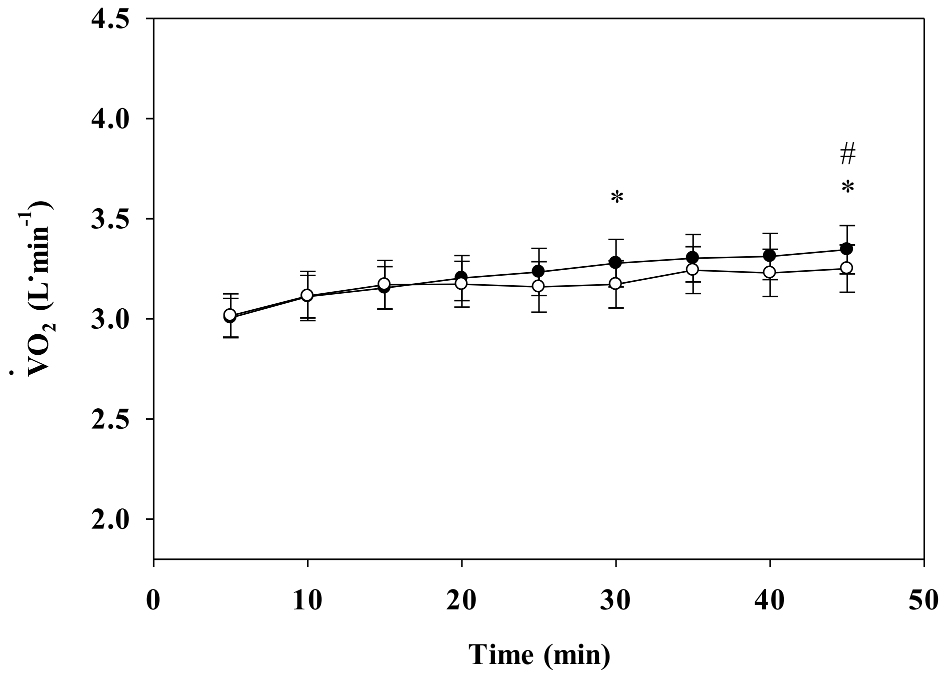

Figure 2.3. Mean (±SE) oxygen uptake ($\dot{V}O_2$) during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within the loaded condition. n=15

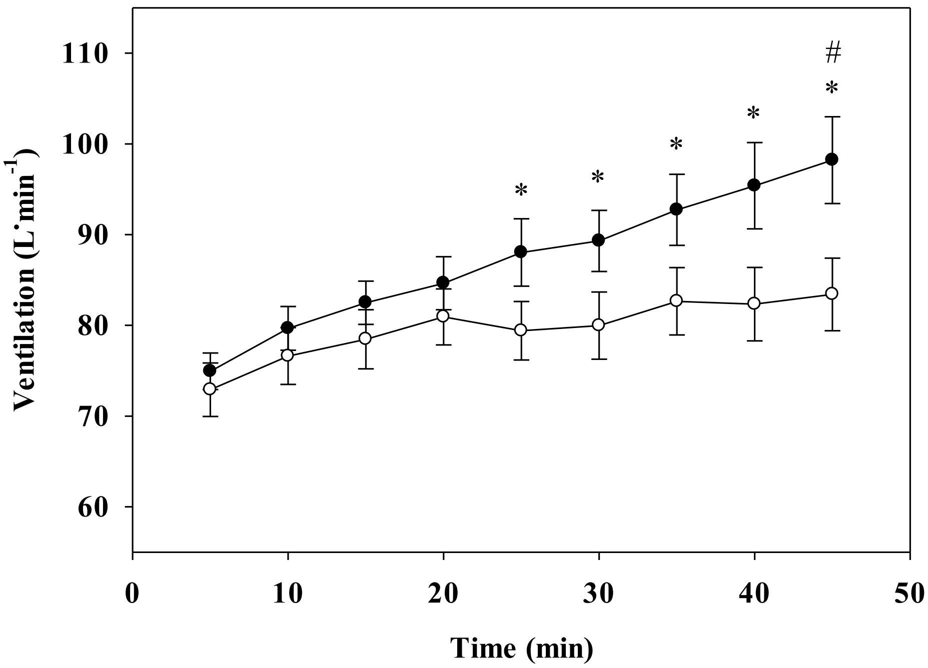

Figure 2.4. Mean (±SE) ventilation during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within the loaded condition. n=15

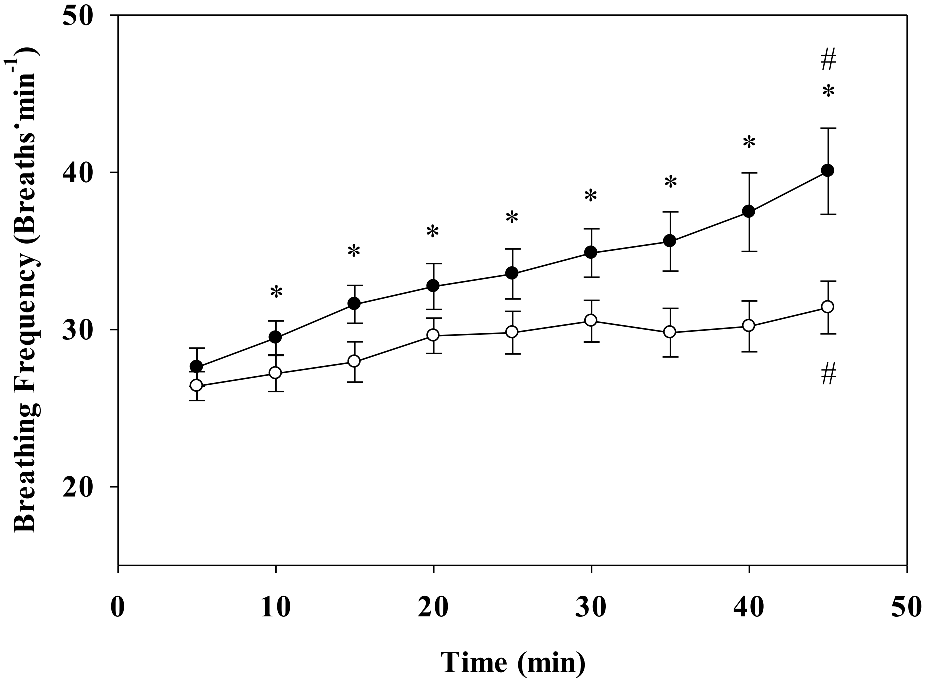

Figure 2.5. Mean (±SE) breathing frequency during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within conditions. n=15

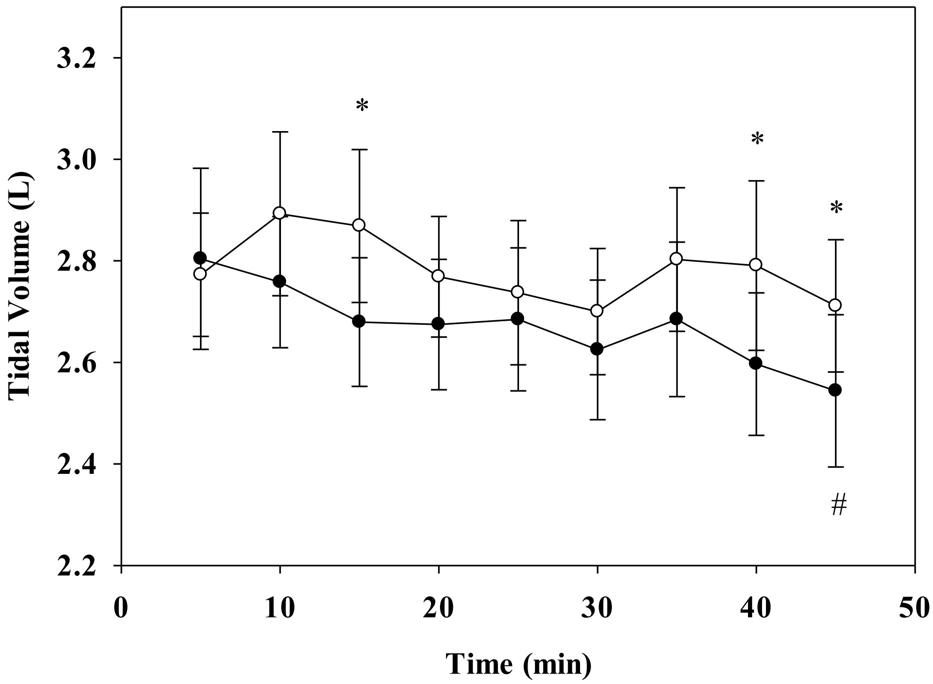

Figure 2.6. Mean (±SE) tidal volume during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within the loaded condition. n=15

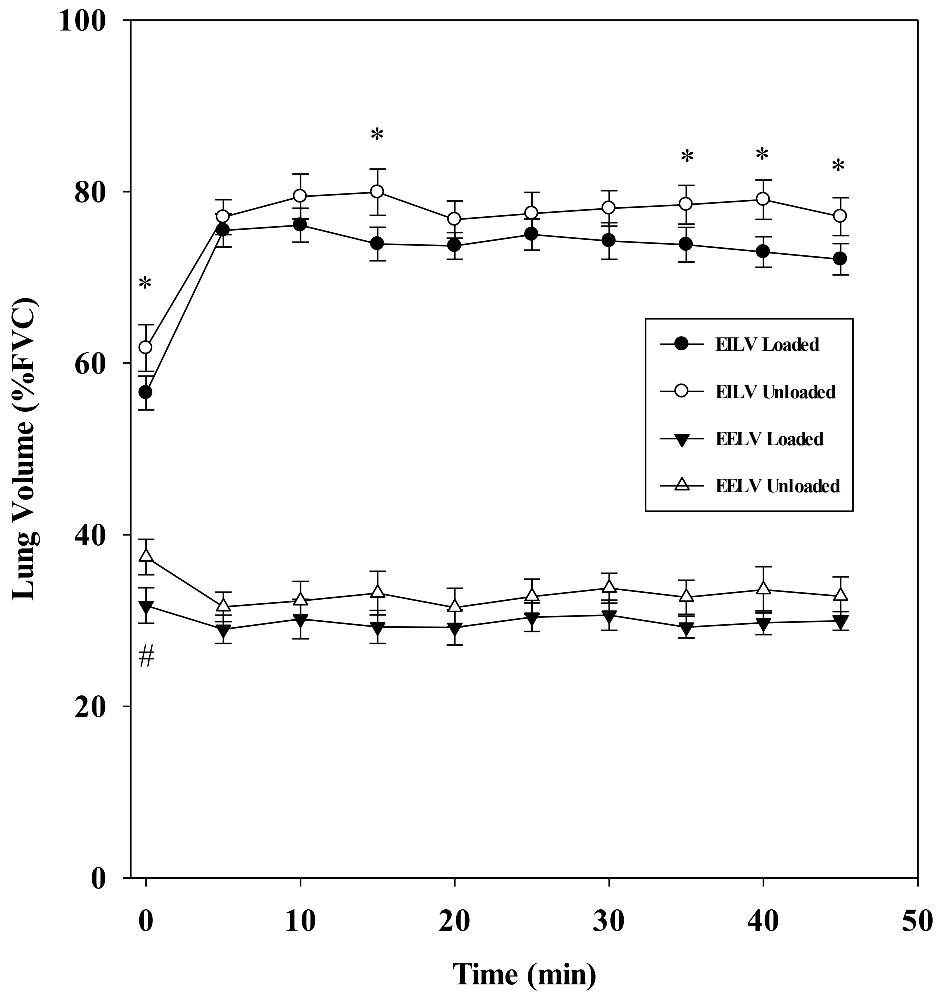

Figure 2.7. Mean (±SE) resting and operational lung volume in loaded and unloaded conditions shown as a percentage of the measured forced vital capacity. Asterisk (*) indicates significant difference (P < 0.05) EILV (end-expiratory lung volume) between conditions; Number sign (#) indicates significant different EELV (end-expiratory lung volume) between conditions. n=15

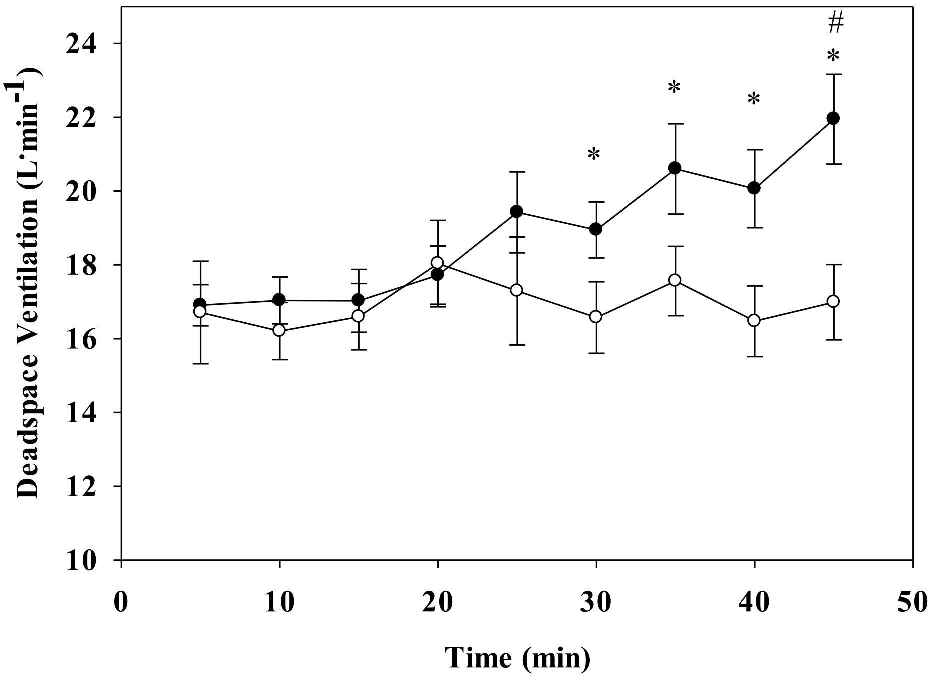

Figure 2.8. Mean (±SE) deadspace ventilation during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05.) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within the loaded condition. n=15

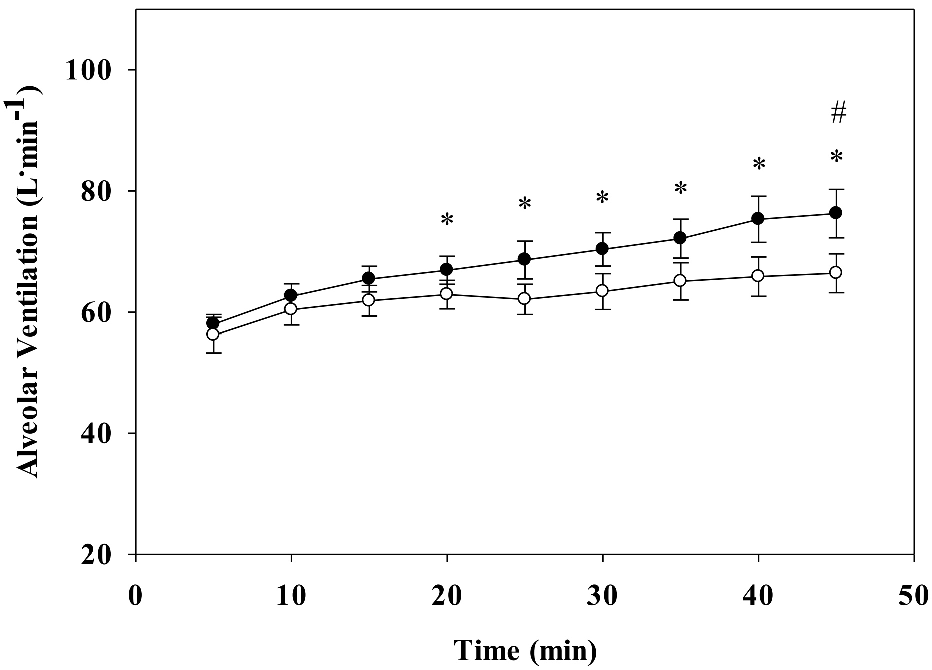

Figure 2.9. Mean (±SE) alveolar ventilation during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within the loaded condition. n=15

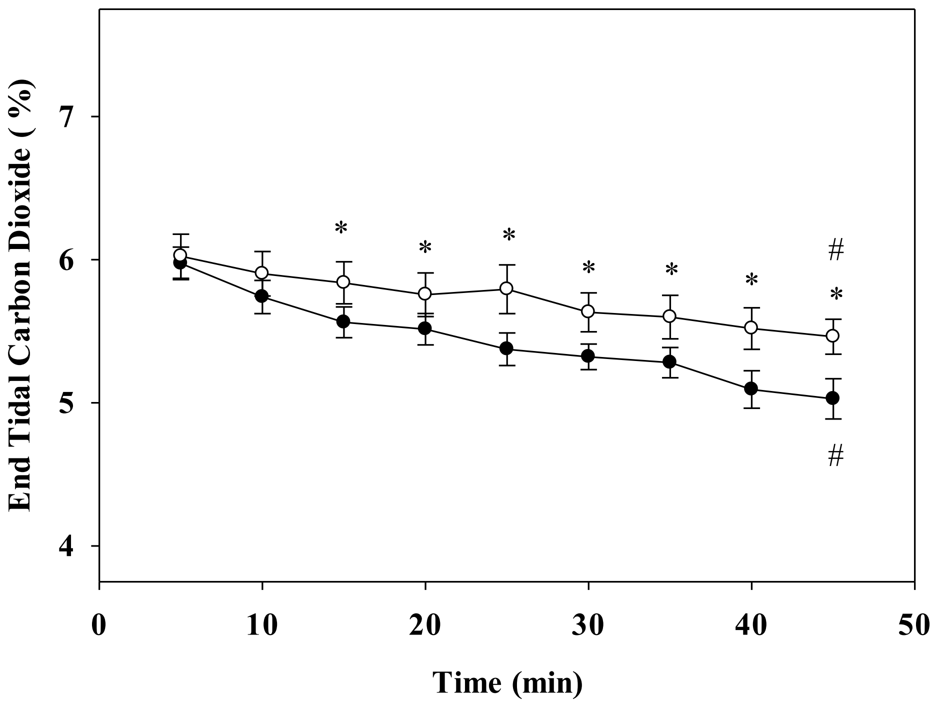

Figure 2.10. Mean (±SE) end tidal carbon dioxide production during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within conditions. n=15

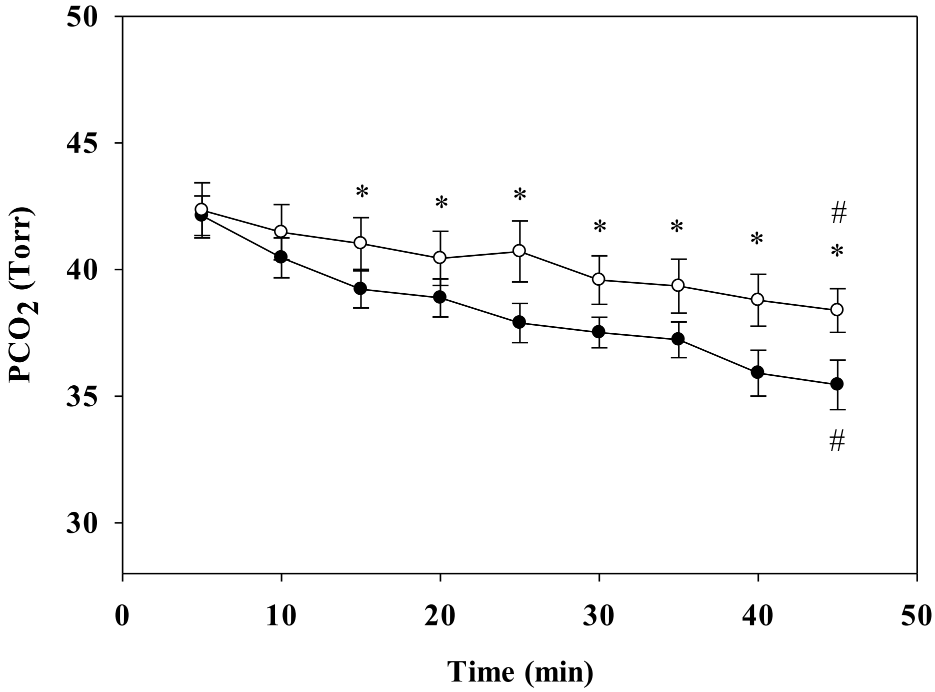

Figure 2.11. Mean (±SE) pressure of carbon dioxide (PCO_2) during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within conditions. n=15

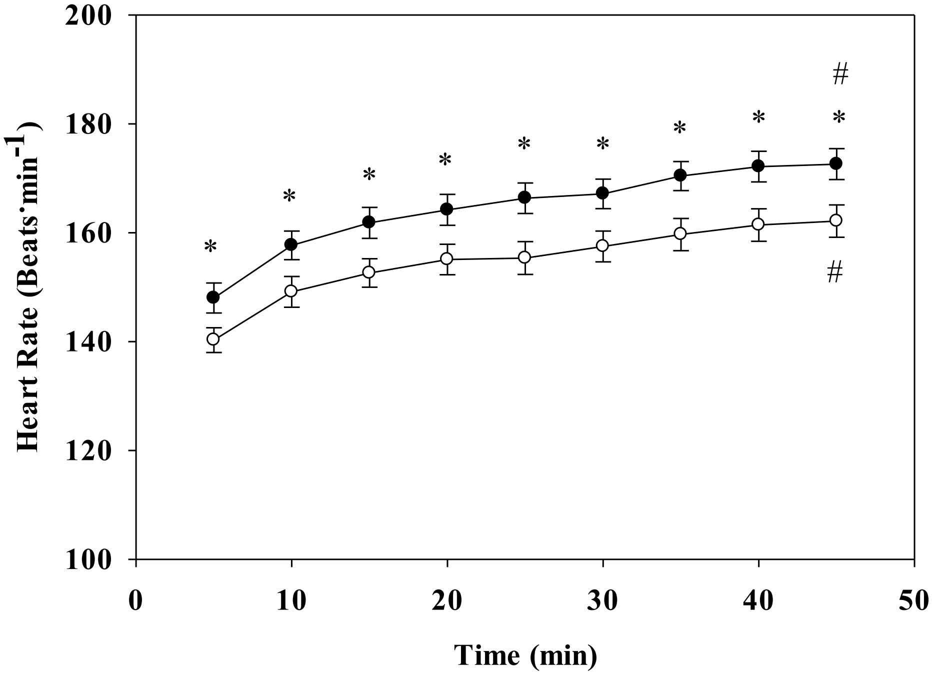

Figure 2.12. Mean (±SE) heart rate during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference ($P < 0.05$.) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within conditions. n=15

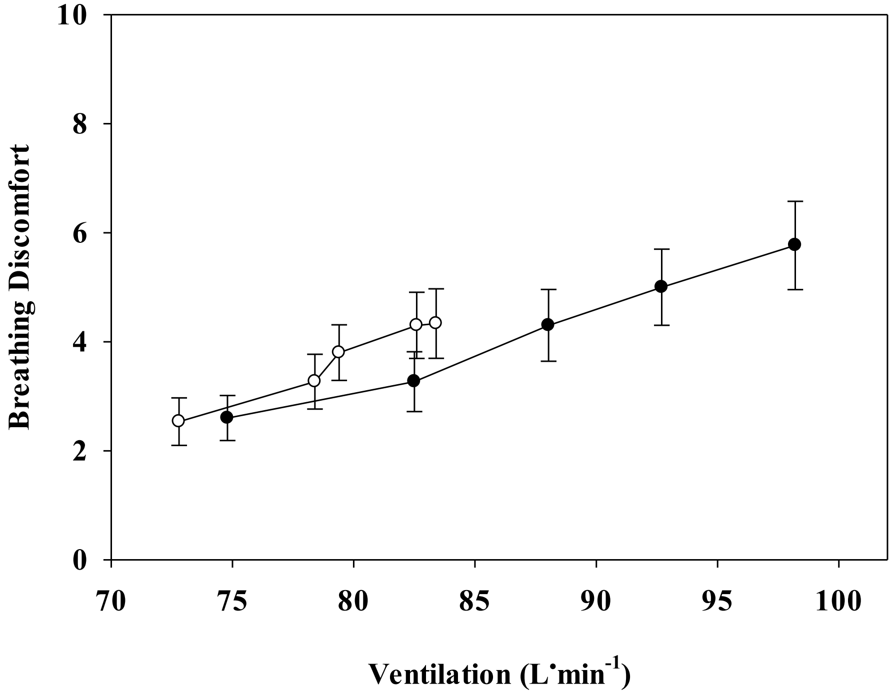

Figure 2.13. Mean (±SE) breathing discomfort compared to ventilation during exercise in loaded (closed circles) and unloaded (open circles) conditions. Loaded; $y = 0.140x - 8.043$, $r^2 = 0.986$. Unloaded; $y = 0.176x - 10.321$, $r^2 = 0.969$. n=15

Chapter Three – General Discussion and Commentary

3.1 Occupational relevance

Exercise with heavy load carriage significantly decreases exercise capacity. The contribution of respiratory muscles during exercise has been well documented in occupations that use a breathing apparatus such as firefighters and rescue divers (Brown and McConnell, 2012). The respiratory impairments imposed in these occupations fatigue the respiratory muscles as breathing demand increases (Butcher et al., 2006). If the work is time sensitive and exercise is required for a prolonged period, these impairments can intensify breathing and peripheral muscle discomfort and ultimately decrease occupational effectiveness. Our results suggest that a respiratory impairment occurs progressively during 45 min of exercise with a 25 kg backpack. Expanding the exercise protocol time or increasing the load carried could lead to further increases in breathing intensity, peripheral muscle discomfort and could severely impair occupational effectiveness and safety.

3.2 General findings

Ventilation is known to increase progressively over time during prolonged exercise (3 h) as a result of increased V_D (Stickland et al., 2004). The increased V_D is result of a rapid and shallow breathing. We observed a similar increase in V_E and alteration in breathing mechanics during 45 min of exercise, which suggests that 45 min of loaded and 3 h of unloaded exercise at approximately the same VO_2 have similar increases in V_E. This suggests that exercise with heavy load carriage exacerbated the increase in V_E during prolonged exercise.

3.3 Individual responses

There was considerable variability in ventilatory responses during this experiment. One subject had no change in V_E at 45 min between conditions while other subjects showed large increases (20-30 $L \cdot min^{-1}$) in loaded V_E at 45 min, compared to the unloaded condition (Figure G.2). Table G.5 illustrates the low correlations between ΔV_E and body mass, body surface area (BSA), TLC, FEV_1 and VO_{2peak}. These results suggest that size, pulmonary function and aerobic fitness of subjects did not explain the difference in V_E between conditions during prolonged exercise. It appears that some subjects were better able to overcome the mechanical disadvantage placed on the respiratory system during prolonged exercise with heavy load carriage. Further research is required to determine the precise mechanisms that lead to individual variability in V_E during prolonged exercise with heavy load carriage.

3.4 Limitations

Our understanding of the changes in ventilatory mechanics during exercise would be improved by measuring WOB. Measuring SV and arterial-venous difference would aid understanding why HR is higher during exercise under load. To determine the role of the metaboreflex during exercise, leg blood flow measurements would be required. The present investigation suggests that altered ventilatory mechanics during exercise under load may result in changes in cardiovascular function, which justifies shifting to invasive experimental design.

It appeared that body position was slightly affected towards the end of the exercise bouts with heavy load carriage. Subjects showed a tendency for forward trunk lean and increased hip flexion while walking with the backpack. Changing body position may alter IC values and operational lung volumes, however, gas exchange data were recorded simultaneously, which should dissolve any discrepancy between ventilatory and lung volume data as a result of altered body position under load.

3.5 Future research direction

Heavy load carriage is common in many recreational and occupational settings. Recreational hikers often carry weighted packs that are proportional to their own body weight. In occupations such as search and rescue, military and firefighting, an absolute load must be carried in order to complete the mission with the required supplies. The purpose of our study was to quantify ventilatory responses to prolonged exercise while carrying an absolute load. Regardless of body mass, the participants carried the same 25 kg pack throughout the experiment. Participants carried about 30% of their body mass with the smallest and largest participants carrying 34 and 23% of their body mass, respectively. In future research, load carriage that is relative to body mass could give more information on physiological responses to exercise under load. If we were to repeat our experiment, a homogenous group of participants with similar physical characteristics (ie. height and body mass) could be recruited. This would dissolve any changes in ventilatory responses as a result of a large range of body mass.

If work of breathing increased during prolonged bouts of exercise with heavy load carriage, a competition for Q could occur, resulting in decrease peripheral blood flow, increased perceived exertion, increased fatigue and decreased performance (Dempsey et al., 2008). Designing a study that measures WOB during exercise minute ventilation rates, between loaded and unloaded conditions, would provide a better understanding of the effects of WOB on ventilatory mechanics.

The ventilatory response to exercise is known to increase intra-thoracic and gastric pressure swings and has an effect on venous return from the limbs (Dempsey et al., 2006). If exercise with heavy load carriage increases WOB, then intra-thoracic pressure swings may be altered and could negatively affect venous return and ventricular output (Stark-Leyva et al., 2004). Measuring left ventricular function and SV would further our understanding of venous return and Q during exercise with heavy load carriage. Heart rate was always higher in the loaded condition and oxygen cost was identical, compared to the unloaded condition. These results suggest that left ventricle filling and stroke volume is being altered when exercising under load.

Measurements of leg blood flow during exercise would aid in understanding the role of the sympathetic mediated metaboreflex during exercise with heavy load carriage. The increased V_D, decreased respiratory muscle strength post-exercise, increased perceived exercise stress, breathing discomfort and leg fatigue would suggest that the O_2 cost of breathing is increasing. As mentioned above, this increased respiratory muscle blood flow would create a competition for blood distribution, ultimately leading to a decreased leg blood flow.

The fitted backpack covers a large surface area of the back. During exercise, there is limited water vapor permeability across the back. Changes in core temperature were the same between conditions, which suggests that thermoregulation efficiency did not decrease although a large surface area of the body was covered. This may be the result of a change in skin blood flow and/or change in evaporative cooling sites on the body. Further investigation is required to determine the alteration in heat removal mechanisms while exercising with heavy load carriage.

Trained females are known to be susceptible to expiratory flow limitation and increased WOB at lower levels of V_E. This is a result of woman having smaller airway diameter, smaller lung volumes and lower peak expiratory flow rates, compared to age- and height- matched man (Guennette et al., 2007). The presence of expiratory flow limitation could result in dynamic hyperinflation to increase expiratory flow. The increase in lung volumes comes at the expense of decreased lung compliance and increased elastic work of breathing which could hasten the onset of respiratory muscle fatigue (Pellegrino et al., 1993). Adding load carriage could exacerbate the alteration of lung volumes, increased WOB and onset of respiratory muscle fatigue during prolonged exercise in females, however, further research is required.

Aging of the respiratory system is associated with a decline in pulmonary function. Physiological changes include decreased static elastic recoil of the lung, increased RV and functional residual capacity, and decrease respiratory muscle strength (Janssens et al., 1999). Chest wall compliance decreases and WOB increases during exercise, compared to younger individuals. Exercise with heavy load carriage could further a decrease in lung compliance and increased WOB in older populations. Increased WOB and the decline in respiratory muscle strength may hasten the fatigue of the respiratory muscles during prolonged exercise under load. Investigating ventilatory mechanics during loaded exercise in older populations could provide a better understanding of the effect of age on respiratory system performance.

3.6 Commentary

While completing a Master's level research project I have learned many valuable skills that include the ability to coordinate a research laboratory, administer complex exercise physiology protocols, interpret and analyze recorded data, and organize my findings into a comprehensive report.

The organization of day-to-day lab operation was important to ensure reliable data collection. The laboratory technicians involved needed to understand and be proficient with their duties and responsibilities in order to ensure consistent laboratory setup, instrument calibration and administration of the exercise sessions. Organizing and scheduling multiple participants to volunteer their time and complete seven sessions was very difficult and effective communication was required to ensure that participants felt comfortable volunteering their time and the laboratory was available at their convenience.

As a primary investigator in a research study, I learned to operate and maintain laboratory instrumentation, data recording hardware and data analysis software. A detailed knowledge laboratory equipment operation is required to ensure proper data collection, entry and analysis. Being able to troubleshoot any technical issues that may arise during data collection is important to ensure reliability of the data set. For example, on a few occasions during the experiment, there were small errors with the flow meter calibration of the metabolic measurement cart. In order to continue through the experimental protocol, I was required to determine the source of error in the calibration reading. Due to my extensive training and experience gained during pilot experimental trials, I was able to locate the source of error and correct the calibration. Without noticing the small changes in calibration, the results would report inaccurate expired gas volumes.

While organizing and administering the investigation, I became very proficient with the assessment and interpretation of physiological data from each protocol. It was important to ensure consistent administration of the protocols and diligent interpretation of the results to avoid incorrect data entry and errors in data analysis. It was required that oxygen demand be matched between conditions at a sub-threshold exercise intensity that was sustainable for 45 min. Incorrect determination of T_V and/or improper use of linear regression could result in incorrect exercise intensity or a difference in oxygen demand between conditions. If oxygen demand was different between conditions at the beginning of the exercise protocol, any direct comparison of ventilatory mechanics between conditions would be inconclusive.

Throughout the investigation, data were recorded on multiple platforms, which included digital displays on data acquisition software, computer printouts from the metabolic measurement cart and hand written results on a data sheet. I learned the importance of organizing this data in a comprehensive manner so it could be exported into a data analysis program.

In summary, learning to organize and manage a laboratory, administer complex physiological procedures, and analyze and interpret data have been key factors that have contributed to the completion of this investigation. The combination of graduate classwork, previous research assistant positions, pilot project work and extensive consultation with my supervisory committee have been critical factors that have aided in learning the process of creating a comprehensive report based off the findings of this investigation.

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Appendix A – Literature Review

A.1 Background

Human lungs are rarely the limiting factor during vigorous exercise in healthy males (McKenzie, 2012). Pulmonary limitations to exercise are seen with diseases such as fibrosis, chronic obstructive pulmonary disease (COPD) and obesity. With the presence of a respiratory resistance to inspiration or expiration during exercise, a mechanical disadvantage can be placed on the respiratory system, which could overload the respiratory muscles and result in a sympathetic mediated competition for blood between the respiratory and limb muscles (Harms et al., 1998; Romer et al., 2005). In obesity, the extra weight placed on the thorax and abdomen acts as an inspiratory resistance, altering ventilatory mechanics, decreasing pulmonary function, respiratory compliance and exercise capacity (Wang et al., 2004).

Carrying a heavy load increases the weight on the thorax and creates an inspiratory resistance. During acute exercise, breathing patterns and operational lung volumes are altered. In an attempt to minimize the work of breathing (WOB), alveolar ventilation (V_A) is maintained by adopting a rapid shallow breathing pattern is adopted. Prolonged exercise with heavy load carriage could exacerbate the changes in breathing pattern and operational lung volume. If the rapid shallow breathing pattern progressed during prolonged exercise with heavy load carriage, dead space ventilation (V_D) and minute ventilation (V_E) would increase in order to maintain V_A. This could lead to increased WOB, perceived breathing discomfort and respiratory muscle fatigue may occur. It is currently unknown how ventilatory mechanics are affected by prolonged exercise with heavy load carriage.

While the mechanics of chest wall loading with obese populations and lean subjects wearing a heavy backpack are similar, there are fundamental differences between the conditions that must be addressed through separate, load-carriage specific, experiments.

A review is needed to compare and contrast this thesis with the available literature to identify the mechanisms involved that could give rise to the hypothesis that 45 minutes of prolonged exercise with heavy load carriage (25 kg) could alter breathing pattern, operational lung volume and respiratory muscle strength.

A.2 Load carriage and exercise

Exercise with a loaded pack is common in many time-sensitive occupations such as infantry, firefighting and search and rescue. Load carriage can be classified into light (1-10 kg), moderate (10-20 kg), heavy (20-30 kg) and very heavy (above 30 kg). Load carriage has been shown to increase metabolic demand at a given work rate (Patton et al., 1991; Dominelli et al., 2011; Epstein et al., 1988). Epstein et al. (1988) observed a 24 % increase in VO_2, compared to an unloaded control, while marching with a 25 kg load at a constant speed (1.33 $m \cdot s^{-1}$) and grade (5%). This suggests that, as the total weight (body weight + load carriage) increases, metabolic demand increases.

Abe et al. (2004) suggested that carrying a load on the back yields a saving in energy cost compared to carrying the load on the legs or in the hands. Carrying a load on the back is thought to decrease energy cost via an interaction between rotational torque around the center of the body mass and an excessive burden on the lower limbs. This economy of energy is termed *free-ride* due to the reduction in oxygen cost at a given load

(Bastien et al., 2005). This information is useful for occupations such as infantry and search and rescue, to evaluate physical exertion and metabolic demand during time-sensitive rescue missions with heavy loads.

Search and rescue technicians (SAR TECHS) use a backpack to carry equipment during a mountain rescue operation. Further, SAR TECHs are required to perform a hike or ski during a mountain rescue, which would require a prolonged vigorous effort with a heavy pack weighing at least 25 kg (Petersen et al., 2011).

A.3 Effect of walking speed combined with load carriage

An ideal walking speed on the treadmill with a loaded pack, where steady state was achieved, was determined to be approximately 1.33 $m \cdot s^{-1}$ (Abe et al., 2004; Epstein et al., 1988). Patton et al. (1991) suggested that a speed of 1.6 $m \cdot s^{-1}$ with a 31 kg load constantly increased oxygen cost and steady state was not achieved (Epstein et al., 1988). From the literature reviewed, a speed of approximately 1.33 $m \cdot s^{-1}$ is ideal for long bouts of marching with heavy load carriage. Furthermore, the oxygen cost of walking ($ml \cdot kg \cdot meter^{-1}$) increases at faster and slower speeds (Abe et al., 2004).

A.4 Prolonged exercise, load carriage and metabolic efficiency

According to Epstein et al. (1988), during prolonged exercise (2h) with a 25 kg pack, there was minimal loss in metabolic efficiency. Exercising while carrying a 40 kg pack will fatigue much quicker then exercise at the same workload with a 25 kg pack (Schoenfeld et al., 1977). This is likely due to an alteration in marching biomechanics (ie. forward trunk lean) and increased muscle recruitment, which resulted in an increased energy demand. A load carriage threshold was determined during a 12 km march with various loads and speeds. At a constant marching speed with a 31.5 kg pack, there was no significant increase in VO_2 over time. Any increase in load saw a constant increase in VO_2 and an inability to achieve steady state during exercise, which according to Epstein et al. (1988) might be too difficult to maintain for sustainable operation.

A.5 Chest wall restriction and resting pulmonary function with load carriage

Chest wall restriction is commonly seen in patients with respiratory disorders such as fibrosis. Chest wall restriction is known to decrease total lung capacity (TLC) and chest wall compliance (Douglas et al., 1981). The reduction in TLC results in a rapid shallow breathing pattern, which is characteristic of hyperventilation. Harty et al. (1999) observed a decreased tidal volume (V_T) and increased breathing frequency (B_F) and V_E ($p<0.05$) when exercising with a thoracic restriction, compared to the control condition. The altered breathing pattern increased V_D. In order to maintain V_A, V_E increased in the restrictive conditions, compared to the control condition.

When wearing a pack, there is a small amount of chest wall restriction due to the strapping around the waist and chest to fit the pack close to the trunk (Bygrave et al., 2004). Without load, the backpack straps have no significant change in FVC or FEV_1 (Dominelli et al, 2011). With a 25 kg pack, FVC and FEV_1 decreased by 5 and 4% respectively. These results demonstrated that a mild decrease in forced expiratory flow was due to the load in the pack and not the chest strap restriction (Dominelli et al., 2011). These results are similar to work done by Lesser et al. (2010), who showed a decrease in FVC and FEV_1 with a 25 kg pack by 3 and 3%, respectively. There was no change in the

FEV_1/FVC ratio, which suggested there was no limitation in the effort-independent portion of the flow volume curve. The effect of the heavy pack on TLC requires the use of either full body plethysmography or oxygen rebreathing techniques to determine residual volume (RV). Without one of these techniques, it is difficult to determine precise mechanism(s) for the change in TLC. Due to the minimal restrictive nature of the pack, it is assumed that RV would be increased slightly in order to maintain TLC, however, further investigation is required.

In summary, wearing a 25 kg pack shows minimal decreases in pulmonary function. Without obtaining residual volume, the mechanism for changes in TLC are unknown.

A.6 Mass loading

Any mass applied to the torso can affect pulmonary function and alter ventilatory mechanics. This increase of weight on the torso is termed mass loading (Wang et al., 2004). In obese subjects, the increased fat storage on the chest and abdomen loads both the chest wall and the diaphragm. In lean subjects wearing a heavy backpack, the load is primarily placed on the posterior chest wall. Assuming a proper fit, the backpack is designed to distribute the weight of the pack evenly on the posterior areas of the thorax with minimal load being placed on the diaphragm and abdominal region.

Mass loading is seen in obese subjects and can be simulated by externally loading the chest wall or abdomen. Chest wall loading decreases compliance by shifting the pressure-volume curve to the right while maintaining the slope. In abdominal loading, which simulates obesity and large amounts of fat tissue in the lower abdomen, it is suggested there is a larger rightward shift in the pressure volume curve compared to chest wall loading (Sharp et al., 1964). Wang et al. (2004) reported that, in order to optimize the WOB during chest wall loading, lung volumes were reduced at rest. Inspiratory capacity (IC) and end-expiratory lung volume (EELV) remained the same at rest and during graded exercise in a chest wall loaded condition with a simulated BMI of 32 kg/m^2. The normal response to exercise, in a healthy lean subject, is a decrease in EELV from rest to exercise. The results suggested that EELV was unchanged during exercise and a mechanical impairment was present (Wang et al., 2004).

The mass of a heavy pack loads the thorax, however, it differs from obesity in that abdominal loading is not present in lean participants carrying a loaded pack. During acute exercise (5 min), end-inspiratory lung volume (EILV) was decreased while EELV remained the same, compared to an unloaded condition (Lesser, 2010). The decrease in EILV was result of a lower V_T. There are currently no reports on the effect of wearing a heavy pack on resting lung volumes and chest wall compliance. If wearing a 25 kg pack decreased EELV at rest, it is possible that EELV may not decrease at the onset of exercise and a mechanical impairment may arise.

A.7 Respiratory resistance and work of breathing with load carriage

Airway resistance is known to increase to respiratory muscle WOB in order to maintain adequate airflow in and out of the lungs at rest and during exercise (Romer et al., 2006). Respiratory resistance can affect both the inspiratory and expiratory muscles during exercise. Restrictive diseases such as fibrosis are known to stiffen the lungs and create a resistance to airflow at rest and during exercise. In obesity, the extra weight carried on the chest and abdomen mass-loads the thorax and is known to nearly double the inspiratory-resistive WOB (Sharp et al., 1964).

Expiratory muscle loading can be seen in patients with chronic obstructive pulmonary disease (COPD). The loss in lung elasticity decreases expiratory flow and places a heavy burden on the expiratory muscles during exercise. In occupations such as firefighting, a self-contained breathing apparatus (SCBA) provides respiratory protection in dangerous environments (Butcher et al., 2007). However, this protection is at the cost of increased expiratory flow resistance, which will ultimately increase the WOB during vigorous exercise (Butcher et al., 2006).

There is minimal literature studying the affects of carrying a backpack on the WOB during acute and prolonged exercise. Carrying a load carriage will mass load the thorax and may increase inspiratory resistance during exercise; however, more investigation on the WOB while wearing load carriage is required.

During acute exercise (5 min) with varying pack loads at a set speed and grade, Dominelli et al. (2011) saw a linear increase in the power of breathing, ($WOB \cdot B_F$) as the pack weight increased. Assuming the linear relationship between VO_2 and V_E at sub-anaerobic threshold intensities, the heavy backpack did not appear to impair the progressive decrease in EELV. While this is useful information, it would be beneficial to match the workloads (VO_2) between loaded and unloaded conditions and investigate the changes in inspiratory resistance and WOB. To our knowledge, there is currently no literature investigating the effect of load carriage on WOB during prolonged exercise.

A.8 Ventilatory response to exercise

During exercise, increases in VO_2 are governed by the Fick equation. The normal response from rest to moderate exercise is an increase in minute ventilation in order to match the increased metabolic demand (termed exercise hyperpnea) (Stickland et al. 2012). Minute ventilation consists of V_A and V_D.

$$V_E = V_A + V_D$$

Minute ventilation is increased in order to match V_A with metabolic demand during exercise and is achieved by an alteration in V_T and B_F. Tidal volume is increased by reduced EELV below functional residual capacity (FRC) and increased EILV. Breathing frequency is increased by decrease inspiratory (T_I) and expiratory (T_E) times. During light exercise, V_T and B_F increase roughly in proportion to exercise intensity (Stickland et al. 2012). During heavy exercise, V_T reaches a plateau, at approximately ~70% of the vital capacity (VC), and any further increases in V_E will be the result of increased B_F (Dempsey and Johnson, 1992).

Although V_E is known to match oxygen demand up to about the anaerobic threshold, V_E can increase disproportionally to VO_2 during prolonged bouts of vigorous exercise at sub-threshold intensities. Stickland et al. (2004) documented an increase in V_E of 23% during prolonged (2.5 h) exercise at 70% VO_{2peak}. The authors suggest the increase in V_E was a result of an increase in V_D. According to Hopkins et al. (1998), pulmonary artery pressure decreases progressively during prolonged exercise (1 h). A decline in pulmonary vascular pressure during exercise would have the effect of decreasing capillary recruitment and increasing physiological dead space, resulting in an increased V_D. The increased V_D may also be the result of a progressive ventilation perfusion mismatch (V_A/Q) caused by a development of interstitial edema (Hopkins et al., 1998).

Studies have shown an influence of concomitant increases in body temperature on resting V_E. Increased core temperature (1°C) is responsible for significant increases in V_E at rest, however, it is more difficult to demonstrate an independent influence of core temperature on V_E, during exercise (White, 2006). The rationale that breathing is increased in order to serve a heat loss role and/or as a result of increased V_D makes it difficult to determine the precise mechanisms that lead to increased V_E, disproportional to VO_2, during prolonged exercise.

A.9 Ventilatory response to exercise with load carriage

Heavy load carriage can alter breathing pattern and EILV during short duration (5 min) high intensity exercise (75% VO_{2peak}). Lesser (2011) found a 14% increase in B_F and a 9% decrease in V_T during 5 minutes of loaded exercise (25 kg) at approximately 75% VO_{2peak}. End inspiratory lung volume was decreased by approximately 6%. Although ventilatory mechanics were slightly altered, V_E was unchanged compared to an unloaded control. It remains unknown how V_E may change during prolonged exercise with heavy load carriage. In infantry and search and rescue, prolonged bouts of exercise under load are common. Extending exercise with load carriage to prolonged exercise durations could potentially reach significant changes in ventilatory mechanics, specifically: breathing pattern, operational lung volume and minute ventilation. If EILV continued to drop throughout prolonged bouts of exercise, V_E would have to continually rise in order to overcome V_D. It is known that during prolonged high intensity exercise,

V_E will rise in order to maintain V_A in controlled unloaded conditions (Stickland et al., 2004). Heavy exercise with a pack could exacerbate the increase in V_D and may result in significant increases in V_E. The increases in V_E would be driven mainly by B_F and could lead to a significant increase in the WOB, which could result in respiratory muscle fatigue and potentially decrease operational effectiveness.

A.10 Inspiratory loading, respiratory muscle fatigue and exercise

Loading the inspiratory muscles with an external load or a fixed breathing resistance valve is known to increase the inspiratory resistive WOB. An increase in inspiratory muscle WOB would increase blood flow to the area in order to match the metabolic demand. This increase in cardiac output (Q) demand could create a "competition" for blood between the respiratory and limb muscles, increasing perceived exertion and possibly decreasing exercise performance (Sheel et al., 2001).

Inspiratory loading (3-5 cmH_2O) at maximal exercise increased the WOB by approximately 28% while maintaining a similar V_E (Harms et al., 1997). If B_F and V_E were to rise in order to maintain V_A during submaximal loaded exercise, the inspiratory WOB breathing would rise significantly and increase blood demand, resulting in a sympathetically mediated vasoconstrictor response in limbs known as the "inspiratory muscle metaboreflex" (Sheel et al., 2001). If B_F and V_E continued to rise throughout a prolonged bout of loaded exercise, eventually the energy demand would exceed the energy supply, resulting in fatigue. Respiratory muscle fatigue is largely due to the increased work of breathing of respiratory muscles (Dempsey et al., 2008).

The mass load effect of the pack loads the inspiratory muscles and adds an inspiratory resistance. Load carriage could reduce respiratory compliance and increase the WOB during exercise (Dominelli et al., 2011).

A.11 Limb blood flow limitation and peripheral fatigue

The increased inspiratory WOB may result in a decrease blood flow to the legs during prolonged exercise with a heavy pack. This decrease in leg blood flow could initially increase perceived exertion during exercise and eventually increase Q demand, resulting in metabolite accumulation and decreased exercise performance (Harms et al., 1997; Dempsey et al., 2008).

Respiratory muscles account for approximately 14-16% of Q during exercise. The increase in flow to the respiratory muscles during exercise decreases blood flow to peripheral muscles (Harms et al., 1998). An increase in inspiratory resistance will decrease limb blood flow even further and decline exercise performance (Dempsey et al., 2008).

With inspiratory unloading, there is a decrease in O_2 consumption in the respiratory muscles; however, limb O_2 consumption does not seem to be affected (Harms et al., 1998). Conversely, during inspiratory loading, there is a marked increase in inspiratory muscle O_2 consumption and a decrease in limb O_2 consumption, which suggest a marked decrease in peripheral blood flow as respiratory muscle work increases (Harms et al., 1997). Harms et al. (1998) conclude that as WOB goes up at maximal exercise, two effects occur: 1) an increase of Q is sent to the respiratory muscles in order to meet metabolic demands; and 2) limb blood flow is reduced due to a sympathetic mediated "metaboreflex" vasoconstriction.

Peripheral fatigue is defined as the loss of force due to the processes occurring at or distal to the neuromuscular junction (Romer et al., 2005). As mentioned above, respiratory muscle fatigue results in a decreased limb blood flow. The decrease in blood (O_2) delivered to the limbs (peripheral muscles) via vasoconstriction limits the maintenance of adequate blood supply to the peripheral muscles and may then limit the ability to maintain power output.

Inspiratory muscle training has been shown to decrease metabolite accumulation and can blunt the inspiratory muscle metaboreflex (Callegaro et al., 2011). An increase in inspiratory oxidative capacity and capillary density could prove important in increasing overall exercise performance by limiting inspiratory muscle fatigue and sympathetic vasoconstriction in the limbs. Regular exercise with a heavy pack could effectively train the inspiratory muscles and blunt the inspiratory muscle metaboreflex, however, further investigation is required.

In summary, carrying a heavy pack may alter ventilatory mechanics and increase work of breathing, resulting in decreased limb blood flow. This decreased limb blood flow could lead to peripheral fatigue, decreasing exercise performance.

A.12 Inspiratory muscle loading, load carriage and ventilatory mechanics

It is known that during brief bouts of exercise with heavy load carriage (25 kg), V_A is maintained by a 9% decrease in V_T and a 14% increase in B_F (Lesser et al., 2010). The increase in B_F coupled with a possible increased WOB could overload and fatigue the respiratory muscles over a prolonged period of vigorous exercise. A sympathetic-mediated competition for blood, via the metaboreflex, may then occur, limiting blood flow to the limbs during submaximal exercise (Harms et al., 1998; Dempsey et al., 2008). This could result in an increased perceived exertion or further, a decreased exercise performance. The effect of prolonged exercise with heavy load carriage on ventilatory mechanics, specifically: breathing patterns and operational lung volume has not been reported.

A.13 Summary

Studies have shown that packs between 25 and 31 kg are usually the heaviest loads that can be carried without constant increases in metabolic demand during sustained exercise (Robertson et al., 1992; Patton et al, 1991; Epstein et al., 1988). A 25 kg load decreases FEV_1 and FVC slightly at rest. The decrease in pulmonary function is due to the mass loading on the thorax and not the restrictive nature of the pack (Bygrave et al., 2004; Lesser et al., 2011; Dominelli et al., 2011; Muza et al., 1989). During short bouts (5 min) of high intensity exercise with load carriage of 25 kg, ventilatory mechanics are altered, specifically; increased B_F and decreased EILV, in order to maintain V_A (Lesser et al., 2011; Dominelli et al., 2011). Prolonging the exercise may exacerbate these findings and overload the respiratory muscles and increase inspiratory WOB. Increased WOB may lead to a competition for blood flow, resulting in a sympathetic mediated “metaboreflex”, causing a decrease in submaximal exercise performance (Dempsey et al., 2008;Harms et al., 1998;Romer et al., 2005).

It is important to investigate the effect of prolonged exercise with heavy load carriage on ventilatory mechanics. Increasing the understanding of these ventilatory responses to exercise could be used to increase performance and safety in occupations such as infantry, firefighting and search and rescue.

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Appendix B – Linear regression

B.1 Determining EP workload using linear regression

1. Loaded EP workload
   1.1. Determine grade that elicits T_V in the loaded GXT.
   1.2. Calculate the average VO_2 for the 2-minute penultimate stage (use second minute) that elicited T_V. The grade should be the EP workload for the loaded condition and the VO_2 will be used to match the workloads between conditions.
2. Unloaded EP workload
   2.1. Calculate average VO_2 for each 2-minute sub-threshold stage (use second minute).
   2.2. Plot treadmill grade (%) on the y-axis and VO_2 ($ml \cdot kg \cdot min^{-1}$) on the x-axis.
   2.3. Determine the y-slope equation, use VO_2 from the loaded workload and solve for y. The y value calculated will be set as the treadmill grade (%) for the unloaded EP.
      2.3.1. Example:
         2.3.1.1. Grade at stage of loaded GXT just prior to T_V = 8%
         2.3.1.2. Average VO_2 for EP (Loaded) at 8% grade = 30.4 $ml \cdot kg^{-1} \cdot min^{-1}$
         2.3.1.3. Unloaded y intercept equation: $y = 0.7974x - 13.162$
         2.3.1.4. Unloaded treadmill grade (%) at 30.4 $ml \cdot kg \cdot min^{-1}$ = 11.1

Appendix C – Visual analogue scales

C.1 Exercise stress

Subjects were asked to quantify their exercise stress during exercise. Subjects were instructed that a 0 represented "no exercise stress at all" and a 10 represented "the most severe exercise stress they have ever experienced."

0. Nothing at all

1. Very weak

2. Weak

3. Moderate

4. Somewhat strong

5. Strong

6.

7. Very strong

8.

9.

10. Maximal

C.2 Breathing Discomfort

Subjects were asked to quantify their breathing discomfort during exercise. Subjects were instructed that a 0 represented “no breathing discomfort at all” and a 10 represented “the most severe breathing discomfort they have ever experienced.”

0. Nothing at all

1. Very weak

2. Weak

3. Moderate

4. Somewhat strong

5. Strong

6.

7. Very strong

8.

9.

10. Maximal

C.3 Leg Fatigue

Subjects were asked to quantify their leg fatigue during exercise. Subjects were instructed that a 0 represented “no leg fatigue at all” and a 10 represented “the most severe leg fatigue they have ever experienced.”

0. Nothing at all

1. Very weak

2. Weak

3. Moderate

4. Somewhat strong

5. Strong

6.

7. Very strong

8.

9.

10. Maximal

Appendix D – Pack sizing and fitting

D.1 Sizing Chart

BORA 80 Male	**Sizing Chart**		
	Small	Medium	Tall
	16-19 inches 40.5-48 cm	18-21 inches 45.5-53 cm	20-23 inches 51-58 cm

D.2 Measuring back length

- Back length is measured from the C7 vertebrae to the top of the iliac crest as shown in the diagram to the right
- If a measurement falls between two sizes the smaller of the two sizes is used

D.3 Hipbelt sizing

- Locate the Iliac Crest, (the top of the most prominent point of the hipbone) and measure around the hips on this point
- When the hipbelt is properly centered on the hip crest and tightened, the ends of the pads should extend at least 3 inches past the hip crest

D.4 Shoulder strap adjustments

- The shoulder straps should contour smoothly and be in contact throughout the entire length of the shoulder strap padding

D.5 Fine tuning: load lifters

Range of acceptable load lifter strap angle

- The purpose of the load lifters is to slightly lift the shoulder straps from the shoulders, not to bring the pack in against the back.
- The ideal angle for the load lifter straps is 45 degrees, however, an angle of 30 to 60 degrees is quite acceptable

D.6 Fine tuning: load stabilizer

- Reduce movement of the load weight by maximally tightening the strap depicted above

D.7 Organization of load weight

1. Open all compartments of Arc Teryx backpack
2. Place a sleeping bag or heavy rolled cloth in the sleeping bag compartment of the backpack leaving the separating zipper open
3. Roll three standard red bricks in three towels and place three vertically along the anterior of the backpack
4. Replicate this until you have placed 2 layers of 3 sets of bricks anteriorly
5. Layer the pack posteriorly with towels until the backpack is stable vertically
6. Place a heavy rolled cloth at the top of the pack to fill the volume of the pack
7. Check the weight of the pack to ensure that the load is 25 kg if the pack is too light then fill two standard water bottles evenly until load has been reached. Water bottles can be placed in the water bottle holders on either side of the pack

Materials
1. Arc Teryx expedition pack; Bora 80 for men in small, regular or tall
2. Six 3 kg concrete or clay bricks that are no larger than 2 inches by 2 inches by 4 inches
3. 6-10 small towels
4. One sleeping bag
5. One thick blanket

Appendix E – Detailed methods

E.1 Screening for exercise induced bronchoconstriction

Post-exercise spirometry was performed at 1, 5, 10, 15 and 20 minutes after exercise completion to monitor for exercise induced bronchoconstriction (EIB). A positive assessment of EIB is defined by a 10% or more decrease in forced expiratory volume in 1 second (FEV_1) post-exercise compared to baseline. Based on this criterion, subjects were excluded if EIB is detected. One subject was excluded from our study for having symptoms of EIB

E.2 Fluid Sampling

Subjects provided a mid-stream urine sample using a pocket refractometer (LES Instruments, Japan). This measurement was completed in order to ensure proper hydration status ($U_{sg} \leq 1.020$) prior to exercise (Oppliger et al., 2005).

E.3 Graded exercise test

The GXT consisted of a constant speed ($1.5\ m\cdot s^{-1}$) walking protocol on a motorized treadmill (Standard Industries, Fargo, ND). The treadmill setting began at 0% grade and increased by 2% every 2 minutes until T_V is detected. Once T_V is confirmed, the grade was then increased 2 % every minute until volitional exhaustion (Nelson et al., 2008). Ventilatory threshold was determined by an increase in V_E/VO_2 ratio, while V_E/VCO_2 remains steady or increases slightly (Wasserman, 1987).

Following completion of the GXTs, workloads were derived for the EP in both conditions. For the loaded condition, the grade selected for the EP was 2% below the grade that elicited T_V during the GXT. Using linear regression, oxygen demand (VO_2) was matched in both the loaded and unloaded conditions to ensure the same aerobic demand is require (± 0.1 L/min).

E.4 Practice session

Subjects completed a practice session to ensure that the aerobic demands derived from the GXT were matched between conditions. Subjects completed two-20 minute bouts of walking, at the predetermined grade, with 20 minutes recovery in between. The first bout of exercise was in the loaded condition followed by the unloaded condition. If the VO_2 in the unloaded condition was inconsistent with the VO_2 in the loaded condition, treadmill grade was adjusted to ensure VO_2 (± 0.1 L/min) was matched between conditions.

Spirometry and maximal inspiratory/expiratory pressures (MIP/MEP) maneuvers were practiced prior to exercise and again within 5 minutes of exercise completion. Inspiratory capacity maneuvers were practiced during baseline and at 5-minute intervals during exercise.

E.5 Experimental exercise protocol

Subjects performed 45 minutes of exercise at a constant speed ($1.5\ m \cdot s^{-1}$) and grade. Baseline measurements were recorded 5 minutes prior to exercise. Exercise was preceded with 3 minutes of warm up at the same speed and an increase in grade every minute (0, 33 and 66% of determined exercise grade). After exercise, a 3-minute cool down was completed at 0% grade and approximately $1.1\ m \cdot s^{1}$.

Spirometry and MIP/MEP maneuvers were performed before exercise and again within 5 minutes of exercise completion. Inspiratory capacity maneuvers were completed at baseline and at 5-minute intervals during exercise.

E.6 Visual analogue scales

Subjects were asked to quantify their perceptual responses to exercise by signaling to modified Borg scales of perceived exertion (Borg, 1982). Perceptual responses were recorded in the first 5-minute measurement cycle and were repeated every 10 minutes throughout the experimental trial. Perceived exercise stress, breathing discomfort and leg fatigue were measured using three separate 10-point systems. The scales were anchored such that 0 represents " no exercise stress, breathing discomfort or leg fatigue" and 10 represents "the most severe exercise stress, breathing discomfort or leg fatigue they have ever experienced or could imagine experiencing" (Eves et al., 2003; O'Donnell et al., 2000).

E.7 Sample hose replacement

In order to minimize any drift in signal display due to excess moisture accumulation, the sample hose was replaced at 25 minutes during the EP. An exact duplicate of the hose was used to minimize any variation in flow meter calibration.

Appendix F - Experimental protocol measurement cycle

F.1 Experimental protocol measurement cycle

Time (min)	Measurement
1	
2	
3	Cardio-respiratory * (3:00 – 4:00)
4	Perceptual scales ** (4:00 - 4:30) Inspiratory capacity (4:30 – 5:00)
5	

* Cardio-respiratory measurements included all open circuit dependent variables (VO_2, V_E, B_F, V_T, HR and $ETCO_2$).
**Perceptual responses were recorded in the first measurement cycle and every second measurement cycle throughout the experimental trial.

Appendix G – Additional Results

Table G-1. Individual subject characteristics

Subject No.	Age (y)	Height (cm)	Weight (kg)	UL-VO_{2peak} (ml·kg·min^{-1})	L-VO_{2peak} (ml·kg·min^{-1})
1	24	177	85.6	55.1	51.4
2	31	190	78.8	53.8	54.0
3	28	183	81.7	46.7	47.2
4	27	185	72.7	51.4	51.6
5	24	182	91.5	52.8	54.0
6	34	177	82.4	55.5	52.6
7	23	189	89.9	57.1	55.2
8	33	190	81.4	61.9	60.6
9	29	193	112.7	51.3	49.7
10	29	180	72.1	60.1	58.8
11	33	178	83.0	60.5	56.9
12	29	178	75.3	65.2	61.9
13	31	180	83.1	53.8	56.4
14	29	178	79.8	59.8	54.0
15	28	178	87.7	46.0	44.4
Mean	29	182	83.4	55.0	53.6*
± SD	3	5	9.6	5.5	4.8

VO_{2peak}, peak oxygen consumption. Asterisk (*) indicates significant difference in VO_{2peak} ($P < 0.05$) between conditions. n=15

Table G-2. Individual spirometry values in unloaded (UL) and loaded (L) conditions

	FVC		FEV_1		FEV_1/FVC	
Subject No.	UL	L	UL	L	UL	L
1	5.82	5.72	4.71	4.56	0.81	0.81
2	5.64	5.54	4.62	4.19	0.82	0.82
3	6.92	6.37	5.49	5.02	0.79	0.79
4	6.67	6.38	4.89	4.63	0.73	0.73
5	6.71	6.70	5.60	5.59	0.83	0.83
6	6.32	5.97	4.51	4.28	0.71	0.71
7	6.44	6.25	4.89	4.66	0.76	0.76
8	6.34	5.63	4.61	4.21	0.73	0.73
9	6.39	6.26	4.89	4.89	0.77	0.77
10	5.93	5.66	4.48	4.17	0.76	0.76
11	5.38	5.32	4.42	4.47	0.82	0.82
12	5.66	5.41	4.46	4.24	0.79	0.79
13	7.95	7.64	6.23	5.88	0.78	0.78
14	6.21	6.10	5.08	5.95	0.82	0.82
15	5.10	5.08	4.22	4.13	0.83	0.83
Mean	6.23	6.00*	4.87	4.66*	0.78	0.78
±SD	0.70	0.64	0.54	0.51	0.04	0.04

FVC, forced vital capacity; FEV_1, forced expiratory volume in one second; FEV_1/FVC, ratio of forced expiratory lung volume and forced vital capacity. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions. n=15

Table G-3. Mean (±SD) body mass and urine specific gravity in unloaded (UL) and loaded (L) conditions

	UL	L
Pre-Mass (kg)	83.9 (10.1)	84.0 (10.0)
Post-Mass (kg)	82.7 (10.0)	82.6 (10.1)
Δ Mass (kg)	1.2 (0.3)	1.4 (0.2)
USG (U)	1.014 (0.006)	1.011 (0.007)

Δ Mass, change in body mass; USG, urine specific gravity. n=15

Table G-4. Mean (±SE) blood pressure during exercise in unloaded (UL) and loaded (L) conditions

	5 min		25 min		45 min	
	UL	L	UL	L	UL	L
Systolic BP (mmHg)	148 (4)	147 (4)	147 (3)	146 (4)	143 (3)	143 (4)
Diastolic BP (mmHg)	58 (2)	58 (2)	57 (2)	59 (2)	57 (2)	60 (2)

BP, blood pressure. n=15

Table G-5. Correlations between the difference in minute ventilation between loaded and unloaded conditions and selected indices of size, pulmonary function and fitness at 15 and 45 minutes of exercise

Variable	15 min	45 min
Δ V_E vs. Body Mass	r = -0.078	r = -0.218
Δ V_E vs. BSA	r = -0.177	r = -0.274
Δ V_E vs. TLC	r = -0.480	r = -0.441
Δ V_E vs. FEV_1	r = -0.189	r = -0.543
Δ V_E vs. VO_{2peak}	r = -0.183	r = -0.244

Δ V_E, difference in V_E between conditions; BSA, body surface area; TLC, total lung capacity; FEV_1, forced expiratory volume in one second; VO_2, peak oxygen consumption. n=15

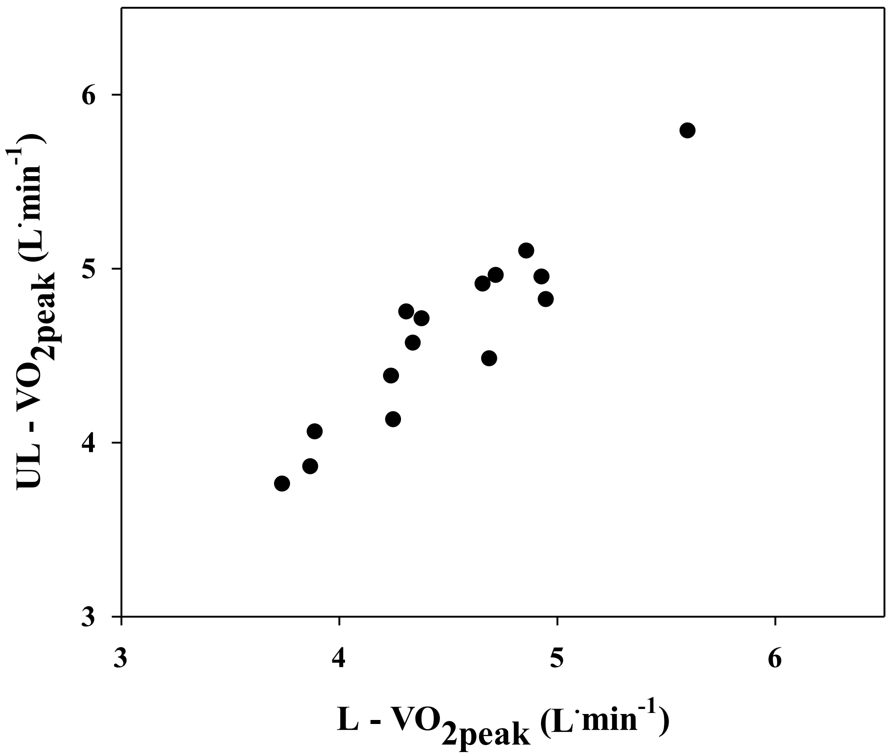


Figure G.1. Individual maximal oxygen uptake (VO_{2peak}) responses in loaded (L) and unloaded (UL) conditions. 10 subjects had a higher VO_{2peak} in the unloaded conditions and 5 subjects had a higher VO_{2peak} in the loaded condition.

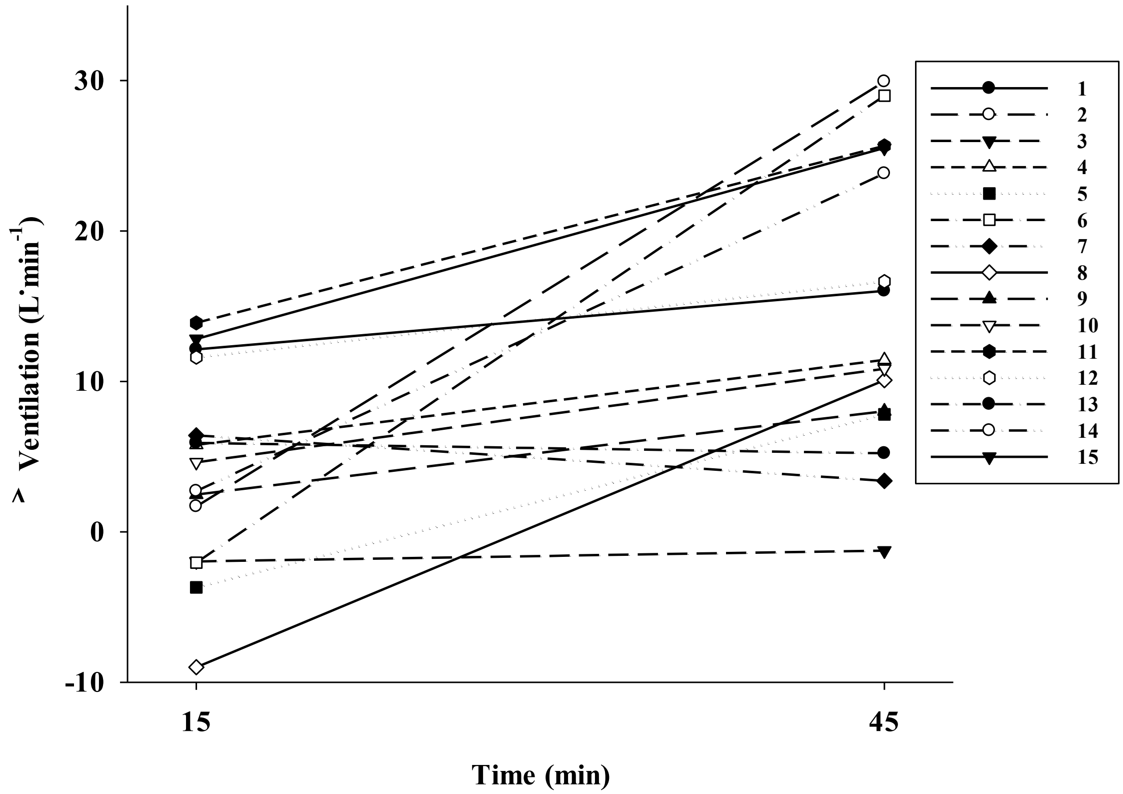


Figure G.2. Individual changes in ventilation between conditions (loaded – unloaded) at 15 and 45 min of exercise.

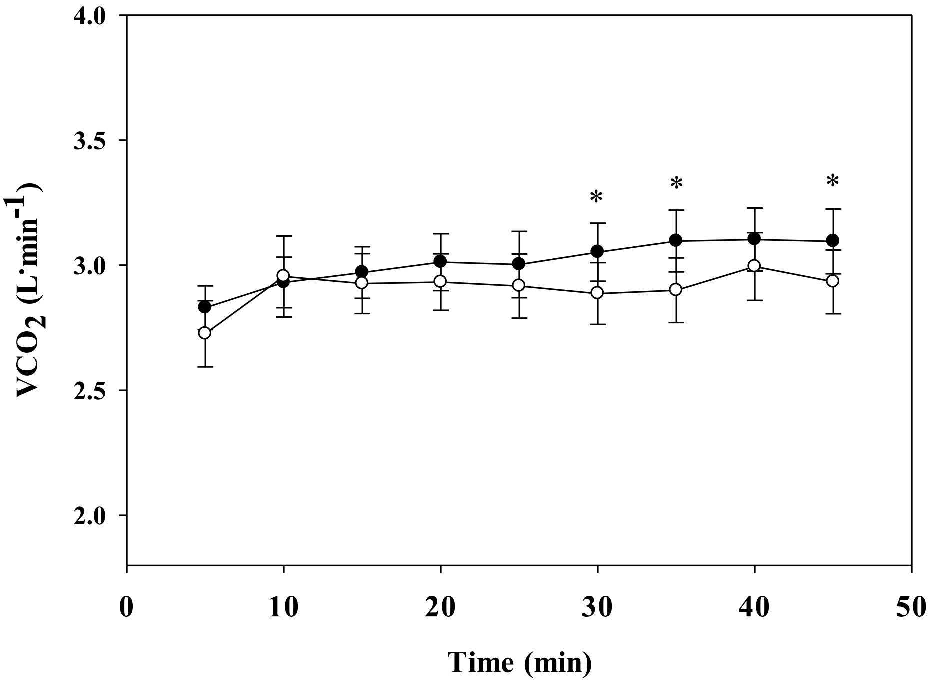


Figure G.3. Mean (±SE) carbon dioxide production during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions. n=15

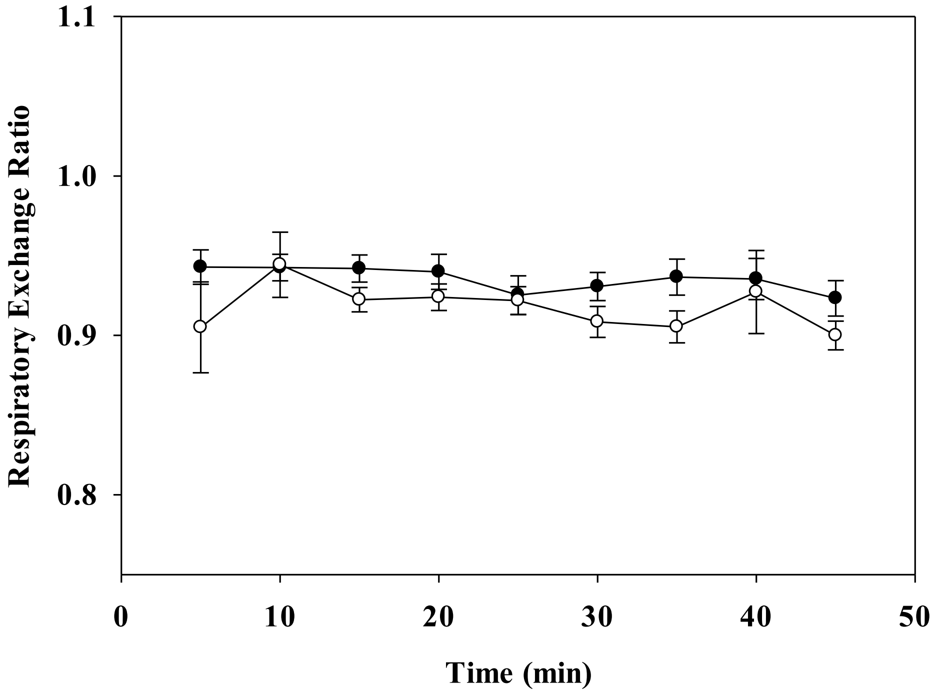


Figure G.4. Mean (±SE) respiratory exchange ratio during exercise in loaded (closed circles) and unloaded (open circles) conditions. n=15

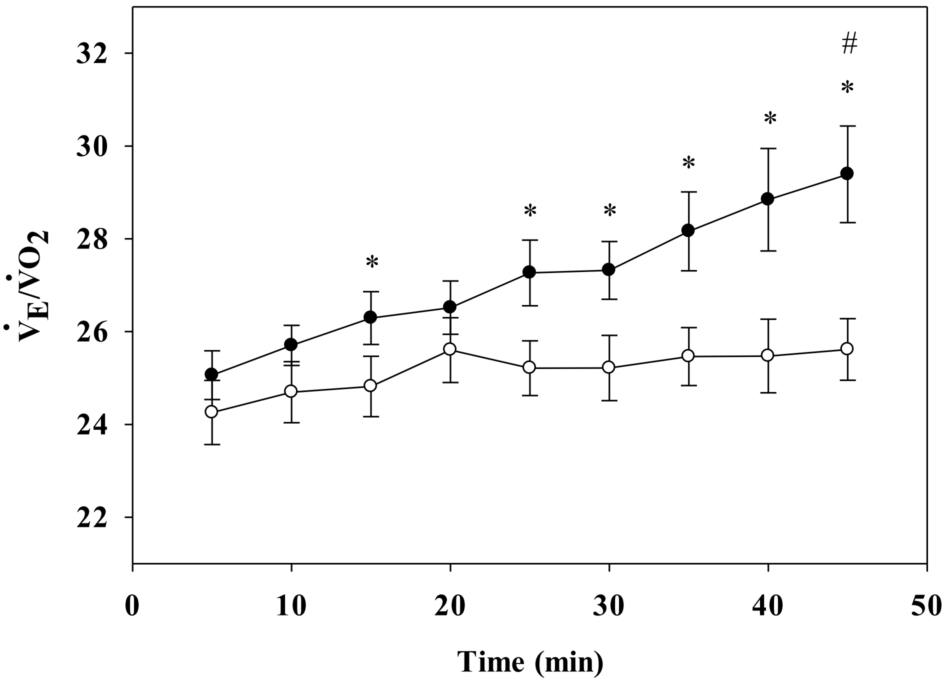


Figure G.5. Mean (±SE) ventilation (V_E) over oxygen uptake (O_2) during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within the loaded condition. n=15

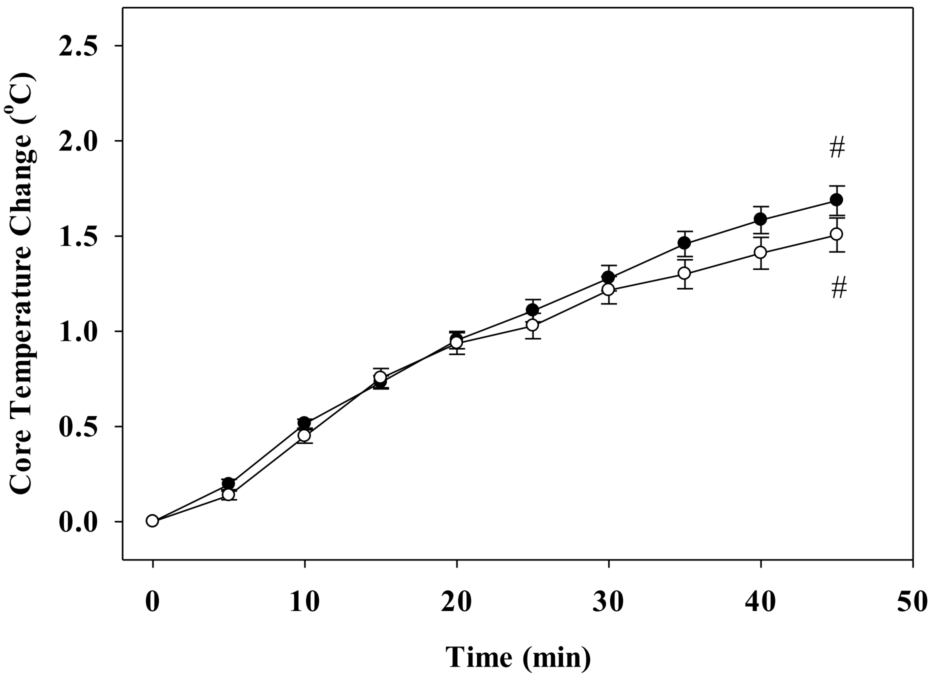


Figure G.6. Mean (±SE) change in core temperature during exercise in loaded (closed circles) and unloaded (open circles) conditions. . Number sign (#) indicates significant difference between 15 and 45 min within conditions (P < 0.05). n=10

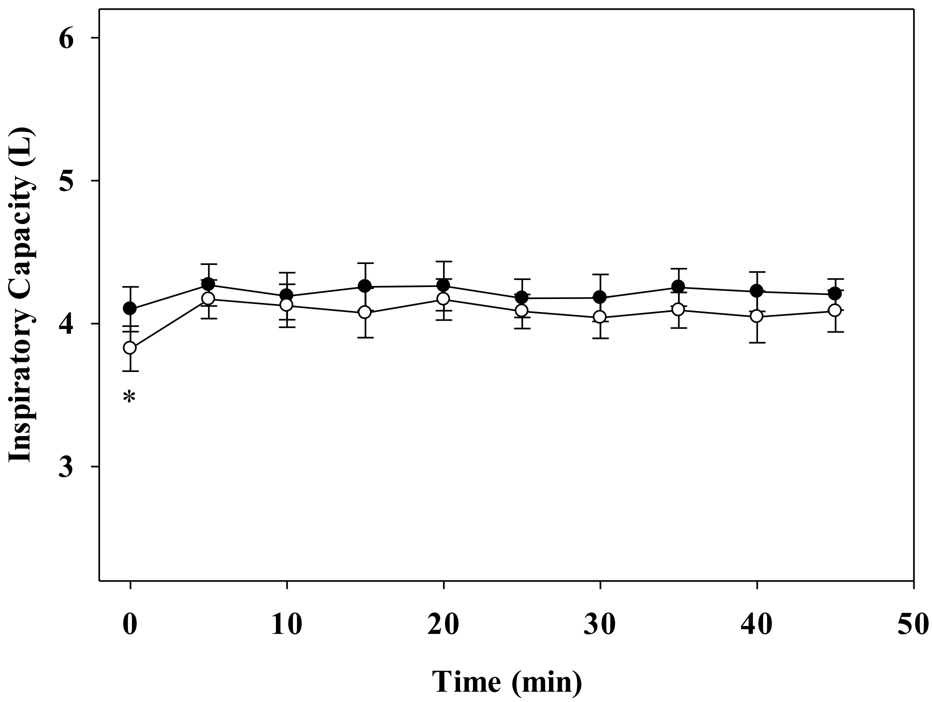
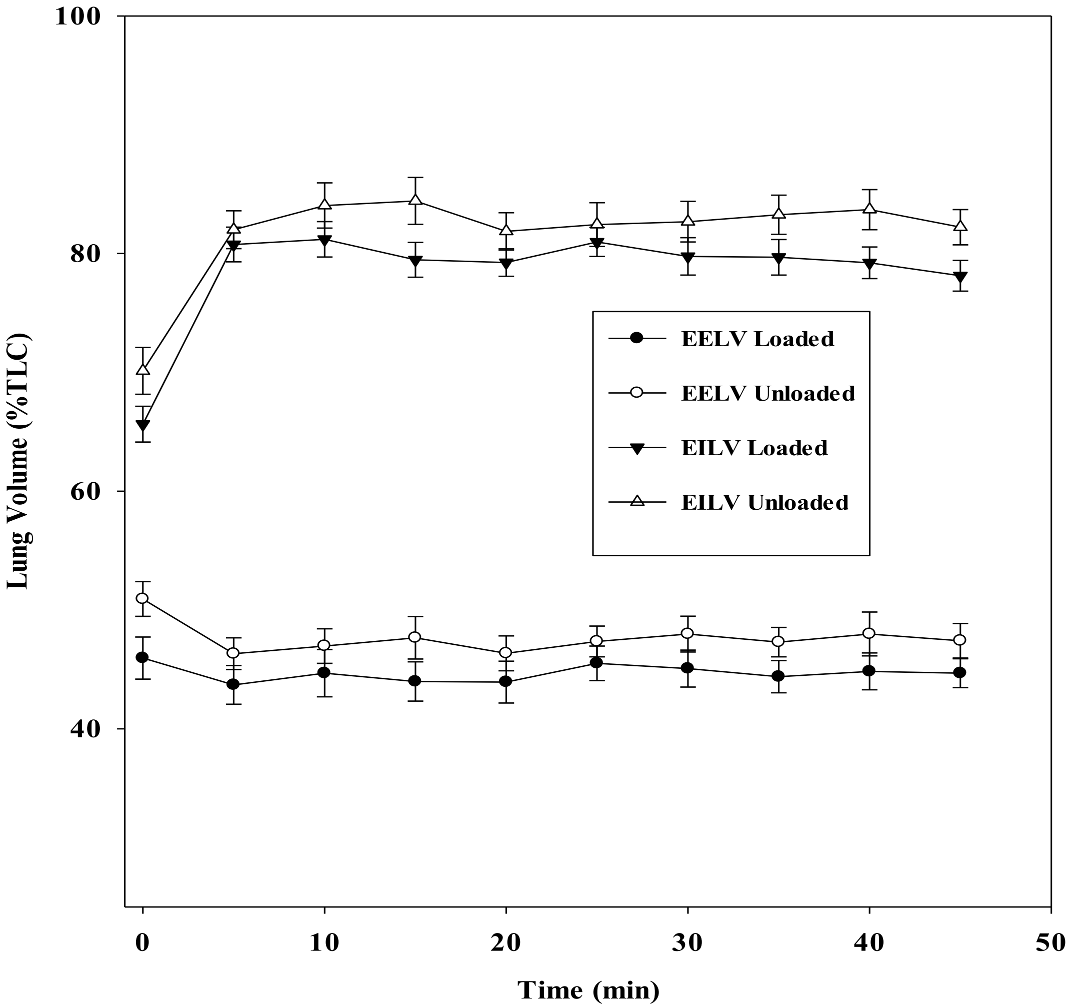


Figure G.7. Mean (±SE) inspiratory capacity during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference ($P < 0.05$) between conditions. n=15


100
80
60
40
Lung Volume (%TLC)
EELV Loaded
EELV Unloaded
EILV Loaded
EILV Unloaded
0
10
20
30
40
50
Time (min)

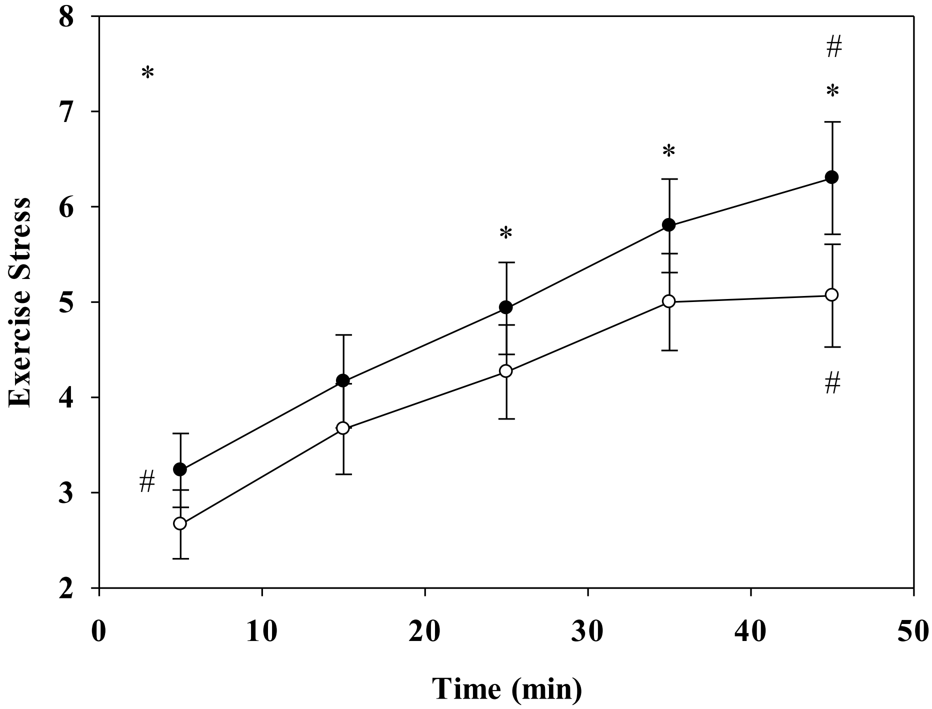
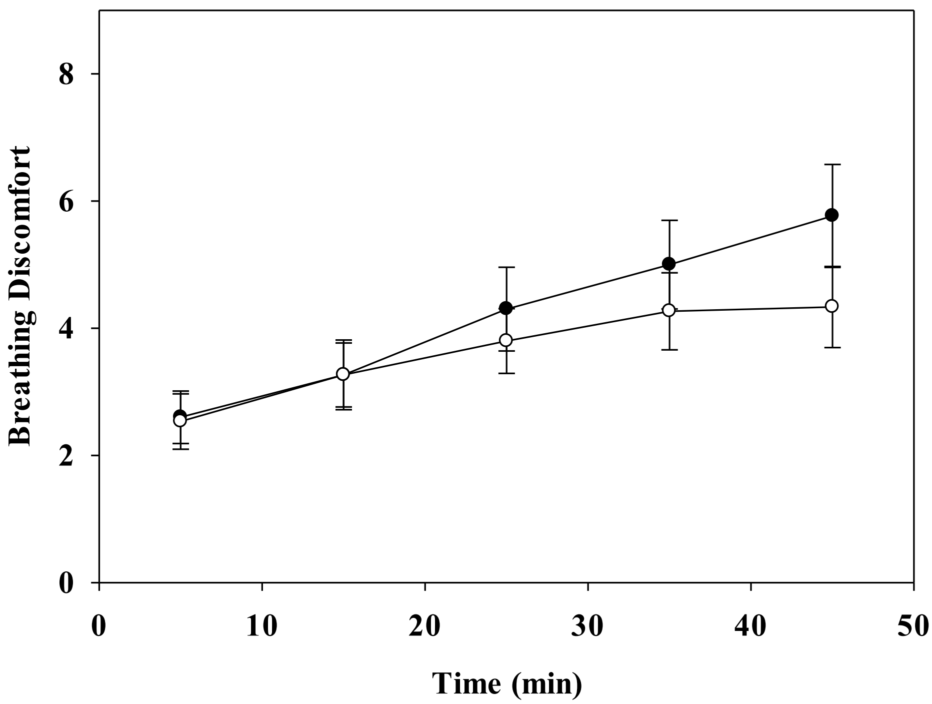


Figure G.9. Mean (±SE) exercise stress during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between time points within conditions. n=15

Figure G.8. Mean (±SE) resting and operational lung volume in loaded and unloaded conditions shown as a percentage of the measured total lung capacity. Asterisk (*) indicates significant different (P < 0.05) EILV (end expiratory lung volume) between conditions; Number sign (#) indicates significant different EELV (end expiratory lung volume) between conditions. n=15

Figure F.12. Mean (±SE) resting and operational lung volume in loaded and unloaded conditions shown as a percentage of the measured total lung capacity. Asterisk (*) indicates significant different (P < 0.05.) EILV (end expiratory lung volume) between conditions; Number sign (#) indicates significant different EELV (end expiratory lung volume) between conditions. n=15



Breathing Discomfort
8
6
4
2
0
0
10
20
30
40
50
Time (min)

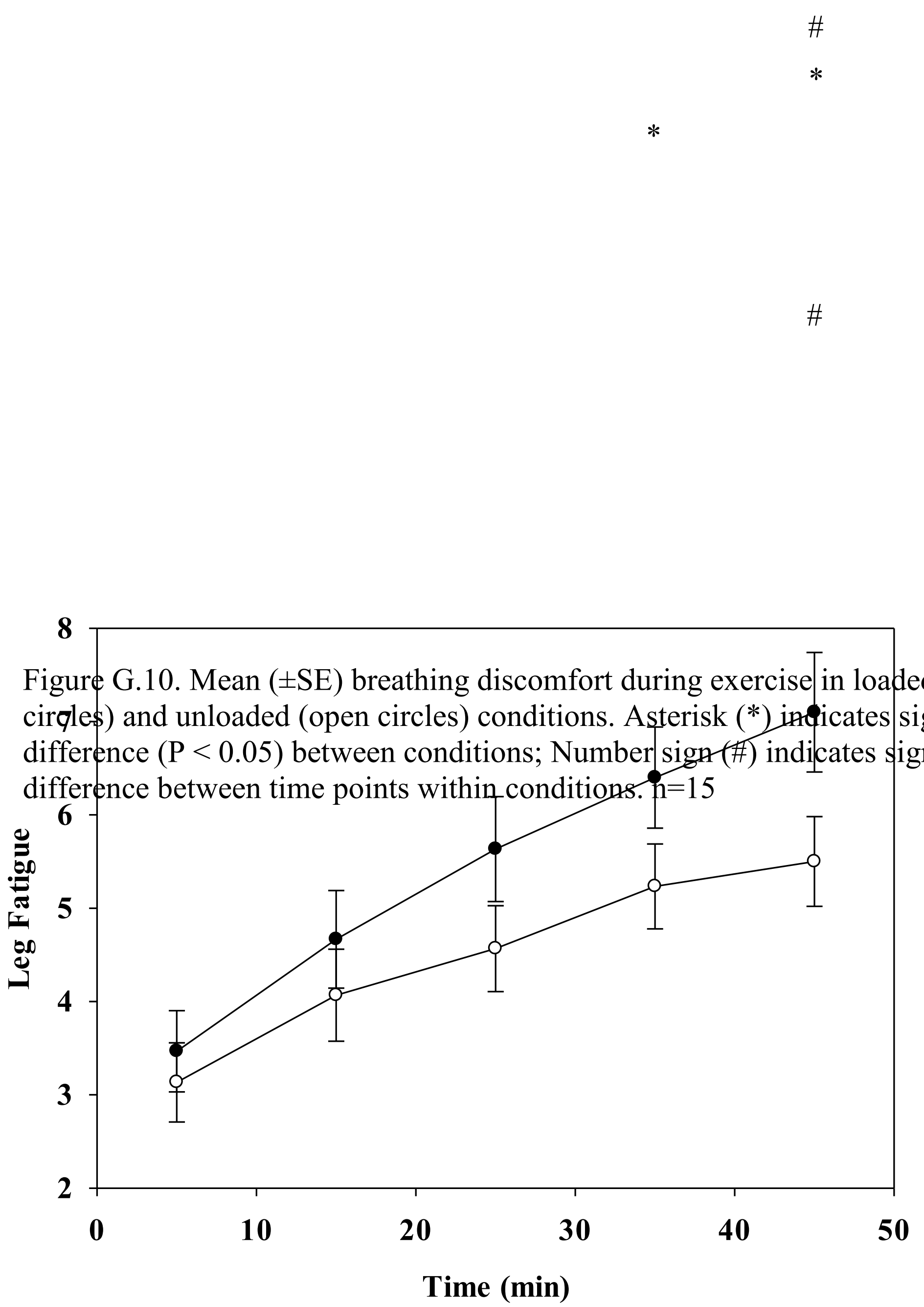


Figure G.10. Mean (±SE) breathing discomfort during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between time points within conditions. n=15

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Figure G.11. Mean (±SE) leg fatigue during exercise in loaded (closed circles) and unloaded (open circles) conditions. Asterisk (*) indicates significant difference (P < 0.05) between conditions; Number sign (#) indicates significant difference between 15 and 45 min within conditions. n=15

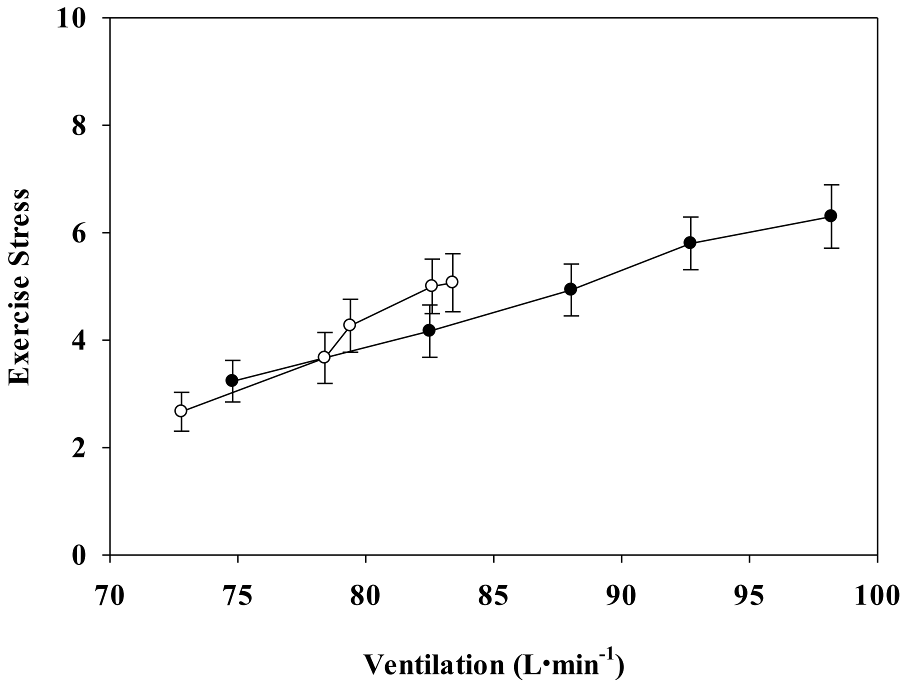

Figure G.12. Mean (±SE) exercise stress compared to ventilation during exercise in loaded (closed circles) and unloaded (open circles) conditions. Loaded; y = 0.1357x – 6.9565, r^2 = 0.993. Unloaded; y = 0.2353x – 14.532, r^2 = 0.978. Slopes between conditions were significantly different ($P < 0.05$). n=15

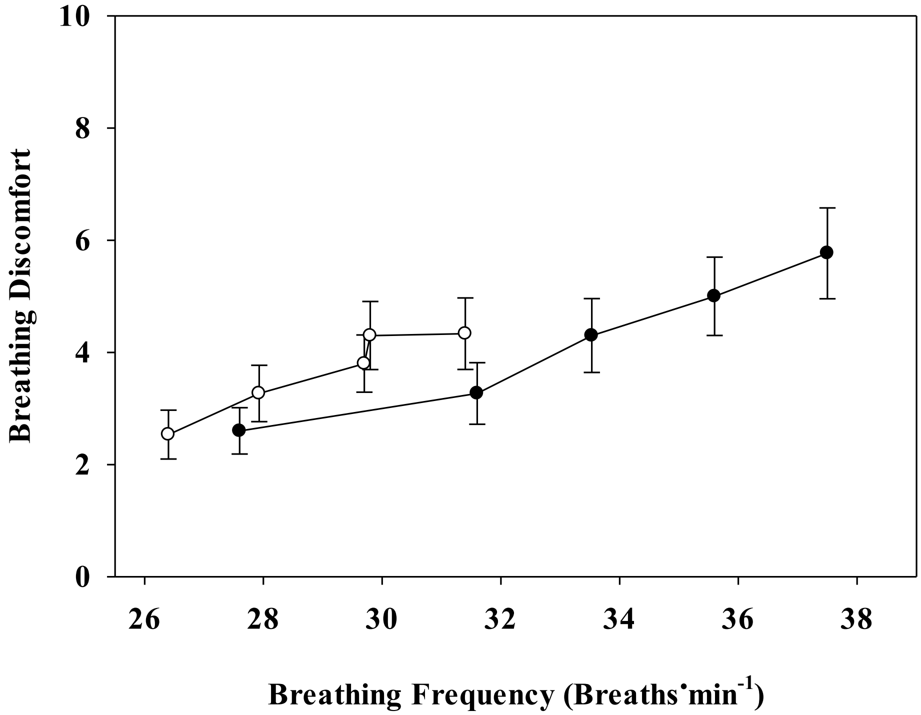

Figure G.13. Mean (±SE) breathing discomfort compared to breathing frequency during exercise in loaded (closed circles) and unloaded (open circles) conditions. Loaded; $y = 0.329x – 6.729$, $r^2 = 0.962$. Unloaded; $y = 0.373x – 7.212$, $r^2 = 0.919$. n=15

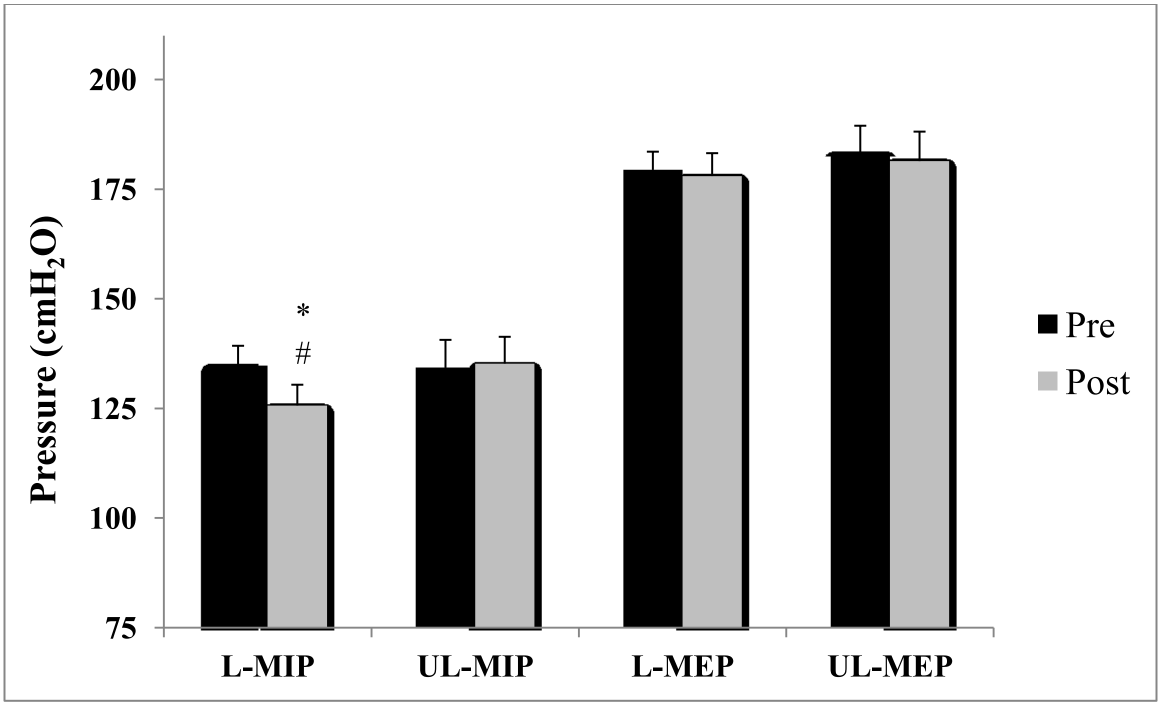

Figure G.14. Mean (±SE) maximal inspiratory (MIP) and maximal expiratory pressures (MEP) before and after exercise in loaded and unloaded conditions. Asterisk (*) indicates significant different ($P < 0.05$) post-MIP between conditions; Number sign (#) indicates significant difference between pre and post MIP in the loaded condition. n=15