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The effect of heavy load carriage on respiratory mechanics and breathing pattern during graded exercise

by

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Abstract

The effect of heavy load carriage on pulmonary function at rest and on breathing pattern and lung volumes during graded exercise was studied. Fifteen males completed treadmill tests to measure VO_{2peak} with and without a 25-kg pack. Subsequently, each subject completed short periods of treadmill walking in loaded and unloaded conditions at intensities equivalent to 55, 65, 75 and 85% of VO_{2peak}. At rest, in the loaded condition, forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) both were reduced by 3% with no change in FEV_1/FVC. During exercise with the pack, tidal volume (V_T) and end-inspiratory lung volume (EILV) were reduced by 14 and 5%, respectively, while ventilation (V_E) was maintained by a 9% increase in breathing frequency (Bf). Rating of perceived exertion (RPE) was always higher during the loaded trial, despite identical oxygen consumption (VO_2) and heart rate (HR) responses. During graded exercise under heavy load up to 85% of VO_{2peak}, breathing pattern is altered to maintain V_E while respiratory mechanics were not altered.

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Chapter One - Introduction

1.1. Background

Chest wall restriction reduces chest wall compliance (Sharp et al., 1964; Suratt et al., 1984) and concurrently reduces operating lung volumes (O'Donnell et al., 2000; Miller et al., 2002) and exercise capacity (O'Connor et al., 2000; O'Donnell et al., 2000). External restriction has been shown to reduce forced vital capacity (FVC), forced expiratory volume in one second (FEV_1) and maximal voluntary ventilation (MVV) with no change in the FEV_1/FVC ratio (Wang and Cerny, 2004).

In tidal breathing, end expiratory lung volume (EELV) is the lung volume at the end of expiration (i.e., the relaxed volume of the respiratory system) while end inspiratory lung volume (EILV) is the lung volume at the end of a tidal inspiratory breath. End expiratory lung volume is a dynamic volume determined by expiratory and inspiratory muscle recruitment (Johnson et al., 1999). The response of EELV is important because it is a major component of the normal ventilatory response to exercise and reflects alterations in respiratory mechanics during exercise (Babb et al., 1999). End inspiratory lung volume is usually expressed as a percentage of total lung capacity (TLC) and typically approaches 75 to 90% of TLC in heavy exercise in normal subjects. In healthy subjects, EELV decreases and EILV increases proportionately in exercise to allow for a larger tidal breath to support increasing metabolic demands (Pellegrino et al., 1993). A reduction in EELV below resting functional residual capacity (FRC) occurs with an increase in tidal volume and breathing frequency and a decrease in expiratory time (McClaran et al., 1999). With a reduction in EELV, inspiration is aided by optimizing inspiratory diaphragmatic length, and permitting elastic recoil of the chest wall (Henke et al., 1988). Placing the diaphragm at a more optimal force generating length reduces the inspiratory work of breathing by recovering some of the work done by the expiratory muscles during the previous expiration (Henke et al., 1988).

Certain conditions such as restrictive disease (Miller et al., 2002) and moderate obesity (Delorey et al., 2005) may lead to a reduction in EELV at rest compared to healthy individuals. End expiratory lung volume tends to remain depressed during moderate intensity exercise in restrictive disease and moderate obesity, and increase during heavy intensity exercise to avoid flow limitation. If EELV were to be reduced further with exercise, as seen in healthy individuals, then expiratory flow limitation (EFL) would be more likely to occur as tidal breathing would overlap on the flow volume loop (Johnson et al., 1999). If EFL becomes significant with 40-50% of the tidal breath overlapping with the flow volume loop, EELV typically increases (Johnson et al., 1999). Dynamically increasing EELV has been shown to minimize flow limitation but at the cost of increasing inspiratory work of breathing as the tidal breath moves closer to total lung capacity (Johnson et al., 1992). A failure to increase EILV in the presence of expiratory flow limitation may occur with constraint imposed by the chest wall (Johnson et al., 1999).

The degree of respiratory impairment created by restriction on the chest wall is dependant on the amount of restriction. Restriction of the chest wall leaves little reserve for increasing tidal volume with exercise. Breathing patterns may be altered with chest wall restriction as shown by a decrease in tidal volume and an increase in breathing frequency at submaximal intensities (DiMarco et al., 1981; Hussain and Pardy., 1985; Harty et al., 1999; O'Connor et al., 2000; O'Donnell et al., 2000; Miller et al., 2002). The degree of change in tidal volume and breathing frequency is determined by the amount of restriction placed on the chest wall. Therefore, tidal volume reserve is generally reduced and breathing frequency increased in an effort to maintain ventilation (Delorey et al., 2005) with lung volume-related constraints, as total lung capacity is reduced in chest wall restriction.

Load carriage commonly involves carrying a heavy load on the back. Both the heavy load as well as waist and chest straps are used to keep the load close to the body. It has been shown that wearing a backpack reduces FVC (by 8.1%), FEV_1 (by 9.1%), $FEF_{0.2-1.2}$ (by 7.3%), and $FEF_{25-75\%}$ (by 21%) with no change in the ratio of FEV_1/FVC. This suggests a restrictive change in lung function imposed by the backpack. This restrictive effect has been shown to be altered by tightness of fit more so than the weight of the pack alone (Bygrave et al., 2004).

It has previously been shown that backpacks create a restriction effect on the chest wall which alters lung volumes (Bygrave et al., 2004). Research on chest wall restriction suggests that breathing pattern is altered during exercise (O'Connor et al., 2000; O'Donnell et al., 2000), and a reduction in chest wall compliance suggests alterations in respiratory mechanics (Sharp et al., 1964; Suratt et al., 1984). The effect of load carriage on lung volumes and breathing pattern during exercise has not been reported. It remains unknown whether load carriage alters respiratory mechanics and breathing pattern during exercise.

1.2. Purpose

The purpose of this investigation was to study respiratory mechanics and breathing pattern during graded exercise with a heavy backpack (25 kg) in young, healthy and physically active males.

1.3. Hypotheses

It was hypothesized that:

- With load carriage, during exercise, EELV would be lower at all exercise intensities compared to the unloaded condition.
- With load carriage, during exercise EILV would be lower at all exercise intensities.
- With load carriage, during exercise, breathing frequency would increase and tidal volume would decrease compared to the unloaded condition.

1.4. Limitations

Limitations of this study included:

Technical

- There was a possibility that the flow volume loop could be overestimated due to gas compression artifact using the PowerLab Spirometry system (ADI Instruments). However, the inspiratory capacity maneuver was compared to the flow volume loop completed on the same spirometry system. Therefore, if any error existed it would be systematic.

- Proper pack fit was based on subjective evaluation of tightness of fit by the subject and the investigator. Variability of tightness of fit could have occurred, however, in order to ascertain that backpack fit was standardized subjects were asked to tighten backpack straps in the following order; waist, shoulder, chest. Subjects were also advised to pull on straps until a maximal tightness was achieved.

Subject compliance

- Inspiratory capacity maneuvers require maximal effort by the subject and can be inaccurate if the inspiratory maneuver was too slow, due to a poor effort, hesitation, or premature closure of the glottis (ATS, 2005). Maximal effort by the subject was determined by detecting a plateau in flow during the maneuver as well as observing reproducibility in a subsequent maneuver.
- Subject adherence to pre participation guidelines such as; refrain from ingesting food, alcohol, or caffeine within 3 hours of testing and avoiding significant exertion or exercise on the day of assessment (ACSM, 2006) was required in order to ensure within-subject physiological reliability. This limitation was addressed by instructing subjects of pre participation guidelines and questioning their adherence.
- The ability to achieve maximal results on graded exercise tests is largely dependent on subject motivation. In order to ensure that maximal performance was achieved an RER of greater than 1.10 was required.
- In order to complete a forced vital capacity maneuver a maximal effort is required on both inspiration and expiration. This limitation was addressed by ensuring that three FVC maneuvers were completed and were within 0.2 L (ATS Guidelines, 2005).

Possible confounding factors

- Forced vital capacity was used in order to assess dynamic lung volumes due to technical limitations. This does not account for residual volume and therefore cannot account for any changes that may occur with exercise or the backpack.

1.5. Delimitations

Delimitations of this study included:

- Generalizability of the results are to young and healthy males with normal lung function
- The load used in this study was set at 25 kg and the pack was a large volume hiking backpack (Arc Teryx). The results may not directly apply to other types of packs or load carriage applications.

1.6. Ethical considerations

- Subjects were recruited through word of mouth
- Subjects were screened prior to enrollment using a self-reported health history questionnaire (PAR-Q and You).
- Subjects provided informed consent prior to enrollment in the exercise study.
- Subjects were given the opportunity to ask questions and were informed of their right to withdraw, without penalty, at any point in the investigation.
- The subjects exercised to the point of exhaustion in order to get an accurate measurement of peak oxygen consumption. This is a routine test in exercise laboratories and presents minimal risk to healthy subjects but has been estimated to be one death per year for every 133,000 young athletic males (Van Camp et al., 1995). Subjects were required to carry backpacks loaded to 25 kg during an exercise bout to exhaustion. Risks of carrying backpack loads in heavily weighted packs were minimal but may have included foot blisters, stress fractures, back strains, metatarsalgia, rucksack palsy and knee pain (Knapik et al., 2004). Risks to investigators

were minimal but may have included lifting of heavy loads and exposure to body fluids (saliva, sweat).

- In case of an emergency in the lab during data collection a direct call to 911 would have been made if the subject was non-responsive or immobile. If immediate medical aid was not required, first aid would have been administered by the investigator or the Glen Sather Sports Medicine clinic would have assessed the injury. Treatment would have either been administered, the participant would have been sent to the emergency room (with EMS being called for transport and the department determining the appropriate location for medical care), or the participant would have been sent to their physician.
- The benefits to participants in this study were minimal but included knowledge about their resting and exercise lung function, their ventilatory threshold and maximal oxygen consumption as well as proper pack fitting with a standard hiking backpack. Benefits to the researchers included information on the physiology of load carriage.
- Participants were informed of their physiological test results at the end of the study. This included information relating to lung volumes, spirometric values, maximal oxygen consumption, maximal heart rate, ventilatory threshold and operating lung volumes during exercise.
- Participants were acknowledged for their time with a small gift (e.g; gift certificate).
- Data was not shared or disclosed to other subjects at any time. Data was only shared amongst co-investigators on the project.
- All participant information was encoded using initials.
- All raw data will be retained for five years in a locked file cabinet at the Van Vliet centre at the University of Alberta after publication of the results. During the duration of the study all raw data was kept on a computer with a protected password.
- Results of this study will be used for thesis, conference presentation and publication in a peer-reviewed exercise physiology journal.

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Chapter Two - The effect of a heavy backpack load on respiratory mechanics and breathing pattern during graded exercise[1]

[1] A version of this chapter will be submitted to the Journal of Applied Physiology Nutrition and Metabolism

2.1. Introduction

Many recreational and occupational pursuits involve carrying additional weight in a backpack (i.e. load carriage). Previously, the effects of load carriage have been studied when load is relative to body mass (Quesada et al., 2000; Beekley et al., 2007) or when the load is absolute (same weight regardless of body mass) (Lyons et al., 2005). According to Astrand and Rodahl (1986), load carriage of 30% body mass on flat ground for 40 minutes has been classified as heavy to very heavy work (Quesada et al., 2000), while a 20 kg load carriage up a 9% grade for five minutes has been classified as heavy work (Lyons et al., 2005). Metabolic cost has been shown to increase in proportion to the weight of the load (Quesada et al., 2000; Beekley et al., 2007) with larger increases in metabolic cost observed for smaller individuals carrying an absolute load (Lyons et al., 2005). Carrying an absolute load has been shown to reduce performance to a greater extent in subjects of smaller size due to the greater relative load (Bilzon et al., 2001).

Waist and chest straps commonly used to position the load properly may act to restrict chest wall movement during load carriage exercise. Wearing a backpack has previously been shown to reduce forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) without a corresponding decrement in FEV_1/FVC (Legg and Mahanty, 1985; Muza et al., 1989). Tightening the chest straps of a 15 kg backpack from a comfortable fit to a 3cm decrease in length decreases FVC from 3.6 to 8.1% and FEV_1 from 4.3 to 9.1% with no effect on the ratio of FEV_1/FVC (Bygrave et al., 2004). Spirometry with a backpack results in a pattern of restriction that is consistent with chest wall strapping (Miller et al., 2002) where impedance on the thoracic wall reduces the ability to expand the chest wall during inspiration.

The effect of load carriage on breathing pattern and respiratory mechanics during exercise is unknown. Multiple layers of protective clothing such as a chemical defense uniform, load bearing equipment and body armor, have been shown to increase breathing frequency and decrease tidal volume while maintaining ventilation during exercise (Muza et al., 1996). In load carriage, the straps used to maintain load position may be similar to models of restrictive disease involving the use of an external thoracic device which decreases compliance of the chest wall and causes an absolute reduction in vital capacity (Hussain and Pardy, 1985; Harty et al., 1999; O'Connor et al., 2000; Miller et al., 2002). Studies using external thoracic restriction have been shown to result in a higher breathing frequency and a lower tidal volume during exercise with no change in maximal ventilation (Hussain and Pardy, 1985) while other studies report higher minute ventilation during submaximal exercise (Harty et al., 1999; O'Connor et al., 2000; Miller et al., 2002) coupled with a decrease in end tidal carbon dioxide (Harty et al., 1999, O'Connor et al., 2000).

In lean, healthy subjects end-expiratory lung volume (EELV) is reduced during exercise, which allows increased mechanical efficiency of the diaphragm while lowering the inspiratory work of breathing. Failure to increase end-inspiratory lung volume (EILV) in the presence of expiratory flow limitation may result from constraint imposed by the chest wall (Johnson et al., 1999). The effect of the restraint of a heavy backpack load on the chest wall may alter lung volumes during exercise.

Therefore, the purpose of this study was to investigate the effect of heavy load carriage on breathing pattern and respiratory mechanics during short-term exposure to exercise at selected submaximal intensities. We hypothesized that heavy load carriage may lead to a restrictive breathing pattern. As a result of the restraint on the chest wall imposed by the backpack design, it was expected that EELV would be reduced during exercise.

2.2. Methods

2.2.1. Design and Subjects

A within-subject, repeated measures design was used to study the effects of heavy load carriage on respiratory mechanics and breathing pattern during brief exposure to selected exercise intensities. The two experimental conditions were designated as loaded (L) and unloaded (U). In the loaded condition, the subjects wore a properly sized and fitted 25 kg backpack (Arc Tery'x Bora 80, North

Vancouver, BC) filled so that volume was consistent. Subjects wore normal exercise clothing (shorts, t-shirt and running shoes) during all experimental trials.

Fifteen healthy physically active males provided written informed consent to participate in this study which had received approval from the appropriate institutional ethics review board. All participants were physically active (vigorous exercise at least 3 times per week); had normal lung function with no airway obstruction and were free from exercise-induced broncho-constriction. Subject characteristics are reported in Table 1.

2.2.2. Experimental Protocol

Each subject attended the laboratory three times during a period of approximately one week, designated as "Day one", "Day two" and "Day three".

Day One

During the first visit, each subject completed resting spirometry with and without a properly sized and fitted 25-kg pack to evaluate lung function. He then completed a graded exercise test (GXT) to exhaustion to measure VO_{2peak}, either with or without the pack. The order of the conditions was determined by flipping a coin. At 5, 10, 15 and 20 min after the completion of the GXT, the subject performed forced flow-volume maneuvers to evaluate the presence of exercise-induced broncho-constriction (Crapo 2000).

Day Two

After at least 24 hours (typically 48 hours) of recovery, the subject returned to the laboratory and completed the second GXT, in the alternate condition.

Day Three

After at least 24 hours (typically 48 hours) of recovery, the subject completed two graded exercise protocols (GXP) in L and UNL conditions separated by 60 minutes of rest. Each GXP consisted of short-term (typically 5 min) exercise at intensities equivalent to 55, 65, 75, and 85% of the VO_{2peak} observed during the corresponding GXT. The order of the graded exercise protocols for each subject was determined by the outcome of flipping a coin.

Before and after exercise, each subject completed forced expiratory maneuvers with the bag-in-box and spirometer system used to measure operational lung volumes during exercise. During each stage of the protocol, the subject walked for approximately three minutes or until stable physiological responses were observed (e.g., heart rate, VO_2, V_E) from a mixing chamber metabolic measurement system. The subject was then switched to a breathing circuit that incorporated the bag-in-box and spirometer, for approximately 60 s to acquire data for the evaluation of lung volumes. Subsequently, the breathing circuit was switched back to the metabolic measurement system for approximately 30 s to ensure that the physiological state was consistent with that observed prior to the measurement of lung volumes.

After the completion of the first GXP, the subject rested for at least 60 min in the laboratory. The subjects were encouraged to drink moderate amounts of bottled water. Body mass and heart rate were monitored at the beginning of the second trial to compare pre test heart rate and body mass and ensure appropriate recovery.

2.2.3. Procedures and Instrumentation

Pack fitting

Backpack (Arc Tery'x Bora 80, North Vancouver, BC) size was determined by length of the torso as measured from the C7 vertebrae to the top of the iliac crest. Each subject was instructed to tighten the straps in the following order; hip belt, shoulder straps and chest strap. Straps were tightened so that no movement occurred around the torso, shoulder or low back regions.

Resting Spirometry

Spirometry was performed (SpiroLab III, Medical International Research, Rome Italy) according to the guidelines of the American Thoracic Society (2005).

At least three forced flow-volume maneuvers were completed while standing with minimal forward lean in both the loaded and unloaded conditions.

Exercise Protocols

The GXT was performed on a treadmill (Standard Industries, Fargo, ND) with a constant walking speed of 91.2 $m \cdot min^{-1}$ while grade increased from the initial setting of 0% in increments of 2% every two minutes until volitional exhaustion. Gas exchange data were averaged in 30 s intervals and VO_{2peak} was defined as the highest oxygen consumption attained before volitional exhaustion.

Following both GXTs, linear regression was used to establish the relationship between treadmill grade and VO_2. Workload was solved by using 55, 65, 75 and 85% of the VO_{2peak} in the regression equation. This allowed for appropriate workloads to be determined based on the linear response of oxygen consumption to gradient in each of the conditions.

The GXP was performed on the same treadmill with subjects walking at the same speed (91.2 $m \cdot min^{-1}$) throughout the protocol, but with the grade set to achieve the workloads described above. Each stage was approximately 4-5 min in duration.

Cardio - respiratory and perceived exertion measurements

Expired gases were collected from a two way breathing valve and airflow was measured by a heated pneumotachograph (Hans Rudolph, Kansas City, MO, USA). Measurements of oxygen consumption, expired carbon dioxide, ventilation, tidal volume and breathing frequency were calculated (TrueOne, ParvoMedics, Salt Lake City, UT, USA). Calibration of the system was performed according to the manufacturer's specifications immediately prior to each test. Calibration was checked immediately following each test and there were no instances where calibration failed to be maintained during an experiment. Heart rate was recorded every minute using a telemetric heart rate monitor (FS1 receiver and T-31 transmitter, Polar Electro Canada Inc, Lachine QC, Canada).

The subject provided a rating of perceived exertion from the 15-point scale (range 6-20) at the end of each stage of the exercise test (Borg, 1990).

Lung volumes

Lung volumes were monitored by switching the subject from breathing room air to a bag-in-box system (BBS) in series with a low resistance mechanical spirometer (SensorMedics Corporation, Yorba Linda, CA). Calibration of the spirometer was performed prior to each experiment using a known volume to ensure the appropriate output voltage was generated following displacement from known volumes of air. The voltage outputs from the spirometer were converted to digital signals using a data acquisition system (PowerLab/8SP, ADInstruments 7.0, Castle Hill, Australia). All data were sampled at 10 Hz and stored on a computer for subsequent analysis.

Assuming that FVC does not change with exercise (Stubbing et al., 1980), inspiratory capacity (IC) maneuvers were performed at every exercise stage. End expiratory lung volume was measured as FVC-IC and EILV was estimated as the addition of tidal volume to the EELV. Previously it has been shown that this method of determining EELV is reliable and accurate if a maximal inspiratory effort is given (Babb et al., 1999). In order to ascertain that subjects did not change their EELV prior to an IC measurement subjects were told to complete an IC maneuver on the subsequent breath to minimize any anticipation. Changes in EELV and EILV were expressed as a percentage of forced vital capacity.

Analysis

A two-way analysis of variance for repeated measures was used to measure changes between conditions throughout each work bout. Upon detection of a main effect, Tukey's post hoc test was performed to define each difference. Student's t-test was used to detect differences between maximal exercise data. All statistical analysis was performed using Sigma Plot Version 11.0 (Systat Software Inc., Chicago, IL, USA, 2010). Significance was set *a priori* at p <

0.05. Data are presented as mean ± standard deviation (SD) unless indicated otherwise.

2.3. Results

Effect of the backpack on resting pulmonary function

Forced vital capacity was 5.82±0.55 L and 5.62±0.57 L ($p<.05$), while FEV_1 was 4.6±0.36 L and 4.45±0.43 L ($p<.05$) in the unloaded and loaded conditions, respectively. This represents a reduction of 3.4 and 3.3% in volume for FVC and FEV_1, respectively, in the loaded condition. The ratio of FEV_1/FVC was not significantly different (0.79±0.05 and 0.79±0.04 in the unloaded and loaded conditions, respectively).

Effect of the backpack on maximal cardiorespiratory function

A paired t-test, comparing the results of the loaded versus unloaded GXT, revealed a significant difference between peak oxygen consumption (VO_{2peak}), breathing frequency (B_f) and tidal volume (V_T). Peak oxygen uptake was 5% lower in the loaded condition. At peak exercise, breathing frequency was 8% greater in the loaded condition, while V_T was 9% lower (see Table 3) At end-exercise in both loaded and unloaded conditions, there was a ventilatory reserve of 9% with no difference in peak V_E.

Effect of backpack on submaximal cardiorespiratory function

Ventilation, VO_2, VCO_2, RER and HR were not different between conditions but as expected were significantly greater with each progressive exercise intensity (See table 3). Breathing frequency, V_T and RPE were significantly different between the loaded and unloaded conditions. On average, breathing frequency was 14% higher, regardless of intensity in the loaded condition. Similarly, tidal volume V_T was approximately 9% lower in the loaded condition. Rating of perceived exertion was always higher in the loaded condition at the same metabolic rate (Table 3).

Effect of the backpack on respiratory mechanics

Inspiratory capacity and end-expiratory lung volume were not different between conditions but did show significant changes with increasing exercise intensity (See Figure 1). End-inspiratory lung volume was reduced by 5% at the highest exercise intensity in the loaded condition ($P<0.05$). See Table 4.

2.4. Discussion

The novel results of this experiment showed that carrying a heavy backpack load during submaximal exercise decreases tidal volume and increases breathing frequency while maintaining ventilation. Contrary to our hypothesis, during exercise, end-expiratory lung volume was not altered when carrying a heavy backpack load. In correspondence with our hypothesis end-inspiratory lung volume is decreased when carrying a heavy backpack load. In accordance with previous findings on load carriage (Bygrave et al., 2004) resting spirometry values (FVC and FEV_1) were decreased in the loaded condition. This finding is consistent with changes previously observed with a restrictive alteration, as there was no change in the FEV_1/FVC ratio.

Oxygen cost and heart rate were the same between the loaded and unloaded condition suggesting that workloads were appropriately matched between conditions and as a result physiological comparisons are justified. Breathing pattern was altered in the loaded condition, which is consistent with a restrictive pattern. During submaximal exercise tidal volume was 9% lower in the loaded condition while breathing frequency was 14% higher resulting in no change in ventilation between conditions. During graded exercise under heavy load up to 85% of VO_{2peak}, it seems likely that breathing pattern is altered in an attempt to reduce work of breathing while maintaining V_E. This finding confirms the work by Muza et al., (1996) which showed no alteration in ventilation during exercise with chemical defense clothing despite a lower tidal volume and a higher breathing frequency.

There was no significant correlation between body size (height or mass) and the change in Bf, V_E, V_T and VO_2 between the loaded and unloaded conditions. This suggests that despite the “absolute” load (not proportional to the mass of the subject), it did not have a greater effect on breathing pattern in smaller subjects. There was no significant correlation between either height or body mass and VO_2peak. Other studies on "absolute" load carriage have reported negative effects on exercise performance in smaller individuals (Bilzon et al., 2001). This suggests that the effect of load carriage on breathing pattern is not dependant on the same factors that are relevant in relation to the performance of load carriage in smaller individuals. Future research would suggest a more detailed look at differences between taller and shorter individuals during load carriage to determine whether differences in lung volume have an effect on breathing pattern.

The unchanged ventilation between the loaded and unloaded conditions in our study is different from other studies on chest wall restriction which found an alteration to breathing pattern as well as an increase in ventilation (O'Donnell et al., 2000, Harty et al., 1999). It is possible that the unaffected ventilation in the present study could be due to the minimal amount of restriction caused by backpack strapping. Previous studies in chest wall restriction have largely used an elastic strapping device to alter thoracic movement (Miller et al., 2002) resulting in a decrease in forced vital capacity of up to 35%. It is well known that with rapid, shallow breathing pattern a greater amount of ventilation is dead space ventilation due to a percentage of every tidal breath going to anatomical dead space. It is possible that the restrictive effect of the pack does not cause a severe enough reduction in tidal volume to significantly alter dead space ventilation. Harty et al., (1999) hypothesized that the variance in breathing pattern amongst restrictive studies is due to the methodology behind the restriction. Backpack straps are a surrogate for elastic strapping which has been shown to have a minimal effect on respiratory mechanics compared to external thoracic restriction which enforces a specific vital capacity.

Further research involving the effect of heavy backpack loading during prolonged exercise bouts is required. Prolonged exercise in normal exercise conditions has been associated with hyperthermia induced hyperventilation where a linear increase in ventilation is seen with core temperature over time (Hayashi et al., 2006). It is unknown whether load carriage has a more pronounced effect on ventilation when wearing a backpack due to the alteration seen in breathing pattern.

End-expiratory lung volume was not different between loaded and unloaded conditions. This suggests that any restraint placed on the thoracic cage with heavy load carriage does not have an effect of lung volumes during exercise as inspiratory capacity was the same. This could be due to the appropriate ergonomic design of the backpacks used in this study. The use of load bearing straps aids in reducing the amount of weight placed directly against the torso and therefore the chest wall. Also, chest wall straps were elastic and therefore the chest wall was able to expand against the resistance of the straps. End-inspiratory lung volume was reduced in the loaded condition, which accounts for the difference seen in tidal volume between the two conditions. The decrease in tidal volume could potentially be due to the difficulty of inspiration with the amount of load on the torso. The assisting inspiratory muscles may have been fatigued by the weight placed on the trapezius muscle through the shoulder straps. These are novel findings as lung volumes during exercise with a heavy backpack load have not previously been reported.

Limitations to this study include the lack of information regarding residual volume in both loaded and unloaded conditions. The use of the helium-dilution technique would allow for further conclusions to be drawn regarding residual volume. Measurements of end tidal carbon dioxide would have aided our understanding of the effect of a rapid, shallow breathing pattern on alveolar ventilation / dead space ventilation.

In conclusion, load carriage altered breathing pattern during exercise with tidal volumes decreasing and breathing frequency increasing during short term, submaximal exercise. During graded exercise under heavy load up to 85% of VO_{2peak}, it seems likely that breathing pattern is altered in an attempt to reduce work of breathing while maintaining V_E. Respiratory mechanics were not altered suggesting that heavy load carriage does not have an effect on lung volumes during exercise.

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Table 2-1. Individual Subject Characteristics

Subject	Weight (kg)	Height (cm)	Age (yr)	VO_{2peak} ($ml.kg^{-1}.min^{-1}$)
1	93.9	179	25	50.0
2	71.7	179	23	50.4
3	81.4	183	24	43.4
4	75.2	182	22	54.3
5	93.9	181	25	51.7
6	73.5	175	23	49.8
7	91.3	185	24	41.6
8	100.1	188	21	43.4
9	72.9	179	22	48.4
10	95.9	178	26	44.5
11	72.1	177	22	50.7
12	72.2	178	23	50.0
13	96.2	189	23	43.9
14	69.4	180	26	58.3
15	86.5	171	34	46.6
Mean	83.1	180	24	48.5
± SD	11.2	4.8	3	4.6

Table 2-2. Cardiorespiratory and rating of perceived exertion responses during exercise in loaded (LOAD) and unloaded (UNLOAD) conditions

	55%		65%		75%		85%	
	UNLOAD	LOAD	UNLOAD	LOAD	UNLOAD	LOAD	UNLOAD	LOAD
VO_2 ($L \cdot min^{-1}$)	2.1 (0.2)	2.1 (0.3)	2.5 (0.2)	2.5 (0.3)	3.0 (0.3)	3.0 (0.4)	3.5 (0.3)	3.5 (0.4)
VCO_2 ($L \cdot min^{-1}$)	1.8 (0.2)	1.8 (0.2)	2.3 (0.2)	2.3 (0.3)	2.8 (0.4)	2.8 (0.3)	3.6 (0.3)	3.5 (0.5)
RER	0.86 (0.05)	0.86 (0.05)	0.92 (0.03)	0.92 (0.03)	0.90 (0.10)	0.95 (0.03)	1.01 (0.03)	1.00 (0.03)
HR ($beats \cdot min^{-1}$)	123 (7)	124 (8)	143 (7)	144 (8)	162 (7)	165 (8)	175 (3)	178 (7)
RPE	8.1 (1.9)	9.7* (2.0)	10.7 (2.0)	11.8* (2.1)	13.9 (1.3)	14.4* (1.5)	15.8 (1.3)	16.6* (1.4)

Values are means ± SD. VO_2, volume of oxygen consumed; VCO_2, volume of carbon dioxide expired; RER, respiratory exchange ratio; HR, heart rate per minute; RPE, rating of perceived exertion. $P<0.05$ * n=15.

Table 2-3. Breathing pattern during exercise in loaded (LOAD) and unloaded (UNLOAD) conditions

	55%		65%		75%		85%	
	UNLOAD	LOAD	UNLOAD	LOAD	UNLOAD	LOAD	UNLOAD	LOAD
V_E ($L \cdot min^{-1}$)	48.9 (4.6)	49.9 (5.4)	61.8 (7.4)	64.2 (8.8)	78.2 (8.8)	81.3 (11.9)	100.4 (13.8)	105.7 (17.3)
V_T (L)	2.06 (0.37)	1.90* (0.40)	2.34 (0.39)	2.06* (0.40)	2.63 (0.40)	2.39* (0.40)	2.89 (4.57)	2.63* (0.40)
Bf ($breaths \cdot min^{-1}$)	25 (6)	28* (7)	27 (7)	32* (8)	30 (7)	35* (8)	36 (9)	42* (10)
Ti/Ttot	0.64 (0.01)	0.64 (0.02)	0.64 (0.02)	0.63 (0.01)	0.63 (0.04)	0.62 (0.01)	0.59 (0.06)	0.60 (0.03)

Values are means ± SD. $V_{E,}$ minute ventilation; V_T, tidal volume; Bf, breathing frequency ; Ti/Ttot, duty cycle. P<0.05 * n=15.

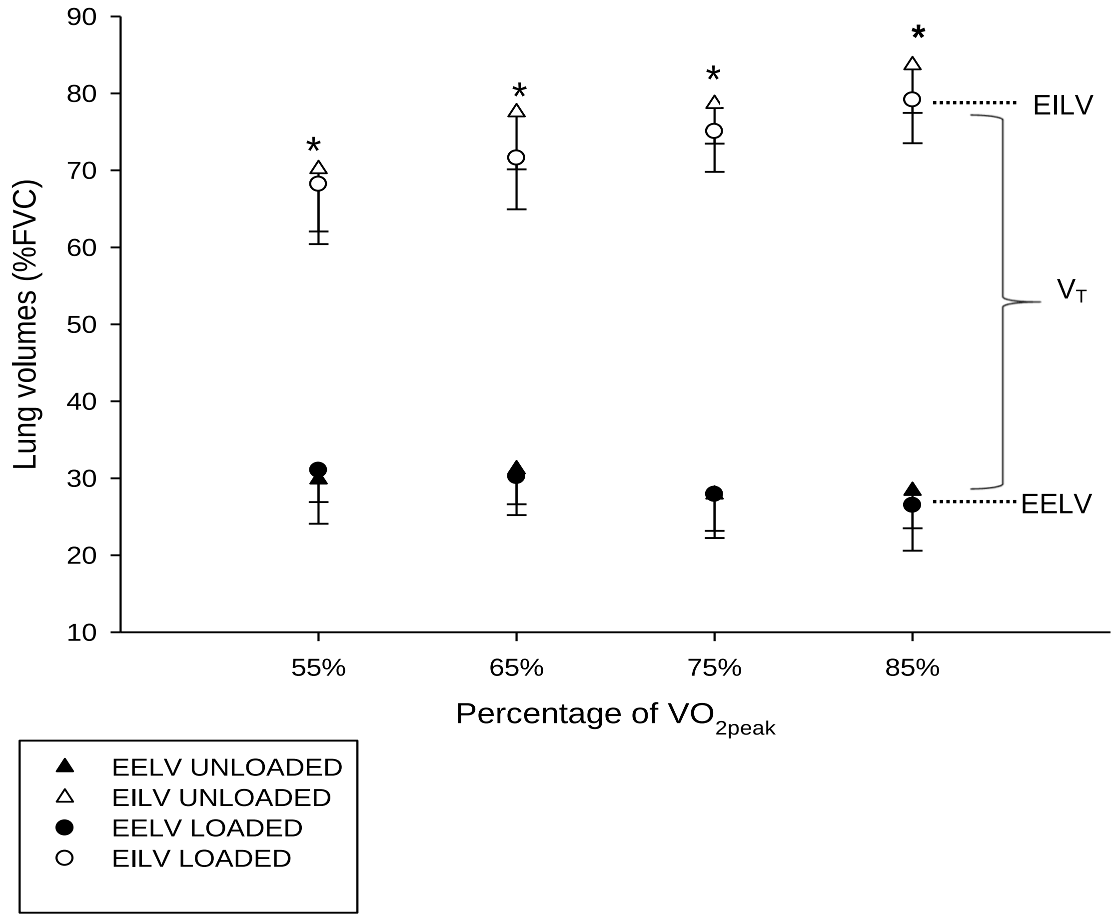

Figure 2-1. Resting and dynamic lung volumes shown as a percentage of the measured forced vital capacity $P<0.05$ * n=15.

Chapter Three - General Discussions and Conclusion

3.1. Location of load

Single and double strap backpacks have both been shown to impair resting pulmonary function however the severity of the impairment is different suggesting that location of straps plays a role on the degree of restriction. Despite maintaining the same load of 6kg; single strap backpacks were shown to have a greater effect on FVC and FEV_1 than double strap backpacks despite both packs showing a restrictive effect on pulmonary function (Legg and Cruz, 2004). Similar decrements in resting pulmonary function were seen when subjects were measured while wearing body armor of less than 10 kg (Legg 1988).

Respiratory mechanical limitations in obesity studies (Delorey et al., 2005, Babb et al., 2002) have been correlated with degree of adiposity and BMI. Plethysmographic EELV has been shown to correlate with the degree of adipose tissue around the trunk ($r^2 = 0.57$), suggesting that location of abdominal fat has an effect on resting respiratory mechanics. Adipose tissue on the rib cage has been shown to push inwards on the ribs and concurrently the lungs (Babb et al., 2002), while abdominal tissue has been shown to push inward on the diaphragm (Delorey et al., 2005). Babb et al., (2008), observed no difference in location of adipose tissue in relation to EELV. The cumulative effect of chest wall adipose tissue affects the chest wall by pressing the diaphragm upwards and the rib cage inwards. Upper body adiposity comparatively to lower body adiposity has been shown to result in a higher oxygen requirement, greater rapid, shallow breathing and higher ventilatory demand (Li et al., 2001). This suggests that distribution of body fat has an effect on the degree of respiratory impairment experienced both at rest and during exercise.

The reported differences in location and severity of the load propose that the location of the load when wearing a double strap backpack, as used in this study, is not great enough to create the respiratory mechanical limitations seen in obesity where the load has a direct effect on the action of the diaphragm. Chest wall strapping is the common experimental methodology for inducing a restrictive model of disease in experimental studies. Strapping is typically in the form of either an external elastic load or external thoracic and/or abdominal restriction. It is suggested that elastic loading may not create a severe enough restrictive effect to create a large reduction in lung volume (Harty et al., 1999). This is in comparison to external thoracic restriction where changes in chest wall compliance are induced typically resulting in a forced reduction of FVC of 35% (Miller et al., 2002). The backpack used in this study was fitted with elastic straps that were external to the body and therefore unlikely to result in the same severity of restriction experience with external thoracic restriction.

3.2. Rating of perceived exertion during load carriage

Rating of perceived exertion was significantly greater when carrying a backpack load despite no change in heart rate and oxygen consumption. In a study by Kirk and Schneider (1992) females reported an increase in their rating of perceived exertion when carrying a load up a gradient despite matching for oxygen cost. Since the exercise stages in our study involved carrying a 25 kg backpack load it is possible that walking on the gradient while loaded caused greater muscular fatigue. Surface electromyography has shown an increase in activation of the rectus abdominus during walking as load weight is increased (Al-Khabbaz et al., 2008). Subjective complaints of pain in the areas of the hip, low back, knee and foot have also been noted after completing a one hour load carriage march (Birrell and Haslam, 2009). It is therefore possible that it is discomfort of specific muscles, breathing distress or other irritation factors that are causing an increase in the rating of perceived exertion during load carriage.

3.3. Rapid, shallow breathing pattern and its implications

The decreased tidal volume and increased breathing frequency seen in the loaded condition may have been adopted in an attempt to reduce the elastic work of breathing. Elastic work of breathing has been shown to be minimized when adopting a rapid, shallow breathing pattern (Luce 1980). This form of breathing has been shown to be negatively correlated with work of breathing when measured at rest in healthy individuals (Dellweg et al., 2008). It is often adopted by obese individuals in order to reduce respiratory muscle work during resting breathing (Chlif et al., 2009). However, an increase in breathing frequency results in an increase in anatomical deadspace which can have an affect on alveolar ventilation.

3.4. Limitations

Walking efficiency is potentially affected by both gradient and load suggesting that alterations in technical walking capability may be affected at the higher exercise intensities where the gradient is steep. However, this could have potentially affected body position as subjects tended to increase forward lean at the higher gradients. Subjects were encouraged to maintain an upright position for the duration of the inspiratory capacity maneuvers to avoid this problem

3.5. Future research directions

Measurements of respiratory pressures, breathing resistance and work of breathing would further the understanding of respiratory mechanics during exercise with a heavy backpack load.

Knowledge of resting pulmonary mechanics with load carriage would aid in the understanding of the translation between resting and exercise lung volumes. While resting lung volumes were measured, the increased metabolic demand of standing with a pack makes these values difficult to interpret. Although not significant and having the potential for error resting EELV in the loaded condition was shown to be the same as seen during exercise while in the unloaded condition EELV is higher at rest. This is similar to what is shown with mildly obese women during treadmill walking at 50-80% of VO_2 max (Babb et al., 1989). These results would suggest that EELV is decreased at rest in the loaded condition and does not decrease further during exercise, while EELV is able to decrease during exercise in the unloaded condition as it is higher at rest. Pulmonary function tests while wearing a pack would allow for further conclusions to be drawn regarding residual volume and expiratory reserve volumes at rest.

Further research regarding the effect of a heavy backpack load during exercise on females is required. Females may be at greater risk for respiratory limitations during exercise due to mechanical constraints. Anatomically women have smaller lung volume (Mead 1980), narrower airways and smaller surface area for diffusion comparatively to height matched men (Schwartz 1988). Adult men have airways that are approximately 17% larger in diameter than their female counterparts (Mead 1980). Even when matched for total lung capacity females are shown to have a tracheal cross sectional area that is 40% smaller than males. This suggests that biological sex has an effect on lung structure (Sheel and Guenette, 2008). These morphological differences increase the susceptibility of females to expiratory flow limitation and a shift in operational lung volumes leading to an increase in work of breathing (Harms and Rosencranz 2008). McClaran et al., (1998) and Guenette et al., (2007) observed a higher presence of EFL (30% in males and 86 and 90% in females) during heavy exercise in females. The occurrence of EFL was shown to occur at lower levels of ventilation than seen in males. Females have been shown to have a higher end expiratory lung volume and end inspiratory lung volume comparatively to males at maximal exercise (Sheel and Guenette, 2008). Hyperinflation results in an increased work of breathing as the respiratory muscles are no longer working at their optimal length requiring greater muscular force to maintain ventilation (McClaran et al., 1998). Total work of breathing is predicted to be greater in women because of the increased dynamic hyperinflation resulting in greater respiratory muscle work as increased resistance from turbulent airflow. The work of breathing in women has been shown to rise at a rate significantly greater than men, approximately doubling at ventilations beyond 90L/min. As EILV approaches 90% of FVC there is an increase in the elastic load placed on the inspiratory muscles (Sheel and Guenette 2008). The above research suggests potential differences in the effect of load carriage on respiratory mechanics during exercise in women. Since a growing number of women are entering physically demanding occupations that involve carrying heavy loads an understanding of the physiological impact may provide further insight into bona fide occupational requirements.

Measurements of end tidal carbon dioxide would aid the understanding of the effect of a rapid, shallow breathing pattern on alveolar ventilation/dead space. An observation of an increase in end tidal CO_2 during exercise would suggest alveolar hypoventilation with load carriage. We found that ventilation tended to be higher in the loaded condition (though not significant) which is consistent with increased dead space however a measurement of alveolar CO_2 as reflected by end-tidal CO_2 would aid our understanding.

It is difficult to separate the restriction created by the amount of load or the tightness of the straps when looking at the backpack model. Since the load weight was absolute in this study it does not allow for generalizability to heavier or lighter pack weights. Further research looking at other loads, other degrees of strapping as well as a comparison with no load and strapping would determine which factor is affecting breathing pattern during exercise.

The form of exercise studied in this thesis is of four to five minutes in duration. Although this was a long enough period of time to reach metabolic steady state it does not provide information regarding effects of load carriage during prolonged exercise. Prolonged load carriage has been shown to have an effect on metabolic efficiency and biomechanics (Epstein et al., 1988). Hussain and Pardy (1985) found evidence of diaphragmatic fatigue during time to exhaustion trials with chest wall restriction suggesting that there is the potential for fatigue to occur earlier. As well, results may be dependent on the slower temporal dynamics that have been observed with chest wall restriction (Coast and Cline, 2004).

It is evident that there are future directions in this area of research. This was the first study to look at the effect of load carriage on breathing pattern and respiratory mechanics during exercise.

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Appendix A - Literature Review

A.1. Load Carriage

Carrying external loads for long periods of time is a requirement of a number of physically demanding occupations. One of the most demanding military loads recorded occurred during the Falklands operation, where up to 68 kg was required for transport (McCaig and Gooderson, 1986). There is physiological evidence that mechanical efficiency begins to fail with heavy load carriage, especially when travelling up inclines at fast walking speeds (Durnin and Passmore, 1967). Shoenfeld et al., (1977), state that for distances greater than 20 km in length, load carriage should not exceed 25 kg or approximately 33% of body mass.

A.2. Effect of velocity of walking on load carriage performance

Speed of walking has an affect on both the metabolic cost of walking and biomechanical efficiency. It has been well established that there is an optimal walking speed which allows for minimal energy expenditure per unit of distance traveled (Abe et al., 2004). When carrying a load this optimal walking speed has been shown to be at a speed of 1.3 m/s with load weight up to 75% of body mass (Bastien et al., 2005). At speeds greater than 1.5 m/s energy expenditure increases disproportionately due to a loss in mechanical efficiency (Abe et al., 2004). The alteration in stride from walking to running occurs at 2.3 m/s when carrying loads. The change from walking to running occurs at a lower speed in shorter individuals because of their shorter stride length (Keren et al., 1981).

Biomechanical alterations occur when walking with a backpack load. LaFiandra et al., (2003) found that pelvic rotation is decreased comparatively to unloaded walking. Decreased hip movement shortens stride length and increases stride frequency in order to maintain a constant walking speed of 0.6 to 1.6 m/s (LaFiandra et al., 2003).

A.3. Effect of incline on load carriage performance

An increase in gradient results in an increase in oxygen cost due to an increase in muscular activation. The net energy costs of walking are increased when walking uphill and decreased when walking downhill (Santee et al., 2001). A model for load carriage on sloped terrain has been developed to account for increased energy cost of walking uphill with a load. This equation assumes that energy cost is equal to the sum of the energy cost of level walking and the energy cost of vertical displacement for the total mass. The vertical displacement of the total mass is dependent on the body mass in addition to the external load multiplied by an efficiency factor for vertical displacement (Santee et al., 2001).

A.4. Effect of duration on load carriage performance

Duration of load carriage has an effect on the metabolic cost of movement. This is due to alterations in efficiency that occur with the onset of fatigue during prolonged load carriage. An increase in oxygen consumption of 10% at slower speeds and 18% at faster speeds has been shown to occur over time when carrying loads of 31.5 to 49.4 on the back (Patton et al., 1991). Prediction equations of the metabolic cost of load carriage are based on short durations (Pandolf et al., 1977). Prolonged load carriage, as determined by a 12 kilometer time trial, has shown that the predicted metabolic cost of load carriage is underestimated by 10-16% (Patton et al., 1991) despite intensities being less than 30% of $V0_2$ max.

Altered metabolic cost over prolonged exercise does not appear to be related to changes in cardio-respiratory function. Load carriage duration of 240 minutes resulted in little to no change in left ventricular systolic function, hemodynamics and cardiovascular responses (Sagiv et al., 1994). Biomechanical research strongly supports an alteration in mechanical efficiency. Prolonged load carriage of 120 minutes was associated with a higher energy cost due to an alteration in the biomechanics of locomotion (Epstein et al., 1988). An increase in knee moment in order to attenuate shock reduction during load carriage has been shown to be reduced towards the end of 120 minutes of treadmill marching. This alteration to mechanics during prolonged load carriage is suggestive of excessive knee extensor fatigue (Queseda et al., 2000).

A.5. Metabolic cost of load carriage

The energy expenditure of walking is dependant on external factors such as; speed, gradient and external load (Haisman et al., 1988). Prediction equations have been developed with these factors as variables in order to aid in the estimation of the metabolic cost of walking and running with and without backpack loads (Epstein et al., 1987, Pandolf et al., 1977, Giovanni and Goldman, 1971).

When carrying a load between 7.5 and 15% of body weight there does not appear to be an increase in metabolic cost compared to unloaded walking (Robertson et al., 1982). This appears to be the critical weight limit for external loads that can be transported without increasing the metabolic cost of the workload when moving body weight alone. Increases in load beyond this critical weight limit results in an increase in oxygen cost. This is shown by increases in measures of rating of perceived exertion and metabolic cost. When matching a lighter and heavier load carriage condition for oxygen cost results in the heavier load placing greater strain on the cardiopulmonary system and increasing the perception of exertion (Beekley et al., 2007). Self pacing of load carriage is altered by decreasing speed of walking when load is increased in order to maintain metabolic cost seen when carrying lighter loads. Despite the alteration in speed to maintain metabolic cost there is an increase in cardiopulmonary strain and rating of perceived exertion with heavy loads (Myles and Saunders, 1979).

A.6. Effect of body size on load carriage performance

Body weight and exercise time have been shown to be moderately correlated when carrying an 18 kg load in young male cadets with heavier individuals having faster completion times (Bilzon et al., 2001). This correlation is most strongly in relation to lean body mass as found by Lyons et al., (2005). Most military fitness protocols are dependant on relative tasks such as push ups, sit ups and two mile runs while load carriage performance is not dependant on these tasks (Vanderburgh, 2008). This suggests that performance in fitness protocols that are relative to body mass are not good predictors of load carriage performance. Vanderburgh and Flanagan (2000) found that the inclusion of a backpack run test eliminated the bias against heavier personnel. Keren at al., 1981, found that more robust individuals were able to complete load carriage at a higher treadmill velocity for a longer period of time than smaller individuals.

In relation to the metabolic demand of heavy load carriage, maximal oxygen consumption in absolute values produces the strongest correlation. Lyons et al., (2005) derived a model which shows that 82% of the variability in load carriage performance comes from gradient and load alone, while 89% comes from the inclusion of both anthropometric and physiological measures. The conclusion is that selection criteria for load carriage occupations should be based on lean muscle mass rather than running speed as currently measured by aerobic fitness tests, making a backpack model a more valid test (Bilzon et al., 2001, Lyons et al., 2005, Keren et al., 1981).

A.7. Chest wall restriction with load carriage

Backpacks use waist and chest straps to keep the load close to the body. This can create restriction of the chest wall. Carrying heavy loads close to the trunk has been shown to mimic the decrement in lung function generally observed with restrictive ventilatory impairment (Ghesquiere et al., 1979, Legg and Mahanty., 1985 and Legg 1988). Load carriage has been shown to decrease forced vital capacity (FVC), forced expiratory volume in one second (FEV_1) but have no effect on the FEV_1/FVC ratio (Legg and Mahanty, 1985). This reduction is slightly lower then what is observed when an equivalent weight is carried in the form of a weighted vest. The weighted vest decreased respiratory function by 12% in FVC, FEV_1 and MVV while the equivalent weight in a military backpack showed decrements of 5, 6 and 8% respectively (Legg and Mahanty, 1985). Tightness of fit of a backpack has an affect on the degree of restriction created by the backpack load. Bygrave et al., (2004) found a greater decrease in measures of FVC, FEV_1 and FEV_1/FVC ratio when a 12 kg pack was fitted tightly comparatively to a 3 cm reduction in tightness of chest straps in a loose fitting comparison.

A.8. Chest wall restriction in occupational settings

Body armor is often worn in occupational settings as part of chemical defense clothing. It generally consists of a sleeveless vest that covers the torso down to the umbilicus and is weighted between 2.9 and 6.2 kg. Body armor is associated with a mild restrictive type of reduction in pulmonary function with a reduction in FVC and FEV_1 of up to 2.9%. A 4.9% reduction in peak expiratory flow was associated with the heaviest form of body armor. Maximal voluntary ventilation in 15 seconds was decreased to the greatest extent in the lightest version of body armor leaving the authors to suggest that tightness of fit may by the cause of respiratory restriction rather than the absolute weight of the vest (Legg, 1988). Legg and Mahanty (1985) found that a vest weighted to 35% of subjects’ body weight reduced MVV by 12% whereas a vest weighted at 2.9 kg reduced MVV by 10.4%.

Chemical defense clothing is composed of multiple layers of protective clothing, body armor and load bearing equipment. The chemical defense uniform results in a greater external constraint on the chest wall when compared to a physical training uniform. At rest the chemical defense uniform significantly decreases maximal voluntary ventilation and lung volumes with an increase in total respiratory system elastance. During sustained exercise, minute ventilation was comparable between the two conditions, however there was a smaller tidal volume and greater breathing frequency observed in the chemical defense clothing. Alterations to breathing pattern were consistent with the increase in respiratory system elastance. Perceptions of anxiety were related to not getting enough air, not breathing the way one usually does and not being relaxed (Muza et al., 1996).

A.9. Introduction to lung volumes

At the onset of exercise there is an increase in ventilation that is resolved by an increase in breathing frequency and tidal volume. In order to increase tidal volume during exercise there is an increase in end inspiratory lung volumes (EILV) and a decrease in end expiratory lung volumes (EELV) in young and healthy individuals. Reducing EELV during exercise allows for the greatest mechanical advantage to the inspiratory muscles by reducing the resting length of the diaphragm and minimizing the inspiratory work of breathing (Jenkins and Moxham, 1981). Flow volume and pressure volume responses during tidal breathing at maximal exercise are below the maximal capacity for pressure generation of the inspiratory muscles in young, healthy individuals (Johnson et al., 1992).

End expiratory lung volume has been shown to increase during exercise in specific populations; restrictive diseases (Miller, 2002), seniors and elderly (Delorey and Babb, 1999), highly trained endurance athletes (Johnson et al., 1992) and moderate obesity (Delorey, 2005). Increases in EELV in the above mentioned populations allow for attenuation of flow limitation by shifting the tidal breath down on the maximal flow volume loop. The alteration in positioning of EELV has a negative consequence for the respiratory muscles, specifically the inspiratory muscles, as inspiratory muscle work is increased when the diaphragm is in a lengthened state. The lengthened position of the diaphragm is at a less optimal portion of the compliance curve requiring a greater increase in pressure for force generation.

The response of EELV during exercise can allow for strong conclusions regarding expiratory flow limitation, respiratory muscle work, shortness of breath and tidal expiratory flow. The increase or decrease in EELV that is observed with exercise is impacted by the resting EELV as it determines the end positioning of the EELV with exercise. A decrease in EELV at rest alters the inherent positioning of the diaphragm that normally occurs with exercise.

A.10. Compliance curves with chest wall restriction

The pattern of response of the lung is determined by the physical impedance of the chest wall system. Inhalation requires the chest wall to expand so the lungs can increase in volume as they are filling with air. When restriction is placed on the chest wall it reduces the ability of the chest wall to expand and concurrently reduces the lung allowance for volume (Bradley and Anthonisen, 1980). With restriction of the chest wall, the pressure-volume curve of the total respiratory system is displaced to higher pressure levels, with little change in the shape of the curves (Sharp et al., 1964). Total respiratory system compliance is decreased at the level of FRC to 1.5 L above FRC (the lung volumes of tidal breathing), while the upper portion of the lung volume curve is decreased only slightly and inconsistently (Sharp et al., 1964). Lung pressure-volume curves are less steep and shifted to the right comparatively to controls reflecting an increase in elastic recoil pressure and a decrease in pulmonary compliance (Klineberg et al., 1981). When the breathing pattern imposed by chest wall restriction is mimicked through rapid and shallow breathing at low lung volumes, lung compliance curves are of the same shape and slope but compliance is reduced (Klineberg et al., 1981).

It is evident that restricting the thoracic cavity decreases compliance of the total respiratory system with emphasis on the chest wall while having only a residual effect on lung compliance. At larger lung volumes there is an increased recoil pressure with chest wall restriction creating an additive effect by amplifying the reduction in compliance normally seen at these lung volumes. As a result, breathing at larger lung volumes is avoided due to the large work of breathing at this low compliance portion of the respiratory curve. In response, breathing at lower lung volumes, becomes more effective in terms of absolute work required from the respiratory system.

A.11. Chest Wall Restriction and Resting Pulmonary Function

Diseases resulting in reduced compliance of the lungs and/or chest wall are considered to be restrictive in nature. Restrictive disorders are characterized by high ratios of tidal volume to inspiratory capacity and relative tachypnea. Chest wall restriction can alter respiratory mechanics at a given exercise intensity with a resultant increase in dyspnea (O’Donnell et al., 2000). Research that involves restriction of the chest wall through restrictive disease, restriction mimicking devices or occupational situations, has revealed significant reductions in measures of resting lung volumes, pulmonary function and exercise capacity. Inspiratory capacity is produced mostly by rib cage displacement (Konno and Mead., 1967), therefore vital capacity is reduced with thoracic restriction. Pulmonary function tests reveal that total lung capacity (TLC), functional residual capacity (FRC) and inspiratory capacity (IC) are reduced with external thoracic restriction at rest (O'Donnell et al., 2000, Miller et al., 2002) with some restriction showing a reduction in residual volume at rest (Harty et al., 1999, Miller et al., 2002). Forced spirometry in restrictive disease or with external restriction has been associated with depressed values of FVC, FEV_1 and MVV with no change in the FEV_1/FVC ratio (Harty et al., 1999). Flow rates are not altered within the effort independent range of the flow volume loop. This preservation of tidal expiratory flow rates at lower lung volumes is due to improved airway conductance (O'Donnell et al., 2000).

A.12. Chest Wall Restriction and Exercise

Restrictive chest wall disease has been mimicked in healthy subjects with the use of either external elastic loads or external thoracic and/or abdominal restriction. These experimental methods have been shown to have different physiological effects as elastic loading may not induce a large reduction in lung volumes (Harty et al., 1999). Chest wall restriction has been shown to lower peak exercise capacity by 15-30% in young, healthy subjects (Hussain and Pardy, 1985, O'Donnell et al., 2000). Decrements in peak work capacity have primarily been attributed to an inefficient ventilatory pattern, an increased work of breathing and a heighted sensation of dyspnea (O'Connor et al., 2000, Miller et al., 2002 and O'Donnell et al., 2000).

A.13. Chest Wall Restriction and Exercise Capacity

Maximal exercise data with varying degrees of chest wall restriction show a reduction in time to exhaustion, oxygen uptake and tidal volume (Hussain et al., 1985, O'Donnell et al., 2000 and O'Connor et al., 2000). Respiratory rate has been shown to be maintained (Coast and Cline, 2004) or increased (O'Connor et al., 2000) in conditions of chest wall restriction at peak exercise. Chest wall restriction reduces exercise capacity in the cases where ventilation is no longer able to increase to meet metabolic demand. It is likely that once maximal breathing rate is reached exercise capacity is reduced as ventilation can only be maintained with an increase in volume which is cumbersome with reduced compliance of the chest wall. Maximal ventilation has been shown to be lower with chest wall restriction (O'Connor et al., 2000) in some scenarios and unaffected by chest wall restriction in others (O' Donnell et al., 2000). In the latter case this increased ventilation correlated with the increased oxygen consumption and carbon dioxide production observed with chest wall restriction. Ventilation is proportional to inspiratory muscle shortening and the mechanical properties of the chest wall and lungs with restriction (Harty et al., 1999).

A.14.Breathing pattern and gas exchange with chest wall restriction during exercise

The presence of mechanical constraints during variable exercise intensities has an affect on the mechanics of ventilation as well as the regulation of ventilation (Delorey and Babb, 1999). Altered ventilatory patterns at submaximal exercise intensities were observed with chest wall restriction. Predominantly, there is a consistent decrease in tidal volume and an increase in breathing frequency with reductions in both inspiratory and expiratory time (Harty et al., 1999, O'Connor et al., 2000 and O'Donnell et al., 2000, Hussain and Pardy, 1985, DiMarco et al., 1981, Miller et al., 2002). Thus tidal volume reserve is greatly reduced and breathing frequency is increased in an effort to maintain ventilation (Delorey and Babb, 2005). Breathing frequency is thought to be chosen for maintaining ventilation when EILV rises to near 85% of TLC. This occurs in order to prevent lung volumes from encroaching on the stiffer portion of the lung and chest wall pressure-volumes curves (McClaran et al., 1999).

Compensation for a decreased tidal volume by increasing respiratory frequency determines ventilation. Minute ventilation has been shown to increase progressively over a constant workload exercise test with proportionately greater increases in oxygen consumption and carbon dioxide production (O'Donnell et al., 2000, O'Connor et al., 2000 and Harty et al., 1999). Hyperventilation is associated with an increase in the steady state response of the system during thoracic restriction and is correlated with a drop in PCO_2 values suggestive of alveolar hyperventilation. Klineberg et al., (1981) found no significant change in the ratio of dead space to tidal volume when comparing seated chest wall restriction to control suggesting no evidence of alveolar hyperventilation when this condition is studied at rest. Comparatively in exercise conditions alveolar hyperventilation is supported by the observed decrease in PCO_2 during exercise in the restricted condition (Harty et al., 1999, O'Connor et al., 2000). An increase in dead space accelerates ventilation unless significant flow limitation is reached attenuating the hyperventilatory response (McClaran et al., 1999). Increased sensation of dyspnea was observed under conditions which elicited a hyperventilatory response which is in line with sensory consequences of an inappropriate hyperventilation (Chonan et al., 1990). Delorey and Babb (1999), found that progressively greater ventilations observed at submaximal exercise intensities in elderly were the result of an increase in dead space rather than a hyperventilatory response. This was shown in elevated ratios of VE/VO_2 and VE/VCO_2 with no change in PET_{CO2} to a given workload.

In contradiction to the above observations of tachypnea with chest wall restriction and a resultant increase in alveolar ventilation, Hussain et al., (1985), found that ventilation was similar across all conditions at the same workload. This suggests that subjects were unable to further increase ventilation as they were already at maximal ventilation and therefore could only continue to increase breathing frequency. The opposing findings are potentially due to discrepancies in exercise intensity. The higher exercise intensity used in this study showed evidence of diaphragmatic muscle fatigue reducing ones' ability to maintain ventilation.

External thoracic restriction decreases arterial oxygen saturation during submaximal exercise reaching statistical significance but not clinical significance (a level at which arterial oxygen desaturation has an effect on gas exchange) (Harty et al., 1999). However, when 600 mL of dead space was added to the breathing circuit with chest wall restriction there was a clinically significant drop in arterial oxygen saturation. These observed gas exchange abnormalities were greater with added dead space toward the end of progressive exercise (O'Donnell et al., 2000). This is partially due to alveolar hypoventilation which would be expected with mechanical restriction and tachypnea. Other possibilities for arterial oxygen desaturation are; ventilation-perfusion inequalities which may be due to atelectasis from breathing at low lung volumes and a reduction in residual volume in restricted conditions, as well as possible right-to-left shunting (Harty et al., 1999, O'Donnell et al., 2000). Low ventilation to perfusion ratios in seated chest wall restriction show no evidence of shunting as P_{aO2} values are normal. Atelectasis with chest wall restriction has been debated in the literature with Klineberg et al., 1981 finding no evidence of airway closure with subsequent atelectasis whereas Caro et al., 1960 found evidence of trapped gas in the airways with removal of chest wall restriction.

It is evident that chest wall restriction alters breathing pattern. When respiratory patterns are rapid and shallow in nature dead space is increased as shown by a decrease in PCO_2 or $PETCO_2$. The result is alveolar hyperventilation and an increase in minute ventilation with an expected decrease in arterial oxygen saturation if dead space is significant. Inefficiencies in gas exchange become more pronounced during exercise as metabolic demands are increased.

A.15. Respiratory Discomfort with Chest Wall Restriction

Chest strapping does not replicate the intrinsic mechanical loads of restrictive disorders however it does reproduce some of the mechanical effects of the disease at rest and during exercise (reduced inspiratory capacity, increased tidal volume as a percentage of inspiratory capacity, relative tachypnea and an increased esophageal pressure for a given tidal volume). Chest wall restriction has been shown to impose the same severe exertional dyspnea that is often seen in restrictive disease (O'Donnell et al., 2000, Harty et al., 1999). Respiratory discomfort is greater than expected from exercise hyperpnea alone suggesting that chest wall restriction is enhancing respiratory discomfort (Harty et al., 1999). Respiratory discomfort was equivalently high at the same workload in both constant- workload exercise as well as incremental exercise despite there being no change in ventilation in the latter (O'Connor et al., 2000). The source of dyspnea at rest may reflect an awareness of increased impedance to thoracic expansion imposed by the restrictive device which would affect lung and chest wall afferents (O'Donnell et al., 2000). Possible causes of enhanced respiratory discomfort are regional differences in ventilation- perfusion (however hypoxemia would result), increased respiratory pressures, decreased airway resistance, diaphragmatic fatigue, changes in alveolar compliance and alterations in lung volumes (Harty et al., 1999). Dyspnea correlated with the ratio of esophageal pressure to tidal volume at any given ventilation with chest wall restriction suggests a role of mechanical factors in breathlessness. An inability to expand the thorax appropriately may be the link behind breathlessness descriptors such as “unsatisfied inspiration” and “shallow breathing”. These authors suggest that limitation to chest wall expansion in the setting of increased ventilatory drive is the best correlation of exertional dyspnea intensity (O’Donnell et al., 2000). Mild hypoxemia is unlikely to be a trigger of exertional dyspnea as there was no correlation between arterial oxygen desaturation and severity of dyspnea suggesting that ventilation-perfusion inequality is not the cause of respiratory discomfort (O’Donnell et al., 2000) In addition, administration of supplemental oxygen does not decrease the severity of dyspnea (Harty et al., 1999) and added dead space does not significantly increase the severity of dyspnea (O’Donnell et al., 2000).

Subjective complaints of respiratory discomfort or dyspnea can relay a great deal of information about respiratory limitations. The sense of an increase in respiratory effort is the conscious awareness of an increase in voluntary activation of the respiratory muscles. This sense of effort is dependant on the ratio of the pressure generation by the respiratory muscles to the maximal pressure generating capacity of the muscles (Manning and Schwartzstein, 1995). It can be denoted that an increase in respiratory discomfort is due to an increase in work of breathing which can allude to mechanical limitations.

A.16. Respiratory Mechanics with Chest Wall Restriction

Flow limitation imposed on the tidal breath is an important determinant of EELV, tidal volume, respiratory motor output and ventilation during heavy exercise (McClaran et al., 1999). With chest wall restriction there is a reduction in inspiratory capacity and inspiratory reserve volume at rest and during exercise. End expiratory lung volume is lower than control at rest due to encroachment on the inspiratory reserve. There is no significant dynamic hyperinflation during exercise, but EELV is progressively increased with exercise (O'Donnell et al., 2000). Tidal flow rates come close, but do not reach maximal available expiratory flow rates at the highest exercise intensity achieved due to an upward shift in EELV (Miller et al., 2002. The observed lung volumes are also observed with elderly and senior populations as they have a reduction in compliance of the chest wall and lungs due to a reduction in lung elastic recoil as well as stiffening of the chest wall. When these populations are studied during exercise there is an increase in EELV and EILV which encroaches on TLC (Delorey and Babb, 1999).

A.17.Work of Breathing during Exercise with Chest Wall Restriction

Selective restriction of either rib cage or abdominal movement results in a compensatory increase in the volume of the tidal breath from the portion of the chest that is not restricted (DiMarco et al., 1981). The mechanical consequence of chest wall restriction is a greater inspiratory effort for a reduced tidal volume expansion compared to control (O'Donnell et al., 2000, DiMarco et al., 1981). A decrease in elastic work was noted with chest wall restriction which was thought to allow for an increase in flow resistive work with a slight elevation in total work performed on the lung at the highest exercise intensity (Miller et al., 2002).

Respiratory effort has been shown to be elevated with chest wall restriction as observed by an increase in tidal esophageal pressure and a decrease in maximal inspiratory pressure. It is suggested that the adoption of a rapid, shallow breathing pattern as seen in chest wall restriction attenuates increases in tidal pressure swings making it an effective compensatory strategy for elastic loading (O'Donnell et al., 2000). The esophageal pressure to tidal volume ratio was similar throughout exercise suggesting a strong coupling between thoracic displacement and increased inspiratory effort (O'Donnell et al., 2000).

Restriction of the chest wall alters stimulus to the inspiratory muscles due to reduced chest wall compliance and lowered lung volumes during exercise. When the rib cage is forcibly restricted the diaphragm is flattened during inspiration altering the diaphragmatic shortening and reducing the ability of the diaphragm to generate force for a given electrical stimulation. (Hussain and Pardy, 1985). Significant increases in the diaphragmatic pressure time integral with chest wall restriction indicates an increase in diaphragmatic work (Miller et al., 2002). Measures of diaphragmatic muscle activation is increased for a given transdiaphragmatic pressure during exercise. With progressively increasing ventilation there is an increase in the percentage of the tidal breath that is resulting from the rib cage tidal volume. Therefore, with chest wall restriction there is an increase in phrenic efferent activity in an attempt to displace the diaphragm under restriction (DiMarco., 1981) while there is no change in the transdiaphragmatic pressure (Hussain et al., 1985). Impaired diaphragmatic contractility is presumably due to a shorter operating length (Hussain et al., 1985).

Pressure across the diaphragm decreases post exercise suggesting diaphragmatic fatigue with chest wall restriction (Hussain and Pardy., 1985). During exercise the intercostal accessory muscles aid in inspiration in order to reduce the work of the diaphragm. With chest wall restriction the interference with chest wall movement neutralizes the ability of the rib cage muscles to aid in inspiratory work. This results in a greater potential for diaphragmatic fatigue as the diaphragm has to perform all inspiratory work (Hussain and Pardy, 1985). The abdominal muscles produce strong muscular recruitment as shown by greater expiratory abdominal pressure swing with chest wall restriction. This results in storage of elastic energy in the abdominal muscles allowing for inspiratory work (Hussain et al., 1985).

A.18. Mass loading of the chest wall

Obesity is a known cause of respiratory restriction and low lung volumes (Behazin et al., 2010). The decrease in pulmonary function is due primarily to the affect of an increase in weight on the chest wall, a condition known as mass loading. It has been shown that chest wall fat in general has an affect on lung volume without regard for specific fat deposits. Chest wall adiposity is comprised of fat around the rib cage (ribs and sternum), diaphragm and abdominal contents displaced by fat (Babb et al., 2008).

Obesity has been associated with a decrease in the elastic properties of the chest wall due to mass loading. Total pressure-volume curves in obese are flatter comparatively to normal individuals resulting in a downward shift of the curve. This is largely attributed to a decrease in the pressure-volume curve of the chest wall as the compliance of the lungs is virtually the same as non obese. Total mechanical work is increased in obese subjects with a slight increase in mechanical work done on the lung and a large increase in mechanical work required for thoracic movement (Naimark and Cherniack, 1960). Other evidence suggests that mass loading has an equivalent reduction in compliance of the chest wall and lung (Pelosi et al., 1996). Further, chest wall compliance has been shown to be unaffected by obesity in other studies (Suratt et al., 1984) with the reduction in compliance occurring solely at the level of the lung. Discrepancy in these methodologies may be due to the elastic loading of the chest wall comparatively to true mass loading (Behazin et al., 2009). This reduction in compliance results in an increased work of breathing in order to maintain adequate ventilation in the face of increased metabolic demands such as during exercise (Sharp et al., 1980).

A.19. Mass loading and resting pulmonary function

The effect of obesity on resting lung function is related to the amount of adiposity that surrounds the thorax. This is most prominent when the weight to height ratio reaches or exceeds a value of 1.0 indicative of extreme obesity (Ray et al., 1983). Obese subjects have a lower TLC and VC with FRC often reduced towards RV (Behazin et al., 2010). Dynamic spirometry in obese men shows a decrease in FEV_1 inversely related to BMI. Decreases in FEV_1 are generally in proportion to the observed decreases in FVC so that there is no change in the FEV_1/FVC ratio (Zerah et al., 1993). At rest obese individuals, regardless of the severity of obesity, have been observed to have a reduction in functional residual capacity or end expiratory lung volume (Ray et al., 1983), a widened alveolar to arterial oxygen difference in relation to a decreased PaO_2 (Zavorsky and Hoffman 2008, Jenkins and Moxham, 1991) as well as an increase in the diffusing capacity for carbon monoxide (D_{LCO}) (Zavorsky et al., 2008). Obese individuals have been shown to have high pleural pressures surrounding the lung at relaxed volumes which can result in tidal breathing occurring from a low EELV where the lungs are less compliant and the airways are more prone to closure (Behazin et al., 2009). EELV therefore starts at a lower lung volume during exercise leaving little reserve for increasing tidal volume with an increase in exercise intensity (Ray et al., 1983). This can yield mechanical ventilatory constraints and potentially initiate flow limitation during exercise. Peak work rate has been shown to be diminished with mass loading of the chest wall (Wang and Cerny, 2004).

A.20. Effect of mass loading on breathing pattern and gas exchange

Mechanical limitations to tidal breathing result in a predisposition to an increased ventilatory drive (Burki, 1983). Ventilatory response below threshold is significantly greater in obese comparatively to controls due to an increased metabolic demand of carrying excess body weight (Babb, 2002). With mass loading of the chest wall breathing patterns are altered under conditions of both rest and exercise. Breathing related constraints have been correlated with breathing at lower lung volumes suggesting that alterations to breathing pattern are partially due to a volume related constraint on breathing (Babb et al., 2002). When measured at rest obese subjects have smaller tidal volumes and a greater frequency of breathing comparatively to lean individuals (Chlif et al., 2009). This breathing pattern is thought to preserve the same inspiratory flow rate while minimizing the work of breathing by reducing the increase in pressure against elastic forces and avoiding diaphragmatic fatigue (Chlif et al., 2009). Reductions in maximal inspiratory pressure are observed in obesity and are thought to be due to overstretching of the diaphragm forcing it to operate on a less optimal position of the length- tension curve (Chlif et al., 2009). Reductions in tidal volume are thought to occur in an attempt to reduce inspiratory pressure but may also reflect mechanical limitation. The increased breathing frequency observed in the obese is associated with shorter inspiratory and expiratory times with expiratory times being of the greatest significance. This results in an alteration of the duty cycle as a greater portion of total breath time is spent on inspiration (Chlif et al., 2009).

The adoption of a rapid, shallow breathing pattern has been observed in morbid obesity as it has been thought to be associated with a decreased oxygen cost of breathing at any given ventilation (Luce, 1980) which in effect minimizes the sensation of dyspnea commonly associated with morbid obesity (Sahebjami, 1998). However, as ventilation is increased with an acceleration of breathing frequency there is an increase in dead space making this form of breathing less favorable for gas exchange (Macklem, 1985). During exercise gas exchange improves markedly with A-aDO2 difference decreasing and PaO_2 increasing but morbidly obese individuals showed poor compensatory hyperventilation during strenuous exercise (Zavorsky and Hoffman, 2008). The increased pulmonary diffusion per unit increase in alveolar volume in morbidly obese is possibly due to a lower rise in alveolar volume per unit increase in oxygen consumption during exercise (Zavorsky et al., 2008).

While obesity studies have shown an alteration to alveolar ventilation, studies of mass loading have shown maintenance of end tidal CO_2. This suggests an adequate compensatory mechanism at lower exercise intensities to maintain homeostasis. However, at peak exercise chest loading shows a relative hyperventilation potentially due to earlier termination of the breath (Wang and Cerny, 2004).

End expiratory lung volume is determined by both respiratory mechanics and respiratory muscle recruitment during exercise and is influenced by airflow limitation during exercise (Babb 1999). EELV is therefore an important determinant of the normal ventilatory response to exercise and is a useful measure for depicting alterations in respiratory mechanics that occur in conjunction with airflow limitation. The EELV observed during exercise can have an affect on airflow limitation, prevalence of dyspnea, respiratory muscle function and work of breathing (Babb, 1999).

EELV is markedly reduced in obesity at rest and as a result EELV does not drop farther during exercise in contrast to non obese individuals. EELV has been shown to be significantly lower in obese males during exercise at ventilatory threshold while EELV increases back to resting values at peak exercise (Delorey et al., 2005). An inability to decrease EELV with exercise increases inspiratory muscle work as work of breathing is not partitioned between the inspiratory and expiratory muscles. In response there is an increase in dependence on inspiratory muscles in tidal breathing. The presence of expiratory flow limitation increases with exercise in the obese as breathing at a lower EELV diminishes reserve and forces EELV upwards at higher ventilatory requirements (Babb, 1999). The greater ventilation at ventilatory threshold in obese men results in a greater total mechanical work of breathing against the lung. Decreases in EELV in obese males are reflected by the higher gastric and transpulmonary pressures. Increases in pressure are potentially due to abdominal adiposity increasing expiratory abdominal forces and pushing the diaphragm upwards. Decreased EELV in obese men and women has been shown to be the result of the cumulative increase in chest wall fat (inclusive of abdominal fat which affects the diaphragm) rather than a specific regional fat deposit (Babb et al., 1998). Pressure increases are most likely amplified by accessory muscle recruitment during expiration. Increases in transpulmonary pressure at end expiration in obese at rest through to peak exercise represent an increased expiratory resistance due to breathing at lower lung volumes.

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Appendix B

Rating of Perceived Exertion

6

7. very,very light

8

9. very light

10

11. fairly light

12

13. somewhat hard

14

15. hard

16

17. very hard

18

19. very, very hard

20

Appendix C

C.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

C.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	

C.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	

C.4. Shoulder strap adjustments

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

C.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

C.6. Fine tuning: load stabilizer

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

C.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

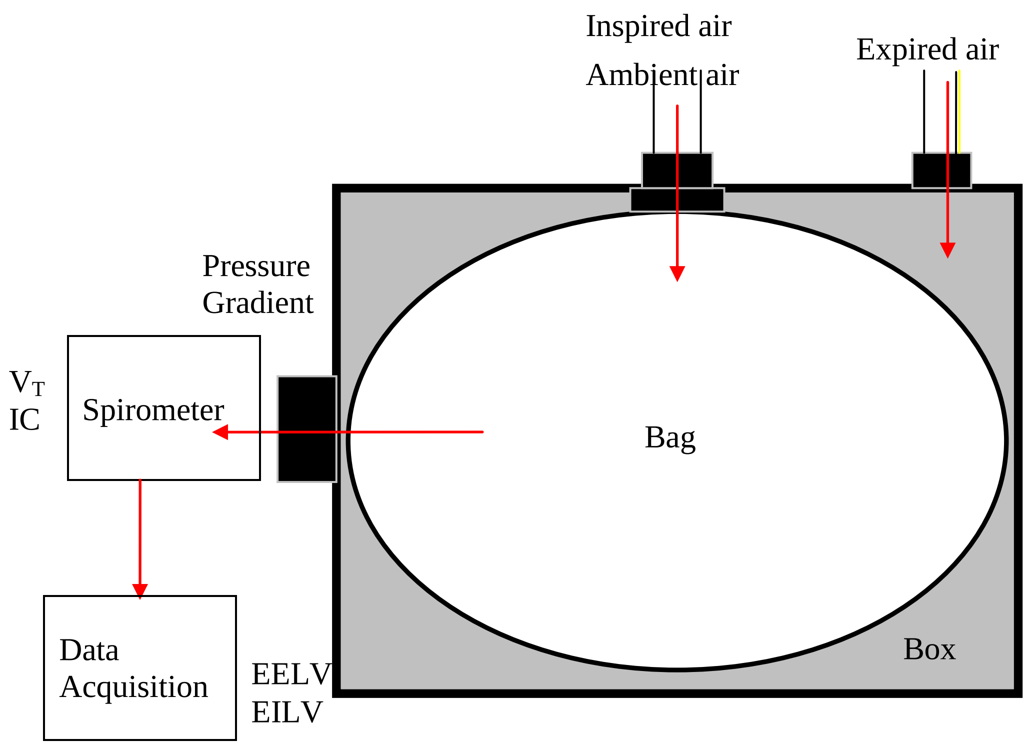
Materials

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 D – Bag-in-box system

A bag-in-box system (BBS) monitored volume where a change in volume is measured by a mechanical spirometer (SensorMedics Corporation, Yorba Linda, CA). The BBS is a convenient system for measurement of respiratory response as inspired gas concentrations can be controlled and there is continuous measurement of volume over an extended period of time with minimum apparatus dead space (Bates et al., 1984). In order to ascertain that this system was appropriately calibrated a 3 L syringe was used to calibrate the spirometer and this volume was matched with a known voltage. Sampling rates at the spirometer were collected at 10 Hz. Prior to the exercise test each subject completed forced vital capacity maneuvers with the largest of three maneuvers used for analysis. Maneuvers were completed by having the subject inspire and expire through the BBS. This movement of airflow allows for the mechanical response of the spirometer which is recorded by the PowerLab system for determination of volumes through the differentiation of the flow signal. Changes in EELV are estimated from the subtraction of inspiratory capacity (IC) taken at rest and during each exercise stage from forced vital capacity. EILV is estimated as the addition of tidal volume to the EELV. Previous studies have shown that subjects have no trouble performing the IC maneuver and that this method of determining EELV is accurate if a maximal inspiratory effort is given (Babb et al., 1999). Changes in EELV and EILV were expressed as a percentage of the forced vital capacity.

Diagram of bag-in-box system



Appendix E - Detailed Methods

The design of this study was a randomized, within-subject control. The experimental condition involved load carriage hereafter termed loaded, and the control condition involved unloaded exercise hereafter termed unloaded. Subjects attended the laboratory on three separate occasions designated as day one, day two and day three.

E.1. Baseline Spirometry

Each subject completed baseline pulmonary function testing in two conditions: first, unloaded; and second loaded (see below). Spirometry was performed using a portable spirometer (SpiroLab III, Medical International Research, Roma, Italy). Pulmonary function testing was performed according to the guidelines of the American Thoracic Society (2005) with the best of three maneuvers used for analysis. Spirometry was done while standing with minimal forward lean to ensure reliability of values. Each subject was instructed to maintain an upright posture during maneuvers.

E.2. Backpack fitting

Each subject was fitted with a backpack. Packs were filled to a standardized 25 kg weight and volume. Torso height was measured from the C7 vertebrae to the top of the iliac crest (See C.2.). Backpack size was chosen based on the torso length (See C.1.). Each subject was instructed to tighten the straps in the following order; hip belt (See C.3.), shoulder straps (See C.4.), weight bearing straps (See C.5. and C.6.) and chest strap. Straps were tightened so that no movement occurred around the torso, shoulder or low back region. Once a proper pack fit was obtained spirometry was repeated to obtain maximal flow volume loops.

E.3. Graded Exercise Testing

The results of a coin toss randomly assigned each subject to either the loaded or unloaded condition. During the first visit subjects were familiarized with the research techniques and underwent graded exercise testing. The nose was occluded and all expired gases were collected and passed through a moisture trap and drying filter located proximal to the pneumotach. The graded exercise test began at 91.2 m/min and 0% grade. At 2 minute intervals the grade was increase by 2% until the subject reached peak effort. Gas exchange variables (VO_2, carbon dioxide production (CO_2), respiratory exchange ratio (RER), tidal volume (V_T), breathing frequency (Fb) and ventilation (V_E)) were calculated and averaged over 20 second time intervals (ParvoMedics True One 2400). Heart rate was recorded every minute using a telemetric heart rate monitor (FS1 receiver and T-31 transmitter, Polar Electro Canada Inc., Lachine, QC, Canada). On the second day of testing this procedure was repeated in the condition not previously completed.

E.4. Screening for exercise induced bronchoconstriction

Each subject completed pulmonary function testing in the unloaded condition at 5, 10, 15 and 20 minutes post exercise to test for exercise induced bronchoconstriction. Spirometry was performed using a calibrated spirometer (SpiroLab III, Medical International Research, Roma, Italy). Spirometry was done while standing with minimal forward lean. Exercise induced bronchoconstriction (EIB) was assessed as positive if FEV_1 is diminished by more than 10% in the best attempt made by the subject. If EIB is detected based on the first FVC maneuver up to three maneuvers were performed to ensure constriction is not motivation dependant. Subject exclusion occurred if EIB was detected; two participants were excluded based on this criterion.

E.5. Inspiratory capacity maneuvers

Each subject was familiarized with the volume measurement techniques to be completed on day three of testing. The subject was instructed on the position of their normal end expiration and how to do a quick maximal inspiration. Instructions were given as follows. “At the end of the next breath take a big breath in, in, in and breathe normally”. Subjects completed two successful maneuvers before moving on.

E.6. Graded exercise protocol

Body mass was recorded on each subject. Each subject was randomly assigned to either the unloaded or loaded condition. Each subject completed baseline spirometry by breathing through a low resistance breathing valve with the nose occluded. The volume of air was assessed by a spirometer that sent a voltage signal to the PowerLab. A bag in box system (see Appendix D) was used to complete a minimum of three acceptable forced vital capacity maneuvers in a standing position with minimal forward lean.

The subject began to exercise at the workload assigned based on 55, 65, 75 and 85% of the peak oxygen consumption achieved in the maximal exercise test in the appropriate condition. Graded workloads were determined in advance through linear regression from oxygen consumption and workload. Each subject breathed through the metabolic cart until steady state was achieved or for a maximum of three minutes. Each subject then breathed through the bag and box system. The subject was instructed to breathe normally until six tidal breaths were obtained in sequence of similar volume as determine by the investigator. The subject was then instructed to take a maximal breathe in at the end of the next normal expiration. This sequence of breathing was repeated to ensure a reliable maneuver was obtained. Intensity was increased to the subsequent workload where this timing of measurements was repeated for the following three stages of exercise. At the completion of the exercise bouts the subject began a five minute cool down.

The subject began a 60 minute recovery at the completion of the cool down. Body mass was recorded and the subject was given a bottle of water to consume during this recovery. At the end of the one hour recovery body mass and heart rate were recorded for the subject after a five minute seated rest in order to ensure that the subject has returned to a resting physiological state. Subjects completed the same exercise testing procedure as outlined in the alternate condition.

E.7. Subjective assessment of perceived exertion

Each subject was asked to quantify their rating of perceived exertion by giving a signal when the tester stated the numerical intensity which they believed they were working. This occurred at each stage of the graded exercise test as well as within the first three minutes of each incremental workload using the Borg scale of perceived exertion (1990) (See Appendix B). This scale runs from 6 to 20 with 6 representing very, very light intensity and 20 representing very, very hard or maximal intensity exercise. After the test is completed the subjects are debriefed on their rating of perceived exertion at termination of the exercise trial to determine a maximal effort.

E.8. References

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Appendix F - Additional Results

Table F-1. Individual spirometric values in unloaded and loaded conditions

	FVC		FEV_1		FEV_1/FVC	
Subject No.	UNLOAD	LOAD	UNLOAD	LOAD	UNLOAD	LOAD
1	6.90	6.93	5.07	5.01	0.73	0.72
2	5.78	5.74	4.50	4.41	0.78	0.77
3	5.80	5.53	4.39	4.19	0.76	0.76
4	5.39	5.49	4.32	4.42	0.80	0.81
5	5.99	5.88	4.46	4.27	0.74	0.73
6	6.04	5.75	4.77	4.59	0.79	0.80
7	6.18	5.86	5.13	4.84	0.83	0.83
8	6.00	5.84	4.47	4.87	0.75	0.83
9	5.19	5.03	4.43	4.42	0.85	0.88
10	6.31	5.96	5.05	4.75	0.80	0.80
11	5.02	4.68	3.94	3.31	0.78	0.71
12	5.97	5.39	4.99	4.55	0.84	0.84
13	6.31	6.19	4.78	4.76	0.76	0.77
14	5.49	5.23	4.63	4.41	0.84	0.84
15	4.86	4.74	4.06	3.91	0.84	0.82
Mean	5.82	5.62 *	4.60	4.45 *	0.79	0.79
±SD	0.55	0.57	0.36	0.43	0.04	0.05

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 $P<0.05$. n=15.

Table F-2. Dynamic lung volume measurements during exercise in loaded and unloaded conditions

	55%		65%		75%		85%	
	UNLOAD	LOAD	UNLOAD	LOAD	UNLOAD	LOAD	UNLOAD	LOAD
IC	3.77 (0.47)	3.64 (0.45)	3.70 (0.50)	3.69 (0.49)	3.87 (0.46)	3.81 (0.50)	3.84 (0.42)	3.88 (0.48)
EELV	1.61 (0.37)	1.64 (0.33)	1.67 (0.28)	1.60 (0.35)	1.50 (0.3)	1.48 (0.38)	1.53 (0.32)	1.41 (0.40)
EILV	3.83 (0.60)	3.61* (0.61)	4.15 (0.52)	3.78* (0.56)	4.22 (0.47)	3.97* (0.54)	4.49 (0.53)	4.19* (0.60)
EELV (% FVC)	30 (6)	31 (4)	31 (5)	30 (5)	28 (5)	28 (6)	28 (5)	27 (6)
EILV (% FVC)	70 (8)	68* (8)	78 (7)	72* (7)	79 (5)	75* (5)	84 (6)	79* (6)

Values are means ± SD. IC, inspiratory capacity (BTPS); EELV, end-expiratory lung volume (BTPS); EILV, end-inspiratory lung volume (BTPS); EELV(% FVC), end-expiratory lung volumes as a percentage of forced vital capacity; EELV (% FVC), end-inspiratory lung volume as a percentage of forced vital capacity. $P<0.05$*. n=15.

Table F-3. Maximal exercise data in loaded and unloaded conditions

	VO_{2peak}	
	UNLOAD	LOAD
VO_2 ($L \cdot min^{-1}$)	4.1 (0.4)	3.9* (0.4)
Bf ($breaths \cdot min^{-1}$)	52 (10)	56 (9)
V_T (L)	2.9 (5.2)	2.6 (4.2)
V_E ($L \cdot min^{-1}$)	146.4 (16.0)	142.5 (14.7)

Values are means ± SD. VO_2, volume of oxygen consumed; VCO_2, volume of carbon dioxide expired; Fb, breathing frequency; V_T, tidal volume; V_E ,ventilation. $P<0.05$*. n=15.

Table F-4. Body size analysis at submaximal exercise

	Pearson correlation		
	Breathing Frequency	Tidal Volume	Ventilation
Body Mass	0.035	- 0.051	- 0.225
Height	0.413	0.211	- 0.419

Pearson correlation (r values) for body mass and height in relation to the change in breathing frequency, tidal volume and ventilation between loaded and unloaded condition at 85% of VO_2 peak. n=15.

Table F-5. Body size analysis at peak exercise

	Pearson Correlation			
	Breathing Frequency	Tidal Volume	Ventilation	Oxygen Consumption
Body Mass	0.0648	-0.114	-0.1356	-0.1652
Height	0.3979	-0.2702	-0.3979	-0.241

Pearson correlation (r values) for body mass and height in relation to the change in breathing frequency, tidal volume and ventilation between loaded and unloaded condition at VO_2 peak. n=15.

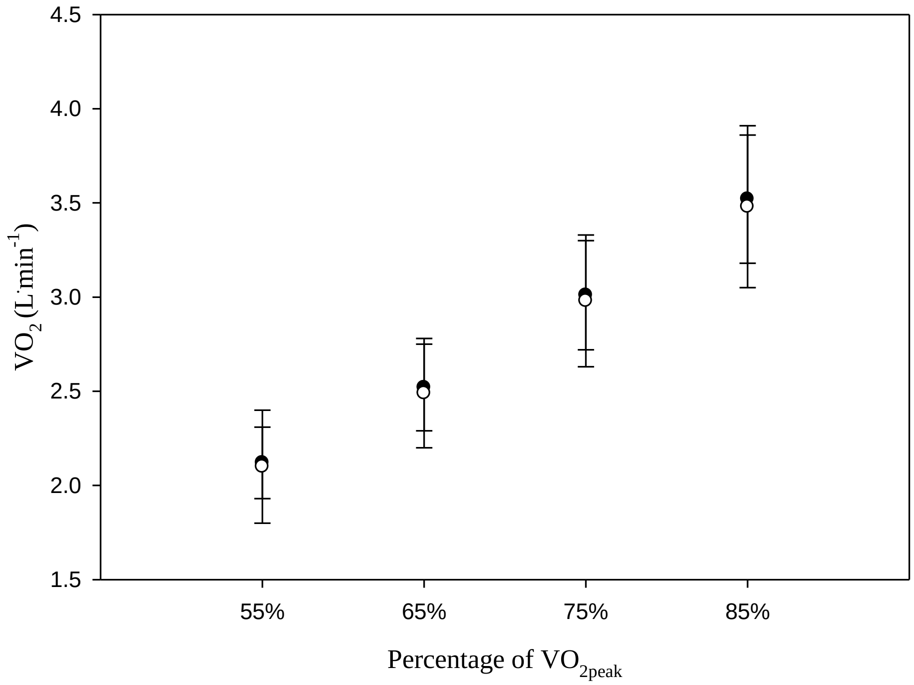

Fig.F-1. Oxygen consumption during exercise in unloaded and loaded conditions. Open circles represent loaded and closed circles represent unloaded conditions. n=15.

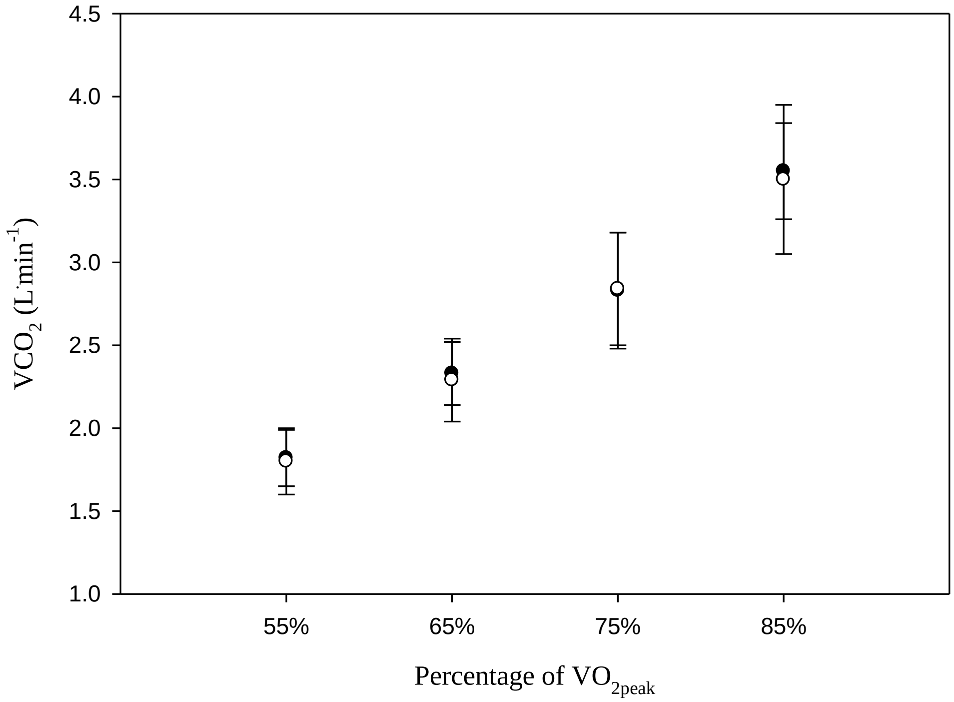

Fig.F-2. Carbon dioxide production during exercise in unloaded and loaded conditions. Open circles represent loaded and closed circles represent unloaded conditions. n=15.

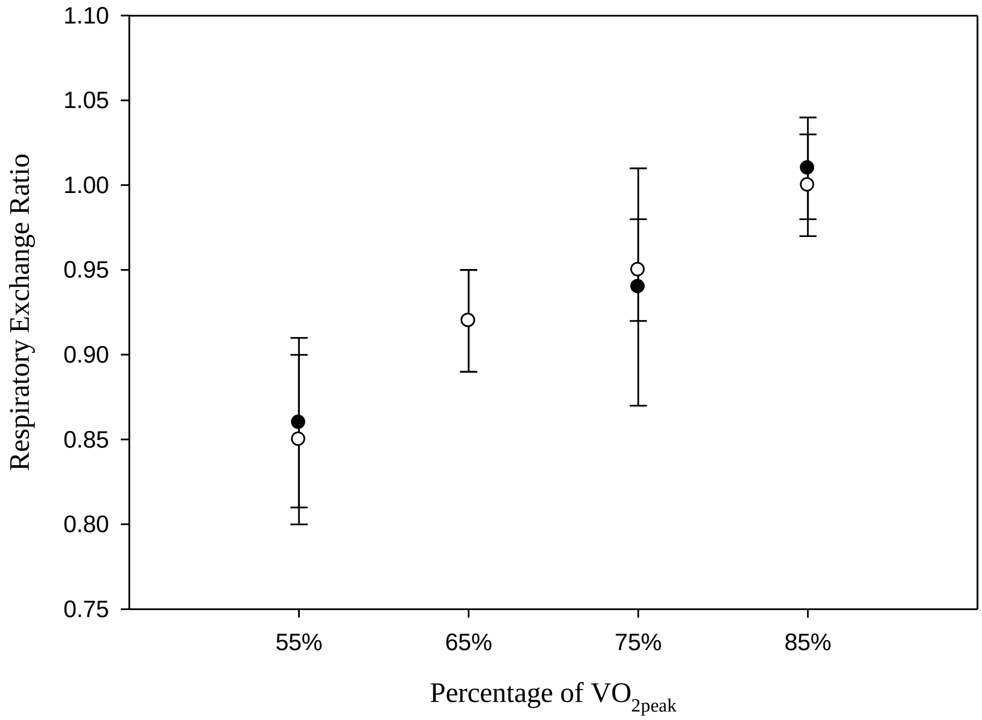

Fig.F-3. Respiratory exchange ratio during exercise in unloaded and loaded conditions. Open circles represent loaded and closed circles represent unloaded conditions. n=15.

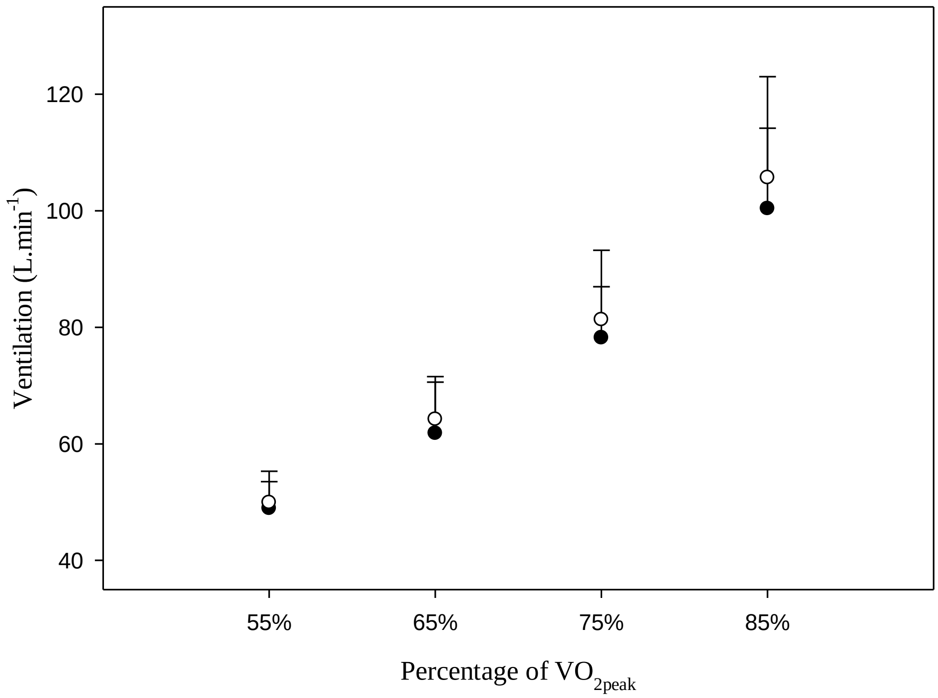

Fig.F-4. Ventilation during exercise in unloaded and loaded conditions. Open circles represent loaded and closed circles represent unloaded conditions. n=15.

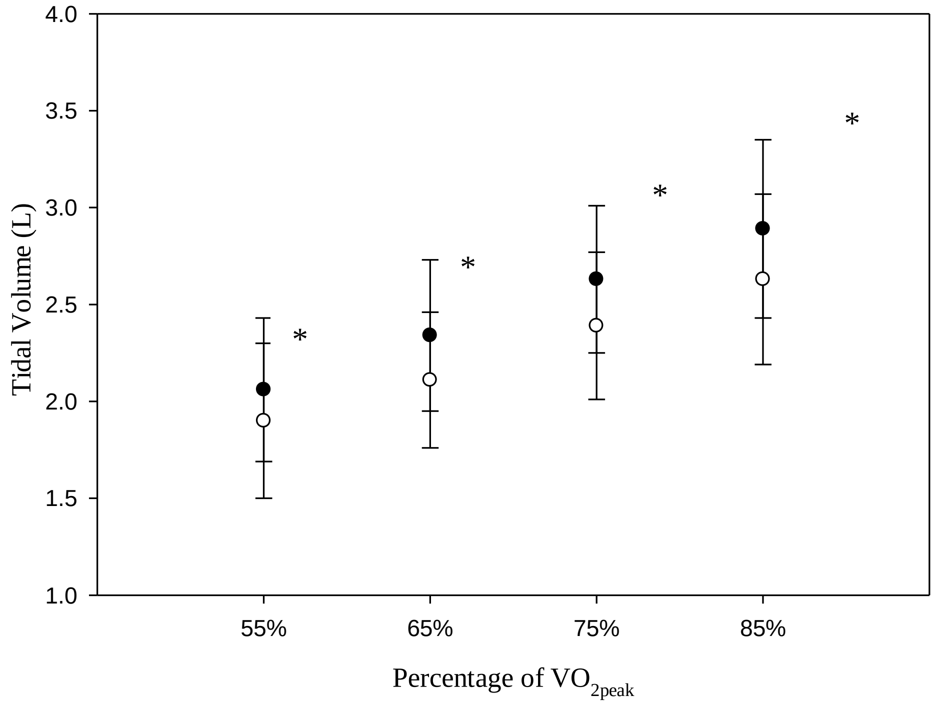

Fig.F-5. Tidal volume during exercise in loaded and unloaded conditions.
Open circles represent loaded and closed circles represent unloaded conditions. n=15.

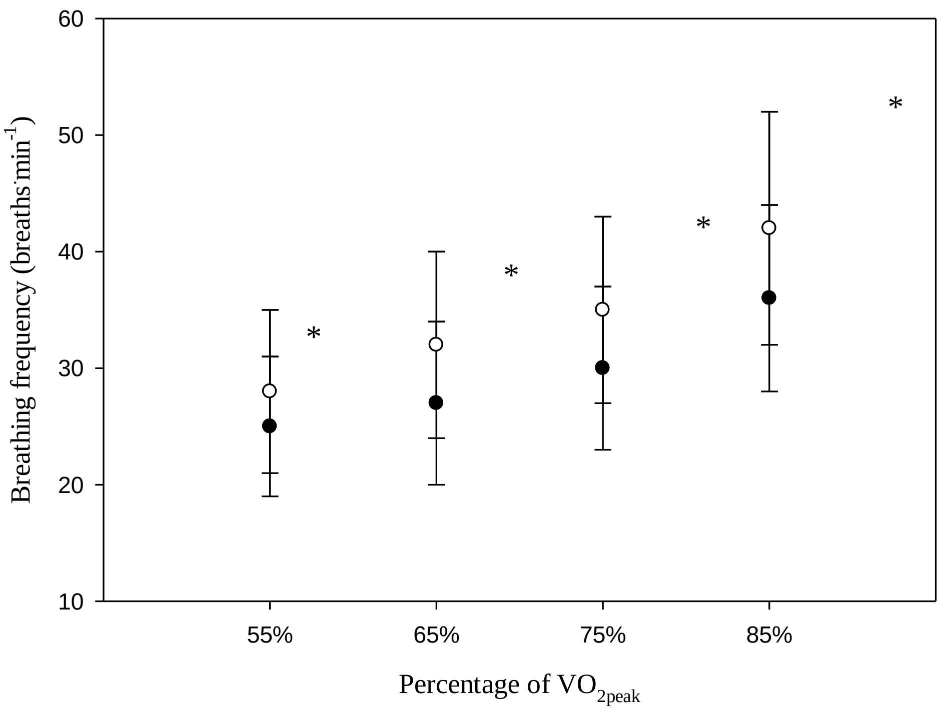

Fig.F-6. Breathing frequency during exercise in loaded and unloaded conditions. Open circles represent loaded and closed circles represent unloaded conditions.
* P<0.05. n=15.

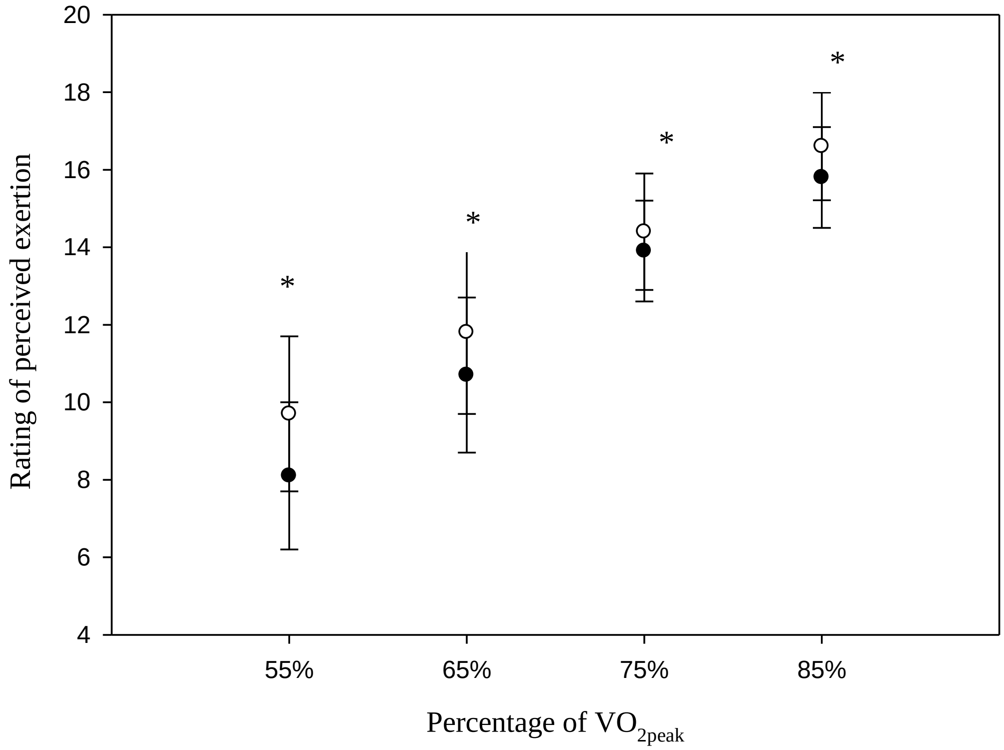

Fig.F-7. Ratings of perceived exertion during exercise in loaded and unloaded conditions. Open circles represent loaded and closed circles represent unloaded conditions.* P<0.05. n=15.

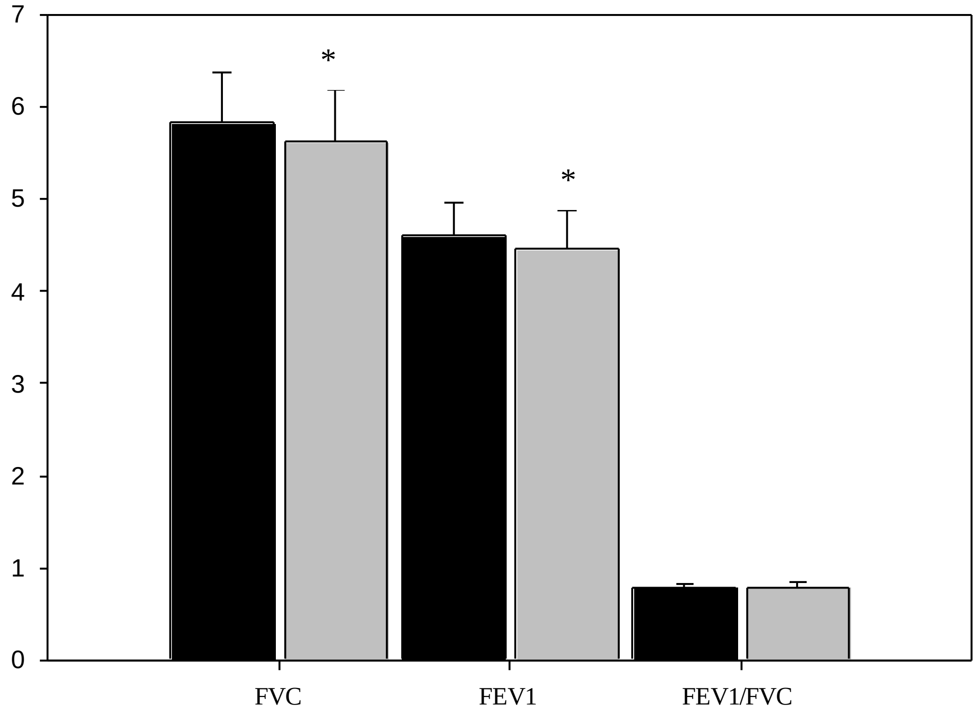

Fig.F-8. Measurements of forced vital capacity, forced expiratory volume in one second and the ratio of forced expiratory volume in one second to forced vital capacity at rest in unloaded and loaded conditions. Gray bars represent loaded conditions and black bars represent unloaded conditions. *P<0.05. n=15.