Wearing body armour and backpack loads increase the likelihood of expiratory flow limitation and respiratory muscle fatigue during marching.

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Wearing body armour and backpack loads increases the likelihood of expiratory flow limitation and respiratory muscle fatigue during marching.

The effect of load carriage on pulmonary function was investigated during a treadmill march of increasing intensity. 24 male infantry soldiers marched on six occasions wearing either: no load, 15 kg, 30 kg, 40 kg or 50 kg. Each loaded configuration included body armour which was worn as battle-fit or loose-fit (40 kg only). FVC and FEV_1 were reduced by 6% to 15% with load. Maximal mouth pressures were reduced post load carriage by up to 11% (inspiratory) and 17% (expiratory). Increased ventilatory demands associated with increased mass were met by increases in breathing frequency (from 3 to 26 $breaths.min^{-1}$) with minimal changes to tidal volume. 72% of participants experienced expiratory flow limitation whilst wearing the heaviest load. Loosening the armour had minimal effects on pulmonary function. It was concluded that as mass and exercise intensity are increased, the degree of expiratory flow limitation also increases.

Keywords: load carriage; pulmonary function; operating lung volumes; fit

Practitioner summary

This study investigated the effect of soldier load carriage on pulmonary function, to inform the trade-off between protection and burden. Load carriage caused an inefficient breathing pattern, respiratory muscle fatigue and expiratory flow limitation during marching. These effects were exacerbated by increases in mass carried and march intensity.

Introduction

The mass carried by soldiers continues to rise, and there are examples where soldier loads approach their own body mass (Lloyd-Williams and Fordy 2013). Marching with load on the torso reduces energy cost by up to 45% compared with carrying the load on other areas of the body (Datta and Ramanathan 1971). Furthermore, carrying load on the torso is more comfortable than carrying it further from the bodies centre of mass (Legg and Mahanty 1985). However, torso loads cause a mild restrictive ventilatory defect characterised as a reduction in forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) without a reduction in the ratio of these values (Armstrong and Gay 2016; Bygrave et al. 2004; Legg 1988; Legg and Cruz 2004).

At rest this restriction is in the order of 2% (Legg 1988) to 11% (Walker et al. 2015) which has been measured in loads of 6 kg (Legg 1988) to 45 kg (Phillips et al. 2016). During exercise increasing the mass carried in a backpack alters breathing pattern, increases the energy cost of a given task and leads to reduced exercise capacity during sub-maximal and maximal exercise (Dominelli, Sheel, and Foster 2012; Phillips et al. 2016; Phillips, Stickland, and Petersen 2016a; Wang and Cerny 2004). Load-induced alterations to breathing pattern increase the likelihood of expiratory flow limitation (Dominelli, Sheel, and Foster 2012) and are associated with fatigue of the respiratory muscles (Faghy and Brown 2014; Phillips, Stickland, and Petersen 2016b, 2016a; Shei et al. 2018).

Studies investigating the effect of load on pulmonary function have predominantly used backpack loads. As body armour is an essential part of the soldier system, backpack loads alone do not fully represent the load carried by the soldier. The distribution and fit of backpacks and body armour are different thus the degree of inertial (increased mass carried) and elastic (chest wall restriction) forces imposed on the torso which restrict shoulder elevation and chest wall expansion may also differ. As such, it is unlikely that studies undertaken using backpacks fully represent the demands placed on the soldier wearing body armour.

Considering chest wall restriction, Coast and Cline (2004) developed a chest wall restriction device that produced similar decrements in FVC (1.2% to 11.9%) to that observed in body armour (Majumdar et al. 1997; Armstrong and Gay 2016). The authors demonstrated that this restriction was sufficient to reduce $\dot{V}O_{2max}$ by up to 9% and time to exhaustion by up to 8%. Others have compared marching in a weighted vest, representative of a body armour configuration, to chest wall strapping and have concluded that a reduction in mass specific peak aerobic power had the greatest influence on exercise performance, rather than chest wall restriction (Peoples et al. 2016). These studies highlight the influence of the independent load characteristics (mass, fit, distribution) on pulmonary function and the importance of ensuring that the configurations being evaluated represent the real world application of the research.

There is a requirement to quantify the effect of wearing body armour on pulmonary function at rest and during exercise so that future armours minimise breathing restriction and the capabilities of the equipment are balanced against the burden it imposes on the wearer. Thus, the purpose of this study was to define the physiological response to wearing body armour with loads of varying masses on the soldier and identify the conditions under which soldiers may become susceptible to respiratory muscle fatigue and expiratory flow limitation.

The following hypotheses were tested [1] increasing mass carried would increase the severity of respiratory muscle fatigue; [2] increasing mass carried would increase the likelihood of expiratory flow limitation and [3] reductions in FVC, FEV_1 and mouth pressures and increases in EILV would be less when loose fitting armour is worn with load.

Materials and methods

Participants

This study received favourable opinion from the Ministry of Defence Research Ethics Committee (protocol 518MODREC14). Following informed consent, 24 male infantry soldiers volunteered to participate in the study; their physical characteristics were (mean and standard deviation): age 25.8 (4.7) years; stature 1.76 (0.08) m; mass 78.2 (13.3) kg; BMI 25.08 (2.89). Nine were smokers and all met the laboratory health / history screening requirements. All participants had normal lung function (*i.e*. FVC and FEV_1 greater than 80% of predicted) and were free from musculoskeletal injury / respiratory tract infections for at least one month prior to the start of the study.

Clothing and load configurations

Five load configurations (Table 1) were investigated in a repeated measures design. The order in which the configurations were worn was counterbalanced using a five by five Latin square, with one configuration being worn per day for five consecutive days.

The body armour (United Shields T45 modular tactical vest, Andover, UK) was similar in design to the in-service UK military body armour. It consisted of a soft armour vest which covered the front, rear and sides of the torso secured using a cummerbund. Two hard armour plates were inserted into the front and rear of the vest. The armour was available in five sizes ranging from small to extra, extra large.

The procedure developed by Armstrong and Gay (2016) was used to fit the body armour. Once a correct size was established, the armour was loosened and participants were asked to breathe normally. After approximately 30 seconds, when a stable breathing pattern was established, participants were asked to hold their breath at the end of a tidal inspiration and the armour was tightened. The body armour was marked to ensure that fit was standardised each time it was worn.

The additional load was carried in four webbing pouches attached to the sides of the body armour and carried in a military issue daysack. The daysack straps were also marked to ensure the tightness of fit was the same for each test session. Load distribution and bulk were standardised across the configurations that involved additional load carriage. No weapon was carried or helmet worn so that the focus of the investigation be on torso borne load.

To investigate the effect of loosening the body armour on pulmonary function, a sixth load configuration was included where participants wore BA25 with loose fitting armour (LBA25). This was not part of the counterbalanced design as LBA25 was only compared to BA25. To accommodate this configuration into the study timetable, the LBA25 test session was conducted on the same day as NBA, with a minimum of three hours of rest between the two sessions.

To fit the LBA25 configuration, participants were asked to inhale to total lung capacity before the body armour and backpack straps were fastened to ensure that the tightness of the configuration did not affect the participant's ability to inflate their lungs. This method was based on a similar approach previously conducted using backpack loads (Bygrave et al. 2004).

[TABLE 1 HERE]

Pre-study procedures

Participants attended a training session, during which they received training in all the procedures and baseline measurements were taken. Baseline mouth pressure measurements included an inspiratory muscle warm-up using the PowerLung (Sport model, PowerLung, USA) to ensure that peak pressures were attained. This comprised two sets of 30 inspiratory breaths at 40% of peak inspiratory pressure (PImax); one minute of recovery was given between sets (Lomax, Grant, and Corbett 2011).

Participants were asked to refrain from additional strenuous physical activity from 48 hours prior to the start of the study, alcohol consumption from 24 hours prior to the start of the study and smoking for two hours prior to the start of measurements.

Pre-exercise test measurements

A comparison of pre and post-exercise mouth pressures was used to identify respiratory muscle fatigue. At the start of each session, PImax and peak expiratory mouth pressures (PEmax) were measured without load. The peak pressure sustained for 1 second was determined using a respiratory pressure meter (Morgan Medical Ltd, UK), based on the procedures provided by the American Thoracic Society (American Thoracic Society and European Respiratory Society 2002). Measurements were made using a flanged mouthpiece whilst standing. Three to eight measurements were conducted until serial measurements were within 10% or 10 $cm \cdot H_2O$. If Pmax values were 10% lower than baseline values participants were asked to complete an inspiratory muscle warm-up as detailed previously.

FEV_1, FVC, peak inspiratory flow (PIF), peak expiratory flow (PEF) and maximum voluntary ventilation (MVV) were measured with load. Measurements were taken using the Metamax 3B (in stationary mode *i.e.* not worn by the participant, Cortex, Germany) using the spirometry module (MetaSoft 3 version 10.0), and were based on the procedures of the American Thoracic Society (Miller et al. 2005). Measurements were taken whilst standing.

Exercise test

Participants progressed to the exercise test immediately on completion of MVV measurements. Following a ten-minute rest period (five minutes seated and five minutes standing), participants walked for 40 minutes on a motor driven slatted belt treadmill (Woodway Pro-XL, USA). The speed and incline of the treadmill (Table 2) were increased every ten minutes to represent the following military tasks; a cautious patrol (light exercise), low threat patrol (moderate exercise), forced march (heavy exercise) and a contact situation (very heavy exercise).

The test was designed in collaboration with UK Military Advisors and subject matter experts to ensure that the exercise intensity was representative of military tasks. Further, piloting in six military participants was undertaken prior to the start of the main study, to ensure that the treadmill speeds and inclines elicited the required work rates and recovery between test sessions was sufficient. Participants maintained a walking pace throughout.

[TABLE 2 HERE]

Exercise-test measurements

Beat-by-beat heart rate (Polar, RS800, UK) and breath-by-breath gas analysis were recorded using a metabolic cart (Metamax 3B – in stationary mode, Cortex, Germany). Mean data at 15 second intervals were used for statistical comparisons. Participants provided ratings of perceived exertion (6 to 20) and breathlessness (0 to 10) (Borg 1982) in the ninth minute of each exercise period.

Operating lung volumes were calculated by superimposing tidal breaths within the maximal flow volume loops (MFVL) measured with load. This was achieved using the spirometry module of MetaSoft 3. Following training (which was conducted during the familiarisation session), a forced inspiratory capacity (IC) manoeuvre conducted at the end of a tidal expiration was used to position the tidal breath within the MFVL (Johnson, Weisman, et al. 1999). The IC manoeuvre was conducted during the eighth and ninth minute of each exercise period. The first measurement was used for analysis unless it did not meet the criteria defined below. Thermodynamic drift was accounted for by the metabolic cart by correcting the inspiratory and expiratory flow/volume signals to BTPS (Guenette et al. 2013).

Post-test, each manoeuvre was reviewed by an investigator to ensure that a minimum of six breaths were recorded prior to the inspiratory capacity manoeuvre; and the IC was initiated at the correct EELV (Guenette et al. 2013). Expiratory flow limitation was characterised as the percentage of VT that met or exceeded the expiratory boundary of the maximum flow volume loop envelope (Johnson, Beck, et al. 1999; Johnson, Weisman, et al. 1999), end expiratory lung volume (EELV) and end inspiratory lung volume (EILV) were also recorded.

Not all of the measured exercise flow volume loops were initiated at the appropriate EELV as some participants were unable to correctly perform the inspiratory capacity manoeuvre in the heaviest load configurations. Where this occurred the entire data set for that participant was excluded leaving n=15 for analysis (Table 6).

Temperature and relative humidity were maintained by an air conditioning unit and recorded at the start of rest (Squirrel 1000 series, Grant Instruments, UK). Mean (standard deviation) air temperature was 19.9 (0.5) ºC and relative humidity 49.4 (2.4)%.

Post-exercise test measurements

At the end of the exercise test, the load configuration was removed immediately. Pmax measurements were recorded within five minutes of test completion.

Data analysis and statistics

Data were checked for normality (skewness, kurtosis, analysis of outliers and the Shapiro-Wilk test). One-way (load) or two-way (load × time point) repeated measures ANOVA followed by Bonferroni post-hoc test was used to compare the difference between the configurations. The Greenhouse-Geisser correction was applied where the assumption of sphericity was not met. Data that were not normally distributed were transformed using a log transformation. Where this was unsuccessful, Friedman followed by Wilcoxon post-hoc test was used. Comparisons between BA25 and LBA25 were made using a paired t-test. α was set at 0.05 for all comparisons. Where the effect of load, time and interaction were significant, the interaction effects are reported.

Effect sizes were calculated using partial eta squared (η_p^2) for the main ANOVA effects, where 0.01, 0.06 and 0.14 were considered small, moderate and large effects respectively (Richardson 2011). Cohens d (d) was calculated for comparisons between the individual load configurations and interpreted as 0.2 - small, 0.6 - moderate, 1.2 - large, 2.0 - very large and 4.0 - extremely large (Hopkins et al. 2009). Statistical analysis was performed using SPSS statistics version 24.

Results

Pre-exercise test measurements

There was a main effect of load on FVC (p=<0.0001, η_p^2=0.44), FEV_1 (p =<0.0001, η_p^2=0.37) but not the ratio of these values (p=0.511, η_p^2=0.03). Reductions were evident in all loaded configurations and were in the order of 8% to 15% and 6% to 14% for FVC and FEV_1 respectively (Table 3).

There was a main effect of load on MVV (p =<0.0001, η_p^2=0.20) which was reduced by 18% in BA25 (p=0.003, d=0.69) and 14% (p=0.005, d=0.55) in BA35. No differences in expiratory (p=0.109, η_p^2=0.08) or inspiratory flows (p=0.427, η_p^2=0.04) were identified.

When BA25 and LBA25 were compared, no differences were observed except for MVV, which was 11% greater in LBA25 (p=0.003, d = 0.37).

[TABLE 3 HERE]

Exercise test measurements

Four out of 24 participants (17%) were unable to complete the exercise test wearing BA35. Two participants reached volitional exhaustion in the final work period (very heavy). A fourth participant was withdrawn by the chief investigator as he reported dizziness during very heavy exercise. These three participants were engaged in remedial physical training programmes at the time of the study. One participant terminated the test at the end of light work, due to discomfort. Data for these four participants was removed from further analysis. As such, exercise test data are presented for 20 participants unless otherwise stated.

Exercise test data are presented in Figure 1 and Table 4 to demonstrate trends and to identify where statistical differences between the configurations were observed. During the exercise test there was a significant interaction between load and time for $\dot{V}O_2$ (p=<0.0001, η_p^2=0.81), HR (p=<0.0001, η_p^2=0.80), $\dot{V}_E$ (p=<0.0001, η_p^2=0.78), percentage of HR maximum (p=<0.0001, η_p^2=0.80), breathing frequency (fb) (p=<0.0001, η_p^2=0.57), perceived exertion (p=<0.0001) and rating of breathlessness (p=<0.0001). These parameters increased with load and time, with the size of the increase being greater in the heavier loads (Figure 1 and Table 4).

End tidal CO2 ($P_{ET}CO_2$) was reduced (p=<0.0001, η_p^2=0.30) during very heavy exercise when body armour was worn with a backpack which coincided with a rise in $\dot{V}_E/\dot{V}CO_2$ (p=<0.0001, η_p^2=0.19) indicating hyperventilation during very heavy exercise in the heaviest loads. Analysis of tidal volume (V_T) indicated a significant interaction between load and time (p=<0.0001, η_p^2=0.14). V_T increased with time in all configurations however, increases with load were only observed during very heavy exercise in the heaviest loads.

When load was expressed relative to total mass carried (body mass + configuration mass) $\dot{V}O_2$ (mL·kg^{-1}·min^{-1}) did not differ with load (p=0.119, η_p^2=0.14).

No differences between BA25 and LBA25 were identified for exercise test data (p>0.184, d<0.24)

[FIGURE 1 HERE]

[TABLE 4 HERE]

Operating lung volumes

There was an effect of load and time on EILV (load: p=<0.0001, η_p^2=0.45; time: p=<0.0001, η_p^2=0.77) and EELV (load: p=0.039, η_p^2=0.16; time: p=<0.0001, η_p^2=0.44) but no interaction between load and time ($p>0.060$, $\eta_p^2<0.134$) (Table 5 and Figure 2). Loosening the body armour did not affect operating lung volumes ($p>0.219$, $d<0.24$)

[TABLE 5 HERE]

[FIGURE 2 HERE]

Expiratory flow limitation

Expiratory flow limitation was identified when load was worn. The occurrence and size of the encroachment on the MFVL envelope increased as mass and exercise intensity increased (Table 6). When BA25 was loosened, expiratory flow limitation was absent in three of the participants who developed expiratory flow limitation wearing BA25. The percentage encroachment on the MFVL envelope was similar for the remaining three participants.

[TABLE 6 HERE]

Inspiratory and expiratory mouth pressure measurements (PImax and PEmax)

There was no effect of load on PImax ($p=0.555$, $\eta_p^2=0.03$) or PEmax ($p=0.209$, $\eta_p^2=0.08$). There was an effect of time on both PImax ($p=0.001$, $\eta_p^2=0.45$) and PEmax ($p=<0.0001$, $\eta_p^2=0.84$). PImax was not reduced post exercise in participants wearing NBA or BA ($p>0.401$, $d>0.15$), however there was a reduction in PImax post-exercise in loaded conditions worn with a backpack. Reductions in PEmax were identified for all configurations. For both PImax and PEmax, the reduction in mouth pressures post-exercise increased with mass carried (Table 7).

No differences in PImax ($p=0.575$, $d=0.05$) or PEmax ($p=0.540$, $d=0.19$) were observed between BA25 and LBA25.

[TABLE 7]

Discussion

This study is the first to characterise the effect of wearing body armour with additional load on pulmonary function at rest and during incremental fixed speed marching. The novel findings were:

- Reductions in FVC and FEV_1 observed with body armour were greater than previously reported in studies using backpacks of a similar mass.
- Respiratory muscle fatigue was observed with load and this increased as mass carried increased.
- Expiratory flow limitation was evident with load during very heavy exercise, the severity of which increased with mass carried
- Loosening the body armour had minimal effect on pulmonary function during rest and exercise.

Resting pulmonary function

A mild restrictive ventilatory defect was observed with body armour where FVC and FEV_1 were reduced by 8% and 6% respectively (Table 3). Further reductions up to 15% for FVC and 14% for FEV_1 were measured when mass carried increased (Table 3). The decrements in FVC and FEV_1 observed were comparable to other studies using body armour of a similar mass (Armstrong and Gay 2016; Majumdar et al. 1997). However, studies using loaded backpacks matched for mass, have reported smaller decrements in these measures (Dominelli, Sheel, and Foster 2012; Muza et al. 1989; Phillips et al. 2016). This difference is likely caused by additional elastic and inertial forces imposed by the body armour plate and cummerbund on the anterior chest wall and suggests that greater reductions in FVC and FEV_1 may occur when body armour is worn compared to a backpack of similar mass.

Expiratory flow limitation and respiratory muscle fatigue

Expiratory flow limitation was observed in over half of the participants when body armour was worn with additional load (Table 6). This was accompanied by inspiratory muscle fatigue which occurred when body armour was worn with a backpack. Expiratory muscle fatigue was identified in all configurations, but was greatest in the heaviest loads (Table 7). Inspiratory muscle fatigue typically occurs during unloaded exercise of severe intensities (>85% of $\dot{V}O_{2peak}$) (Johnson et al. 1993) however, Faghy and Brown (2014) have suggested that this threshold is reduced when load is carried. In the current study, participants marched at 78% of age predicted maximum heart rate when respiratory muscle fatigue was evident (Table 4). These data support the findings of Faghy and Brown (2014) and also indicate that as mass carried increases this threshold will continue to reduce.

During the current study, $\dot{V}O_2$ and $\dot{V}_E$ increased with mass carried and exercise intensity (Table 4). These additional ventilatory requirements were met by increases in f_b rather than V_T leading to a rapid and shallow breathing pattern (Table 4). A concomitant rise in $\dot{V}_E/\dot{V}CO_2$ and reduction in $P_{ET}CO_2$ was also present during very heavy exercise in the heaviest loads which is indicative of hyperventilation (Table 4). This inefficient pattern of breathing will have increased work of breathing and contributed to the observed respiratory muscle fatigue.

Review of operating lung volumes provides further insight into the reported respiratory muscle fatigue. This data reflects trends typically seen with increases in $\dot{V}_E$ (Sheel and Romer 2012). However, when the loads were compared EELV and EILV were increased in the heavier loads without a change in V_T (Table 5). This pattern differs from the findings of others who found reductions in both EILV and EELV during fixed speed/incline marching tests (Dominelli, Sheel, and Foster 2012; Phillips, Stickland, and Petersen 2016b, 2016a) and graded exercise tests (Phillips et al. 2016; Phillips et al. 2019) with load carriage. This difference may be a reflection on the use Infantry soldiers in the current study who are experienced load carriers and may have developed adaptations to mitigate against expiratory flow limitation with load. Increases in EELV and EILV with load carriage would reduce the likelihood / severity of expiratory flow limitation, but would move tidal breathing against a greater elastic load thus increasing the work of breathing and likelihood of respiratory muscle fatigue.

Reductions in EELV are usually observed with increasing exercise intensities as the expiratory muscles are recruited to maintain the diaphragm at an optimum length (Johnson *et al.* 1999b). With load carriage, the expiratory muscles have additional work as soldiers typically develop a forward lean (Attwells et al. 2006) which places extra stress on the abdominal muscles to maintain posture. The upward shift in operational lung volumes observed in the current study may also be an adjustment to mitigate against the extra stress placed on the abdominal muscles for the maintenance of posture as mass carried increases, however expiratory muscle fatigue still increased as mass carried increased.

The expiratory mouth pressures recorded in the current study were noticeably greater than observed by others who have used similar data collection methods (*e.g.* Current: 213cm·H_2O; Faghy and Brown 2014: 158 cm·H_2O; Faghy *et al.*, 2016: 132 cm·H_2O; Phillips *et al* 2015: 183 cm·H_2O; Shei *et al.*, 2018: 166 cm·H_2O). Again, this may be a reflection on the difference between Infantry soldiers and the general civilian active male population. It is possible that regularly training with load will inadvertently offer training of the respiratory muscles in the same way that has been demonstrated with inspiratory muscle training devices (Shei et al. 2018; Faghy and Brown 2016).

The effect of wearing loose body armour

To investigate the effect of reducing the elastic forces imposed by body armour, an additional configuration where BA25 was loosened was included in the study design. MVV was reduced by 11% less in the loose configuration compared to battle-fit, but no other differences in spirometry, cardiovascular parameters, mouth pressures or operating lung volumes were observed. Others have reported that loosening a 15 kg backpack attenuated the reduction in FVC and FEV_1 by 5%, but potential benefits during exercise were not examined (Bygrave et al. 2004).

A study designed to mimic the elastic loading of body armour without the inertial component, showed that chest strapping reduced MVV by 5% less than a weighted vest, but had minimal impact during exercise (Peoples et al. 2016). In contrast a chest wall restriction device that produced similar decrements in FVC (1% to 12%) to that observed with body armour, reduced $\dot{V}O_{2max}$ by up to 9% and time to maximum exhaustion by up to 8% during cycle ergometry (Coast and Cline

2004). The differences in these findings were attributed to the characteristics of the chest wall restriction method.

Taken together, these data highlight the contributions of both the elastic and inertial components of the soldier's load, both of which have the potential to restrict lung function. The findings of the current study suggest that during exercise reducing the elastic component of the soldiers load - by introducing a flexible body armour for example (Armstrong and Gay 2016) - may be of less value compared to reducing the mass carried. Thus investments in lighter weight rather than flexible body armours may be a more effective strategy to minimise the breathing restriction imposed by body armour.

Implications for soldier performance

Soldiers are likely to develop fatigue of the respiratory muscles during loaded marching. This fatigue will reduce exercise tolerance by activation of the metaboreflex (Harms et al. 2000; Romer et al. 2006). Briefly, when the respiratory muscles exhibit fatiguing contractions, blood flow to the locomotor muscles is reduced which augments the onset of locomotor muscle fatigue. In the operational environment, activation of the metaboreflex would have the potential to [1] reduce the length of time that soldiers could operate for, [2] add a requirement for longer recovery periods and [3] reduce physical performance during intermittent high intensity tasks.

This study and the work of others (Faghy and Brown 2014; Phillips, Stickland, and Petersen 2016b) indicates that respiratory muscle fatigue occurs at a lower exercise intensities with load carriage. As such, soldiers are at greater risk of activating the metaboreflex with load carriage. The magnitude of inspiratory muscle fatigue required to trigger the metaboreflex is approximately 19% (McConnell and Lomax 2006). This threshold was not reached by the participants in the current study, but the additional stressors associated with the operating environment (*e.g.* terrain, altitude and climate) will place extra demands on the soldier and their respiratory system which will increase the likelihood that they cross this threshold.

When this study was undertaken, women in the UK were excluded from ground close combat roles, thus women were not recruited as participants. This exclusion has since been lifted therefore it is important to consider the influence of sex differences on these results. Women are more susceptible to expiratory flow limitation during exercise (Guenette et al. 2007; Harms and Rosenkranz 2008), but have demonstrated a greater resistance to exercise-induced fatigue of the diaphragm (Guenette et al. 2010). Future work in this area should be extended to include women to fully understand the implications for all soldiers.

Limitations

Due to the limited amount of time the military participants were available for, it was not possible to include an additional day of testing for $\dot{V}O_{2max}$ assessment. As such it was not possible to confirm the %$\dot{V}O_{2max}$ that the participants were exercising at and thus the exercise intensity above which respiratory muscle fatigue occurred. However, age predicted heart rate maximum was calculated to provide an indication of exercise intensity. Furthermore, it is acknowledged that gas exchange threshold was not measured therefore the use of the terms moderate and heavy are not related to the classification of exercise domains.

This study has relied on volitional based mouth pressure measures as an indication of respiratory muscle fatigue as opposed to the direct measurement of this parameter. To ensure the validity and reliability of this measurement, participants attended a training session prior to the data collection and were allowed a warm-up if pre-exercise pressures were lower than achieved previously. Further, participants were paired with the same investigator throughout the study to ensure motivation was consistent and reduce the impact that rater variability and test administration differences would have on the measurements.

Operating lung volume data was not measured independently of the increases in $\dot{V}_E$ that occur when additional mass is carried. The purpose of this study was to understand the consequence of adding load to the soldier, thus comparing the loads during a fixed task was considered the most representative of the military environment. Indeed increases in metabolic cost and breathing restriction are both consequences of adding load to the soldier and both factors contribute to the reported effects on pulmonary function during exercise.

Summary

This work has identified that wearing body armour with load causes a restrictive ventilatory defect. This impairment is likely to be greater when body armour is worn compared with backpacks of a similar mass. Even at light intensities, carrying load will increase the demands placed on soldiers during marching. When torso-borne loads which include body armour are worn, the likelihood and severity of expiratory flow limitation and respiratory muscle fatigue will increase with mass carried.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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List of Abbreviations

ANOVA	Analysis of variance
BA	Body armour
BA15	Body armour + 15 kg
BA25	Body armour + 25 kg
BA35	Body armour + 35 kg
f_b	Breathing frequency
EELV	End expiratory lung volume
EILV	End inspiratory lung volume
FEV_1	Forced expiratory volume in one second
FVC	Forced vital capacity
HR	Heart rate
LBA25	Loose body armour + 25 kg
MVV	Maximal voluntary ventilation
NBA	No body armour
PEF	Peak expiratory flow
PIF	Peak inspiratory flow
PEmax	Maximal expiratory mouth pressure
$P_{ET}CO_2$	End tidal carbon dioxide
PImax	Maximal inspiratory mouth pressure
Pmax	Maximal mouth pressure
$\dot{V}_E$	Minute ventilation
$\dot{V}_E$/ $\dot{V}CO_2$	Ventilatory equivalent for carbon dioxide
$\dot{V}O_2$	Rate of oxygen uptake
V_T	Tidal volume

Table 1: Clothing and Load Configurations (mean (SD)). Note that variations is masses were due to different sizes.

Configuration	Abbreviation	Clothing	Total mass (kg)	Torso borne mass (kg)
No body armour	NBA	Underpants, Socks, Issue boots, Personal Clothing System (PCS) trousers, Under Body Armour Clothing System (UBACS) shirt	3.01 (0.65)	0
Body armour	BA	NBA configuration, body armour (10.9 kg).	14.97 (1.00)	11.96
Body armour + 15 kg	BA15	BA configuration, 4 x body armour pouches (8.8 kg), day sack (6.2 kg).	30.37 (1.40)	27.36
Body armour + 25 kg	BA25	BA configuration, 4 x body armour pouches (8.8 kg), day sack (16.2 kg)	40.23 (0.85)	37.22
Body armour + 35 kg	BA35	BA configuration, 4 x body armour pouches (8.8 kg), day sack (26.2 kg)	50.28 (0.83)	47.27

Table 2: Speed and inclines used during each phase of the exercise test.

	Cautious patrol (Light)	Low threat patrol (Moderate)	Forced march (Heavy)	Enemy contact (Very Heavy)
Speed ($km\cdot h^{-1}$)	3	4	5	6
Incline (%)	0	3	4	5

Table 3: Spirometry data (mean (SD) n=24). Measurements were recorded immediately prior to the exercise test wearing each load configuration. “a “and “b” indicate difference from NBA and BA respectively ($\alpha = 0.05$).

	NBA	**BA**	**BA15**	**BA25**	**BA35**
FVC (L)	5.54	5.12[a]	4.85[a]	4.85[a]	4.71[a,b]
	(0.76)	(0.79)	(0.76)	(0.68)	(0.82)
FEV_1 (L)	4.17	3.92[a]	3.80[a]	3.82[a]	3.60[a,b]
	(0.58)	(0.56)	(0.66)	(0.59)	(0.53)
FEV_1/FVC	76.59	77.25	78.47	78.94	77.40
	(8.15)	(8.47)	(7.13)	(7.92)	(9.70)
PEF ($L\cdot second^{-1}$)	9.76	8.48	9.29	9.05	8.80
	(1.93)	(2.44)	(2.47)	(2.29)	(1.62)
PIF ($L\cdot second^{-1}$)	8.24	7.49	8.28	7.84	7.87
	(2.51)	(2.58)	(2.57)	(2.36)	(2.41)
MVV ($L\cdot minute^{-1}$)	161.67	150.87	146.83	132.03[a,b]	138.64[a]
	(48.52)	(32.22)	(43.27)	(38.88)	(34.15)

Table 7: Inspiratory (PImax) and expiratory (PEmax) mouth pressures (Mean (SD) n=20). Mouth pressure sustained for 1 second is reported. $p<0.01$=; $p<0.001$=***.**

	PImax (cm·H_2O)					PEmax (cm·H_2O)				
	NBA	BA	BA15	BA25	BA35	NBA	BA	BA15	BA25	BA35
Pre	138.6 (29.0)	136.2 (26.6)	138.3 (23.4)	139.1 (25.9)	137.5 (24.9)	202.3 (48.0)	212.6 (51.2)	209.2 (53.3)	208.1 (45.7)	204.9 (48.2)
Post	133.45 (36.12)	132.10 (26.19)	128.05 (21.69)	128.25 (24.66)	122.95 (36.03)	178.15 (44.04)	188.90 (43.09)	174.00 (42.63)	183.95 (49.84)	170.90 (44.73)
% change	-3.7	-3.0	-7.4**	-7.7**	-10.6***	-11.9***	-11.1***	-16.8***	-11.6***	-16.6***

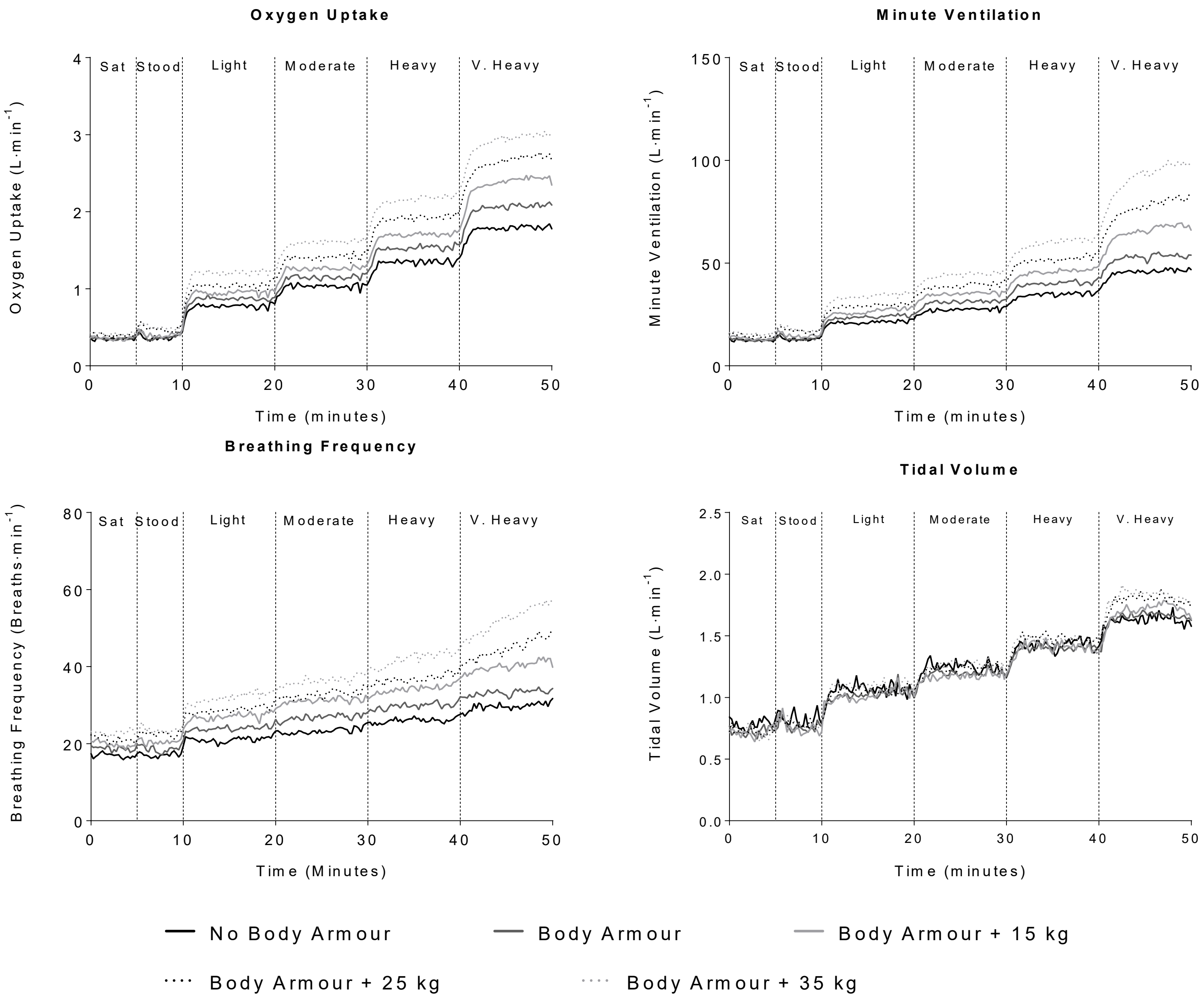

Figure 1: Mean rate of oxygen uptake, minute ventilation, breathing frequency and tidal volume measured during the exercise test (n=20).

Table 4: Exercise test parameters. Mean (SD) are reported (n=20). HR maximum was estimated using the formula 220-age. $\dot{V}O_2$ expressed relative to mass used total mass carried (body mass +mass of load configuration).

"a" indicates a difference from NBA; "b" indicates a difference from BA; "c" indicates a difference from BA15; "d" indicates a difference from BA25; α=0.05.

	NBA				**BA**				**BA15**				**BA25**				**BA35**			
	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy
VO_2	0.78	1.04	1.33	1.83	0.86^{a}	1.16^{a}	1.55^{a}	2.10^{a}	0.95^{ab}	1.28^{ab}	1.72^{ab}	2.44^{ab}	1.07^{abc}	1.43^{abc}	1.95^{abc}	2.72^{abc}	1.23^{abcd}	1.62^{abcd}	2.21^{abcd}	3.00^{abcd}
L/min	(0.12)	(0.15)	(0.18)	(0.23)	(0.12)	(0.19)	(0.21)	(0.27)	(0.14)	(0.17)	(0.17)	(0.24)	(0.13)	(0.18)	(0.20)	(0.26)	(0.22)	(0.19)	(0.24)	(0.38)
VO_2	9.99	13.34	17.12	23.17	9.29	12.56	16.83	22.77	8.91	11.89	16.07	22.86	9.09	12.15	16.59	23.24	9.47	12.60	17.13	23.24
mL/kg/min	(1.11)	(2.38)	(2.48)	(3.65)	(0.86)	(1.15)	(1.47)	(2.14)	(1.10)	(1.04)	(1.18)	(2.09)	(0.99)	(1.05)	(1.30)	(2.10)	(1.38)	(1.61)	(2.23)	(2.65)
V_E	21.82	27.95	35.22	46.49	24.33^{a}	31.51^{a}	40.60^{a}	52.93^{a}	27.89^{ab}	35.27^{ab}	47.26^{ab}	68.19^{ab}	30.23^{abc}	40.19^{abc}	53.49^{abc}	80.89^{abc}	35.70^{abcd}	45.49^{abcd}	61.48^{abcd}	98.05^{abcd}
L/min	(4.49)	(4.85)	(6.75)	(9.50)	(5.61)	(6.34)	(7.98)	(10.45)	(5.12)	(6.02)	(7.85)	(13.74)	(4.72)	(6.31)	(7.92)	(15.11)	(6.97)	(7.53)	(9.62)	(21.20)
V_E/VCO_2	30.94	29.51	28.35	27.12	30.22	28.74	27.54	26.22	31.06	29.19	28.77	27.81^{b}	30.77	28.87	27.79	28.18^{b}	29.77	28.21	27.43	29.99^{abc}
L/min	(3.36)	(3.16)	(2.60)	(2.76)	(3.42)	(3.02)	(2.81)	(3.13)	(2.56)	(2.11)	(3.01)	(3.35)	(2.79)	(2.63)	(2.73)	(3.03)	(2.46)	(2.23)	(2.34)	(3.81)
V_E/VO_2	(30.94)	(29.51)	(28.35)	(27.12)	(30.22)	(28.74)	(27.54)	(26.22)	(31.06)	(29.19)	(28.77)	27.81^{b}	(30.77)	(28.87)	(27.79)	28.18^{b}	(29.77)	(28.21)	(27.43)	30.00^{abc}
L/min	(3.36)	(3.16)	(2.60)	(2.76)	(3.42)	(3.02)	(2.81)	(3.13)	(2.56)	(2.11)	(3.01)	(3.35)	(2.79)	(2.63)	(2.73)	(3.03)	(2.46)	(2.23)	(2.34)	(3.81)
$PETCO_2$	38.55	39.44	40.46	41.06	39.02	39.68	41.17	42.48	38.46	39.64	39.93	39.73^{b}	38.79	39.70	40.48	38.81^{b}	38.86	39.96	40.39	36.6^{abc}
mmHg	(2.65)	(2.82)	(2.81)	(3.30)	(3.41)	(3.60)	(4.01)	(4.55)	(2.40)	(2.49)	(2.88)	(4.00)	(2.57)	(3.06)	(3.45)	(3.92)	(2.51)	(3.14)	(3.61)	(4.28)
HR	80.5	87.4	96.6	112.9	84.4^{a}	92.5^{a}	106.5^{a}	128.9^{a}	89.6^{a}	100.2^{ab}	118.1^{ab}	150.6^{ab}	94.4^{ab}	106.9^{abc}	128.8^{abc}	161.6^{abc}	102.6^{abcd}	120.1^{abcd}	145.2^{abcd}	175.0^{abcd}
beats/min	(7.4)	(8.4)	(8.3)	(9.5)	(6.8)	(6.0)	(7.4)	(8.4)	(8.9)	(9.2)	(10.7)	(14.4)	(8.8)	(8.7)	(11.8)	(13.1)	(12.3)	(13.5)	(13.5)	(10.6)
HR	41.51	45.05	49.80	58.19	43.51^{a}	47.71^{a}	54.90^{a}	66.41^{a}	46.13^{a}	51.61^{ab}	60.82^{ab}	77.54^{ab}	48.63^{abc}	55.09^{abc}	66.36^{abc}	83.27^{abc}	52.86^{abcd}	61.85^{abcd}	74.78^{abcd}	90.18^{abcd}
% max	(3.69)	(4.09)	(4.31)	(4.89)	(3.56)	(3.05)	(3.49)	(4.06)	(4.17)	(4.13)	(4.76)	(6.34)	(4.15)	(4.00)	(5.33)	(5.99)	(5.86)	(6.38)	(6.28)	(4.99)
f_b	21.88	24.26	26.69	30.45	24.43^{a}	27.52^{a}	30.10^{a}	33.35^{a}	28.29^{ab}	31.45^{ab}	35.85^{ab}	41.97^{ab}	29.49^{ab}	33.80^{abc}	38.32^{abc}	47.68^{abc}	33.33^{abcd}	38.14^{abcd}	43.36^{abcd}	56.34^{abcd}
breaths/min	(4.98)	(6.21)	(6.93)	(7.96)	(6.08)	(6.02)	(7.59)	(7.93)	(6.13)	(7.09)	(8.87)	(11.11)	(5.13)	(7.60)	(9.25)	(12.90)	(6.87)	(7.58)	(9.70)	(13.10)
V_T	1.04	1.22	1.46	1.60	1.05	1.19	1.40	1.65	1.05	1.17	1.41	1.70	1.08	1.25	1.47	1.77^{ab}	1.13	1.26	1.49^{b}	1.79^{ab}
L/min	(0.22)	(0.29)	(0.40)	(0.37)	(0.22)	(0.24)	(0.29)	(0.35)	(0.23)	(0.23)	(0.31)	(0.31)	(0.21)	(0.25)	(0.30)	(0.31)	(0.27)	(0.23)	(0.27)	(0.33)

Table 5: Operating lung volumes (L). Mean (SD) is presented for n=15.

“a” indicates a difference from Light; “b” indicates a difference from Moderate; “c” indicates a difference from Heavy; α=0.05.

	NBA				**BA**				**BA15**				**BA25**				**BA35**			
	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy	Light	Mod	Heavy	V. Heavy
EILV (L)	2.79 (0.96)	2.94 (0.79)	3.17 (0.82)	3.34^{ab} (0.74)	2.86 (0.76)	2.87 (0.81)	3.05 (0.81)	3.32^{abc} (0.78)	2.58 (0.61)	2.84 (0.66)	2.97^{a} (0.73)	3.21^{abc} (0.70)	2.82 (0.46)	3.06 (0.47)	3.28^{a} (0.58)	3.28^{a} (0.62)	3.06 (0.77)	3.19 (0.73)	3.43^{a} (0.72)	3.51^{ab} (0.75)
EELV (L)	2.04 (0.64)	1.94 (0.74)	1.81 (0.57)	1.96 (0.71)	2.01 (0.66)	1.96 (0.63)	1.99 (0.74)	1.84 (0.59)	1.87 (0.61)	1.86 (0.71)	1.79 (0.67)	1.52^{ab} (0.65)	2.01 (0.56)	1.94 (0.56)	1.99 (0.58)	1.72^{a} (0.54)	2.13 (0.54)	2.16 (0.60)	1.97 (0.48)	1.75^{a} (0.62)
EILV (%)	52.07 (12.78)	55.13 (9.33)	59.80 (12.38)	63.20^{ab} (9.56)	54.47 (10.43)	54.40 (10.89)	57.73 (9.67)	63.07^{abc} (9.15)	53.93 (10.30)	59.27 (9.93)	61.80^{a} (11.82)	67.00^{abc} (9.78)	58.40 (8.85)	63.27 (8.94)	66.20^{ac} (9.06)	67.40^{ac} (8.71)	63.40 (9.48)	66.33 (11.08)	71.07^{a} (9.00)	73.07^{ab} (11.16)
ELV (%)	35.40 (11.76)	35.00 (9.84)	37.07 (12.88)	34.00 (9.53)	38.87 (12.01)	34.47 (10.45)	34.00 (9.86)	34.67 (9.95)	34.73 (11.30)	37.00 (9.04)	35.53 (12.49)	32.13^{b} (11.19)	39.20 (9.63)	39.87 (10.25)	38.00 (11.10)	33.13^{abc} (9.22)	44.27 (9.53)	42.73 (10.11)	41.67 (9.01)	35.47^{abc} (10.90)

Table 6: Incidence and size of expiratory flow limitation. Frequency and the mean percentage encroachment on the maximal envelope (SD) are presented.

	NBA	BA	BA15	BA25	BA35
Heavy	0/15	0/15	1/15	2/15	0/15
			25 %	23.5 (9.2) %	
Very Heavy	0/15	1/15	7/15	7/15	11/15
		25 %	45.1 (27.3) %	68.4 (15.8) %	71.6 (12.7)

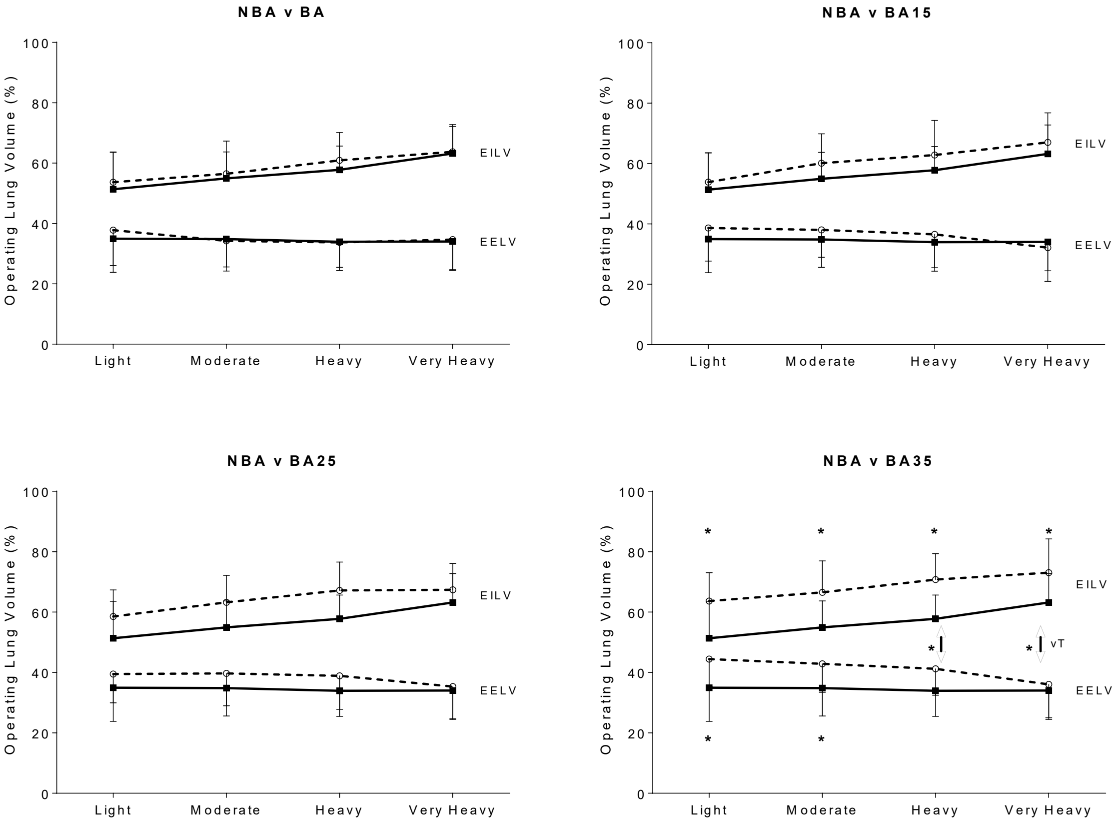

Figure 2: Operating Lung Volumes (expressed as a percentage of FVC).

Mean (SD) is presented for n=15. Closed squares (solid line) represent NBA, open circles (dashed line) represent the loaded configuration. * indicates a significant difference from NBA (α=0.05).

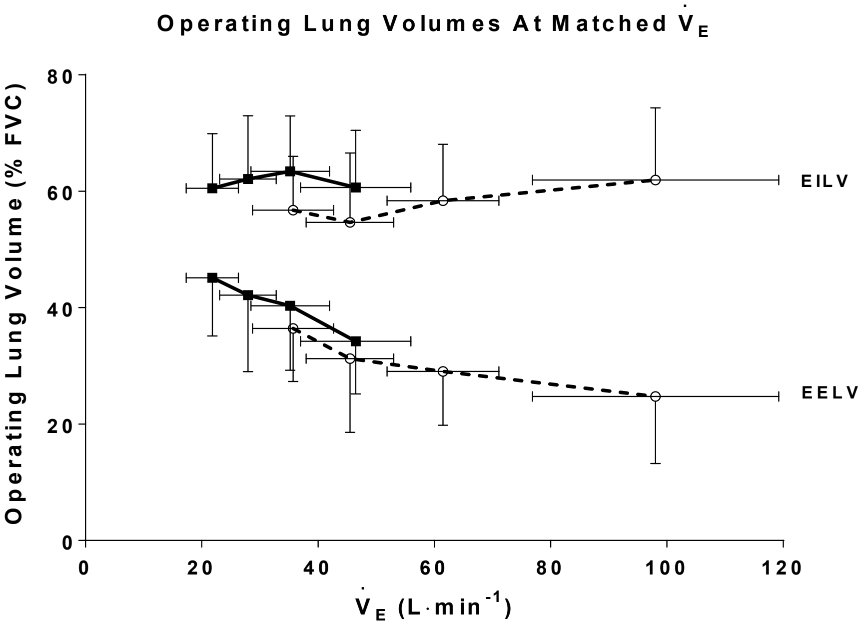

Figure 3: Operating lung volumes expressed relative to $\dot{V}_E$. Mean (SD) are presented for NBA (Closed squares, solid line) and (BA35=open circles, dashed line).