Running Title:

Load Carriage and Respiratory Muscle fatigue

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Thoracic load carriage-induced respiratory muscle fatigue

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Abstract

Purpose:

We investigated the effect of carrying a 25 kg backpack upon exercise-induced respiratory muscle fatigue, pulmonary function and physiological and perceptual responses to exercise.

Methods:

Nineteen healthy males performed 60 min walking at 6.5 km·h^{-1} and 0% gradient with a 25 kg backpack (load carriage; LC). Following 15 min recovery participants then completed a 2.4 km time trial with the load (LC_{TT}) and on a different day, repeated the trials without the load (CON and CON_{TT} respectively). Respiratory muscle fatigue was determined by the transient change in maximal inspiratory (P_{Imax}) and expiratory (P_{Emax}) pressure prior to and immediately following exercise.

Results:

P_{Imax} and P_{Emax} were reduced from baseline by 11% and 13% (P<0.05), respectively, post-LC but remained unchanged post-CON. Following the time trial P_{Imax} and P_{Emax} were reduced 16% and 19% respectively post-LC_{TT} (P<0.05) and by 6% and 10% respectively (P<0.05) post CON_{TT} compared to baseline. Both FVC and FEV_1 were reduced both by 4 ± 13 and 1 ± 9%, respectively during LC when compared to CON. Relative to CON all physiological and perceptual responses were greater in LC, both post LC and LC_{TT} (P<0.01). Time trial performance was faster during CON_{TT} (11.08 ± 1.62 min) relative to LC_{TT} (15.93± 1.91 min; P<0.05).

Conclusions:

This study provides novel evidence that constant speed walking and time trial exercise with 25 kg thoracic load carriage induces significant inspiratory and expiratory muscle fatigue and may have important performance implications in some recreational and occupational settings.

Key Words
Respiratory muscle fatigue, work of breathing, load carriage, reduced whole body performance

Abbreviations

CON – control trial

CON_{TT} – control time trial

FEV_1 - forced expiratory volume in 1 s

FVC – forced vital capacity

$[glucose]_B$ - blood glucose

HR – heart Rate

$[lac^-]_B$ - blood lactate

LC – load carriage trial

LC_{TT} – load carriage time trial

PEF - peak expiratory flow

P_{Imax} - maximal inspiratory mouth pressure

P_{Emax} - maximal expiratory mouth pressure

RER – respiratory exchange ration

$\dot{V}_{E,}$ - minute ventilation

$\dot{V}CO_2$- carbon dioxide production

$\dot{V}O_2$ – oxygen consumption

Introduction

Load carriage is defined as locomotion while bearing a mass upon the torso supported by shoulder straps and/or a hip belt (i.e., a backpack) (Knapik, Harman, & Reynolds, 1996) and it is often essential to integrate wearing a backpack with recreational activities such as hiking and in some occupational settings such as the military and emergency services (Birrell & Haslam, 2010). Furthermore, the backpack remains one of the most economical modes to carry the necessary consumables and equipment for a given task (Bastien, Willems, Schepens, & Heglund, 2005).

The mass of a backpack in some occupational settings can exceed 75 kg (Brown & McConnell, 2012) and previous studies utilising far lighter loads (25kg) demonstrated impaired force generating capacity of locomotor muscles (Blacker, Williams, Fallowfield, Bilzon, & Willems, 2010); however, there is a dearth of literature quantifying the effects upon the respiratory musculature. Load carriage presents a unique challenge to the respiratory system by combining chest wall restriction and loading, with recent evidence demonstrating impaired pulmonary function and breathing mechanics during exercise (Tomczak, Guenette, Reid, McKenzie, & Sheel, 2011).

During normal unloaded breathing, initial increases in tidal volume occur through a decrease in end-expiratory lung volume (EELV) which serves to optimise diaphragm function. However, the external restrictive constraint and mass of the backpack further reduces EELV and impairs the normal increase in end-inspiratory lung volume (EILV). This change in breathing mechanics increases the energy cost of breathing (Dominelli, Sheel, & Foster, 2012a) and reduces the efficiency of the respiratory muscles as they work outside of their optimal length-tension relationship (Brown & McConnell, 2012). Interestingly, studies which have mimicked this inspiratory volume limitation (but not the mass of the load) through chest wall restriction using inelastic strapping demonstrate significant diaphragm fatigue (Tomczak et al., 2011). Recent indirect assessment of the accessory musculature which are tasked with increasing thoracic volume, demonstrated a reduction in the mean power frequency of the external intercostals and the sternocleidomastoid with 15kg load, which the authors suggest is illustrative of impaired respiratory muscle function (Nadiv et al., 2012). The effects of load carriage upon the pressure generating capacity of the respiratory muscles is however yet to be determined. Therefore the aim of this study was to examine the effects of 25kg thoracic load carriage upon respiratory muscle fatigue, pulmonary function, physiological and perceptual responses during whole body exercise (constant load and time trial performance).

Methods

Participants

Following ethical approval from the host University 19 healthy, non-smoking and physically active males provided written informed consent to participate in the study (Table 1). Participants did not engage in any strenuous exercise on the day preceding and the day of an exercise test. Each participant completed a 24h diet record prior to their first exercise trial, which was then repeated prior to all subsequent trials. Participants abstained from alcohol and caffeine in the 24h prior to testing and arrived at the laboratory 2h post-prandial.

Experimental Procedures

Preliminary Trials

Participants attended a briefing session where the experimental design was explained. Following this, participants completed two preliminary trials. During the first preliminary trial body composition was assessed using dual energy x-ray absorptiometry (Lunar iDXA, GE Healthcare, Hertfordshire, UK). Subjects then performed a maximal incremental exercise test whilst running on a motorised treadmill (Desmo, Woodway, Germany) to determine $\dot{V}O_2max$ without the backpack. Following a 5 min warm-up at 8 $km \cdot h^{-1}$ and 1% gradient, the gradient was subsequently increased to 4% and the speed was increased by $1 km \cdot h^{-1} \cdot min^{-1}$ until the limit of volitional tolerance (Brown, Hughes, & Tong, 2008). Online breath by breath gas analysis (MetaLyser ll, Cortex Biophysik, Birmingham, UK) was used to determine $\dot{V}O_2max$ defined as the highest 30s $\dot{V}O_2$ recorded during the test.

During the second preliminary visit participants were familiarised with all testing equipment and protocols and completed baseline pulmonary function, maximal inspiratory (P_{Imax}) and expiratory pressure (P_{Emax}) measurements. All manoeuvers were performed in accordance with published guidelines (American Thoracic Society & European Respiratory Society, 2002, 2005). Pulmonary function was assessed using a pneumotachograph (MS03, Micro Medical, Buckinghamshire, UK) and expressed relative to predicted values using reference equations (Quanjer et al., 2012). A hand-held mouth pressure meter (MicroRPM, Micro Medical, Kent, UK) measured P_{Imax} and P_{Emax} from residual volume and total lung capacity, respectively, as an index of global inspiratory and expiratory muscle strength respectively as described previously (Brown, Sharpe, & Johnson, 2012). The mouthpiece assembly incorporated a 1 mm orifice to prevent glottic closure during inspiratory efforts. Both P_{Imax} and P_{Emax} were expressed relative to predicted values according to reference equations (Wilson, Cooke, Edwards, & Spiro, 1984). Following this participants were familiarised with the 25 kg backpack (Web Tex, Bedford, UK) and the experimental protocol (see below). The load mass was evenly distributed within the backpack and worn in accordance with the manufacturer's guidelines. The backpack incorporated adjustable shoulder straps and a waist strap which were adjusted individually and recorded to the nearest mm for subsequent trials. All trials were performed on a motorised treadmill (Desmo, Woodway, Germany).

Experimental trial with load carriage (LC)

Participants completed two experimental trials and the order of the experimental trials was randomised for each participant and separated by a minimum of one week. Following baseline measurements of respiratory muscle strength, pulmonary function and physiological variables (see below), participants walked for 60 min with a 0% gradient at 6.5 $km \cdot h^{-1}$ carrying a 25 kg backpack (hereon referred to as LC). Following a 15 min recovery period participants then completed a 2.4 km time trial (LC_{TT}) where the speed of the treadmill was manually adjusted by the participant under the instruction to complete the distance in the quickest time possible. The walking speed and duration, time trial distance and absolute mass were selected to reflect realistic occupational requirements as described previously (Blacker et al., 2010; Rayson, Holliman, & Belyavin, 2000).

Throughout LC physiological parameters were measured immediately prior to commencement of the experimental protocol, before LC_{TT} and immediately post-LC_{TT}. Heart rate was measured using short-range telemetry (HR, Polar T31, Kempele, Finland), expired pulmonary gases were assessed using the Douglas bag method (Hitech, GIR250, Cranlea and Co, Birmingham, UK), blood lactate concentration ($[lac^-]_B$, Accu-Check, Safe T-Pro, Birmingham, UK) and glucose concentration ($[glucose]_B$, Accutrend blood glucose, Birmingham, UK) were measured from arterialised-venous fingertip blood samples. Ratings of whole body perceived exertion (RPE) were measured using the Borg scale (Borg, 1982). Perceptions of effort were further separated for leg (RPE_{legs}) and breathing ($RPE_{breathing}$) discomfort using a visual analogue scale: where 0 = no exertion and 10 = maximal exertion (Verges, Lenherr, Haner, Schulz, & Spengler, 2007). The metabolic cost of walking was calculated using the equation ($Mw = 1.5 \cdot W + 2.0 \cdot (W + L) \cdot (L / W)^2 + T \cdot (W + L) \cdot (1.5 \cdot V^2 + 0.35 \cdot V \cdot G)$) of (Pandolf, Givoni, & Goldman, 1977) validated for the range of body mass and exercise intensities observed in this study; Where Mw (watts) is the metabolic cost of load carriage, W (kg) is the mass of the participant, L (kg) is the mass of the load being carried, V ($m \cdot s^{-1}$) is the velocity travelled and G (%) is the gradient.

Experimental Trial: without load carriage (CON)

The control trial (hereon referred to as CON) was identical to LC comprising 60 min walking, 0% gradient at 6.5 $km \cdot h^{-1}$ followed by a 15 min rest period and a 2.4 km time trial (CON_{TT}) but performed without the backpack.

Statistical Analysis

Changes in dependent variables over time throughout the experimental trials were assessed using one-way or two-way repeated measures ANOVA with Bonferroni post-hoc analysis. Interactions were defined for "trial" (LC vs. CON) and "time" (baseline vs. post-60 min vs. post-time trial). Paired samples t-test were used to determine differences between selected variables at specific time points. A priori α was set at 0.05 and all results are presented as mean ± SD. Statistical analysis was performed using SPSS for Windows (SPSS, Chicago, IL, USA).

Results

Respiratory muscle strength

Baseline and changes over time in P_{Imax} and P_{Emax} for LC and CON are shown in Figs 1 and 2 respectively. Baseline P_{Imax} and P_{Emax} were within normal limits and were not different between trials. Relative to baseline, P_{Imax} was reduced 11% following LC (pre-vs post: 141 ± 30 vs. 124 ± 29 cmH_2O; $P<0.001$) and a further 5% post LC_{TT} (118 ± 25 cmH_2O; $P<0.001$). Between experimental trials, P_{Imax} was significantly lower post-LC (P=0.004) and post LC_{TT} (P=0.002) compared to CON and CON_{TT}, respectively (trial x time interaction effect post-LC and post- LC_{TT}, P<0.001). P_{Emax} was reduced 13% following LC (pre-vs post: 158 ± 37 vs. 139 ± 34 cmH_2O; $P<0.001$) and a further 6% post-LC_{TT} (130 ± 31 cmH_2O; P=0.01) (trial x time interaction effect post-LC and post- LC_{TT}, $P<0.001$). Following CON P_{Imax} (P=0.456) and P_{Emax} (P=0.487) were unchanged relative to baseline. Conversely, following CON_{TT} P_{Imax} (6%; P>0.05) and P_{Emax} (10%; P<0.01) were reduced relative to post-CON.

Pulmonary function

Baseline pulmonary function was within normal limits (Table 2) during CON and reduced at baseline for the LC trial (FVC and FEV_1 by 6 ± 13% and 3 ± 9%, respectively). Relative to baseline FVC was reduced by 2 ± 11% following LC and 5 ± 6% following LC_{TT}, where FVC was unchanged following CON and reduced 2 ± 7% following CON_{TT} (P=0.03). Relative to baseline there was a 7 ± 23% reduction in FEV_1 post-LC (P<0.05) which was remained unchanged post-LC_{TT} and FEV_1 was unchanged throughout CON and CON_{TT}. PEF remained unchanged over time in both trials. Increases in FEV_1/FVC relative to baseline were observed during LC and CON and remained unchanged post- CON_{TT} and LC_{TT}.

Pulmonary gas exchange and cardiovascular responses

Changes over time in pulmonary gas exchange and cardiovascular responses for both trials are shown in Table 3. With the exception of RER, gas exchange variables: $\dot{V}_{E}$, $\dot{V}O_2$ and $\dot{V}CO_2$ were greater than baseline post-LC and post-CON. Responses were further increased post-time trial in both conditions (P<0.05) with the greatest increase following CON_{TT} (P<0.05). HR was also greater than baseline following LC and CON (P<0.05). The increase in HR post-LC (absolute increase 46 ± 17 beats·min^{-1}) was greater than post-CON (absolute increase 19 ± 13 beats·min^{-1}, P<0.05) and was further increased post-time trial (absolute increase LC_{TT}: 43 ± 18 beats·min^{-1}; CON_{TT}: 76 ± 11 beats·min^{-1}; P<0.05).

Physiological and perceptual responses

Changes in the metabolic responses for both experimental trials are shown in Table 3. The metabolic cost was 21 ± 2% greater in LC (40.2 ± 3.2 KJ·min^{-1}) relative to CON (31.8 ± 3.4 KJ·min^{-1}, *P<0.01*). Conversely, the metabolic cost in CON_{TT} was 34 ± 8% greater (109.4 ± 26.2 KJ·min^{-1}) than LC_{TT} (72.4 ± 15.4 KJ·min^{-1}, *P<0.01*). $[glucose]_B$ was similar at baseline between trials and remained unchanged over time. $[lac^-]_B$ decreased following LC (absolute decrease 0.4 ± 1.1mmol·l^{-1}, P>0.05) and CON (0.4 ± 0.5 mmol·l^{-1}, P>0.05) and subsequently increased post-time trial in both conditions with the greatest response observed post-CON_{TT} (absolute increase LC_{TT}: 7.2 ± 3.9 mmol·l^{-1}; CON_{TT}: 9.4 ± 2.7 mmol·l^{-1}, P>0.05). Changes in the perceptual responses for both experimental trials are shown in Table 3. All perceptual responses were similar at baseline between trials, but were greater post-LC relative to post-CON (interaction effect: trial x time, P<0.01). Responses were further increased (P<0.05) following the time trial in both conditions (P<0.05) but the absolute increase was not different between trials P<0.05).

Time trial performance

Group mean changes in 2.4 km time trial performance are shown in Figure 3. Time to completion was 30 ± 5% slower in LC_{TT} (15.9 ± 1.9 min) compared to CON_{TT} (11.1 ± 1.6 min; P<0.01). The average speed during LC_{TT} and CON_{TT} was 9.2 ± 1.1 km.h^{-1} and 13.2 ±1.8 km.h^{-1}, respectively (P<0.01).

Discussion

Main findings

The purpose of this study was to investigate the effects of 25 kg load carriage during whole body walking exercise upon respiratory muscle fatigue, pulmonary function, physiological and perceptual variables and a 2.4 km time trial performance. The novel finding of this study was that 60 min load carriage induced significant inspiratory and expiratory muscle fatigue which was further exacerbated by the 2.4 km time trial.

Respiratory muscle fatigue

We are the first to demonstrate a significant reduction in the voluntary pressure generating capacity of the respiratory muscles following 60 min walking and a self-paced 2.4 km time trial with 25 kg load carriage. We observed an 11% reduction in P_{Imax} and a 13% reduction in P_{Emax} (P<0.05), following LC (no change in CON) which was exacerbated by a further 5 and 6%, respectively, post- LC_{TT} (P<0.05). Despite our observations, evidence from whole body-exercise suggests that respiratory muscle fatigue only occurs following constant power high intensity exercise to exhaustion (>85% $\dot{V}O_2$max), time trial events (Johnson, Sharpe, & Brown, 2007; Leddy et al., 2007; Romer, McConnell, & Jones, 2002; Volianitis et al., 2001); or prolonged sub-maximal (marathon) exercise (Ross, Middleton, Shave, George, & McConnell, 2008). Previous occupational research has observed reductions in P_{Imax} and P_{Emax} (10-12%) following sub-maximal and intense treadmill exercise while wearing self-contained breathing apparatus and fire-fighter apparel (Butcher, Jones, Mayne, Hartley, & Petersen, 2007). However this model provides difficulty in distinguishing the effects of the load mass secured to the thorax (gas cylinders) and the positive pressure provided by the face mask since the latter accounts for the majority of the increased work of breathing during exercise (Eves, Jones, & Petersen, 2005). The findings of this study are however in agreement with previous research which mimicked the restrictive characteristics of a backpack (but not the load mass) and observed reductions in twitch trans-diaphragmatic pressure during 10 min cycling exercise at 40% maximal workload (Tomczak, Guenette, Reid, McKenzie, & Sheel, 2011), which presumably would be exacerbated with the addition of chest wall loading (this study). In addition, a reduction in the mean power frequency of both the external intercostals and the sternocleidomastoid was demonstrated following 25kg load carriage which according to the authors is suggestive of impaired respiratory muscle function (Nadiv et al., 2012). However, the validity of these measures has been questioned, such that it correlates poorly with mechanical indices of skeletal muscle fatigue (Sheel & Romer, 2012). Thus, we extend previous findings by demonstrating that load carriage reduces the threshold by which whole body exercise induces respiratory muscle fatigue to include sub-maximal walking exercise (~58% $\dot{V}O_2max$) of which the implications for recreational and occupational activities where the findings may be far reaching (see applied relevance below).

The most likely mechanism(s) accounting for our observations is the elevated work of breathing and impaired breathing mechanics imposed by chest wall loading and restriction. Exercise with load carriage increases the work and power of breathing through a curvi-linear increase in the force and velocity of contraction (Brown & McConnell, 2012a; Dominelli, Sheel, & Foster, 2012). In addition the restrictive component of the backpack limits operational lung volumes and reduces the efficiency of the respiratory muscles as their length tension relationship is altered (Dominelli et al., 2012). Consistent with previous findings (Muza, Latzka, Epstein, & Pandolf, 1989; Richmond, Rayson, Wilkinson, Carter, & Blacker, 2008) we observed a 4% reduction in FVC and 1% reduction in FEV_1 at baseline when wearing the backpack (Table 2). Although small in magnitude, these changes have important consequences for the evolution of the exercise hyperpnoea response. During un-loaded breathing tidal volume increases with a simultaneous decrease in EELV which serves to optimise diaphragm length and respiratory system compliance (Aliverti, 2008). However, during load carriage thoracic volume is reduced and the external limit placed upon the inspiratory reserve capacity lowers EILV and EELV, shifting the operational lung volume to a lower fraction of total lung capacity (Dominelli et al., 2012) reducing efficiency and increasing the work of breathing (Dominelli et al., 2012; Tomczak et al., 2011). Furthermore, subsequent reductions in EELV may also increase expiratory pressures at functional residual capacity, prompting an expiratory flow limitation (McClaran, Wetter, Pegelow, & Dempsey, 1999). Thus the greater prevalence of respiratory muscle fatigue with load carriage is most likely due to a combination of impaired breathing mechanics and elevated work of breathing during exercise. It has also been suggested that a reduction in respiratory muscle pressures generation may also be a result of reflex inhibition and therefore reduced central motor drive (Marcora, 2009) rather than a reduction in capacity for the respiratory muscles to produce force. This was not apparent here as no change in handgrip strength during LC and LCTT was observed in a subset of participants (n=4). Therefore we interpret the reduction in PImax and PEmax as indicative of global respiratory muscle fatigue rather than a reduction in whole body central motor drive.

Applied relevance

Respiratory muscle fatigue identified here may have important consequences for whole body performance with respect to some occupational and recreational situations where thoracic load carriage is a prominent feature. Respiratory muscle fatigue has been shown to exacerbate limb muscle fatigue and impair high intensity whole-body performance through a sympathetically-mediated reflex reduction in limb blood flow (known as the respiratory muscle metaboreflex) presumably in favour of the fatiguing respiratory muscles (Harms et al., 1997; Romer, Lovering, Haverkamp, Pegelow, & Dempsey, 2006). We hypothesise that load carriage reduces the critical threshold for this and may explain in part our observations in LC_{TT}. Furthermore, this process may also increase the perceptual response to exercise (Marcora, 2009) resulting in a reflex inhibition of central motor output from the cortical and / or sub-cortical centres to the locomotor muscles (Amann, 2011).

The diaphragm is also one of few muscles to insert directly on to the lumbar spine, and assists with maintaining trunk and spinal stability (Shirley, Hodges, Eriksson, & Gandevia, 2003). Thus diaphragm fatigue may promote trauma to the vertebral column, intervertebral discs, and/or spinal ligaments, all of which are common causes of low back pain and injury in soldiers carrying heavy loads upon the trunk (Knapik et al., 1996). The respiratory musculature is also tasked with preserving postural control such as preventing falling; such that it contracts autonomously in anticipation of actions that destabilise or load the trunk (P. W. Hodges, Butler, McKenzie, & Gandevia, 1997). This feed-forward control mechanism occurs irrespective of the phase of the breathing cycle; however, respiratory function always takes precedence over its role in postural control (Hodges, Heijnen, & Gandevia, 2001). Consequently load carriage-induced respiratory muscle fatigue may compromise this and increase the risk of lower limb injury since this has been shown to shift the reliance from the respiratory musculature to the lower limbs and ankles for postural control (Janssens, Brumagne, Polspoel, Troosters, & McConnell, 2010) which is clearly important for activities where the terrain / topography is complex.

Methodological limitations

Despite demonstrating significant respiratory muscle fatigue following load carriage (see Figs 1 and 2) it is important to note that we employed volitional measures of muscle force output, which although highly reliable (Romer & McConnell, 2004), difficulty remains in distinguishing between central and peripheral mechanisms of fatigue. However, despite the techniques employed here being highly dependent upon subject motivation we took great care and spent much time ensuring full familiarisation with this measurement technique and strove to maximise motivation throughout all efforts; therefore we are confident that any potential effects of reduced subject motivation and effort were minimised. In addition, we attribute the greater respiratory muscle fatigue to an elevated work of breathing and changes in breathing mechanics. However, unlike previous studies (Dominelli et al., 2012; Tomczak et al., 2011) we did not use intrathoracic pressure balloon catheters to quantify the work of breathing nor did we quantify changes in end-inspiratory, expiratory and total lung volumes. Thus future study is required to quantify respiratory muscle fatigue following load carriage by measuring the changes in intra-thoracic pressures in response to non-volitional (effort-independent) motor nerve stimulation techniques.

Conclusion

Load carriage (25 kg) during sub-maximal walking exercise caused significant respiratory muscle fatigue. In addition the perceptual sensations and metabolic responses were increased and performance during a 2.4 km time trial was markedly reduced. These findings have important implications for some recreational and occupational groups and future research should investigate interventions to attenuate such effects.

Integrity of Research and Reporting

Ethical Standards

All experimental procedures and methods of assessment used in this study were ethically approved by the host universities ethics committee and conform to the laws of the United Kingdom.

Conflicts of interest:

No conflicts of interest for each of the authors.

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None

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