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Running Head: Respiratory muscles and upper-body exercise

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ABSTRACT

Purpose: Diaphragm and abdominal muscles are susceptible to contractile fatigue in response to high-intensity, whole-body exercise. This study assessed whether the ventilatory and mechanical loads imposed by high-intensity, upper-body exercise would be sufficient to elicit respiratory muscle fatigue. **Methods:** Seven healthy men (mean±SD: age 24±4 y; peak O_2 uptake [$\dot{V}O_2$ peak] 31.9±5.3 ml/kg/min) performed asynchronous arm-crank exercise to exhaustion at work rates equivalent to 30% (heavy) and 60% (severe) of the difference between gas-exchange threshold and $\dot{V}O_2$ peak. Contractile fatigue of the diaphragm and abdominal muscles was assessed by measuring pre- to post-exercise changes in potentiated transdiaphragmatic and gastric twitch pressures ($P_{di,tw}$ and $P_{ga,tw}$) evoked by supramaximal magnetic stimulation of the cervical and thoracic nerves, respectively. **Results:** Exercise time was 24.5±5.8 min for heavy exercise and 9.8±1.8 min for severe exercise. Ventilation over the final minute of heavy exercise was 73±20 L/min (39±11% maximum voluntary ventilation [MVV]) and 99±19 L/min (53±11% MVV) for severe exercise. Mean $P_{di,tw}$ did not differ pre- to post-exercise at either intensity (p>0.05). Immediately (5-15 min) after severe exercise, mean $P_{ga,tw}$ was significantly lower than pre-exercise values (41±13 vs. 53±15 cmH_2O, p<0.05), with the difference no longer significant after 25-35 min. Abdominal muscle fatigue (defined as ≥15% reduction in $P_{ga,tw}$) occurred in 1/7 subjects after heavy exercise and 5/7 subjects after severe exercise. **Conclusions:** High-intensity, upper-body exercise elicits significant abdominal, but not diaphragm, muscle fatigue in healthy men. The increased magnitude and prevalence of fatigue during severe-intensity exercise is likely due to additional (non-respiratory) loading of the thorax.

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Keywords

abdominals; arm-cranking; arm exercise; diaphragm; nerve stimulation

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INTRODUCTION

The diaphragm and abdominal muscles of healthy human beings exhibit contractile fatigue after whole-body exercise sustained to exhaustion at intensities greater than 80% maximum O_2 uptake ($\dot{V}O_2$ max). Such exercise-induced respiratory muscle fatigue has been documented after cycle ergometry and treadmill running, whereby transdiaphragmatic (P_{di}) and gastric (P_{ga}) pressures evoked by supramaximal magnetic stimulation of the phrenic and thoracic nerves, respectively, were reduced by 15 - 30% relative to pre-exercise values and took ~2 h to recover (20, 35). The magnitude and prevalence of diaphragmatic fatigue were significantly correlated with the ventilatory demands of exercise (20). Moreover, fatigue of the diaphragm was prevented when exercise-induced diaphragmatic work was reduced using a proportional assist ventilator (5). Together, these findings suggest that diaphragmatic fatigue is, in part, due to the high work of breathing that must be sustained throughout intense, whole-body exercise.

By contrast, contractile fatigue of the diaphragm did not occur when rested subjects mimicked the magnitude and duration of diaphragmatic work incurred during whole-body exercise; fatigue was only observed when diaphragmatic work was voluntarily increased two-fold greater than that required during maximal exercise (4). Furthermore, non-significant correlations have been noted between the magnitude of abdominal muscle fatigue and the ventilatory requirements of exercise (35, 40). Collectively, these findings suggest that mechanisms other than ventilatory load must contribute to the development of exercise-induced respiratory muscle fatigue. One possible mechanism is competition between respiratory and locomotor muscles for the limited available cardiac output during intense, whole-body exercise

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(14). Less blood flow to the respiratory muscles would promote inadequate O_2 transport, thereby contributing to the development of fatigue.

The cardio-ventilatory demands of intense, upper-body exercise are considerably less than for whole-body exercise (34). These relatively low demands for ventilation and blood flow would be expected to reduce the likelihood of respiratory muscle fatigue during upper-body exercise. However, upper-body tasks place additional mechanical loads on the thoracic complex. For example, the respiratory muscles function to ventilate the lungs while simultaneously stiffening the spine (16, 17) and maintaining torso stabilisation and arm position (9). Specifically, the diaphragm aids trunk stability prior to rapid arm movements (15), and the abdominals contract to dynamically flex and rotate the torso (10). Given the combined ventilatory, postural and locomotor functions of the diaphragm and abdominals, these muscles likely undergo substantial contractile work during upper-body exercise, possibly predisposing to contractile fatigue. While previous studies have demonstrated significant reductions in volitional measures of respiratory muscle function after activities involving the upper-body (e.g., rowing [41] and swimming [24]), such measures are highly dependent on subject motivation and cannot be used to infer a reduction in contractile function of the respiratory muscles.

Accordingly, the aim of the present study was to assess the fatigability of respiratory muscles, using non-volitional (effort independent) motor nerve stimulation techniques, after sustained, intense, upper-body exercise in healthy subjects. It was hypothesised that: 1) the additional mechanical demands imposed by upper-body exercise would induce contractile

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fatigue of the diaphragm and abdominal muscles, and 2) the magnitude and prevalence of respiratory muscle fatigue would be dependent upon exercise intensity.

METHODS

Subjects

After providing written informed consent, seven healthy, non-smoking men between the ages of 18 and 35 y volunteered to participate in the study (mean ± SD: age 24 ± 4 y, stature 1.77 ± 0.06 m, body mass 75.5 ± 6.3 kg). The subjects were physically-active, but not engaged in specific upper-body exercise training. Experimental procedures were approved by the institutional research ethics committee. Subjects were asked to abstain from exercise for 48 h, alcohol and caffeine for 12 h, and food for 3 h before each visit.

Experimental Overview

Each subject visited the laboratory on four separate occasions within a two-week period and with at least 48 h between visits. At the first visit, subjects underwent pulmonary function testing and were thoroughly familiarised with the neuromuscular function and arm-crank exercise protocols. At the second visit, subjects completed maximal incremental, asynchronous arm-crank exercise for the determination of gas-exchange threshold and peak O_2 uptake ($\dot{V}O_2$ peak). The subsequent

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two visits were the experimental trials and were performed in a random order and at the same time of day. The experimental trials comprised constant-load arm-crank exercise to exhaustion at heavy and severe intensities with the assessment of cardiorespiratory, metabolic, perceptual, and respiratory neuromechanical responses. Contractile fatigue of the diaphragm and abdominal muscles was assessed in both experimental trials by measuring the pre- to post-exercise change in transdiaphragmatic twitch ($P_{di,tw}$) and gastric twitch pressures ($P_{ga,tw}$) in response to magnetic stimulation of the phrenic and thoracic nerves, respectively.

Pulmonary Function, Visit 1

Pulmonary volumes, capacities, flows, resistance and diffusion were assessed using a fully integrated system (Masterscreen, CareFusion, Hampshire, UK). Maximum inspiratory pressure at residual volume (RV) and maximum expiratory pressure at total lung capacity (TLC) were assessed using a handheld device (MicroRPM, CareFusion).

Maximal Incremental Exercise, Visit 2

Subjects completed a maximal incremental exercise test on an electromagnetically-braked arm-crank ergometer set in the hyperbolic mode (Angio, Lode, Groningen, The Netherlands). The ergometer was wall-mounted and positioned so that the scapula-humeral joint and the distal end of the crank pedal were horizontally aligned. Subjects were instructed to sit upright, maintain

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form at all times, and keep their feet flat to the floor to minimise bracing. After 3 min of rest, subjects exercised for 3 min at 20 W after which the work rate was increased in a ramp fashion by 15 $W \cdot min^{-1}$. Cadence was standardised at 75 $rev \cdot min^{-1}$ to reflect the spontaneously-chosen cadence of subjects performing maximal arm-cranking (32). The test was terminated when cadence dropped below 65 $rev \cdot min^{-1}$ for more than 3 s despite verbal encouragement. Cardiorespiratory variables were assessed continuously (see below) and peak values reported as the highest 30 s average. The gas-exchange threshold was identified independently by two investigators using multiple parallel methods (6).

Constant-load Exercise, Visits 3 & 4

After 3 min of rest and 3 min of light arm-crank exercise at 20 W, subjects abruptly transitioned to a work rate equivalent to 30% or 60% of the difference between gas-exchange threshold and $\dot{V}O_2$ peak (i.e., the work rate at gas exchange threshold plus 30% or 60% of the difference between the work rate at gas exchange threshold and the work rate at $\dot{V}O_2$ peak). The absolute work rates were reduced by 10 W (two-thirds of the initial ramp rate) to accommodate the mean lag time in $\dot{V}O_2$ that occurs during ramp exercise (42). The final work rates (Δ30% and Δ60%) were expected to result in physiological responses that are consistent with heavy- and severe-intensity exercise, respectively (23). Cadence was fixed at 75 $rev \cdot min^{-1}$ and the test was terminated if cadence dropped below 65 $rev \cdot min^{-1}$ for more than 3 s or if exercise duration exceeded 30 min.

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Cardiorespiratory, Metabolic and Perceptual Responses

Continuous measures of heart rate were made by telemetry (Vantage NV, Polar Electro, Kempele, Finland), arterial oxygen saturation (SpO_2) by forehead pulse oximetry (OxiMax N-560, Nellcor, Tyco Healthcare, Pleasanton, CA), and pulmonary ventilation and gas exchange via online gas analysis (Oxycon Pro, CareFusion, Hampshire, UK). Lactate concentration in whole-blood ([BLa]) was measured at resting baseline and immediately post-exercise via a 10 µl earlobe capillary sample (Biosen C-Line, EKF Diagnostic GmbH, Barleben, Germany). Intensity of breathing discomfort (dyspnea) and intensity of limb discomfort were rated using Borg's modified CR10 scale (7). Cardiorespiratory and perceptual responses to exercise were assessed on alternate minutes and at the point of exhaustion.

Respiratory Neuromuscular Responses

Electromyography and pressures. Neuromuscular activation of the crural diaphragm (EMG_{di}) was assessed using a bespoke multi-pair esophageal electrode catheter (Gaeltec Devices Ltd, Dunvegan, Isle of Sky, UK). The catheter comprised a 100 cm silicon shaft (2.7 mm diameter) with 7 platinum electrodes spaced 1 cm apart. Esophageal pressure (P_{es}) and gastric pressure (P_{ga}) were measured using two independent pressure transducers that were integrated with the esophageal catheter and positioned proximally and distally to the electrodes. The transducers were calibrated across the physiological range by placing the catheter within a sealed, air-filled tube to which positive and negative pressures were applied using a glass syringe (33). The

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calibration tube was connected to an electro-manometer (C9553, Comark, Norwich, Norfolk, UK), and the voltage outputs of each pressure transducer were calibrated against the reference pressures. The catheter was passed pernasally into the stomach until the diaphragm produced a positive pressure deflection on inspiration, and re-positioned based on the strength of EMG_{di} recorded simultaneously from different pairs of electrodes. Neuromuscular activation of the rectus abdominis (EMG_{ra}) was assessed using a pair of wireless surface electrodes (Trigno Wireless EMG, Delsys Inc., Natick, MA), positioned on the main belly of the muscle, 2 cm superior and 2-4 cm lateral to the umbilicus on the right-hand side of the torso, and placed in the same orientation as the muscle fibres (35). Raw EMG data were converted to root mean square (RMS) using a time constant of 100 ms and a moving window. All EMG data were expressed as a percentage of maximal EMG activity recorded during any maximal inspiratory or expiratory maneuver performed at rest or during exercise for a given experimental visit.

Respiratory mechanics and operating lung volumes. An analogue airflow signal from the online gas analysis system was input into the data acquisition system (see Data Processing below) and aligned to the pressure signals based upon the sampling delay for flow. Transdiaphragmatic pressure (P_{di}) was obtained by online subtraction of P_{es} from P_{ga}. Tidal pressure swings (ΔP_{es}, ΔP_{ga}, ΔP_{di}) were calculated as the changes in pressure from points of zero flow. Maximum pressures ($P_{es,max}$, $P_{ga,max}$, $P_{di,max}$) were obtained from maximal static inspiratory and expiratory maneuvers performed immediately before exercise. The work of breathing (W_b; work done per minute on the lungs) was calculated as the integral of the P_{es}-volume loop multiplied by respiratory frequency. Our assessment of W_b did not include work performed on the chest wall (e.g., rib cage distortion) and might, therefore, underestimate the mechanical work of breathing

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during exercise. Operating lung volumes were assessed using an inspiratory capacity (IC) maneuver performed in duplicate at resting baseline and during the final 30 s of alternate minutes of exercise starting at the first minute. Verbal encouragement was given to ensure a maximal inspiratory effort, and the maneuver was considered acceptable when P_{es} matched that achieved at baseline. End-expiratory lung volume (EELV) was calculated by subtracting IC from TLC. End-inspiratory lung volume (EILV) was calculated as the sum of tidal volume and EELV. Both EELV and EILV were expressed relative to TLC. To quantify the degree of diaphragm and abdominal muscle function during exercise that was due to locomotor (non-respiratory) loading, we compared intra-thoracic pressure swings and respiratory muscle electromyographic responses during five respiratory cycles at peak exercise to those recorded during five respiratory cycles immediately after exercise cessation.

Neuromuscular Stimulation

A monophasic magnetic stimulator (Magstim 200, The Magstim Company Ltd., Whitland, Wales) was used to deliver magnetic stimuli to the spinal foramina. A circular 90 mm coil was positioned at the cervical or thoracic spinal nerve roots to discriminate between the diaphragm and abdominal muscles, respectively (29, 22). The stimulator was discharged at 100% power when subjects were rested at functional residual capacity with the glottis closed. The catheter-mounted pressure transducer used in the current study has been shown to exhibit baseline drift after several hours of use (33). To minimise the extent of drift, the catheter was soaked in water for one hour before use and the amplifier gain settings were lowered. Furthermore, the pressure

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traces were checked immediately before stimulation and discarded if unstable. Cervical stimulation was favoured over anterolateral stimulation of the phrenic nerves as it allowed co-stimulation of the diaphragm and ribcage muscles, thereby allowing contractile fatigue in these muscles to be independently assessed (30). When stimulating the inspiratory muscles, subjects sat upright in a chair with their neck flexed and the coil positioned between the midline of the 5th (C5) and 7th (C7) cervical vertebrae. For the abdominal muscles, subjects sat facing an inclined bench (~70° from horizontal) with their chest supported, abdomen relaxed, and the coil positioned between the 8th (T8) and 11th (T11) thoracic vertebrae. The coil position that evoked the highest $P_{di,tw}$ or $P_{ga,tw}$ upon stimulation was marked on the skin and used for all subsequent stimulations. To determine whether the respiratory muscles were maximally activated after the delivery of magnetic stimuli, three single twitches were applied to the cervical and thoracic regions at incremental percentages of maximum stimulator output (50, 60, 70, 80, 85, 90, 95 and 100%). Each twitch was separated by 30 s to avoid potentiation. A plateau in mean $P_{di,tw}$ and $P_{ga,tw}$ was assumed to be indicative of maximal activation. Reliability of within-day measurements of respiratory muscle function was assessed by repeating baseline potentiated twitches after 30 min of quiet breathing. The order of diaphragm and abdominal muscle assessment was randomised, but consistent between trials for each subject.

Fatigue was quantified by measuring changes in neuromuscular function from pre-exercise baseline to post-exercise (5-15 and 25-35 min). The potentiated twitch is the most sensitive and valid measure of fatigue when the degree of fatigue is small or when levels of post-activation potentiation are unequal. Therefore, $P_{di,tw}$ and $P_{ga,tw}$ were assessed in response to stimulation of the cervical or thoracic nerves immediately after a maximal inspiratory or

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expiratory pressure maneuver, respectively. The maximal inspiratory and expiratory maneuvers were initiated from RV and TLC, respectively, and were maintained for 5 s against a semi-occluded airway. The procedure was repeated five times and the mean of the final three twitches was used for analysis. The primary outcome measure was the amplitude (baseline-to-peak) of the pressure response. Additional fatigue measures included contraction time (CT) and one-half relaxation time ($RT_{0.5}$). Membrane excitability was determined by measuring the peak-to-peak amplitude and duration of magnetically evoked M-waves. Fatigue was considered to be present if there was a ≥15% reduction in $P_{di,tw}$ or $P_{ga,tw}$ relative to pre-exercise baseline values at any time after exercise (13). This conservative definition of fatigue is based on a change that is approximately two- to threefold greater than the typical variation in rested $P_{di,tw}$ and $P_{ga,tw}$ (see Results).

Data Processing

Cardiorespiratory data during constant-load exercise were averaged over alternate 30 s intervals when ICs maneuvers were not being performed. Pressure signals were passed through an amplifier (1902, Cambridge Electronic Design, Cambridge, UK) and digitised along with airflow at a sampling rate of 150 Hz using an analogue-to-digital converter (micro 1401 mkII, Cambridge Electronic Design). EMG signals were sampled at 4 kHz, high-pass filtered at 100 Hz, and notch-filtered at 50 Hz to suppress power line and harmonic interference. Data were displayed as waveforms using data acquisition software (Spike 2 version 7.0, Cambridge

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Electronic Design). ECG artefacts were removed from the EMG waveforms using a script procedure similar to that described previously (3).

Statistics

Statistical analysis was performed using SPSS 16.0 for Windows (IBM, Chicago, IL). Cardiorespiratory, perceptual and metabolic responses over the final minute of heavy and severe exercise were assessed for differences using paired-samples *t*-test. Respiratory neuromuscular responses to constant-load exercise were assessed using two-way (intensity × time) repeated measures ANOVA. Supramaximality of twitch responses and differences in respiratory neuromuscular function across time (pre-exercise, 10 and 30 min post-exercise) were assessed using one-way repeated measures ANOVA with Fisher's LSD for post-hoc comparisons. Pearson's correlation coefficient (*r*) was computed to assess the relationship between pre- to post-exercise percent changes in respiratory muscle function and selected parameters. Reliability of evoked pressures ($P_{di,tw}$ and $P_{ga,tw}$) was assessed using coefficient of variation (CV) and intra-class correlation coefficient (ICC). A two-tailed α level of 0.05 was used as the cut-off for statistical significance. Results are presented as means ± SD.

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RESULTS

Pulmonary Function and Incremental Exercise

All subjects exhibited normal pulmonary function (VC [%pred] 5.76 ± 0.63 L [111 ± 10%]; FEV_1 4.99 ± 0.61 L [113 ± 11%]; FEV_1/VC 86.3 ± 2.7% [104 ± 3%]; TLC 7.55 ± 0.77 L [106 ± 8%]; MVV_{12} 186 ± 14 $L \cdot min^{-1}$ [108 ± 9%]; $D_{L,CO}$ 13.1 ± 1.6 $mmol \cdot min^{-1} \cdot kPa^{-1}$ [109 ± 12%]; P_{Imax} 132 ± 39 cmH_2O [113 ± 37%]; P_{Emax} 128 ± 20 cmH_2O [81 ± 14%]). Peak values for work rate and O_2 uptake during maximal incremental exercise were 126 ± 25 W and 2.06 ± 0.41 $L \cdot min^{-1}$ (27.3 ± 3.3 $ml \cdot kg^{-1} \cdot min^{-1}$), respectively. Work rate and $\dot{V}O_2$ at gas-exchange threshold were 60 ± 17 W and 1.17 ± 0.22 $L \cdot min^{-1}$ (57 ± 5% $\dot{V}O_2$ peak). The work rates predicted to elicit 30% and 60% of the difference between gas-exchange threshold and $\dot{V}O_2$peak (Δ30% and Δ60%) were 69 ± 18 W and 89 ± 20 W.

Constant-load Exercise

Cardiorespiratory, metabolic and perceptual responses. Peak values for heavy (Δ30%) and severe (Δ60%) exercise are shown in Table 1. Exercise duration was significantly shorter for severe compared to heavy exercise ($p < 0.001$). Three subjects reached the 30 min limit imposed for heavy exercise. However, all three subjects were considered to be close to their limit of tolerance as final minute responses and temporal profiles were similar to the remaining subjects. Heavy exercise elicited 81 ± 5% of the $\dot{V}O_2$ peak attained during incremental exercise, whereas

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severe exercise elicited values that were slightly, but not significantly, higher than attained during incremental exercise (108 ± 5%). Compared to heavy exercise, severe exercise elicited higher peak values for $\dot{V}O_2$ ($p < 0.001$), $\dot{V}CO_2$ ($p < 0.001$), RER ($p = 0.025$), $\dot{V}_E$ ($p = 0.022$), V_T ($p = 0.043$), V_T/T_I ($p < 0.001$), heart rate ($p = 0.005$), and [BLa] ($p = 0.006$). Temporal profiles for $\dot{V}O_2$, $\dot{V}_E$, V_T and f_R during heavy and severe exercise are shown in Fig. 1. During heavy exercise, $\dot{V}O_2$ and $\dot{V}_E$ rose sharply after exercise onset before approaching a steady-state. During severe exercise, $\dot{V}O_2$ and $\dot{V}_E$ continued to rise towards maximum values. At both intensities, the initial sharp rise in $\dot{V}_E$ was accounted for by progressive increases in f_R and V_T, whereas during the latter stages of exercise $\dot{V}_E$ was achieved primarily by increases in f_R (i.e., tachypnea). Minute ventilation over the final minute of heavy and severe exercise was 39 ± 11 and 53 ± 11% of maximum voluntary ventilation (MVV), respectively. Perceptual ratings of dyspnea were also higher during severe compared to heavy exercise ($p = 0.042$), as were the ratings of limb discomfort ($p = 0.031$). At the cessation of both exercise trials, 5 of 7 subjects reported higher ratings for limb discomfort than for dyspnea, with 2 subjects rating both perceptions equal. When asked their reasons for stopping, all seven subjects cited arm fatigue and/or peripheral discomfort.

Respiratory mechanics, electromyography and operating lung volumes. Group mean data for respiratory mechanics are shown in Table 2. Baseline pressure swings were not significantly different between the two trials. Mechanical responses over the final minute were significantly greater during severe exercise for $\Delta P_{di,insp}$ ($p = 0.002$), $\Delta P_{ga,insp}$ ($p = 0.008$), $\Delta P_{es,insp}$ ($p = 0.001$), $\Delta P_{ga,exp}/P_{ga,max}$ ($p = 0.005$), $\Delta P_{es,insp}/P_{es,max}$ ($p = 0.003$), and W_b ($p = 0.027$). Electromyographic activity of the diaphragm and abdominal muscles tended to be higher during severe versus heavy

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exercise, although statistical significance was noted only for the abdominals (p = 0.20 and 0.003, respectively). Operating lung volumes at baseline and during the first and final minute of heavy and severe exercise are shown in Fig. 2. Baseline values for EELV and EILV did not differ between heavy and severe exercise (EELV: 54 ± 6 vs. 55 ± 3% TLC, p = 0.70; EILV: 66 ± 4 vs. 65 ± 3% TLC, p = 0.42). During heavy exercise, EELV decreased below baseline then returned towards baseline as exercise progressed. By contrast, EELV at the first minute of severe exercise was similar to baseline, and elevated above baseline by the final minute (i.e., dynamic hyperinflation). Both EELV and EILV were higher during severe compared with heavy exercise at the first minute (EELV: 52 ± 5 vs. 45 ± 5% TLC; EILV: 77 ± 5 vs. 66 ± 8% TLC) and at the final minute (EELV: 58 ± 3 vs. 54 ± 7% TLC; EILV: 83 ± 7 vs. 77 ± 6% TLC), with significant main effects for exercise intensity (EELV: p = 0.034; EILV: p = 0.009).

Neuromuscular Function

Supramaximal stimulation and reliability. A near plateau in $P_{di,tw}$ and $P_{ga,tw}$ with increasing stimulator intensities was observed at baseline, with no significant differences in $P_{di,tw}$ (p = 0.14) or $P_{ga,tw}$ (p = 1.0) when the intensity was increased from 95 to 100%. There were no systematic differences in within-day, between-occasion measurements of respiratory muscle function, and reliability coefficients were <7% (CV) and >0.94 (ICC). Specifically, $P_{di,tw}$ and $P_{ga,tw}$ measured before and after 30 min of quiet rest were 56 ± 14 vs. 54 ± 11 cmH_2O (p > 0.05; CV 5.4%; ICC 0.96) and 59 ± 17 vs. 56 ± 14 cmH_2O (p > 0.05; CV 7.3%; ICC 0.94), respectively. Mean CV in $P_{di,tw}$ at baseline and at 5-15 and 25-35 min after heavy exercise was 6.9, 7.0, and 5.4% for heavy

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exercise (p = 0.715) and 7.2, 9.5, and 5.3% for severe exercise (p = 0.240), respectively. Corresponding values for $P_{ga,tw}$ were 5.4, 6.2, and 5.6% for heavy exercise (p = 0.860) and 5.9, 9.9, and 8.5% for severe exercise (p = 0.067). There were no significant differences at any time-point at either exercise intensity.

Pre- to post-exercise responses. Data for neuromuscular function before and after exercise are shown in Table 3. Pre-exercise baseline values were not different between the two trials (heavy vs. severe). No differences in diaphragm muscle contractility ($P_{di,tw}$) or inspiratory ribcage muscle function ($P_{es,tw}/P_{ga,tw}$) were noted across time in either trial. Abdominal muscle contractility ($P_{ga,tw}$) was also not different across time for heavy exercise (p = 1.0). After severe exercise, however, $P_{ga,tw}$ was significantly reduced below baseline (−22 ± 18%, p = 0.038) and only partially recovered by 30 min (−15 ± 15%, p = 0.066). Analysis of the individual responses after severe exercise showed that 5 of 7 subjects exhibited a ≥15% reduction in $P_{ga,tw}$ (30 ± 15%) and 2 of 7 subjects exhibited a ≥15% reduction in $P_{di,tw}$. After heavy exercise, 1 of 7 subjects exhibited a ≥15% reduction in $P_{ga,tw}$ with no subjects exhibiting a reduction ≥15% in $P_{di,tw}$. Within-twitch parameters (CT and $RT_{0.5}$) and M-wave characteristics (amplitude and duration) were not significantly different across time at either intensity. The degree of abdominal muscle fatigue (percent change in $P_{ga,tw}$) immediately after severe exercise for all subjects correlated significantly and positively with both exercise duration (r = 0.82, p = 0.024) and peak [BLa] (r = 0.94, p = 0.002), but there were no significant correlations between the degree of fatigue after severe exercise and $\dot{V}O_2$ peak (r = 0.48, p = 0.28), $\dot{V}_E$ peak (r = 0.46, p = 0.30), or P_{ga} (%max) (r = 0.34, p = 0.45). Finally, there were no remarkable differences between fatiguers and non-fatiguers for any of the ventilatory or neuromechanical responses to exercise.

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For the five subjects exhibiting a >15% reduction in abdominal muscle contractile function ($P_{ga,tw}$), there were substantial differences in the peak-to-post-exercise respiratory response (Fig. 3). Tidal volume increased immediately on cessation of both heavy exercise (1.75 to 1.88 L) and severe exercise (2.03 to 2.39 L). Gastric and transdiaphragmatic pressure swings dropped immediately after heavy exercise (ΔP_{ga} 18 to 10 cmH_2O; ΔP_{di} 50 to 30 cmH_2O) and severe exercise (ΔP_{ga} 25 to 12 cmH_2O; ΔP_{di} 72 to 40 cmH_2O). Electromyographic activity of the rectus abdominis and diaphragm also fell substantially after heavy exercise (EMG_{ra} 50 to 21% peak; EMG_{di} 37 to 21% peak) and severe exercise (EMG_{ra} 87 to 60% peak; EMG_{di} 88 to 40% peak).

DISCUSSION

Main Findings

This study is the first to use non-volitional (effort independent) motor nerve stimulation techniques to assess the influence of upper-body exercise on the fatigability of respiratory muscles in normal, healthy subjects. The main finding was that sustained, intense, upper-body exercise impaired abdominal muscle contractility, as evidenced by a significant reduction in $P_{ga,tw}$ immediately after severe, but not heavy, constant-load arm-crank exercise. By contrast, upper-body exercise did not influence the fatigability of the major muscles of inspiration, as demonstrated by non-significant changes in $P_{di,tw}$ (diaphragm) and $P_{es,tw}/P_{ga,tw}$ (inspiratory rib-cage muscles) after both heavy and severe exercise. The increased magnitude (and prevalence)

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of abdominal muscle fatigue associated with severe-intensity exercise might have been due to additional, non-respiratory loading of the thoracic complex (see below).

Exercise-induced Respiratory Muscle Fatigue

Using objective measures of fatigue (i.e., evoked pressures in response to motor nerve stimulation), we found a significant reduction in the $P_{ga,tw}$ response to magnetic stimulation of the thoracic nerves after severe, upper-body exercise. The time course of change in $P_{ga,tw}$ was consistent with previous studies using whole-body exercise (35, 40), with the greatest reduction observed within 5-15 min after exercise and partial recovery to baseline values by 25-35 min. The reduced $P_{ga,tw}$ after severe exercise is indicative of low-frequency peripheral fatigue. The underlying mechanisms are thought to be reduced Ca^{2+} release from the sarcoplasmic reticulum, reduced Ca^{2+} sensitivity of the myofibrils, and/or damaged sarcomeres caused by overextension of the muscle fibre (21). Since $P_{ga,tw}$ had partially returned to baseline by 25-35 min post-exercise, the fatigue observed was likely due to reduced calcium release and/or sensitivity.

The magnitude of the post-exercise reduction in $P_{ga,tw}$ (22%) was similar to that noted by previous studies for intense, whole-body exercise (e.g., 33% [35], 26% [37], 25% [36], and 13% [40]), despite markedly lower levels of ventilation in the present study (99 vs. 153, 138, 136 and 119 $L \cdot min^{-1}$). This observation suggests that abdominal muscle fatigue is largely independent of ventilation and that, irrespective of the mechanical-ventilatory stress imposed by exercise, there is an upper-limit for an acceptable reduction in abdominal muscle contractility beyond which

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exercise ventilation might be impaired (see below). The inter-individual fatigue response after severe exercise was variable, with 5 of 7 subjects (~70%) exhibiting evidence of abdominal muscle fatigue (≥15% reduction in $P_{ga,tw}$) and 2 of 7 subjects (~29%) showing evidence of diaphragmatic fatigue (≥15% reduction in $P_{di,tw}$). Abdominal muscle fatigue was present in 1 of 7 subjects (~14%) after heavy exercise, whereas there was no evidence of diaphragmatic fatigue at this intensity. It is not entirely clear why fatigue was present in some subjects but not others. Subject characteristics were similar and there were no remarkable fatigue-mediated differences in the ventilatory or neuromechanical responses to exercise. However, the significant correlation between the magnitude of fatigue and exercise duration suggests that the prevalence of fatigue might be related to the relative work capacity of the subject and therefore the absolute duration of exercise.

Methodological Considerations

To be confident that nerve stimulation techniques provide a valid measure of fatigue, it is important to consider potential sources of error (see also Methods). First, if pre- to post-exercise changes in twitch pressure are to be attributed to contractile fatigue, then nerve stimulation must be supramaximal. In the present study, there was a trend towards a plateau in both $P_{di,tw}$ and $P_{ga,tw}$ with increasing stimulator output, with no significant differences between 95 and 100%. While submaximal stimulation may underestimate the severity of fatigue (37), it seems unlikely that this would have influenced our finding of a difference in the magnitude and prevalence of fatigue for the diaphragm and abdominal muscles. Importantly, there were no significant

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changes in M-wave characteristics (amplitude and duration) for the stimulations delivered pre- to post-exercise (see Table 3). This latter finding strongly suggests that the reductions in evoked pressure immediately after exercise were attributable to contractile fatigue rather than transmission failure or de-recruitment of muscle fibres. In addition, all stimulations were performed at 100% of stimulator output and the coil positions were marked before exercise to ensure the coil was repositioned in the same location for each stimulation. Therefore, although stimulation may not have been completely maximal, it likely remained constant throughout the study. A second potential source of error is the lung volume, and hence muscle length, at which stimulations are initiated (31). In the present study, it was not possible to use end-expiratory P_{es} for the verification of lung volume due to the baseline-drift inherent to catheter-mounted pressure transducers (33). To enable lung volumes to return to baseline, post-exercise stimulations were initiated at 5 min into recovery. Importantly, the repeatability of evoked pressures ($P_{di,tw}$ and $P_{ga,tw}$) was not significantly different before versus after exercise at either intensity. We are confident, therefore, that all stimulations were initiated at the same lung volume and that differences in lung volume did not account for the influence of exercise intensity on the magnitude (and prevalence) of respiratory muscle fatigue. Third, potentiated (rather than unpotentiated) twitches were used as these provide greater sensitivity when measuring a small degree of fatigue. Potentiated twitches are also more valid for detecting fatigue when there is a differing level of post-activation potentiation, as might be expected in the present study due to differences in exercise duration between trials and, thus, exercise-induced respiratory muscle activation. Despite lower than normal values for maximum expiratory pressure ($P_{E,max}$), we are confident that the degree of potentiation was similar for the diaphragm and abdominal muscles. Indeed, previous studies have shown that twitch potentiation can be

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substantial after submaximal contractions (43) and that the degree of twitch potentiation is not significantly different between submaximal and maximal voluntary contractions (25). Fourth, the differences in fatigue noted in the present study were not merely a function of an inability to detect small within-day, between-trial changes in neuromuscular responses. There were no systematic differences in the measurements of respiratory muscle function when subjects were tested before and after 30 min of quiet breathing. Moreover, the within-day, between-occasion reliability of evoked pressures was excellent (CV range 4.8 - 7.3%) and similar to previously reported values: $P_{di,tw}$, 5.6% (38); $P_{ga,tw}$, 3.8% (35), 2.8% (37), and 7.0% (38). Thus, the methods used were likely sufficiently sensitive and reproducible to detect differences in exercise-induced respiratory muscle fatigue. A final consideration is the short-term recovery that likely occurs during the delay between end-exercise and post-exercise evaluation of neuromuscular function. While such a delay may underestimate the severity of fatigue during exercise (8), it is unlikely to explain the differences in the magnitude and prevalence of diaphragm and abdominal muscle fatigue noted in the current study.

Causes of Abdominal Muscle Fatigue

A time- and intensity-dependent increase in ventilation occurred during exercise (Fig. 1), requiring the progressive recruitment of inspiratory and expiratory muscles (Table 2). However, the overall ventilatory response was relatively low (<55% MVV). Furthermore, perceptual ratings of limb discomfort at end-exercise were higher than those reported for dyspnea, and all of the subjects cited limb fatigue and/or limb discomfort as their principal reasons for terminating

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severe exercise. These data are in general agreement with previous observations for maximal arm-crank exercise (28), suggesting that the exercise limitation was more closely associated with local (peripheral) than with central ventilatory factors. Since the majority of previous studies have only observed diaphragm fatigue at intensities exceeding 80% of whole-body $\dot{V}O_2$ max (see Introduction), it is perhaps unsurprising that arm-crank exercise did not induce contractile fatigue of the diaphragm. Our findings are in accordance with Taylor *et al.* (39) who found no evidence of diaphragm fatigue in athletes with cervical spinal cord injury performing exhaustive arm-crank exercise, during which ventilation peaked at <50 $L \cdot min^{-1}$. More recently, we observed a substantial (33%) reduction in $P_{di,tw}$ in a Paralympic athlete with low-thoracic spinal cord injury performing maximal arms-only rowing, during which ventilation peaked at >150 $L \cdot min^{-1}$ (27). Collectively, these data support the notion that high levels of pulmonary ventilation might be a prerequisite for diaphragm fatigue.

Since the diaphragm has both ventilatory and postural roles, it was expected that intense upper-body exercise would exacerbate diaphragm work, thereby leading to contractile fatigue, and yet this was not found. However, there is strong evidence to suggest that the diaphragm can only coordinate both postural and respiratory functions during transient, intermittent disturbances to trunk stability (e.g., brief arm movements) (19). When ventilation is mediated by humoral factors during sustained exercise, postural drive to the phrenic motoneurons is withdrawn and pontomedullary respiratory input to the diaphragm is instead prioritised (18). During prolonged exercise, therefore, protective mechanisms safeguard ventilation by offloading postural functions, thereby regulating pH and homeostatic balance (18). Although we were unable to assess phrenic postural input, a diminished postural drive to the diaphragm, coupled with a

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modest ventilatory demand, would be a likely explanation for the lack of diaphragm fatigue noted after maximal arm-crank exercise.

Although others have reported a relationship between the magnitude of reduction in $P_{ga,tw}$ after intense whole-body exercise and the ventilatory output or work performed by the abdominal muscles (35), our data suggest that contractile fatigue of the major expiratory muscles is not entirely dependent on ventilation. No significant correlations were found between peak values for $\dot{V}O_2$ or $\dot{V}_E$ during constant-load exercise and the magnitude of abdominal muscle fatigue, in agreement with previous studies (40). Furthermore, force output of the abdominal muscles ($\int P_{ga} \cdot f_R$) during maximal arm-crank ergometry was substantially higher than values reported previously for maximal lower-limb cycle ergometry (756 vs. ~600 $cmH_2O \cdot s \cdot min^{-1}$), despite a substantially lower minute ventilation during the former (99 vs. 153 $L \cdot min^{-1}$) (35). It seems highly likely, therefore, that a substantial proportion of the abdominal muscle force output noted in the present study comprised additional, non-respiratory work.

The abdominals do not exhibit the same respiratory modulation as the diaphragm (19) and, during dynamic upper-body exercise, might undergo excessive loading in carrying out a series of interrelated ventilatory and mechanical functions. As well as contracting to reduce EELV and expand tidal volume during exercise, the abdominals also contract isotonically to flex and rotate the vertebral column (10). Since severe exercise required a greater external power output than heavy exercise, the contribution of the abdominal muscles to locomotion was likely exacerbated. Indeed, neural drive to the rectus abdominis (EMG_{ra}) and abdominal muscle pressure swings (ΔP_{ga}) were significantly greater during severe versus heavy exercise. In an

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effort to quantify the respiratory muscle contribution to locomotor function, we compared the data from five respiratory cycles immediately before the cessation of exhaustive arm-cranking (peak-exercise) to five respiratory cycles performed immediately after the abrupt cessation of exercise when ventilation was still relatively high. When the high thoracic loads imposed by severe-intensity arm-cranking were relinquished, there was an abrupt increase in tidal volume (2.03 to 2.39 L), suggesting that arm-cranking imposes a degree of constraint on the ribcage. Although still present after heavy exercise, the increase in V_T was more modest (1.75 to 1.88 L). More pertinent is that intra-thoracic pressure swings and abdominal and diaphragm electromyographic activity were substantially reduced immediately after exercise cessation (see Fig. 3), suggesting that a substantial portion of the respiratory muscle activity observed during peak arm-cranking was due to non-respiratory loading of the thoracic complex (e.g., for posture and locomotion).

Consequences of Abdominal Muscle Fatigue

Exercise-induced abdominal muscle fatigue did not appear to impede alveolar ventilation or systemic O_2 content ($P_{ET}CO_2$ <25 mmHg over the final minute and SpO_2 >98%). However, end-expiratory (and end-inspiratory) lung volumes represented a significantly higher percentage of total lung capacity from the first minute of severe exercise through to exhaustion (i.e., dynamic hyperinflation) (see Fig. 2). At these high operating lung volumes, the inspiratory muscles must overcome additional elastic loads presented by the lung and chest wall (1). Furthermore, the pressure-generating capacity of the inspiratory muscles is impaired at high lung volumes because

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of alterations in the length-tension characteristics of the diaphragm and the orientation and motion of the ribs (12). There is also an increased dependence on accessory inspiratory muscles at high lung volumes (44). Collectively, these changes in inspiratory muscle function would be expected to increase the O_2 cost of breathing and elevate dyspnea (12).

While our study was not specifically designed to address the underlying mechanisms of dynamic hyperinflation during upper-body exercise, our observations do merit brief discussion. First, the hyperinflation during severe exercise might have been attributable to the greater exercise ventilation at this intensity (relative to heavy exercise). However, others have observed elevated lung volumes during arm-cranking performed by healthy subjects relative to leg-cycling at similar ventilations (2). This suggests that the locomotor mechanics of upper-body exercise might directly influence operating lung volumes. It is unlikely that abdominal muscle fatigue *per se* caused the increase in end-expiratory lung volume because the initial shift in lung volume occurred too early (<1 min) for contractile fatigue to be manifest (26). Moreover, prior fatigue of the abdominal muscles in healthy subjects was found to have no influence on operating lung volumes during subsequent high-intensity cycle exercise (36). It appears, therefore, that contractile fatigue of the abdominal muscles is not a causal factor in the control of operating lung volumes during exercise. As proposed previously (2), the abdominal muscle contribution to the regulation of end-expiratory lung volume during upper-body exercise might be compromised by increased requirements to stabilize the torso.

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Conclusions

This study is the first to present objective evidence of abdominal muscle fatigue in response to sustained, severe-intensity upper-body exercise in normal, healthy men. There was no concurrent fatigue of the diaphragm after heavy or severe upper-body exercise. It seems likely that the ventilatory role of the diaphragm was prioritised during exercise and that upper-body exercise was of insufficient ventilatory stress to induce contractile fatigue of the inspiratory muscles. By contrast, the abdominal muscle fatigue after severe exercise was likely caused by a combination of mechanical, postural and ventilatory demands induced by upper-body locomotor mechanics. This expiratory muscle *multi-tasking* might render the abdominal muscles particularly susceptible to contractile fatigue during intense upper-body exercise. Further research is needed to determine the implications of the findings for athletes involved in upper-body dominant sports and for clinical populations engaged in upper-body rehabilitation programmes.

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CONFLICT OF INTEREST

There were no conflicts of interest in the conception or production of this study. This study is unfunded. The results of the present study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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REFERENCES

1. Agostoni E, Rahn H. Abdominal and thoracic pressures at different lung volumes. *J Appl Physiol.* 1960;15(6):1087-92.

2. Alison JA, Regnis JA, Donnelly PM, Adams RD, Sullivan CE, Bye PT. End-expiratory lung volume during arm and leg exercise in normal participants and patients with cystic fibrosis. *Am J Respir Crit Care Med.* 1998; 158(5pt1):1450-8.

3. Alty SR, Man WD, Moxham J, Lee KC. Denoising of diaphragmatic electromyogram signals for respiratory control and diagnostic purposes. In: *Annual International Conference of the IEEE Engineering in Medicine and Biology Society;* 2008. p. 5560-3.

4. Babcock MA, Pegelow DF, McClaran SR, Suman OE, Dempsey JA. Contribution of diaphragmatic power output to exercise-induced diaphragm fatigue. *J Appl Physiol.* 1995;78(5):1710-9.

5. Babcock MA, Pegelow DF, Harms CA, Dempsey JA. Effects of respiratory muscle unloading on exercise-induced diaphragm fatigue. *J Appl Physiol.* 2002;93(1):201-6.

6. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol.* 1986;60(6):2020-7.

ACCEPTED

7. Borg G. *Borg's Perceived Exertion and Pain Scales.* 1st ed. Champaign (IL): Human Kinetics; 1998. 44-52 p.

8. Carroll TJ, Taylor JL, Gandevia SC. (2016). Recovery of central and peripheral neuromuscular fatigue after exercise. *J Appl Physiol.* 2016; [Epub ahead of print]. jap.00775.2016. http://dx.doi.org/10.1152/japplphysiol.00775.2016

9. Celli B, Criner G, Rassulo J. Ventilatory muscle recruitment during unsupported arm exercise in normal participants. *J Appl Physiol.* 1988;64(5):1936-41.

10. Cresswell AG, Grundstrom H, Thorstensson A. Observations on intra-abdominal pressure and patterns of abdominal intra-muscular activity in man. *Acta Physiol Scand.* 1992; 144(4):409-18.

11. Dempsey JA, Amann M, Romer LM, Miller JD. Respiratory system determinants of peripheral fatigue and endurance performance. Med Sci Sports Exerc. 2009;40(3):457-61.

12. De Troyer A, Wilson TA. Effect of acute inflation on the mechanics of the inspiratory muscles. *J Appl Physiol.* 2009;107(1):315-23.

13. Guenette JA, Romer LM, Querido JS, Chua R, Eves ND, Road JD, McKenzie DC, Sheel AW. Sex differences in exercise-induced diaphragmatic fatigue in endurance-trained athletes. *J Appl Physiol.* 2010; 109(1):35-46.

ACCEPTED

14. Harms CA, Babcock MA, McClaran SR, Pegelow DF, Nickele GA, Nelson WB, Dempsey JA. Respiratory muscle work compromises leg blood flow during maximal exercise. *J Appl Physiol.* 1997;82(5):1573-83.

15. Hodges PW, Butler JE, McKenzie DK, Gandevia SC. Contraction of the human diaphragm during rapid postural adjustments. *J Physiol.* 1997;505(2):539-48.

16. Hodges PW, Cresswell AG, Daggfeldt K, Thorstensson A. In vivo measurement of the effect of intra-abdominal pressure on the human spine. *J Biomech.* 2001;34(3):347-53.

17. Hodges PW, Eriksson AE, Shirley D, Gandevia SC. Intra-abdominal pressure increases stiffness of the lumbar spine. *J Biomech.* 2005;38(9):1873-80.

18. Hodges PW, Heijnen I, Gandevia SC. Postural activity of the diaphragm is reduced in humans when respiratory demand increases. *J Physiol.* 2001;537(3):999-1008.

19. Hodges PW, Gandevia SC. Activation of the human diaphragm during a repetitive postural task. *J Physiol.* 2000;522(1):165-75.

20. Johnson BD, Babcock MA, Suman OE, Dempsey JA. Exercise-induced diaphragmatic fatigue in healthy humans. *J Physiol.* 1993;460(1):385-405.

ACCEPTED

21. Jones DA. High- and low-frequency fatigue revisited. *Acta Physiol Scand.* 1996;156(3):265-70.

22. Kyroussis D, Mills GH, Polkey MI, Hamnegard CH, Koulouris N, Green M, Moxham J. Abdominal muscle fatigue after maximal ventilation in humans. *J Appl Physiol*. 1996;81(4):1477-1483.

23. Lansley KE, DiMenna FJ, Bailey SJ, Jones AM. A 'new' method to normalise exercise intensity. *Int J Sports Med.* 2011;32(7):535-41.

24. Lomax ME, McConnell AK. Inspiratory muscle fatigue in swimmers after a single 200 m swim. *J Sports Sci.* 2003;21(8):659-64.

25. Mador MJ, Magalang UJ, Kufel TJ. Twitch potentiation following voluntary diaphragmatic contraction. *Am J Respir Crit Care Med.* 1994;149(3):739-43.

26. Renggli AS, Verges S, Notter DA, Spengler CM. Development of respiratory muscle contractile fatigue in the course of hyperpnoea. *Respir Physiol Neurobiol.* 2008;164(3):366-72.

ACCEPTED

27. Romer LM, Tiller N, Aggar T, West CR. Exercise-induced diaphragm fatigue in an elite adaptive rower with spinal cord injury. In: *Proceedings of the 19th Annual Congress of the European College of Sport Science*; 2014 Jul 2-5: Amsterdam (The Netherlands). 2014. p. 654.

28. Sawka MN. Physiology of upper body exercise. *Exerc Sport Sci Rev.* 1986;14(1):175-212.

29. Similowski T, Fleury B, Launois S, Cathala HP, Bouche P, Derenne JP. Cervical magnetic stimulation: a new painless method for bilateral phrenic nerve stimulation in conscious humans. *J Appl Physiol.* 1989;67(4):1311-18.

30. Similowski T, Straus C, Attali V, Duguet A, Derenne JP. Cervical magnetic stimulation as a method to discriminate between diaphragm and rib cage muscle fatigue. *J Appl Physiol.* 1998;84(5):1692 – 700.

31. Smith J, Bellemare F. Effect of lung volume on in vivo contraction characteristics of human diaphragm. *J Appl Physiol.* 1987;62(5):1893-900.

32. Smith PM, Doherty M, Price MJ. The effect of crank strategy on peak aerobic power and peak physiological responses during arm-crank ergometry. *J Sports Sci.* 2007;25(6):711-18.

ACCEPTED

33. Stell IM, Tompkins S, Lovell AT, Goldstone JC, Moxham J. An in vivo comparison of a catheter mounted pressure transducer system with conventional balloon catheters. *Eur Respir J.* 1999;13(5):1158-63.

34. Stenberg J, Astrand PO, Ekblom B, Royce J, Saltin B. Hemodynamic responses to work with different muscle groups, sitting and supine. *J Appl Physiol.* 1967;22(1):61-70.

35. Taylor BJ, How SC, Romer LM. Exercise-induced abdominal muscle fatigue in healthy humans. *J Appl Pysiol.* 2006;100(5):1554-62.

36. Taylor BJ, How SC, Romer LM. Expiratory muscle fatigue does not regulate operating lung volumes during high-intensity exercise in healthy humans. *J Appl Physiol.* 2013;114(11):1569-76.

37. Taylor BJ, Romer LM. Effect of expiratory muscle fatigue on exercise tolerance and locomotor muscle fatigue in healthy humans. *J Appl Physiol.* 2008;104(5):1442-51.

38. Taylor BJ, Romer LM. Effect of expiratory resistive loading on inspiratory and expiratory muscle fatigue. *Respir Physiol Neurobiol.* 2009;166(3):164-74.

39. Taylor BJ, West CR, Romer LM. No effect of arm-crank exercise on diaphragmatic fatigue or ventilatory constraint in Paralympic athletes with cervical spinal cord injury. *J Appl Physiol.* 2010;109(2):358-66.

ACCEPTED

40. Verges S, Schulz C, Perret C, Spengler CM. Impaired abdominal muscle contractility after high-intensity exhaustive exercise assessed by magnetic stimulation. *Muscle Nerve.* 2006;34(4):423-30.

41. Volianitis S, McConnell AK, Koutedakis Y, McNaughton L, Backx K, Jones DA. Inspiratory muscle training improves rowing performance. *Med Sci Sports Exerc.* 2001;33(5):803-9.

42. Whipp BJ, Davis JA, Torres F, Wasserman K. A test to determine parameters of aerobic function during exercise. *J Appl Physiol.* 1981;50(1):217-21.

43. Wragg S, Hamnegard C, Road J, Kyroussis D, Moran J, Green M, Moxham J. Potentiation of diaphragmatic twitch after voluntary contraction in normal subjects. *Thorax.* 1994;49(12):1234-7.

44. Yan S, Kayser B. Differential inspiratory muscle pressure contributions to breathing during dynamic hyperinflation. *Am J Respir Crit Care Med.* 1997;156(2pt1):497-503.

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FIGURE CAPTIONS

Fig. 1. O_2 uptake (panel A), minute ventilation (panel B), tidal volume (panel C) and respiratory frequency (panel D) at rest (0 min) and during constant-load arm-crank exercise at heavy (30%Δ) and severe (60%Δ) intensities. Values approached a steady-state during heavy exercise, but continued to rise towards maximum values during severe exercise, with the exception of tidal volume, which showed a characteristic drop at near maximal ventilation. Data are means ± SD for 7 subjects. *$p < 0.05$, **$p < 0.01$.

Fig. 2. Operating lung volumes at resting baseline and during the first minute and final minute of heavy (30%Δ) and severe (60%Δ) constant-load arm-crank exercise. EELV and EILV were similar at rest in both conditions, but represented a higher percentage of TLC throughout severe exercise. During the final minute of severe exercise, EELV and EILV were elevated above rest, indicative of dynamic lung hyperinflation. EELV, end-expiratory lung volume; EILV, end-inspiratory lung volume; IRV, inspiratory reserve volume; V_T, tidal volume; ERV, expiratory reserve volume; IC, inspiratory capacity. Data are means for 7 subjects. Error bars have been removed for clarity. † $p < 0.05$, †† $p < 0.01$; significant main effect for exercise intensity.

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Fig. 3. Respiratory responses during and immediately after exhaustive constant-load arm-crank exercise for the five subjects who exhibited abdominal muscle fatigue (≥15% reduction in $P_{ga,tw}$). Data depict the mean of five respiratory cycles that preceded exercise cessation (peak-ex) compared to the first five respiratory cycles performed immediately after the abrupt cessation of exercise (post-ex). The left and right panels show data for heavy exercise and severe exercise, respectively. Note: one subject did not exhibit reliable EMG traces after heavy exercise, so data are for four subjects at this intensity.

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Figure 1

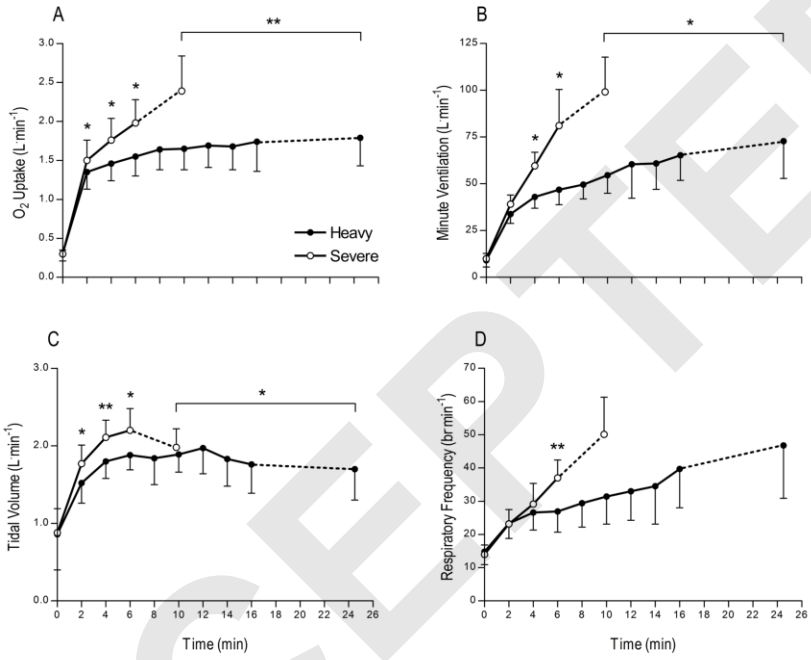

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Figure 2

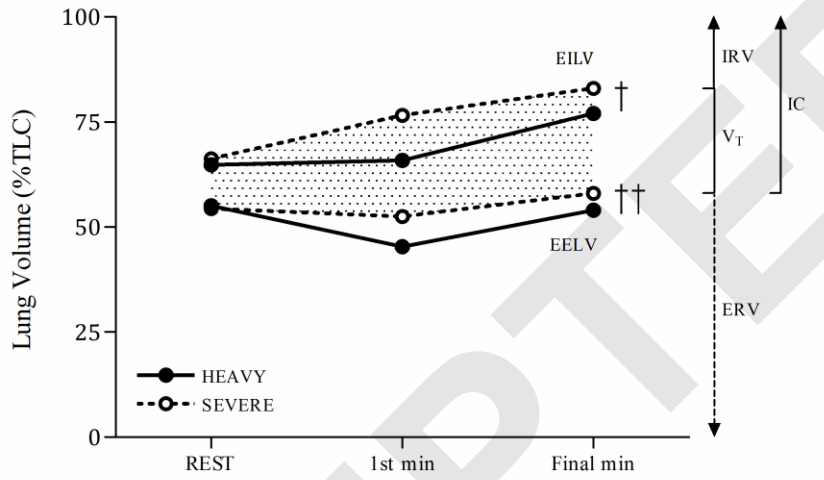

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Figure 3

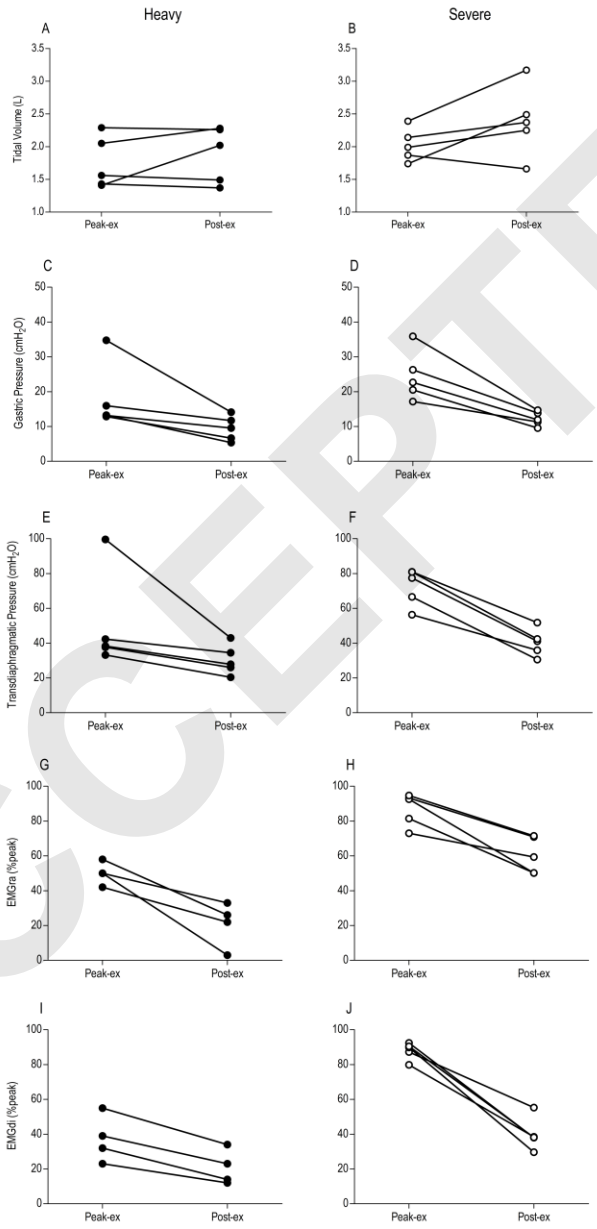

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Table 1. Peak cardiorespiratory, metabolic, and perceptual responses to constant-load exercise

	HEAVY (30%Δ)			SEVERE (60%Δ)		
Work rate, W	69	±	18	89	±	20**
T_{LIM}, min	24.5	±	5.8	9.8	±	1.8**
$\dot{V}O_2$, L/min	1.79	±	0.36	2.39	±	0.45**
$\dot{V}O_2$, %$\dot{V}O_{2peak}$	80	±	5	108	±	5**
$\dot{V}CO_2$, L/min	1.81	±	0.42	2.58	±	0.40**
RER	1.01	±	0.06	1.09	±	0.08*
$\dot{V}_E$, L/min	73	±	20	99	±	19*
$\dot{V}_E$, %MVV	39	±	11	53	±	11
V_T, L	1.70	±	0.40	1.98	±	0.24*
f_R, breaths/min	47	±	16	50	±	11
T_I, s	0.75	±	0.27	0.57	±	0.08
T_{TOT}, s	1.50	±	0.69	1.17	±	0.19
T_I/T_{TOT}	0.52	±	0.06	0.51	±	0.02
V_T/T_I, L/s	2.37	±	0.47	3.51	±	0.03**
$\dot{V}_E/\dot{V}O_2$	42	±	15	43	±	13
$\dot{V}_E/\dot{V}CO_2$	42	±	14	39	±	10
$P_{ET}CO_2$, mmHg	23.4	±	7.3	23.4	±	5.6
Heart rate, beats/min	143	±	11	163	±	5**
SpO_2, %	100	±	1	99	±	1
[BLa], mmol/L	6.4	±	1.7	9.3	±	2.1**
$CR10_{Dyspnea}$ (Dyspnoea)	7.0	±	2.0	8.1	±	2.2*
$CR10_{Limb}$	8.4	±	1.9	10.1	±	0.7*

Values are means ± SD for 7 subjects. T_{LIM}, time to the limit of tolerance; $\dot{V}O_2$, O_2 uptake; $\dot{V}CO_2$, CO_2 output; RER, respiratory exchange ratio; $\dot{V}_E$, minute ventilation; V_T, tidal volume; f_R, respiratory frequency; T_I, inspiratory time; T_{TOT}, total respiratory time; $P_{ET}CO_2$, end-tidal partial pressure of CO_2; SpO_2, arterial oxygen saturation; [BLa], blood lactate concentration; $CR10_{Dyspnoea}$, intensity of breathing discomfort; $CR10_{Limb}$, intensity of limb discomfort. *p < 0.05, **p < 0.01; significantly different vs. heavy exercise.

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Table 2. Peak respiratory neuro-mechanical responses to constant-load exercise

	HEAVY (30%Δ)	SEVERE (60%Δ)
$\Delta P_{di,insp}$, cmH_2O	33 ± 11	53 ± 13**
$\Delta P_{di,insp}/P_{di,max}$, %	21 ± 6	35 ± 10**
$\Delta P_{ga,insp}$, cmH_2O	13.9 ± 5.5	23.2 ± 6.8**
$\Delta P_{es,insp}$, cmH_2O	19.3 ± 6.7	29.7 ± 9.3**
$\Delta P_{ga,exp}/P_{ga,max}$, %	8 ± 2	14 ± 2**
$\Delta P_{es,insp}/P_{es,max}$, %	13 ± 5	20 ± 7**
P_{es}/P_{ga}	1.46 ± 0.49	1.35 ± 0.45
W_b, J/min	168 ± 131	321 ± 169*
$EMG_{di,insp}$, $\%RMS_{max}$	50 ± 33	70 ± 23
$EMG_{ra,exp}$, $\%RMS_{max}$	31 ± 22	60 ± 10**

Values are means ± SD for 7 subjects (6 for EMG). $\Delta P_{di,insp}$, inspiratory tidal transdiaphragmatic pressure; $\Delta P_{di,insp}/P_{di,max}$, inspiratory tidal transdiaphragmatic pressure relative to maximum static inspiratory transdiaphragmatic pressure $\Delta P_{ga,insp}$, inspiratory tidal gastric pressure; $\Delta P_{es,insp}$, inspiratory tidal esophageal pressure; $\Delta P_{ga,exp}/P_{ga,max}$, expiratory tidal gastric pressure relative to maximum static expiratory gastric pressure; $\Delta P_{es,insp}/P_{es,max}$, inspiratory tidal esophageal pressure as a percentage of maximum static inspiratory esophageal pressure; W_b, work of breathing; $EMG_{di,insp}$, electromyographic activity of the diaphragm during inspiration; $EMG_{ra,exp}$, electromyographic activity of the rectus abdominis during expiration. $*p < 0.05$, $**p < 0.01$; significantly different vs. heavy exercise.

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Table 3. Neuromuscular function before and up to 30 min after constant-load exercise

	HEAVY (30%Δ)			SEVERE (60%Δ)		
	Pre-ex	5-15 min	25-35 min	Pre-ex	5-15 min	25-35 min
Inspiratory						
$P_{di,tw}$, cmH_2O	53 ± 13	58 ± 11	57 ± 14	55 ± 10	52 ± 15	54 ± 14
$P_{es,tw}/P_{ga,tw}$	0.69 ±	0.75 ±	0.75 ±	0.71 ±	0.88 ±	0.80 ±
CT, ms	84 ± 10	82 ± 7	84 ± 14	87 ± 6	87 ± 8	80 ± 17
$RT_{0.5}$, ms	66 ± 13	60 ± 14	64 ± 10	65 ± 11	55 ± 12	60 ± 6
M-wave amplitude, mV	3.2 ± 0.1	3.0 ± 0.2	3.0 ± 0.2	2.9 ± 03	2.9 ± 0.4	2.9 ± 0.4
M-wave duration, ms	1.5 ± 0.1	1.5 ± 0.2	1.5 ± 0.2	1.6 ± 0.1	1.5 ± 0.2	1.6 ± 0.1
$P_{I,max}$, cmH_2O	119 ± 27	121 ± 39	109 ± 20	127 ± 38	126 ± 41	130 ± 39
Expiratory						
$P_{ga,tw}$, cmH_2O	54 ± 15	54 ± 18	54 ± 18	53 ± 15	41 ± 13*	46 ± 14
CT, ms	92 ± 33	81 ± 26	81 ± 21	91 ± 24	83 ± 29	80 ± 19
$RT_{0.5}$, ms	133 ± 28	115 ± 29	120 ± 37	126 ± 30	120 ± 42	122 ± 30
M-wave amplitude, mV	2.2 ± 1.0	2.1 ± 1.0	1.7 ± 0.8	2.4 ± 1.5	2.2 ± 1.3	2.1 ± 1.1
M-wave duration, ms	13.7 ± 4.8	12.3 ± 4.6	11 ± 4.6	14.1 ± 3.9	14.1 ± 4.9	14.5 ± 4.3
$P_{E,max}$, cmH_2O	118 ± 16	108 ± 22	109 ± 20	117 ± 21	119 ± 27	113 ± 24

Values are means ± SD for 7 subjects (6 for EMG). $P_{di,tw}$, twitch transdiaphragmatic pressure; $P_{es,tw}$, twitch esophageal pressure; $P_{ga,tw}$, twitch gastric pressure; CT, contraction time; $RT_{0.5}$, one-half relaxation time; $P_{I,max}$, maximum static inspiratory pressure; $P_{E,max}$, maximum static expiratory pressure. *$p < 0.05$, significantly different vs. pre-exercise (Pre-ex) at the same exercise intensity.

ACCEPTED