Eur J Appl Physiol (2005) 95: 52–56
DOI 10.1007/s00421-005-1399-z

ORIGINAL ARTICLE

**Atila Ozkaplan · Edward C. Rhodes · A. William Sheel
Jack E. Taunton**

A comparison of inspiratory muscle fatigue following maximal exercise in moderately trained males and females

Accepted: 12 May 2005 / Published online: 23 June 2005

Abstract Exercise-induced inspiratory muscle fatigue (IMF) has been reported in males but there are few reports of IMF in females. It is not known if a gender difference exists for inspiratory muscle strength following heavy exercise, as is reported in locomotor muscles. Therefore, the relationship between fatigue and subsequent recovery of maximal inspiratory pressure (MIP) following exercise to maximal oxygen consumption ($\dot{V}_{O_{2max}}$) was examined in a group of moderately trained males and females. Eighteen males (23 ± 3 years; mean ± SD) and 16 females (23 ± 2 years) completed ten MIP and ten maximal handgrip (HG) strength maneuvers to establish baseline. Post-exercise MIP and HG were assessed successively immediately following a progressive intensity $\dot{V}_{O_{2max}}$ test on a cycle ergometer and at 1, 2, 3, 4, 5, 10, and 15 min. $\dot{V}_{O_{2max}}$, relative to fat-free mass was not statistically different between males (62 ± 7 ml kg^{-1} min^{-1}) and females (60 ± 8 ml kg^{-1} min^{-1}). Males had higher absolute MIP values than females at all time intervals ($P < 0.05$). Immediately following exercise, MIP was significantly reduced in both genders ($M = 83 \pm 16\%$; $F = 78 \pm 15\%$ of baseline) but HG values were not different than resting values. MIP values remained depressed for both males and females throughout the 15 min ($P < 0.05$). Differences for MIP between males and females were not statistically significant at any measurement time ($P > 0.05$). The findings in this study conclude that IMF, observed immediately following maximal exercise, demonstrated the same pattern of recovery for both genders.

Keywords Male and female · Inspiratory muscle fatigue · Maximal inspiratory pressure · Incremental exercise · Maximal voluntary contraction

Introduction

Whole-body, high intensity endurance exercise causes respiratory muscle (diaphragmatic) fatigue in healthy subjects with a variety of fitness levels (Johnson et al. 1993). The magnitude and likelihood of diaphragmatic fatigue increases at exercise above 85% of $\dot{V}_{O_{2max}}$ (Johnson et al. 1993). Exercise-induced inspiratory muscle fatigue (IMF) is reported in males (Babcock et al. 1996; Boussana et al. 2003; Bye et al. 1984; Coast et al. 1990; Johnson et al. 1993; McConnell et al. 1997; Volianitis et al. 1999), but there are few reports of IMF in females (Coast et al. 1999; Volianitis et al. 2001).

The fatigability of locomotor muscle is reported to be different between males and females. Current evidence suggests that females demonstrate a greater resistance to fatigue, as measured by greater endurance in several locomotor muscles, including the knee extensors (Pincivero et al. 2003). Most studies showing greater resistance to fatigue in females have used submaximal contraction intensities (e.g., 20% maximum voluntary contraction, MVC) to induce fatigue. While the differences vary, depending on the muscle group studied, only one study has concentrated specifically on the muscles of respiration (Gonzales et al. 2003). The majority of studies have focused solely on male subjects. The few studies, that have included females, did not analyze the results in terms of a gender comparison (Coast et al. 1999; Volianitis et al. 2001). It is not known if a gender difference exists for inspiratory muscle strength following heavy exercise.

Therefore, the purpose of this study was to characterize the relationship between fatigue and subsequent recovery of maximal inspiratory pressure (MIP) following exercise to $\dot{V}_{O_{2max}}$ in both males and females.

A. Ozkaplan · E. C. Rhodes (✉) · A. W. Sheel
J. E. Taunton
School of Human Kinetics, University of British Columbia,
UBC War Memorial Gym 210, 6081 University Blvd,
Vancouver, BC, V6T 1Z1, Canada
E-mail: ecrhodes@interchange.ubc.ca
Fax: +1-604-8226842

Methods and procedures

Subjects

Eighteen males and 16 females (non-smokers) with no chronic or acute respiratory conditions (e.g., asthma, cold, flu, etc.) volunteered for the study. Mean values ± SD for age, height, and weight were 23 ± 2 years, 168 ± 5 cm, and 62 ± 8 kg for the women, and 23 ± 3 years, 180 ± 6 cm, and 78 ± 10 kg for the men. Prior to testing, informed consent was received from all subjects. Ethical approval was obtained from the UBC Office of Research Services Clinical Research Ethics Board with the use of human subjects in accordance with the Declaration of Helsinki.

Hydrostatic weighing

As the average female has a higher percentage of body fat (5–10%) and lower muscle mass compared to the average male, it has been suggested that maximal aerobic capacity be indicated relative to fat-free mass (FFM) (Cureton and Sparling 1980; Tarnapolsky and Saris 2001). To calculate body volume, a hydrostatic weighing technique, based on Archimedes' principle was used (McArdle et al. 2001). FFM was estimated for each subject through densitometry, where body density equals body mass divided by body volume (McArdle et al. 2001).

Maximal exercise to fatigue

After a familiarization task, each individual alternated between at least five MIPs and five maximal handgrip (HG) maneuvers to establish a pre-test baseline. Subjects performed a maximum of nine MIPs for establishing their top three. The highest value within 10% of the other trials was considered the maximum effort (Black and Hyatt 1969). Maximal aerobic fitness was evaluated by an incremental stage $\dot{V}_{O_{2max}}$ bicycle ergometer test, utilizing the Sensor Medics Vmax 29 series metabolic measurement cart (Sensor Medics, Yorba Linda, CA USA). Breath-by-breath values were averaged over 20 s intervals and displayed on the monitor. All participants began stage one pedaling at 50 W, with subsequent increases of 30 W per minute, until task failure (exhaustion) (Boussana et al. 2003). All subjects were encouraged to keep their pedaling rate at approximately 75 rpm. Oxygen uptake ($\dot{V}_{O_2}$), CO_2 production ($\dot{V}_{CO_2}$), and minute ventilation ($\dot{V}_E$) were recorded on a breath-by-breath basis and averaged over a 20 s interval. Heart rate (HR) and ratings of perceived exertion (RPE) (Borg and Noble 1974) for dyspnea and locomotor muscle fatigue were measured at 1-min intervals during the exercise task (Harms et al. 2000). An 11-point visual representation of the scale was placed in front of the subject while they continued to pedal. They were asked to point to the value (0–10) corresponding to the breathing and leg discomfort, respectively.

The task was terminated at volitional fatigue, when the pedal cadence fell below 45 rpm. A maximal test was confirmed based on pre-determined indicators; respiratory exchange ratio (RER) above 1.1, HR within ten beats of age predicted maximum HR (220-age), and a plateau in $\dot{V}_{O_{2max}}$ [either a decrease or an increase of < 2 ml kg^{-1} min^{-1}] (ACSM 2000). $\dot{V}_{O_{2max}}$ was determined by averaging the highest $\dot{V}_{O_2}$ values over two consecutive 20 s intervals.

Immediately following the termination of the task, the first post-exercise MIP and HG measures were recorded. Further MIP and HG recordings were taken at 1-min intervals after the immediate MIP. HR measures were continually recorded, corresponding to each MIP/HG measurement interval.

Techniques

MIPs, as produced during a brief, quasi-static contraction (Müeller maneuver), reflect the capacity of the global inspiratory muscles to generate force (Larson et al. 1993). MIP was measured using a hand-held mouth pressure meter [Micro Mouth Pressure Meter (MP01), Micro Medical, UK], that included a 1 mm hole to prevent glottic closure. Similar hand-held devices have been utilized due to their ease of use, portability and accuracy (McConnell et al. 1997; Volianitis et al. 1999, 2001). Portable measurements of maximum mouth pressures have been deemed reliable and accurate in the normal and patient population, when compared to measures utilizing a pressure transducer (Hamnegård et al. 1994). The participants were instructed to expire to residual volume (RV) and then inspire maximally in order to generate the greatest inspiratory pressure. Producing each maximal effort from RV has been suggested to control for the initial length of the inspiratory muscles (Volianitis et al. 2001). More importantly, measuring MIP from RV ensures that the highest pressures are recorded. Subjects placed a nose clip over their nostrils upon expiration to ensure maximal recordings from the mouth. The participants were verbally encouraged by the investigator throughout all trials.

Maximal HG strength measurements were recorded in alternating fashion after each MIP measure. Subjects were advised to hold the HG dynamometer (T.K.K. Grip A, Takei, Tokyo, Japan) in their dominant hand, exhale, and then squeeze forcefully. They were instructed to avoid contacting the dynamometer with any part of their body. The average of the two highest values was used as the maximal value. This additional test was used to confirm, that the anticipated decreases in post-exercise MIP values, were not the result of reduced motivation (Fuller et al. 1996) or general whole-body fatigue (Coast et al. 1999).

Statistics

Mean values and standard deviations were calculated with conventional procedures. Between group (male and female) differences were analyzed by a group (2) by time (9) repeated measures analysis of variance (ANOVA). A similar group (2) by time (5) repeated measures ANOVA was used for analysis of pooled time. Alpha was set at 0.05.

Results

Resting (baseline) HR values were similar between the genders (*M*: 68.9 ± 9.1 bpm; *F*: 68.3 ± 7.4 bpm) ($P > 0.05$). However, males had significantly higher HG (*M*: 51.6 ± 6.9 kg; *F*: 30.5 ± 4.9 kg) and MIP values (*M*: 153.4 ± 28.2-cmH_2O; *F*: 106.4 ± 18.9 cmH_2O) ($P < 0.05$).

Maximal exercise testing (Table 1) showed that males had higher $\dot{V}_{O_{2max}}$ values ($P < 0.05$). However, when these values were calculated relative to FFM, the $\dot{V}_{O_{2max}}$ values were not statistically different ($P > 0.05$). Respiratory parameters during maximal exercise demonstrated varying results. The male subjects had significantly greater minute ventilation ($\dot{V}_E$) and tidal volume (V_T) when compared to the females ($P < 0.05$). The males also had RER ($P < 0.05$). There was no statistically significant difference between the frequency of breathing (fb), RPE (leg), and RPE dyspnea ($P > 0.05$). Peak HR values were significantly higher in males ($P < 0.05$). The males also exerted significantly higher maximal power ($P < 0.05$).

MIP were recorded within 20 s of volitional fatigue (20.6 ± 7.1 s) and at subsequent 1-min intervals. MIP showed a similar pattern of recovery following maximal exercise in both groups (Fig. 1). Both groups demonstrated a significant drop in MIP immediately following exercise, and this remained intact for the 15 min post-exercise. MIP values for the females were similar to the males ($P > 0.05$).

Table 1 Comparison of selected parameters between male and female groups at $\dot{V}_{O_{2max}}$

	Males	Females
N	18	16
$\dot{V}_{O_{2max}}$ (l min^{-1})	3.87 ± 0.5	2.76 ± 0.6*
$\dot{V}_{O_{2max}}$ (ml kg^{-1} min^{-1})	50.3 ± 6.9	44.9 ± 8.3*
$\dot{V}_{O_{2max}}$ FFM (ml kg$[FFM]^{-1}$ min^{-1})	61.6 ± 6.6	59.8 ± 7.6
$\dot{V}_E$ (l min^{-1})	163.4 ± 16.1	107.8 ± 17.0*
RER	1.24 ± 0.1	1.19 ± 0.1*
V_T (l)	3.22 ± 0.5	2.12 ± 0.3*
Fb	48.6 ± 8.6	49.1 ± 5.8
Hrpeak	191.1 ± 9.3	182.6 ± 7.3*
Maximal external power	274.9 ± 71.0	218.7 ± 45.0
Dyspnea (RPE)	7.89 ± 1.5	7.50 ± 1.7
Leg (RPE)	8.33 ± 1.6	8.00 ± 1.8

Values are means ± SD; *n* no of subjects; $\dot{V}_{O_{2max}}$, maximal oxygen consumption; $\dot{V}_E$, minute ventilation; *RQ* respiratory quotient; *VT* tidal volume; *fb* frequency of breathing; *HR* heart rate; *RPE* ratings of perceived exertion; *W* maximal external power

*Significantly different from male group ($P < 0.05$)

The average values for HG over 15 min, also showed no change relative to baseline. The HG values were at 98 and 97% of baseline for males and females, respectively (Fig. 1). The average HG values for each gender, as well as for the group as a whole, were significantly different than baseline at the 3–5 min post-exercise interval ($P < 0.05$). Consequently, the HG measures, in both genders, returned to approximate baseline levels at the 10–15 min time interval.

Discussion

The moderately trained, university-aged, male and female subjects in this study, demonstrated significant decline in their ability to reproduce baseline MIPs following an incremental cycle to volitional fatigue. The failure to develop force and/or velocity, as a result of muscle activity under load, that is reversible with rest, defines fatigue (NHLBI 1980). The found results could be most likely attributed to respiratory muscle fatigue, since our methodology did not include proof with more stringent twitch transdiaphragmatic pressure measurements (Pdi_{twitch}). The data from this study, therefore, contribute further support to the growing literature using similar techniques suggesting that maximal exercise can induce fatigue in the muscles of inspiration (Boussana et al. 2003; Gonzales et al. 2003; Volianitis et al. 2001).

These results are of particular importance because they demonstrated that serial measurement of MIP is a robust method for quantifying fatigue. Specifically, the study showed that the 1-min intervals were long enough to demonstrate valid measures of fatigue within inspiratory muscles.

The differences between the genders in maximal inspiratory muscle strength at each of the time interval were not significant ($P > 0.05$). The two groups presented similar patterns of fatigue and recovery. The results suggest that the underlying mechanisms concerning fatigue and recovery are similar for males and females.

The resultant changes in MIP were not due to generalized fatigue or decreased central effort, since there was no change in HG (Coast et al. 1999). The conversion of HG to percentages of baseline maximum strength, presented slightly unusual results. Significant differences ($P < 0.05$) existed between the 3–5 min time interval and baseline. These results could signify that the serial measures for HG were in themselves fatiguing. In both groups the HG measures presented similar trends. There was no significant difference between baseline HG and HG measures averaged over 15 min. It was likely that these results were due to the frequency of the measurement tasks and not due to overall body fatigue. The apparent lack of overall fatigue in HG, with a corre-

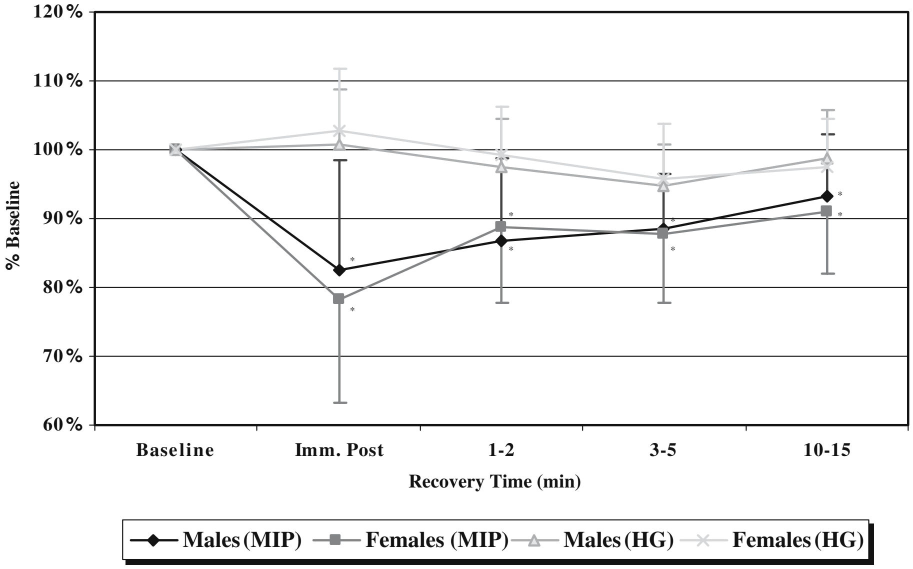

Fig. 1 Baseline and percent recovery of maximal handgrip strength and maximal inspiratory pressure post-maximal exercise. *Values* are percentage means ± SD. HG: $F_{\mathrm{GENDER}} = 0.286$; $P > 0.05$; $F_{\mathrm{TIME}} = 11.638$; $P < 0.001$; $F_{\mathrm{GENDER\,*\,TIME}} = 0.742$; $P > 0.05$. MIP: $F_{\mathrm{GENDER}} = 0.456$; $P > 0.05$; $F_{\mathrm{TIME}} = 22.385$; $P < 0.001$; $F_{\mathrm{GENDER\,*\,TIME}} = 0.992$; $P > 0.05$. *Significantly different from baseline, $P < 0.05$

sponding decrease in MIP, suggests that the exercise task did fatigue the respiratory muscles specifically.

Exercise-induced IMF and the implications of the timeline for recovery

The decline in post-exercise MIP is consistent with several studies that have looked at exercise-induced IMF (Boussana et al. 2003; Coast et al. 1999; Volianitis et al. 1999, 2001). However, these findings are still disputed. A number of studies have not been able to show these similar results (Coast et al. 1990; Johnson et al. 1993; Perret et al. 1999). Also, whole body endurance exercise in healthy subjects has been shown to cause diaphragmatic fatigue in a wide range of fitness levels (Johnson et al. 1993).

MIP values in the present study remained lower than baseline in both groups for the entire 15 min post-exercise timeline. These findings are similar to Coast et al. (1999). They showed a 15% drop in MIP post-maximal exercise that remained lower for 15 min. These findings may be consistent with other studies that have shown IMF to occur after exhaustive exercise and remain lower for up to 24 h post-task (Laghi et al. 1995). However, the comparison cannot be unquestioned and must keep in mind the differences between an incremental exercise test and constant-load exercise. Laghi et al. (1995) showed that recovery of diaphragmatic contractility was not complete 24 h after induction of diaphragmatic fatigue. This statement related to the precision of the techniques used to determine $\mathrm{Pdi}_{\mathrm{twitch}}$, as opposed to MIP, a volitional measure.

Volianitis et al. (2001) presented MIP values that were lower after 6 min of maximal rowing. The use of competitive rowers reiterated Johnson et al.'s (1993) suggestion that even those with high levels of aerobic fitness were not impervious to IMF.

Gender differences in IMF

Our study suggests that recovery from IMF post-exercise was similar between males and females. There were no significant differences for percent baseline MIP between the groups at any time interval. The results demonstrated IMF occurred in both males and females following exhaustive exercise. Post-exercise MIP values were not significantly different between the male and female subjects at each of the time intervals. The pattern of recovery was shown to be similar between the genders. Also, fb was not different between the males and females. Our results showed that females do not rely on a greater fb at any given $\dot{V}_{\mathrm{E}}$ compared to males. No statistically significant differences for RPE (dyspnea and leg) were evidenced between the two groups. Although a paucity of knowledge still exists, results from the present study provide important evidence for the fatigability of inspiratory muscles in female subjects.

Acknowledgements The technical assistance of Rob Langill is greatly appreciated. Our thanks go out to our subjects for their cooperation during the tests.

References

ACSM's guidelines for exercise testing and prescription (2000), 6th edn. Lippincott Williams and Wilkins, Philadelphia, p 77

Babcock MA, Pegelow DF, Johnson BD, Dempsey JA (1996) Aerobic fitness effects on exercise-induced low-frequency diaphragm fatigue. J Appl Physiol 81:2156–2164

Black LF, Hyatt RE (1969) Maximal respiratory pressures: normal values and relationship to age and sex. Am Rev Respir Dis 99:696–702

Borg GAV, Noble BJ (1974) Perceived exertion. Exerc Sport Sci Rev 2:131–153

Boussana A, Galy O, Hue O, Matecki S, Varray A, Ramonatxo M, Le Gallais D (2003) The effects of prior cycling and successive run of respiratory muscle performance in triathletes. Int J Sports Med 24:63–70

Bye PTP, Esau SA, Walley KR, Macklem PT, Pardy RL (1984) Ventilatory muscles during exercise in air and oxygen in normal men. J Appl Physiol 56:464–471

Coast JR, Clifford PS, Henrich TW, Stray-Gundersen J, Johnson RL Jr (1990) Maximal inspiratory pressure following maximal exercise in trained and untrained subjects. Med Sci Sports Exerc 22:811–815

Coast JR, Haverkamp HC, Finkbone CM, Anderson KL, George SO, Herb RA (1999) Alterations in pulmonary function following exercise are not caused by the work of breathing alone. Int J Sports Med 20:470–475

Cureton KJ, Sparling PB (1980) Distance running performance and metabolic responses to running in men and women with excess weight experimentally equated. Med Sci Sports Exerc 12:288–294

Fuller D, Sullivan J, Fregosi RF (1996) Expiratory muscle endurance performance after exhaustive submaximal exercise. J Appl Physiol 8:1495–502

Gonzales JU, Williams JS, Scheuermann BW, James CR (2003) Gender differences in respiratory muscle function following exhaustive exercise. Med Sci Sports Exerc 35:S835 [Abstract]

Hamnegård C-H, Wragg S, Kyroussis D, Aquilina R, Moxham J, Green M (1994) Portable measurement of maximum mouth pressures. Eur Respir J 7:398–401

Harms CA, Wetter TJ, St. Croix CM, Pegelow DF, Dempsey JA (2000) Effects of respiratory muscle work on exercise performance. J Appl Physiol 89:131–138

Johnson BD, Babcock MA, Suman OE, Dempsey JA (1993) Exercise-induced diaphragmatic fatigue in healthy humans. J Physiol 360:385–405

Laghi F, D'Alfonso N, Tobin MJ (1995) Pattern of recovery from diaphragmatic fatigue over 24 hours. J Appl Physiol 79:539–546

Larson JL, Covey MK, Vitalo CA, Alex CG, Patel M, Kim MJ (1993) Maximal inspiratory pressure. Learning effect and test-retest reliability in patients with chronic obstructive pulmonary disease. Chest 104:448–453

McArdle WD, Katch FI, Katch VI (2001) Exercise physiology, 5th edn. Lippincott Williams and Wilkins, Philadelphia, pp 766–772

McConnell AK, Caine MP, Sharpe GR (1997) Inspiratory muscle fatigue following running to volitional fatigue: the influence of baseline strength. Int J Sports Med 18:169–173

NHLBI Workshop Summary (1980) Respiratory muscle fatigue: report of the respiratory muscle fatigue workshop group. Am Rev Respir Dis 142:474–480

Perret C, Pfeiffer R, Boutellier U, Wey HM, Spengler CM (1999) Noninvasive measurement of respiratory muscle performance after exhaustive endurance exercise. Eur Respir J 14:264–269

Pincivero DM, Gandaio CB, Ito Y (2003) Gender-specific knee extensor torque, flexor torque, and muscle fatigue responses during maximal effort contractions. Eur J Appl Physiol 89:134–141

Tarnapolsky MA, Saris WHM (2001) Evaluation of gender differences in physiology: an introduction. Curr Opin Clin Nutr Metab Care 4:489–492

Volianitis S, McConnell AK, Koutedakis Y, Jones DA (1999) The influence of prior activity upon inspiratory muscle strength in rowers and non-rowers. Int J Sports Med 20:542–554

Volianitis S, McConnell AK, Koutedakis Y, Jones DA (2001) Specific respiratory warm-up improves rowing performance and exertional dyspnea. Med Sci Sports Exerc 33:1189–1193