Evaluation of Fatigue of Respiratory and Lower Limb Muscles During Prolonged Aerobic Exercise

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The respiratory muscles may fatigue during prolonged exercises and thereby become a factor that limits extreme physical activity. The aim of the current study was to determine whether respiratory muscle fatigue imposes a limitation on extreme physical activity of well-trained young men. Electromyography (EMG) signals of respiratory (external intercostal and sternomastoid) and calf muscles (gastrocnemius) were measured during 1 hr of treadmill marching at a speed of 8 km/hr with and without a 15 kg backpack. The root mean square (RMS) and the mean power frequency of the EMG signals were evaluated for calculating fatigue indices. The EMG RMS revealed that the respiratory and calf muscles did not fatigue during the marching without a backpack load. The study did show, however, a significant rise in the EMG values when a backpack was carried with respect to the no-load condition (p < .05), which suggests that respiratory muscles should be trained in military recruits who are required to carry loaded backpacks while marching.

Keywords: respiratory muscles, limb muscle, exercise, fatigue, EMG

Respiratory muscle fatigue occurs when the muscles cannot sustain sufficient ventilation, usually because the muscle fibers cannot regenerate energy rapidly enough (Perlovitch et al., 2007). During a whole body dynamic exercise, as ventilator needs increase, the respiratory muscles have to shorten progressively and to increase their velocity and frequency of contraction, which may lead to respiratory muscle fatigue and that might limit performance.

Several studies have shown that intensive ventilation work significantly reduces the time to exhaustion while exercising, which hence reduces performance (Mador et al., 1993; Harms et al., 2000; Romer et al., 2006; Romer & Polkey, 2008; Taylor and Romer, 2008). Unloading the respiratory muscles using mechanical ventilation was found to prevent exercise-induced diaphragmatic fatigue (Mador et al., 2000; Babcock et al., 2002), and to reduce the twitch force in the quadriceps after a cycling exercise (Romer et al., 2006). On the other hand, increasing the work of the respiratory muscles via inspiratory resistive loads showed either a decrease (Dempsey et al., 2006) or no change (Romer et al., 2007) in exercise performances.

One of the possible explanations for respiratory muscles fatigue during heavy exercise is an increasing competition with the limb locomotor muscles for adequate blood flow. The less blood flow available for the respiratory muscle, the less work is required to produce fatigue. A reduced blood flow to the respiratory muscles was shown to decrease the extent of work that is required to cause fatigue (Romer and Polkey, 2008). Measurements of blood flow to the intercostal muscles revealed no increase during exercise intensities exceeding 80% of the maximal work of breathing as compared with a resting hyperpneic condition (Vogiatzis et al., 2008, 2009). This suggests that the circulatory system is incapable of meeting the simultaneous demands of the locomotor and intercostal muscles during high-intensity exercise, and this is likely the mechanism underlying respiratory muscle fatigue.

During breathing at rest, only the inspiratory muscles (i.e., diaphragm, external intercostal) are active, whereas the expiratory muscles remain passive. Expiration becomes active during exercise, however, contributing to the higher breathing frequency and facilitating inspiration by a decreased end expiratory lung volume (Verges et al., 2006). Other studies have shown that the expiratory abdominal muscles also fatigue in response to heavy exercise (Taylor et al., 2006; Verges et al., 2007a). Recently, it was shown that prior loading of these muscles...
(e.g., induced by resistive loading) impairs exercise performance by reducing the distance achieved during a 12 min run (Verges et al., 2007b), and also by decreasing exercise time, elevating perception of dyspnea and leg discomfort, and reducing quadriceps muscle twitch forces (Taylor and Romer, 2008).

In a previous study, we investigated the extents and rates of fatigue of several respiratory muscles as compared with those of the calf muscles using simultaneous measurements of electromyography (EMG) signals in a group of untrained subjects (Perlovitch et al., 2007). The results demonstrated that inspiratory muscles fatigue significantly faster than the calf muscles at the terminal phase of a 2 km marching exercise at a speed of 8 km/hr. Since the literature shows a relationship between respiratory muscle fatigue and exercise limitation, we extended the scope of our interest to explore whether inspiratory muscle fatigue might contribute to exercise limitation at near-exhaustion fatigue conditions that may occur in marathon and triathlon competitions or military training. In this study we examined the contribution of inspiratory muscles fatigue to exercise limitation in aerobically fit young adults during long aerobic exercise with a heavy backpack load.

**Methods**

The analysis of fatigue was performed by surface EMG measurements from two inspiratory muscles (e.g., external intercostals, sternomastoid) and calf muscle (e.g., gastrocnemius) during heavy exercise. The study was approved the Medical Ethical Committee of the Medical Corps of the Israeli Defense Forces and conducted in accordance with its guidelines, and each subject provided a written informed consent to participate.

**Subject**

Eight healthy males at an age of 22.1 ± 3 years (mean ± SD), with body mass index of 23.6 ± 2 and average height of 178 ± 7 cm participated in this study (Table 1). All subjects had recent military training background, which included intensive marching and carrying heavy loads for hours.

**Experimental Design**

The EMG signals of the external intercostals, sternomastoid, and gastrocnemius muscles were acquired noninvasively with disposable surface electrodes (Ag-AgCl), two of which were attached to each muscle as described previously (Ratnovsky et al., 2003; Perlovitch et al., 2007). The external intercostals, sternomastoid and gastrocnemius muscles are superficially located, and are easily identifiable for monitoring by surface EMG. These muscles were hence selected herein to obtain reliable data from the surface EMG electrodes while avoiding “crosstalk” between muscles layers. The EMG signals were sampled at a rate of 1000 Hz using a three-channel portable system of EMG amplifiers (EMG100A, Biopac Co., CA, USA). A laptop equipped with an A/D board (PCI 6024E) and data acquisition software (LabView, National Instruments, TX, USA) was used for recording the EMG data.

Each subject was required to march on a treadmill (GE-Marquette-Series 2000) for 1 hr at a constant velocity of 8 km/h. At the beginning of each marching exercise, the speed of the treadmill’s belt was gradually increased over 2 min, in order for the subject to accommodate to the experimental setup. Each subject performed the marching tasks twice, on different days, once with and once without carrying a 15 kg backpack, which is typical for military activity. Criteria for stopping a test were (i) subject declared exhaustion or (ii) the subject’s heart rate exceeded 180 bpm. A maximal heart rate of 180 bpm was selected as a cardiac load criterion to stop the test based on the well-known physiological formula for predicting a maximally allowed heart rate as function of age, being $SF \times (220 \text{ beats per minute} - \text{age})$, where the safety factor (SF) was set as 90% (Tanaka et al., 2001). This has been a requirement from the Medical Ethical Committee for

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Body Mass (kg)</th>
<th>Marching Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OF</td>
<td>23</td>
<td>187</td>
<td>82.0</td>
<td>60 without Backpack</td>
</tr>
<tr>
<td>BE</td>
<td>23</td>
<td>178</td>
<td>76.2</td>
<td>60 without Backpack</td>
</tr>
<tr>
<td>DV</td>
<td>23</td>
<td>172</td>
<td>74.7</td>
<td>60 without Backpack</td>
</tr>
<tr>
<td>HO</td>
<td>27</td>
<td>174</td>
<td>67.4</td>
<td>60 without Backpack</td>
</tr>
<tr>
<td>AR</td>
<td>18</td>
<td>185</td>
<td>82.7</td>
<td>60 without Backpack</td>
</tr>
<tr>
<td>IT</td>
<td>23</td>
<td>184.5</td>
<td>72.4</td>
<td>60 without Backpack</td>
</tr>
<tr>
<td>GU</td>
<td>18</td>
<td>182</td>
<td>70.7</td>
<td>36 (reached 180 bpm)</td>
</tr>
<tr>
<td>LI</td>
<td>22</td>
<td>164.5</td>
<td>74.8</td>
<td>60 without Backpack</td>
</tr>
</tbody>
</table>
conducting the subject tests. Subjects who were unable to march at least 2 km were excluded from the study.

Data Analysis

The EMG signals were first filtered with a band-pass filter (e.g., sixth-order Butterworth) with a cut-off of 20–500 Hz, to preserve the dynamic range while minimizing high-frequency noise as well as motion artifacts (De Luca, 1997; Potvin & Brown, 2004). Examples of 4 s segments of the filtered signals of the sternomastoid and gastrocnemius muscles from subject OF (Table 1) at different time windows during the marching test (at 5, 15, 25, 40, and 50 min) are depicted in Figure 1 for tests with and without a backpack load.

Then signals were rectified and RMS values were computed for successive segments of 1 s. For each muscle, the average of RMS values at 60 consecutive segments was selected as the measure of fatigue over each minute (Perlovitch et al., 2007).

The RMS reflects the mean power of the EMG signal and it is known to increase with the development of muscle fatigue (Perlovitch et al., 2007). The averaged RMS values per each time point were normalized with respect to the maximum value obtained for all three muscles, throughout the recording. We then fitted linear regression lines to each muscle dataset for each of the no-load and backpack load conditions. The percentage increase in the average RMS value at the beginning and at the end of a test for a backpack-carrying condition with respect to the no-load condition was calculated for each muscle.

The mean power frequency (MPF) of the EMG is an alternative measure of fatigue, at the frequency domain (Rochester, 1988; Ratnovsky et al., 2008). The MPF values were calculated for each muscle per each subject with and without a backpack load. The MPF values were computed using spectral analysis, by analyzing the power spectrum at each minute:

\[
\text{MPF} = \frac{\int_{f_L}^{f_H} f \times \text{PSD}(f) df}{\int_{f_L}^{f_H} \text{PSD}(f) df}
\]

Figure 1 — An example of the filtered EMG signals for the sternomastoids and gastrocnemius muscles of subject OF at different time frames during the test without (top row) and with (bottom row) a backpack load.
where PSD is the power spectral density of the signal and $f_1$ and $f_2$ are the minimum and maximum frequencies of the signal. The averages of MPF for the whole signals were computed for each muscle and each backpack loading conditions by averaging all the minute-MPF values obtained from a signal.

The first 5 min of each march were removed from the signal before either time-domain (RMS) or frequency-domain (MPF) analysis, to avoid potential influences of the subjects’ adaptation to the treadmill. Descriptive statistics was obtained, in terms of means and standard errors of the RMS and MPF parameters. We further conducted two-way analysis of variance (ANOVA) tests, comparing the load versus no-load conditions exercise conditions, for the factors of the muscle type and time (10 min, 20–30 min), separately for the RMS and MPF parameters. These analyses were followed by Tukey-Kramer multiple pairwise comparisons of the load versus no-load data per each parameter (RMS, MPF). A $p$-value less than 0.05 was considered significant.

**Results**

Seven of the eight subjects were able to complete 1 hr marching without a backpack and three of the subjects were able to complete the entire two sessions of 1 hr marching with and without the loaded backpack (Table 1). Regression lines of the normalized RMS versus time of a single subject (i.e., subject BE for example) are depicted in Figure 2. The averaged data for all eight subjects are shown in Figure 3. Weak or nonexistent slopes were found in tests without backpack loading, but clearly visible downward slopes were demonstrated in the RMS datasets of most subjects when carrying the backpack load of 15 kg (Figure 3). The normalized RMS slopes estimated for the respiratory muscle did not differ significantly from that of the calf muscle. Mean normalized RMS values for marching without and with load at the first 10 min of the exercises and during the period between 20 and 30 min are seen in Figure 4. Significantly higher values of average RMS were found in all the monitored muscles while marching with a backpack load ($p < .05$). The percentages of increase in RMS values associated with the backpack load at the first 10 min of marching were highest for the gastrocnemius ($115 \pm 52\%$), less for the sternomastoid ($94 \pm 36\%$) and the lowest for the external intercostal ($49 \pm 15\%$).

The MPF EMG values for marching without a backpack load at the first 10 min were $139 \pm 7$, $133 \pm 1.9$ and $139 \pm 7.16$, whereas with load these value were $136 \pm 5$, $132 \pm 2.24$ and $115 \pm 11.3$ for the external intercostal, sternomastoid and gastrocnemius, respectively. The changes in the MPF EMG values over time as well as the changes in the load/no-load MPF data for all muscles were statistically indistinguishable.

**Discussion**

The present study was designed to evaluate the extent of fatigue of two inspiratory muscles (e.g., external intercostal and sternomastoid) with respect to that of a major lower limb muscle (the gastrocnemius) during intensive marching with and without a backpack load of 15 kg, to determine whether fatigue of the inspiratory muscles is a limiting factor in the performance of well-trained subjects. The rationale for the current study is based on previous results, showing that inspiratory muscle fatigue was reached significantly faster than fatigue of the gastrocnemius in untrained healthy subjects (Perlovitch et al., 2007).

Fatigue of both inspiratory and leg muscles, as was detailed explained in the method section, was evaluated from changes in the EMG parameters, RMS and MPF. For decades, RMS and MPF have been used as an indicator for skeletal muscle fatigue (Viitasalo & Komi, 1977; Basmajian, 1980; Basmajian & Deluca, 1985; Moritani et al., 1986; Mizrahi et al., 2000; Rudroff et al., 2008) and respiratory muscles fatigue (Gross et al., 1979; Belman & Sieck, 1982; Badier et al., 1993; Perlovitch et al., 2007). Measurement of maximal inspiratory mouth pressure ($P_{max}$) is a well-known technique to assess inspiratory muscles’ global performance (Ratnovsky et al., 1999, 2008) and can be a good indicator also for their fatigue. Measuring $P_{max}$ along with the EMG signals would have contributed significantly to the interpretation of the data collected. However, under the experimental protocol used in the current study it was impossible to simultaneously measure mouth pressure.

The general outcome of the current study, where well-trained subjects were tested, shows that when there was no backpack load, none of the muscles monitored for EMG activity experienced fatigue during 1 hr of aerobic exercise without a back load. This finding apparently stands in contradiction to the findings of Perlovitch et al., (2007), but the subjects who participated in the Perlovitch study were nontrained, as opposed to the subjects herein who were all well trained.

Several studies were concerned with the effectiveness of respiratory muscle training (RMT) and its contribution to exercise performance and role in exercise limitation (Markov et al., 2001; Stussi et al., 2001; Sheel, 2002; Holm et al., 2004; Romer et al., 2004; Verges et al., 2006). In these studies it was demonstrated that the respiratory muscles, as other skeletal muscles, specifically adapt to RMT and to whole body exercise training in relation to parameters such as pulmonary function, respiratory muscle endurance, maximal strength and exercise endurance time. However, although the effect of RMT on exercise performance is still controversial, some studies suggest that it may influence relevant measures of physical performance such as improved breathing perception, delay of respiratory muscle fatigue, and increased ventilatory efficiency (Sheel, 2002). Holm et al. (2004) showed that respiratory muscle endurance training improves cycling performance in fit experienced cyclists. Verges et al. (2007a) concluded that RMT decreased the development of respiratory muscles fatigue during intensive exercise, but this change did not seem to improve cycling endurance. Markov et al. (2001)
demonstrated that both RMT and aerobic endurance training (cycling and/or running) increase the cycling endurance time significantly. Summerhill et al. (2007) further suggested that the respiratory muscles can be strengthened with nonrespiratory-specific activities as long as the respiratory muscles are required to work to perform such activities.

The fact that fatigue was not observed in the marching tests without a backpack load may be explained by means similar to the outcome of RMT which adapt the muscles to increased activity. It is reasonable to assume that if the tests would be continued for a longer period beyond the 1 hr, the respiratory muscles will eventually fatigue. Nevertheless, in such well-trained subjects, other factors might have been responsible for limiting the duration of the exercise, not necessarily fatigue of the respiratory muscles.

Muscular fatigue causes changes both in the amplitude and in the frequency parameters of the EMG data (Basmajian & De Luca, 1985). A decrease in the
conduction velocity of the motor actions potentials on the muscle membrane during muscle fatigue causes a decrease in the median or mean power frequency. However, under dynamic movement patterns such as during intense exercise, the spectral analysis is not accurate (Moritani et al., 1986; Jansen et al., 1997) and thus, the preferred index for muscle fatigue is the changes in the EMG amplitude (Basmajian & De Luca, 1985). The amplitude of the EMG increases during muscular fatigue due to recruitment of increasing numbers of motor units needed to perform the same task (Potvin, 1997).

Marching with the 15 kg backpack increases the load on both the legs and respiratory muscles. To sustain the increased load and to perform the marching, more motor units were probably recruited immediately at the beginning of the marching in comparison with the no load condition. This explains the significant increase seen in the level of RMS EMG values in all three measured muscles while marching with a backpack (Figure 4). The increase was higher throughout the duration of marching, however, after about 10 min a reduction in these values was evident (Figure 3). The downward slopes of the RMS-EMG regression lines found in the backpack load condition, although apparently unexpected, are often seen in fatigue tests (Moritani et al., 1986; Mizrahi et al., 2000). This phenomenon may be explained by migration of muscle activity within synergists whose EMG signals have not been measured (Jamison & Caldwell, 1997).

**Figure 3** — Average normalized RMS values for all eight subjects at each time point (dots) with fits of linear regression lines (solid lines).
In the current study only one of the three main plantar flexor muscles of the ankle joint (i.e., the gastrocnemius) and two inspiratory muscles near the surface (i.e., the external intercostal and sternomastoid) were measured. Thus, it is reasonable to assume that their synergist muscles (e.g., the diaphragm and the parasternal for inspiration and the soleus and plantaries for plantar flexion) increased their activity to enable the marching to continue under load and to reduce the efforts of the measured muscles. We believe that if those muscles were monitored their data would have supported our assumption. However, since the current study was the first one to measure simultaneously respiratory muscles and leg muscle during 1 hr of marching the need to monitor the EMG signal from the synergist muscles could not be participated. Moreover, there is a limitation on the number of electrodes that can be connected to volunteers and still allow their free motion.

The percentage increase in the RMS EMG under backpack load condition was higher for the gastrocnemius (115%) compared with that of the inspiratory muscles (94% and 49% for the sternomastoid and external...
intercostals, respectively). However, we should keep in mind that the marching was performed on a treadmill in a constant velocity, without slope and in a room with convenient and steady temperature and humidity. Moreover, all the subjects recruited for this study were extremely well trained. Considering the above limitations of the current study, it is reasonable to infer that if field conditions or in other circumstances and during longer durations of activity at which the physical state of the subject worsen due to lack of sleep, dehydration, hunger, and so on, the increase in the effort of the inspiratory muscles will be higher and their fatigue may develop faster, particularly if the individual is carrying a heavy load.

In conclusion, the current study clearly demonstrated an increased activity of both the leg and respiratory muscles during exercise while carrying a 15 kg backpack load. Despite that most subjects did not actually complete the marching task (Table 1), the differences between marching with a backpack load to marching without it is statistically significant even after 20 min of marching. This main finding suggests that the respiratory muscles should be trained in military recruits who are required to carry heavy backpacks while marching. In addition, since the influence of the aerobic activity and the load on these muscles was well observed in all subjects, monitoring the respiratory muscles in soldiers is recommended and may even be life saving in the field. Moreover, the observation that exercise under extreme conditions influences the performance of the inspiratory muscles may be of interest in other areas such as in regard to extreme sport activity (e.g., marathon, duathlon or triathlon, mountain climbing) or labor which demands extreme physical activity (e.g., construction or mining workers). To establish the above, the study should be expanded to evaluate muscle fatigue by also measuring blood flow, gas exchange and other physiological measures that would have enlightening the results obtained in the current study. In addition, the study should be expanded to examine subjects with different fitness levels and under more extreme conditions, including for example effects of particularly high or low ambient temperature and humidity stresses, which will imitate field conditions or other circumstances in even more realistic ways.

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References


