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Original Article

Characteristics of respiratory muscle fatigue upon inhalation resistance with a maximal inspiratory mouth pressure of 50%

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Abstract. [Purpose] Considering that respiratory muscle fatigue is a cause of respiratory failure, we aimed to clarify the characteristics of respiratory muscle fatigue under inhalation load and investigate its impact on individual respiratory muscles. [Participants and Methods] The study included 14 healthy adult male volunteers. Maximal inspiratory and expiratory mouth pressures were measured under inhalation load and while at rest. The statuses of the trapezius, sternocleidomastoid, pectoralis major, diaphragm, rectus abdominis, and external and internal abdominal oblique muscles were also assessed using electromyographic frequency analysis. [Results] The maximal inspiratory and expiratory mouth pressures decreased over time and recovered after rest. The median power frequency decreased significantly in the sternocleidomastoid and rectus abdominis muscles at maximal inspiratory and expiratory mouth pressures, respectively, under inhalation load. [Conclusion] As a characteristic of respiratory muscle fatigue, there is a possibility that decreases in maximal inspiratory and expiratory mouth pressures as a result of the inhalation load affect muscle fatigue in the sternocleidomastoid and rectus abdominis muscles.

Key words: Respiratory muscle fatigue, Maximal mouth pressure, Surface electromyogram

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INTRODUCTION

Respiratory muscle fatigue was first described in 1977 by Roussos and Macklem[1)] it was identified as a cause of the onset of ventilatory impairment, which is often accompanied by the onset of hypoxemia and hypercapnia. In 1990, the Respiratory Muscle Fatigue Workshop Group[2)] defined respiratory muscle fatigue as “a condition in which there is a loss in the capacity for developing force and/or velocity of a muscle, resulting from muscle activity under load and which is reversible by rest.” Moreover, respiratory muscle fatigue has been identified as one of the major causes of respiratory failure[3)]. The load causing respiratory muscle fatigue is reportedly caused by respiration under mechanical load due to external resistance[2)], and loads with a maximal pressures of ≥40% are important factors related to the onset of respiratory muscle fatigue[4)].

Respiratory muscle fatigue is the cause of respiratory failure in several cases of chronic obstructive pulmonary disease (COPD), which is a typical target for respiratory rehabilitation[5)]. The decrease in the contraction power of the respiratory muscles associated with this condition is thought to play a crucial role in numerous respiratory diseases; it is also assumed to be a major cause of restriction on exercise[6)]. Thus, training techniques, which are collectively known as ventilatory muscle training (VMT), designed to increase the contraction power of fatigued respiratory muscles and to recover their stamina are often conducted for such patients[6, 7)]. However, the importance of respiratory muscle fatigue may not be sufficiently recognized in the clinical setting[8)] resulting in the present state of affairs, whereby respiratory muscle fatigue is almost never

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*Corresponding author. Toshiya Tsukamoto (E-mail: t-tsukamoto@sz.tokoha-u.ac.jp) assessed with respect to inhalation load or exhalation load⁶⁾, Consequently, the efficacy of VMT, including its impact on accessary respiratory muscles, remains largely unknown. Respiratory muscle fatigue is usually diagnosed using noninvasive methods, such as by measuring muscle contractions and generating an electromyogram⁹⁾. The former approach is used to measure the maximal inspiratory (PImax) and expiratory (PEmax) mouth pressures, whereas the latter involves utilizing a surface electromyogram (sEMG) as a noninvasive method to assess the muscle fatigue in each respiratory muscle.

Our previous studies assessing respiratory muscle fatigue10, 11) revealed that a maximal inspiratory load of 50% could quickly fatigue both the inspiration and expiration muscles. However, due to increased inhalation loads, the characteristics of respiratory muscle fatigue, particularly with respect to the inspiration and expiration muscles, remain unknown. Thus, we wanted to identify the characteristics of the inspiration and expiration muscles under respiration loads. We also tried to investigate whether muscle fatigue recovers with rest and, if so, how much time does it take for the fatigue to completely recover. Because respiratory muscle fatigue is a common cause of respiratory failure, we aimed to obtain baseline data that would help tailor VMT methods, which were designed to improve the contraction power of the muscles and increase endurance to fatigue, to the pathophysiology and characteristics of respiratory muscle fatigue.

Thus, we measured the respiratory muscle activity using surface electromyography (sEMG). We also measured PImax and PEmax after rest and under a load of maximal inspiratory mouth pressure of 50% (50% PImax) and used this data to identify the characteristics of respiratory muscle fatigue.

PARTICIPANTS AND METHODS

The study included 14 healthy adult male volunteers (age, 26.0 ± 3.3 years; height, 171.3 ± 4.0 cm; weight, 66.7 ± 6.8 kg; data presented as mean ± standard deviation) with no history of smoking and respiratory, neurological, or neck/trunk diseases requiring orthopedic surgery. They were fully explained about the contents of the study, and their written consent was obtained. This study was approved by the Institutional Review Board of the International University of Health and Welfare (approval no.15-Io-105).The task was to engage in respiration under intermittent inhalation threshold loads (inhalation load) of 50% PImax for 20 min using a pressure threshold loading device for inhalation. In terms of loading method, the participants were subjected to an inhalation load of 50% of PImax for 2 min, followed by a rest period for 1 min, two more minutes of load, and 1 min of rest; the cycle was repeated until the total amount of load time reached 20 min, whereupon loading ceased. Once inhalation loading ceased, participants were given a 30-min rest period. Measurement items comprised PImax, PEmax, and respiratory muscle activity as measured by sEMG during the 1-min rest period taken after every 2 min of inhalation load application. PImax, PEmax, and respiratory muscle activity were then measured every 5 min during the 30-min rest period following cessation of inhalation loading. Respiratory muscle activity was targeted in seven respiratory muscles on the right side: namely the trapezius, sternocleidomastoid, pectoralis major, and diaphragm (inspiratory muscles), and the rectus abdominis, external oblique, and internal oblique (expiratory muscles).

Similar measurements for all the seven abovementioned muscles were again conducted but under no inspiratory load on a different day within four weeks of the initial measurement.

For the measurements, Dual Surface Electromyogram Electrodes (EM-272S, Noraxon; electrodes) were placed at a distance of 2 cm from each other as follows: at the center of a line connecting the scapula with the 7th cervical vertebra (trapezius)12), at the center of the muscle belly (sternocleidomastoid)13), high in the axillary region of the chest (pectoralis major)12), between the 6th and 7th ribs at the center line of the right clavicle (diaphragm)14, 15), at a point that was 2 finger widths lateral from the linea alba 1 cm above the navel (rectus abdominis)16), at the lateral side of the 8th rib (external oblique)17, 18) and below a line connecting the left and right anterior superior iliac spines 1 cm medial to the anterior superior iliac spine (internal oblique)17, 18). A diagnostic ultrasonic imaging device (LOGIQ P6 Expert, GE Healthcare Japan) was used to determine the site of placement of the electrodes for the diaphragm, which was measured using a linear probe in the B-mode with a spatial resolution of 10 MHz and a depth of 5 cm. The electrode placement site for the diaphragm was determined using the probe, which was moved vertically between the 8th and 9th ribs in a line along the right center of the axillary region19); the electrode was then placed between the 6th and 7th ribs at the center line of the right clavicle. All participants were made to engage in diaphragmatic breathing to confirm the presence of an EMG wave.

A considerable array of devices was used to obtain various measurements. For example, 1. respiratory muscle strength was measured using a spirometer (Autospiro AS-507, Minato Medical Science Co., Ltd.) connected to a respiratory muscle strength meter unit (Minato Medical Science Co., Ltd.) to measure both PImax and PEmax and 2. respiratory muscle activity was measured using a surface EMG device (Electromyogram telemetry meter MQ16, KISSEI COMTEC), which was connected to a digital camera (HANDYCAM HDR-CX560, SONY) using an AD converter (ADVANCEDDV ADVC-55, CANOPUS), and this was synchronized to the other equipment to allow acquiring video images of the performed tasks. PImax and PEmax were measured via the bipolar output, the time during which sEMG measurements were used to record myoelectric activity. The myoelectric waves obtained at a sampling frequency of 1,500 Hz were entered into a computer using an A/D converter. The start of muscle activity was considered as the point in time at which the maximum resting amplitude was exceeded, and the myoelectric waves generated during a 0.5-s interval after the start of muscle activity were used for analysis. In cases wherein the EMG data were confounded by EKG waves, we removed the QRS component of EKG to reduce its influence to minimum15, 20) and analyzed the myoelectric waves visible between the QRS components21).

The extracted myoelectric waves were processed using a 20–350 Hz band pass filter. Kineanalyzer Ver. 4 was used for the analysis, which comprised performing frequency analysis using the fast Fourier transform and median power frequency (MDF) settings.

Our measurement procedure involved performing respiratory function tests followed by comparing the obtained results with values normalized from raw data. PImax and PEmax were measured prior to the start of testing and used as the pre-load standards. Measurements were performed using the Black and Hyatt method22); the participants placed a mouth filter equipped with a nose clip onto their faces and then exhaled to their maximal expiratory state from total lung capacity. They then inhaled to their maximal inspiratory state from the residual volume state and maintained that pressure for approximately 3 s. Both inspiration and expiration were measured thrice and the maximum values were used as the maximal mouth pressure (PImax, PEmax). To avoid the closing of the glottis during PImax and the use of buccinators during PEmax, an air leak was created using a tube with a 2-mm inner diameter and 20–30-mm length23). For the measurement, the participants were seated in a chair with a backrest and made to hold the respiratory muscle strength meter in their left hand after being advised to not move their neck or trunk during the process. However, because it was necessary to determine PImax and PEmax at intervals of 1-minute during rest as a measurement of inhalation during load, the first measurement was considered the maximum value. sEMG was continuously recorded from the start of the measurement of respiratory muscle strength at the pre-load standard until the post-load rest period. The respiration conditions were 15 breaths/min at intervals of 2 s each for inspiration and expiration in time with a metronome. The completion conditions were either the time point at which the load pressure became impossible or when the subjects could not continue due to breathing difficulty.

Data were analyzed using repeated measure analyses of variance with the values measured every 2 min during load and every 5 min during rest periods to identify chronological changes in PImax, PEmax, and MDF during inspiration under the 50% PImax load. Cases wherein the primary effect was observed were further processed using the Bonferroni multiple comparison test with the standard of significance set at 5%. Also, to compare the chronological changes in PImax, PEmax, and MDF during the post-load rest period, we performed the same statistical tests on comparisons between 20 min after the start of the inspiration load of 50% PImax and the rest period. We investigated the correlation between PImax and PEmax under the inspiration load of 50% PImax using the Spearman's rank correlation coefficient. The same statistical tests were performed for measurements taken under the no load conditions. Statistical analyses were performed using the JSTAT version 13.0 software.

RESULTS

Respiratory function testing indicated that a forced vital capacity (FVC) of 4.5 ± 0.4 l, %FVC of 107.3% ± 8.0%, and forced expiratory volume in 1 s ($FEV_{1.0\%}$) of 87.3% ± 6.1%, indicating that all subjects were within the normal range.

The chronological changes in PImax and PEmax under the 50% PImax inspiration load and also under no load are presented in Table 1. Upon comparing the chronological changes in PImax and PEmax under load, we found considerable differences in PImax between the values at the start of load application compared with at 14 and 20 min later; further, there were considerable differences in PEmax between the value at the start of load application and at 14, 18, and 20 min later. Comparisons of the results obtained at 20 min after the start of load application and at the post-load rest period revealed significant differences in PImax from 15 to 30 min after the start of the rest period and in PEmax at 30 min after the start of the rest period ($p<0.05$). In contrast, no significant differences were obtained between PImax and PEmax when measured under conditions of no load.

The chronological changes in MDF during PImax and PEmax measurements obtained under the 50% PImax inspiratory pressure and under no pressure are presented in Tables 2–5. By comparing the chronological changes in MDF for each measured muscle when under inspiratory load, we found significant differences in PImax when the sternocleidomastoid was measured at the start of load application and at 20 min later. Furthermore, when comparisons were made between 20 min after the start of load application and the rest period, we again found significant differences in PImax between 5, 15, and 30 min after the start of the rest period ($p<0.05$). Assessments of the differences in PEmax when the rectus abdominis was measured revealed a significant difference between the start of load application and 20 min later ($p<0.05$). In contrast, no significant differences in MDF were revealed for any of the target muscles when measured under the no load condition.

The results of the correlation analyses of PImax and PEmax revealed a positive relationship between both variables under the 50% PImax inspiration load ($r=0.58$, $p<0.05$) as well as under no load conditions ($r=0.58$, $p<0.05$).

DISCUSSION

The present study analyzes respiratory muscle fatigue under an inspiratory load set at 50% of PImax; hence, as a measure of the respiratory muscle strength, we analyzed the maximal mouth pressures (PImax and PEmax) and sEMG frequency for each target respiratory muscle. The results revealed that under the 50% PImax inspiratory pressure, both PImax and PEmax decreased over time and that they recovered during the post-load rest period, clearly indicating the occurrence of respiratory muscle fatigue. Investigation of respiratory muscle fatigue recovery indicated that the pre-load value recovered approximately 30 min after load discontinuation. We also found that respiratory muscle fatigue appeared at both inspiration

Table 1. Chronological changes in PImax and PEmax

	PImax		PEmax	
	Under inspiratory load	No inspiratory load	Under inspiratory load	No inspiratory load
Pre-load	112.7 ± 22.0	121.2 ± 18.0	89.3 ± 17.5	96.4 ± 20.3
2 min	106.8 ± 28.8	112.8 ± 21.4	84.2 ± 17.9	90.9 ± 19.9
4 min	102.4 ± 27.3	118.3 ± 21.6	78.5 ± 23.6	92.4 ± 20.4
6 min	101.6 ± 26.7	117.3 ± 18.8	85.4 ± 19.6	93.9 ± 18.7
8 min	101.2 ± 26.6	119.4 ± 21.7	82.7 ± 21.1	94.2 ± 21.0
10 min	101.4 ± 23.4	118.1 ± 19.0	80.1 ± 20.8	91.2 ± 21.0
12 min	100.5 ± 23.3	120.0 ± 20.9	79.6 ± 24.0	91.3 ± 21.1
14 min	97.7 ± 24.1*	121.9 ± 22.8	76.7 ± 23.3*	93.0 ± 22.2
16 min	98.5 ± 26.7*	119.2 ± 21.0	78.2 ± 20.7	93.0 ± 18.6
18 min	97.7 ± 24.6*	120.3 ± 18.1	75.9 ± 21.5*	94.9 ± 17.6
20 min	90.7 ± 22.5*	123.3 ± 20.1	72.6 ± 21.3*	93.0 ± 21.3
5 min rest	105.2 ± 22.3	120.4 ± 22.6	80.9 ± 18.7	92.1 ± 21.1
10 min rest	103.4 ± 20.0	117.9 ± 22.4	82.3 ± 17.5	93.0 ± 20.5
15 min rest	109.7 ± 20.5†	121.3 ± 17.7	83.8 ± 18.5	93.2 ± 21.1
20 min rest	108.5 ± 19.0†	118.4 ± 20.6	83.6 ± 16.7	92.1 ± 20.1
25 min rest	110.5 ± 14.9†	125.2 ± 18.0	81.9 ± 19.0	95.9 ± 19.6
30 min rest	114.2 ± 18.9†	127.4 ± 20.2	85.5 ± 18.7†	97.0 ± 19.3

Unit: cmH$_2$O (mean ± standard deviation), n=14.
*p<0.05 (Comparison with pre-load), †p<0.05 (Comparison with +20 min load and rest).
PImax: maximal inspiratory mouth pressure; PEmax: maximal expiratory mouth pressure.

Table 2. Chronological changes in respiratory muscle MDF during PImax measurement under inspiratory resistance load

	PImax (n=14)						
	Trapezius	Sternocleido-mastoid	Pectoralis major	Diaphragm	Rectus abdominis	External oblique	Internal oblique
Pre-load	64.8 ± 13.4	78.3 ± 12.7	67.9 ± 10.4	73.2 ± 13.2	73.3 ± 20.3	62.3 ± 12.4	87.3 ± 26.4
2 min	58.6 ± 14.5	70.8 ± 10.2	62.5 ± 12.0	65.8 ± 13.8	72.6 ± 22.7	59.8 ± 16.4	89.4 ± 30.5
4 min	62.4 ± 18.4	71.7 ± 7.5	68.0 ± 8.4	67.8 ± 9.2	74.0 ± 20.2	56.2 ± 11.1	89.9 ± 27.2
6 min	61.3 ± 15.2	72.2 ± 14.5	74.5 ± 11.7	71.4 ± 11.8	72.3 ± 24.2	56.8 ± 12.4	83.4 ± 30.3
8 min	64.6 ± 15.7	73.5 ± 10.9	68.2 ± 13.3	71.8 ± 13.3	74.4 ± 21.1	56.3 ± 12.4	82.7 ± 28.0
10 min	62.4 ± 18.3	73.0 ± 12.3	69.7 ± 13.0	69.3 ± 10.2	71.5 ± 22.2	60.9 ± 16.8	85.8 ± 33.2
12 min	60.9 ± 16.2	73.7 ± 12.5	69.7 ± 13.4	69.1 ± 9.8	74.5 ± 23.3	56.7 ± 12.6	83.5 ± 32.3
14 min	62.7 ± 13.7	72.8 ± 12.4	65.3 ± 9.7	67.9 ± 12.6	73.5 ± 27.3	55.2 ± 10.0	79.9 ± 31.3
16 min	67.9 ± 12.5	74.7 ± 10.4	66.5 ± 15.7	67.9 ± 6.3	69.9 ± 22.9	55.3 ± 15.3	79.3 ± 26.3
18 min	61.0 ± 14.8	70.7 ± 10.9	69.4 ± 16.4	66.0 ± 13.5	66.7 ± 22.4	58.6 ± 11.4	80.2 ± 26.5
20 min	67.2 ± 10.8	65.4 ± 9.6*	71.4 ± 15.9	66.7 ± 12.3	66.9 ± 16.7	57.0 ± 11.2	83.3 ± 34.6
5 min rest	64.2 ± 15.9	78.8 ± 13.0†	67.8 ± 18.9	66.3 ± 12.9	66.8 ± 16.0	57.2 ± 13.2	81.8 ± 31.9
10 min rest	61.6 ± 16.5	73.3 ± 12.4	65.6 ± 18.4	68.8 ± 14.1	68.5 ± 18.1	58.6 ± 9.6	84.4 ± 37.9
15 min rest	59.4 ± 15.1	75.4 ± 9.5†	74.5 ± 16.7	71.0 ± 13.3	69.0 ± 21.9	55.3 ± 10.7	76.3 ± 31.5
20 min rest	65.0 ± 16.0	73.3 ± 10.3	69.3 ± 10.8	66.5 ± 14.1	70.7 ± 19.4	59.9 ± 11.1	80.5 ± 29.5
25 min rest	62.0 ± 14.6	72.9 ± 12.9	68.5 ± 15.2	66.7 ± 13.3	65.9 ± 20.7	54.3 ± 10.6	75.7 ± 32.9
30 min rest	61.0 ± 12.8	75.6 ± 9.8†	68.1 ± 14.1	67.1 ± 15.3	68.4 ± 19.0	55.8 ± 13.4	86.2 ± 33.1

Unit: Hz (mean ± standard deviation), *p<0.05 (Comparison with pre-load), †p<0.05 (Comparison with +20 min load and rest), n=14.
MDF: median power frequency; PImax: maximal inspiratory mouth pressure.

and expiration in response to the inspiratory load and that the two were positively correlated. The results of our sEMG frequency data analysis indicated that both the sternocleidomastoid (inspiratory muscle) and the rectus abdominis (expiratory muscle) showed muscle fatigue.

When analyzing respirational muscle fatigue, it was necessary to investigate the effects that our protocol may have had on

Table 3. Chronological changes in respiratory muscle MDF during PEmax measurement under inspiratory resistance load

	PEmax (n=14)						
	Trapezius	Sternocleido-mastoid	Pectoralis major	Diaphragm	Rectus abdominis	External oblique	Internal oblique
Pre-load	69.5 ± 14.1	67.8 ± 16.1	65.8 ± 11.3	72.8 ± 11.9	80.4 ± 15.7	62.4 ± 13.7	103.3 ± 30.0
2 min	65.7 ± 17.1	68.9 ± 12.7	59.1 ± 9.4	64.6 ± 14.3	70.5 ± 11.6	63.2 ± 15.4	97.4 ± 28.0
4 min	63.4 ± 16.3	68.4 ± 11.6	59.8 ± 12.8	68.8 ± 10.5	72.3 ± 9.1	60.9 ± 18.1	92.4 ± 26.8
6 min	64.2 ± 15.2	72.8 ± 16.3	62.2 ± 11.5	74.7 ± 13.1	76.1 ± 11.7	62.5 ± 16.8	97.2 ± 31.0
8 min	68.7 ± 15.9	67.7 ± 9.3	63.8 ± 11.5	74.1 ± 12.5	75.1 ± 10.7	60.1 ± 13.6	101.4 ± 27.0
10 min	69.2 ± 13.0	66.3 ± 11.4	62.9 ± 12.1	67.3 ± 11.7	71.7 ± 12.7	55.5 ± 13.2	94.3 ± 27.9
12 min	64.2 ± 16.8	68.7 ± 10.3	61.9 ± 8.9	70.8 ± 12.3	72.8 ± 11.2	56.0 ± 11.3	100.0 ± 30.8
14 min	64.4 ± 14.1	66.5 ± 11.5	64.4 ± 11.5	75.3 ± 13.6	69.4 ± 14.9	63.8 ± 18.9	101.5 ± 29.1
16 min	67.3 ± 15.1	73.3 ± 17.5	61.6 ± 13.8	72.8 ± 15.6	70.2 ± 8.8	60.9 ± 16.1	96.7 ± 24.7
18 min	65.1 ± 15.2	73.5 ± 14.8	62.2 ± 12.0	71.4 ± 8.6	66.9 ± 7.5	63.5 ± 16.2	97.8 ± 30.0
20 min	70.7 ± 13.3	70.6 ± 13.6	60.1 ± 10.6	71.3 ± 11.9	63.9 ± 6.6*	57.1 ± 12.4	92.2 ± 23.3
5 min rest	67.1 ± 17.8	73.3 ± 13.2	65.9 ± 13.3	69.3 ± 6.0	68.9 ± 12.0	61.2 ± 17.0	92.2 ± 28.8
10 min rest	64.4 ± 17.8	70.1 ± 13.9	66.7 ± 15.1	69.9 ± 8.7	69.2 ± 14.0	58.8 ± 15.7	96.7 ± 32.6
15 min rest	62.4 ± 16.7	65.3 ± 6.1	65.8 ± 15.0	69.7 ± 13.2	67.0 ± 16.1	59.8 ± 15.9	95.0 ± 26.6
20 min rest	66.6 ± 17.0	70.8 ± 10.7	66.6 ± 9.4	73.3 ± 15.9	72.2 ± 14.4	60.3 ± 16.1	89.7 ± 27.0
25 min rest	62.9 ± 17.9	70.3 ± 11.2	66.5 ± 11.0	73.5 ± 13.7	67.8 ± 12.7	57.9 ± 13.0	94.5 ± 28.5
30 min rest	67.7 ± 15.6	70.9 ± 12.4	64.6 ± 12.4	69.9 ± 16.4	67.6 ± 11.9	58.0 ± 12.2	100.4 ± 22.9

Unit: Hz (mean ± standard deviation), *p<0.05 (Comparison with pre-load), †p<0.05 (Comparison with +20 min load and rest), n=14.
MDF: median power frequency; PEmax: maximal expiratory mouth pressure.

Table 4. Chronological changes in MDF of target muscles during PImax measurement under no load

	PImax (n=14)						
	Trapezius	Sternocleido-mastoid	Pectoralis major	Diaphragm	Rectus abdominis	External oblique	Internal oblique
Pre-load	56.4 ± 13.6	78.7 ± 11.4	68.0 ± 12.5	70.7 ± 13.1	76.5 ± 18.7	57.4 ± 10.3	89.0 ± 30.6
2 min	60.9 ± 15.7	74.9 ± 9.6	78.6 ± 18.0	75.3 ± 14.6	78.6 ± 25.0	58.2 ± 9.1	86.2 ± 33.6
4 min	61.0 ± 15.4	72.1 ± 9.5	76.7 ± 11.7	69.8 ± 15.6	84.7 ± 21.4	54.7 ± 9.5	86.4 ± 35.4
6 min	61.1 ± 11.5	74.0 ± 7.0	76.6 ± 19.0	78.2 ± 18.7	85.4 ± 23.1	58.2 ± 12.5	93.9 ± 25.8
8 min	60.1 ± 15.3	78.7 ± 11.4	76.7 ± 19.6	71.5 ± 16.1	82.1 ± 23.1	57.0 ± 10.5	91.6 ± 34.3
10 min	61.5 ± 13.0	75.5 ± 10.5	79.7 ± 18.3	74.1 ± 16.6	80.5 ± 22.5	53.4 ± 11.4	107.9 ± 42.2
12 min	59.6 ± 14.8	78.5 ± 10.4	78.2 ± 17.0	71.3 ± 13.3	82.9 ± 22.2	55.7 ± 10.7	99.4 ± 37.2
14 min	65.8 ± 19.8	79.5 ± 11.9	71.3 ± 14.3	71.0 ± 15.0	78.5 ± 22.7	54.5 ± 10.2	96.7 ± 33.6
16 min	62.4 ± 18.2	84.1 ± 17.7	69.7 ± 9.1	75.3 ± 15.1	79.9 ± 25.0	57.1 ± 12.0	95.4 ± 27.2
18 min	60.7 ± 14.0	78.9 ± 16.6	72.1 ± 14.4	78.6 ± 16.4	83.5 ± 25.6	58.1 ± 10.3	94.7 ± 31.9
20 min	66.1 ± 17.5	77.2 ± 9.0	71.4 ± 10.4	75.1 ± 16.1	78.8 ± 19.5	58.0 ± 15.3	94.6 ± 32.9
5 min rest	64.6 ± 16.2	79.2 ± 8.4	73.2 ± 10.8	70.4 ± 13.5	82.3 ± 20.4	56.4 ± 10.1	94.7 ± 34.7
10 min rest	63.4 ± 18.1	78.5 ± 16.1	77.3 ± 15.4	71.6 ± 13.5	82.4 ± 24.8	53.3 ± 10.3	90.1 ± 35.7
15 min rest	58.2 ± 20.1	78.2 ± 12.2	72.9 ± 12.2	74.0 ± 14.8	77.0 ± 21.9	60.0 ± 12.2	84.8 ± 24.6
20 min rest	61.8 ± 14.3	77.3 ± 11.7	71.6 ± 13.3	73.8 ± 12.3	80.0 ± 21.9	54.9 ± 10.3	102.4 ± 37.1
25 min rest	60.3 ± 17.5	77.7 ± 11.7	71.5 ± 17.1	76.4 ± 17.5	83.6 ± 21.5	58.4 ± 6.6	94.6 ± 31.0
30 min rest	61.2 ± 15.8	81.0 ± 14.1	70.0 ± 16.8	71.9 ± 12.0	77.7 ± 17.2	60.0 ± 10.4	86.5 ± 29.9

Unit: Hz (mean ± standard deviation), *p<0.05 (Comparison with pre-load), †p<0.05 (Comparison with +20 min load and rest), n=14.
MDF: median power frequency; PImax: maximal inspiratory mouth pressure.

respiratory muscle fatigue. Hence, we performed the same measurements under a no load condition in which there was no chronological decline in PImax, PEmax, or MDF; therefore, there clearly was no respiratory muscle fatigue. This confirmed that the 50% PImax inspiratory load applied in this study was successful in causing respiratory muscle fatigue.

The definitions of muscle fatigue used in the present study were proposed by the Respiratory Muscle Fatigue Workshop

Table 5. Chronological changes in MDF of target muscles during PEmax measurement under no load

	PEmax (n=14)						
	Trapezius	Sternocleido-mastoid	Pectoralis major	Diaphragm	Rectus abdominis	External oblique	Internal oblique
Pre-load	64.7 ± 19.6	72.3 ± 11.6	65.2 ± 18.3	67.3 ± 12.6	81.0 ± 27.1	61.2 ± 11.6	93.0 ± 25.9
2 min	70.6 ± 17.5	72.3 ± 15.3	72.2 ± 21.4	70.5 ± 11.4	80.1 ± 23.0	57.5 ± 12.6	103.0 ± 25.3
4 min	68.4 ± 22.5	79.1 ± 21.8	72.0 ± 23.6	73.2 ± 18.7	75.5 ± 20.4	60.8 ± 20.0	97.1 ± 26.4
6 min	69.8 ± 23.0	73.2 ± 15.1	70.9 ± 21.2	69.6 ± 10.2	85.1 ± 25.7	60.8 ± 13.7	97.8 ± 25.4
8 min	71.4 ± 22.7	78.2 ± 19.2	77.3 ± 27.6	68.3 ± 8.0	80.6 ± 24.3	61.9 ± 11.5	103.2 ± 23.1
10 min	66.9 ± 15.0	76.9 ± 21.1	71.1 ± 20.3	74.8 ± 15.8	85.2 ± 20.0	65.3 ± 21.4	99.1 ± 24.4
12 min	71.3 ± 17.0	68.1 ± 11.9	76.1 ± 26.5	72.5 ± 13.7	82.0 ± 18.3	63.4 ± 16.1	104.7 ± 23.1
14 min	68.1 ± 19.7	76.2 ± 23.1	68.6 ± 24.6	70.1 ± 14.5	81.7 ± 23.9	65.3 ± 25.7	99.0 ± 20.4
16 min	69.5 ± 14.4	80.1 ± 35.3	67.9 ± 17.3	70.9 ± 12.9	75.7 ± 18.5	59.9 ± 13.5	100.9 ± 25.6
18 min	72.8 ± 14.8	86.1 ± 26.8	67.0 ± 18.3	67.3 ± 11.4	77.5 ± 23.5	66.4 ± 20.5	100.9 ± 23.6
20 min	73.4 ± 20.5	83.9 ± 28.2	72.8 ± 26.5	67.5 ± 9.0	76.3 ± 19.1	64.2 ± 12.2	100.3 ± 20.0
5 min rest	68.5 ± 21.0	75.4 ± 21.5	69.0 ± 22.3	70.2 ± 8.5	77.3 ± 16.8	65.3 ± 16.3	100.9 ± 22.1
10 min rest	68.2 ± 18.2	81.0 ± 23.5	70.5 ± 19.4	65.0 ± 12.2	80.4 ± 23.6	74.6 ± 33.5	95.7 ± 20.7
15 min rest	72.4 ± 18.2	74.5 ± 18.9	64.4 ± 19.0	70.0 ± 11.4	75.9 ± 18.9	65.2 ± 19.7	99.1 ± 27.0
20 min rest	77.1 ± 22.3	72.7 ± 16.2	68.4 ± 18.4	69.9 ± 14.5	78.5 ± 24.4	74.9 ± 36.2	98.6 ± 19.7
25 min rest	73.1 ± 19.1	81.3 ± 19.8	72.9 ± 23.8	68.8 ± 10.5	80.1 ± 23.0	66.0 ± 22.1	101.8 ± 24.1
30 min rest	73.3 ± 20.8	77.3 ± 22.6	68.4 ± 22.5	71.3 ± 11.8	80.5 ± 22.1	69.7 ± 14.8	100.5 ± 21.1

Unit: Hz (mean ± standard deviation), *$p<0.05$ (Comparison with pre-load), †$p<0.05$ (Comparison with +20 min load and rest), n=14.
MDF: median power frequency; PEmax: maximal expiratory mouth pressure.

Group (RMFWG)2); the same definition was used by Nagata24) in his EMG frequency analysis. The RMFWG2) defined respiratory muscle fatigue as "a condition in which there is a loss in the capacity for developing force and/or velocity of a muscle, resulting from muscle activity under load and which is reversible by rest." Therefore, we recognized muscle fatigue when PImax and PEmax, the measures of respiratory muscle contraction strength, declined as a result of inspiratory load and then recovered after a period of rest. Muscle fatigue detected using EMG frequency analysis was defined by Nagata24) as "a move of the EMG power spectrum toward low frequencies (wave slowing)." Therefore, we recognized muscle fatigue through decreases in MDF, which is representative of the EMG power spectrum. We found that an inspiratory load of 50% PImax caused an approximately 20% decrease in PImax, which is a measure of inspiratory muscle strength, at 20 min after the start of loading; however, the fatigue recovered after a rest period. Thus, respiratory muscle fatigue indeed occurred. The inspiration muscles include both the main (diaphragm) and the accessory respiratory muscles that act when breathing under load. Contractions of the diaphragm account for between 65% and 75% of the respiratory load when at rest25). Changes in the contractions of the diaphragm considerably affect both maximal mouth pressure and ventilatory function26). In contrast, numerous accessory respiratory muscles are involved, including the sternocleidomastoid, oblique muscle, trapezius, pectoralis major, and pectoralis minor. Of these, the sternocleidomastoid plays an important role27) in increasing the anterior–posterior diameter of the chest by lifting the clavicles and sternum28); thus, its level of activity linearly increases in conjunction with the increases in respiratory load29). Our comparisons of MDF under an inspiratory load of 50% PImax did not show a significant difference in the fatigue of the diaphragm. This indicates that muscle fatigue was instead experienced in the sternocleidomastoid. We believe this is the cause of the decrease in PImax, which indicates a decrease in the inspiratory muscle strength and thus the appearance of muscle fatigue as a result of increased activity of the sternocleidomastoid.

Decreases due to the 50% PImax inspiratory load and recovery with rest were observed not only in PImax but also in PEmax. Thus, both inspiratory and expiratory muscle fatigue were observed. In addition, there were significant declines in the MDF of the rectus abdominis, which is an expiratory muscle; hence, we believe that fatigue occurred here as well. We assume that the rectus abdominis experienced muscle fatigue because the contraction efficiency of the diaphragm associated with ventilation promotion improved.

When breathing at rest, the expiratory muscles cause expiration as a result of the elastic force of the chest and the lungs. The expiratory muscles do not require energy; however, they have a markedly higher amount of activity than inspiratory muscles during exercise or when ventilatory demand is increased due to the deployment of the accessary respiratory muscles in response to inspiratory loads24), such as in the present study. Thus, the activity of the expiratory muscles begins early in the expiratory phase in response to increased ventilation and continues until expiration is completed30). When ventilation promotion occurred as a result of the 50% PImax inspiratory load applied in this study, the diaphragm rose into the chest cavity to create positive abdominal pressure as a result of 1. contractions of the rectus abdominis during expiration, and 2. bringing the length of the myofibers of the diaphragm to near optimum, which is thought to have played a role in improving the contraction efficiency of the diaphragm during the next inspiration6). Because we observed improved contraction efficiency of the diaphragm, we assume that the abdominal pressure decreased. This may have caused a decrease in the diaphragm-derived pressure, which is one of the causes that led to the decrease in PImax. In addition, we believe that the increased abdominal pressure associated with the inspiratory load, which caused the PEmax to decrease as a result of fatigue experienced by the rectus abdominis. Because we observed a decline not only in PImax but also in PEmax when under a 50% PImax inspiratory load, we were able to identify a positive correlation between the two, and we believe that there is a relationship between the inspiratory and expiratory muscles.

Our EMG frequency analysis indicated that a decrease in MDF during PImax and PEmax measurement was a criterion for muscle fatigue. The EMG frequency analysis revealed that both the sternocleidomastoid and the rectus abdominis showed considerable decreases in MDF and therefore experienced muscle fatigue. MDF showed a clear decrease in the EMG power spectrum in association with the increasing muscle fatigue31). The primary reason for this is assumedly the prolongation of the time action potential and delay of the transmission speed32). Hence, reductions in transmission speed are thought to cause changes in the extracellular pH owing to the accumulation of metabolites, such as lactic acid, that form due to muscle contractions, causing the myofiber transmission speed of action potential to decrease31). In addition, factors thought to be related to the muscle fatigue characteristics caused by myofibers include deteriorating durability in the transmission speed of type II fibers. Further, although type I fibers have excellent durability, their transmission speed is slower than that of quick-twitch myofibers33). Frequency analysis assumedly reflects the high frequencies in type II fibers and low frequencies in type I fibers34), and even if type II fiber activity ceases, type I fiber activity persists, although it can seem to an observer that the transmission speed of the entire muscle has decreased33). Based on this, it appears that the decrease in MDF was due to the drop in the transmission speed of the active potential caused by respiratory muscle fatigue and by the simultaneous appearance of the effects on the muscle fatigue characteristics in each of the two myofiber types.

MDF readings obtained during the PImax measurement process showed considerable decreases in the sternocleidomastoid at 20 min after the start of load application, and recovery was observed at 5, 15, and 30 min after the start of the rest period. Various investigations regarding recovery after fatigue after a period of rest have indicated that although high-frequency fatigue recovers early, low-frequency fatigue persists over considerably longer periods of time35). This phenomenon assumedly exists because sternocleidomastoid fatigue is high-frequency in nature. Because such frequencies are reflected in type II fibers and because the sternocleidomastoid contracts quickly, it appears that this muscle fatigue was a result of type II activity, which has a high degree of tensile force.

MDF readings obtained during the PEmax measurement process showed considerable decreases in the rectus abdominis at 20 min after the start of load application. Based on this, it appears that this muscle experienced fatigue as a result of inspiratory load, in spite of it being an expiratory muscle. Because PEmax is a method of measuring the maximum contractive power of all inspiratory muscles, fatigue of the rectus abdominis, which is an expiratory muscle, is likely to show the effects of decreasing PEmax. In addition, because contractions of the rectus abdominis increase abdominal pressure, raise the diaphragm upward, and play a role in extending the dome axis36), expiratory fatigue of this muscle may affect not only PEmax but also PImax. This is because although PImax, which is the pressure derived from the length-tensile force relationship of the diaphragm, is maintained or increased, it does so under disadvantageous conditions.

We measured PImax and PEmax and performed the sEMG frequency analysis to examine respiratory muscle fatigue in healthy adult male volunteers caused by a 50% PImax inspiratory load. Respiratory muscle fatigue is a cause of respiratory failure; therefore, the assessment of respiratory muscle fatigue and respiratory muscle strength is of direct clinical importance. In addition, we believe it is possible that fatigue of the rectus abdominis, caused by a load equal to 50% PImax, affects both PImax and PEmax.

This study has some limitations. First, due to the particulars of determining PImax and PEmax, we were unable to measure lung capacity. Second, because the subjects were all healthy adult males, gender-based biases may exist. Finally, we did not identify the respiratory muscle fatigue in actual cases of COPD and chronic respiratory disease. Therefore, further studies assessing these issues are warranted in the future.

Conflict of interest

The authors declare that neither they nor any of their affiliated institutions have any conflicts of interest.

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