Original Article

Functional electrical stimulation to the abdominal wall muscles synchronized with the expiratory flow does not induce muscle fatigue

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Abstract. [Purpose] Continuous electrical stimulation of abdominal wall muscles is known to induce mild muscle fatigue. However, it is not clear whether this is also true for functional electrical stimulation delivered only during the expiratory phase of breathing. This study aimed to examine whether or not intermittent electrical stimulation delivered to abdominal wall muscles induces muscle fatigue. [Subjects and Methods] The subjects were nine healthy adults. Abdominal electrical stimulation was applied for 1.5 seconds from the start of expiration and then turned off during inspiration. The electrodes were attached to both sides of the abdomen at the lower margin of the 12th rib. Abdominal electrical stimulation was delivered for 15 minutes with the subject in a seated position. Expiratory flow was measured during stimulus. Trunk flexor torque and electromyography activity were measured to evaluate abdominal muscle fatigue. [Results] The mean stimulation on/off ratio was 1:2.3. The declining rate of abdominal muscle torque was 61.1 ± 19.1% before stimulus and 56.5 ± 20.9% after stimulus, not significantly different. The declining rate of mean power frequency was 47.8 ± 11.7% before stimulus and 47.9 ± 10.2% after stimulus, not significantly different. [Conclusion] It was found that intermittent electrical stimulation to abdominal muscles synchronized with the expiratory would not induce muscle fatigue.

Key words: Muscle fatigue, Abdominal wall muscles, Functional electrical stimulation

INTRODUCTION

In patients with cervical cord injuries, the ability to cough is diminished due to paralysis of abdominal wall muscles, which are the expiratory muscles required for forced breathing. An impaired ability to cough results in difficulty clearing secretions from the lungs, thereby increasing the risks of atelectasis, pneumonia, and ventilator failure. In spinal cord injury patients, impaired cough function is a major cause of increased morbidity and mortality rates1. As treatment modalities aimed at improving the ability of these patients to cough, respiratory muscle training using a training device2 and application of electrical stimulation to abdominal wall muscles (expiratory muscles) have both been reported3. Abdominal electrical stimulation (AES), used in recent years, involves the delivery of electrical stimulation with adequate intensity to the abdomen in synchronization with breathing to generate abdominal muscle contractions which increase intra-abdominal pressure. With ongoing treatment for 4 to 6 weeks, cough peak flow can reportedly be increased4, 5.

On the other hand, abdominal wall muscles are comprised mainly of Type II muscle fibers, in which continuous muscle contractions tend to cause muscle fatigue. In our previous study5, subjects also complained of muscle fatigue after functional
electrical stimulation (FES) of their abdominal wall muscles. Suzuki et al.\(^5\) reported that continuous high-frequency stimulation delivered to abdominal wall muscles induced mild muscle fatigue. The conditions of electrical stimulation associated with muscle fatigue include its frequency, intensity, duration, and the on/off ratio. However, it is not clear whether muscle fatigue is also induced by breathing-synchronized FES that stimulates abdominal wall muscles during the expiratory phase only. We hypothesized that intermittent FES to abdominal wall muscles would not induce muscle fatigue.

This study aimed to examine whether or not intermittent electrical stimulation of the abdominal wall muscles induces muscle fatigue.

**SUBJECTS AND METHODS**

The subjects were nine healthy adults, free of cardiopulmonary disease, with a mean ± SD age of 20.8 ± 1.0 years, mean ± SD height of 170.0 ± 10.0 cm, mean ± SD weight of 61.3 ± 5.6 kg, mean ± SD BMI of 21.1 ± 2.4 kg/m\(^2\), and mean ± SD body fat percentage of 14.6 ± 3.0%. This study was conducted with the approval of the ethics committee of Ibaraki Prefectural University of Health Sciences.

Abdominal electrical stimulation (AES): The electrical stimulation device used was NeuroPack MEB-5504 (Nihon Kohden, Tokyo, Japan). With expiratory flow set as the trigger, AES was delivered for 1.5 seconds from the start of expiration and then turned off during inspiration. To achieve maximal abdominal muscle contractions, the electrodes were attached to both sides of the abdomen at the lower margin of the 12th rib, where the intercostal nerves are distributed. We used 4 cm × 15 cm electrodes (split 1180: 3 M Health Care, St. Paul, MN, USA). For electrical stimulation, we used bipolar square wave pulses at a stimulus intensity of 60 mA and stimulus frequency of 50 Hz.

Respiratory flow measurement: During AES, expiratory flow was measured employing a spirometer attached to the face mask. Expiratory flow was measured during AES.

Muscle fatigue evaluation of abdominal wall muscles: To evaluate muscle fatigue, abdominal muscle strength was measured. The subjects were placed in the supine position on a bed with the measurement band of a handheld dynamometer (mobile; SAKAI Medical Co., Ltd., Tokyo, Japan) attached to the chest. They were then asked to keep the trunk elevated for 30 seconds and the torque produced by trunk flexion (abdominal muscle torque) was calculated. Surface electromyography (EMG) activity was measured, using a surface EMG device (P-EMG plus; Oisaka Electronic Equipment Ltd., Hiroshima, Japan), simultaneously with the abdominal muscle strength test. The electrode for surface EMG was placed on the rectus abdominis muscles on the right side (at a width of two fingers above the navel). The indifferent electrode was placed on the anterior superior iliac spine on the right side.

Experimental protocol: AES was applied for 15 minutes with the subject in the sitting position. Before and after AES, abdominal muscle strength and surface EMG activity were measured.

Data analysis and statistical methods: Expiratory flow was analyzed at 1-minute intervals, and the peak expiratory flow (PEF) and mean expiratory flow (MEF) were calculated. Abdominal muscle torque was analyzed every 2 seconds, and the maximum value and the value at completion for each 30-second period were obtained; the declining rate was calculated by dividing the value at completion by the maximum value. Surface EMG activity of the trunk/abdominal muscles was analyzed every 2 seconds, and the mean power frequency (MPF) was calculated; a declining rate was calculated based on the maximum and minimum values during the 30-second period. The declining rates of abdominal muscle torque and MPF before and after AES were compared.

PEF and MEF values were analyzed by repeated measures analysis of variances. Abdominal muscle torque and MPF of abdominal muscles were analyzed employing the paired t-test. We used statistical processing software (IBM SPSS statistics 20.0) and the significance of differences was defined at a p value <0.05.

**RESULTS**

As electrical stimulation was applied in synchronization with breathing, its mean on/off ratio was 1:2.3 (2.1–2.5). Changes in PEF and MEF during stimulation are shown in Table 1. PEF tended to decrease gradually after the first minute (p<0.05) but remained at the same level after 10 minutes. No significant decrease was seen in MEF after the first minute. The declining

| time (min) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
|------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| PEF (L/s)  |    |    |    |    |    |    |    |    | 0.50*| 0.50*| 0.46*| 0.47*| 0.49*| 0.47*| 0.47*|
| Mean       | 0.86| 0.74| 0.68| 0.66*| 0.61*| 0.65| 0.60| 0.53*| 0.50*| 0.50*| 0.46*| 0.47*| 0.49*| 0.47*| 0.47*|
| SD         | 0.44| 0.32| 0.23| 0.25| 0.23| 0.20| 0.21| 0.17| 0.15| 0.15| 0.15| 0.15| 0.13| 0.14|     |
| MEF (L/s)  |    |    |    |    |    |    |    |    | 0.27| 0.29| 0.27| 0.28| 0.28| 0.27| 0.29|
| Mean       | 0.46| 0.43| 0.40| 0.37| 0.37| 0.36| 0.33| 0.30| 0.27| 0.29| 0.27| 0.28| 0.28| 0.27| 0.29|
| SD         | 0.23| 0.19| 0.14| 0.13| 0.12| 0.07| 0.09| 0.11| 0.07| 0.08| 0.09| 0.08| 0.07| 0.07| 0.08|

All variables are mean ± standard deviation (SD). *p<0.05, compared with the value of first minute. PEF: peak expiratory flow; MEF: mean expiratory flow.
rate of abdominal muscle torque was 61.1 ± 19.1% before AES and 56.5 ± 20.9% after AES, not significantly different. The declining rate of MPF was 47.8 ± 11.7% before AES and 47.9 ± 10.2% after AES, not significantly different.

**DISCUSSION**

We have developed a rehabilitation device for supporting an expiratory effort, and have reported the effect of functional electrical stimulation to abdominal wall muscle synchronized with expiratory flow\(^5\). However, it has not been clarified whether the AES induces fatigue of abdominal wall muscles.

This experiment was designed to elucidate whether or not intermittent FES delivered to abdominal wall muscles for a set period of time induces muscle fatigue. Under the conditions of electrical stimulation specified in this study, expiratory flow decreased immediately after the start of stimulation but there was no decrease in either MPF or joint torque, which are indicators of muscle fatigue. This suggests that muscle fatigue was not induced by the electrical stimulation applied under our experimental conditions.

Suzuki et al.\(^6\) reported that delivery of continuous electrical stimulation to abdominal muscle walls induced muscle fatigue and decreased both maximum expiratory pressure and EMG frequency. Our study revealed that intermittent FES delivered for 15 minutes does not induce muscle fatigue. Regarding the on/off ratio of electrical stimulation, it is known that the shorter the off-time, the more likely is the induction of muscle fatigue. In our experiment, we set the start of expiration as the trigger and delivered electrical stimulation for 1.5 seconds at a time, in synchronization with breathing, resulting in a longer resting period as evidenced by the on/off ratio of 1:2.3 (2.1–2.5).

Abdominal wall muscles has the function of expiratory effort, and active in expiratory phase of expiratory effort such as cough and vocalization. Contraction of the abdominal wall muscles increases abdominal pressure and intrathoracic pressure, and increasing the expiratory flow by these internal pressure. In accord with these mechanisms, expiratory flow is reduced if muscle fatigue has been caused. For this reason we decided to use as an indicator of muscle fatigue of the abdominal wall muscles. Immediately after the start of electrical stimulation, PEF started to decrease gradually over time, but remained unchanged after 10 minutes. This might be attributable to skin irritancy factors caused by the electrical stimulation, such as uncomfortable and/or mild pain, contributing to elevated ventilation right after the start of stimulation. Therefore, in this case, the decrease in PEF was not caused by muscle fatigue but, rather, was attributable to the time required for the subjects’ breathing to stabilize.

In conclusion, It was demonstrated that delivering intermittent electrical stimulation to abdominal muscles synchronized with the expiratory would not induce muscle fatigue. Possible contributing factors may include the intensity of stimulation having been set at a level that all subjects could readily tolerate, and the longer off-time resulting from the on/off ratio of stimulation being synchronized with expiration and inspiration.

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