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Original Article

Neuromuscular Electrical Stimulation of Abdominal Muscles to Improve Standing Balance

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Key Words
Abdominal muscles
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Background: Neuromuscular electrical stimulation (NMES) is used for muscle strengthening. While voluntary muscle contraction follows Henneman et al.'s size principle, the NMES-induced muscle training disrespects the neurophysiology, which may lead to unwanted changes (i.e., declined balance ability).

Objects: We examined how the balance was affected by abdominal muscle training with the NMES.

Methods: Fifteen young adults (10 males and 5 females) aged between 21 and 30 received abdominal muscle strengthening with NMES for 23 minutes. Before and after the training, participants' balance was measured through one leg standing on a force plate with eyes open or closed. Outcome variables included mean distance (MDIST), root mean square distance (RDIST), total excursion (TOTEX), mean velocity (MVELO), and 95% confidence circle area (AREA) of center of pressure data. Two-way repeated measures analysis of variance was used to test if these outcome variables were associated with time (pre and post) and vision.

Results: All outcome variables were not associated with time ($p > 0.05$). However, all outcome variables were associated with vision ($p = 0.0001$), and MVELO and TOTEX were 52.4% (45.5 mm/s versus 95.6 mm/s) and 52.4% (364.1 mm versus 764.5 mm) smaller, respectively, in eyes open than eyes closed ($F = 55.8$, $p = 0.0005$; $F = 55.8$, $p = 0.0005$). Furthermore, there was no interaction between time and vision ($F = 0.024$, $p = 0.877$).

Conclusion: Despite the different neurophysiology of muscle contraction, abdominal muscle strengthening with NMES did not affect balance.

INTRODUCTION

Neuromuscular electrical stimulation (NMES) is widely used for muscle strengthening, long-term immobilization, prevention of muscle atrophy, muscle re-education, and edema control [1]. Among them, NMES is mainly used for muscle strengthening [2-4], and research studies support its benefits [5].

The NMES mimics voluntary muscle contraction (VMC) controlled by the central nervous system and delivers an electrical current to the epidermis to depolarize the axons underlying the soft tissue, which then causes the contraction of muscles [6]. However, neurophysiological differences exist in muscle contraction characteristics between the NMES and VMC [7,8]. The VMC follows Henneman et al. [9]'s size principle, and the size of recruited motor units increases with muscle force demand. Furthermore, the VMC changes motor unit recruitment patterns to minimize muscle fatigue by modulating the firing frequency of alpha motor neurons and/or replacing fatigued motor units with un-fatigued units [10]. However, NMES-induced muscle training disrespects this neurophysiology. Therefore, NMES induced muscle training may change the typical neurophysiology of muscle contraction.

Muscle strengthening is known to occur by two main mechanisms. The first is caused by an increase in muscle size (muscle mass adaptation), and the second is caused by improved recruitment of motor units (non-muscle mass adaptation) [11]. Muscle mass adaptation requires several weeks of training. However, shorter training sessions can achieve non-muscle mass adaptation [12], which is why individuals have feelings of improved strength quickly after workouts.

At a loss of balance, individuals react to recover the balance by replacing or keeping the center of pressure (COP) within the base of support. This balance recovery activity involves contractions of different muscles, and core muscles are known to play an important role [13]. The core muscles include the spine, hip, pelvis, and abdominal muscles, and these muscles have closely connected to each other like a chain. Among these core muscles, the transverse abdominal muscle (Tra) is important for stabilizing the lumbar spine [14], and contraction of the abdominal muscles increases abdominal pressure to form a solid cylinder in the abdomen, improving the stability of the lumbar spine [15]. And the rectus abdominis (RA), external and internal oblique muscles (EO, IO) are activated before the extremities move to support the posture [16,17]. Collectively, these abdominal muscles are important for balance and recovery.

Research evidence suggests that slow twitch muscle fibers are activated with a firing frequency of about 10 Hz, fast twitch muscle fibers are contracted at about 30 Hz [18], and about 60% of the abdominal muscles consist of slow twitch fibers [19]. This indicates not only that the abdominal muscles may be easily fatigued with a greater firing frequency, which often happens as most commercially available NMES devices do not provide options to change the frequency of electrical stimulation in the application, but also that the typical neurophysiology of abdominal muscle contraction may change with repetitive use of NMES. This plausible conjecture is partially supported by previous research, where the recruitment of motor units caused by NMES requires a lot of metabolic demand and may cause muscle fatigue [10,20]. While this change, in turn, may affect one's balance performance, it has never been examined.

Against this background, we conducted experiments with humans to examine how muscle strengthening with NMES affects standing balance. We hypothesized that the application of NMES to abdominal muscles would affect the static balance.

MATERIALS AND METHODS

1. Subjects

Fifteen young adults (10 males and 5 females) aged between 21 and 30 participated. Demographic information on the participants is provided in (Table 1). Exclusion criteria included individuals with sensory impairment, metal implants, and other medical conditions that caused discomfort during the experiment [21]. A statistical power analysis using G-power software 3.1.9.4 (Franz Faul, Kiel University, Kiel, Germany) [22] was performed with the results of five subjects. The power analysis with partial eta square (0.13) from the result of pilot testing showed that 11 subjects should be included to achieve 80% statistical power with an alpha of 0.05 and an effect size of 0.4. Informed consent was obtained from all individual participants included in the study. The study protocol was approved by the Institutional Review Board at Yonsei University Mirae campus (IRB no. 1041849-202203-BM-052-02).

2. Experimental Protocol

Participant performed one-leg standing on a force plate (model OR6-7-2000; AMTI, Waltham, MA, USA) for 10 seconds with a bare foot of dominant side and arms at sides (Figure 1A). Three trials were acquired with eyes open and closed with a 30-second rest period between trials. Then, they received muscle strengthening training, where an NMES device (Six pad; MTG Co., Ltd., Nagoya, Japan) was placed on abdominal muscles (RA, EO, IO, Tra) for 23 minutes (Figure 1B). The device provided biphasic square wave pulses (100 μs) at 2–20 Hz (mostly 20 Hz) with stimulation intensity that caused visible, greatest muscle contraction with no pain and discomfort. After the training, participants performed the one-leg standing again.

3. Data Analysis

COP data was sampled at a rate of 1,000 Hz and filtered through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency. Eight seconds exclud-

Table 1. Demographic information of participants

Sex	Height (cm)	Weight (kg)	BMI (kg/m^2)	Age (y)
Male	179.1 ± 3.9	82.6 ± 11.7	25.8 ± 3.7	25.9 ± 2.7
Female	159.4 ± 7.0	55.5 ± 8.0	21.8 ± 2.0	23.6 ± 1.8

Values are presented as mean ± standard deviation. BMI, body mass index.

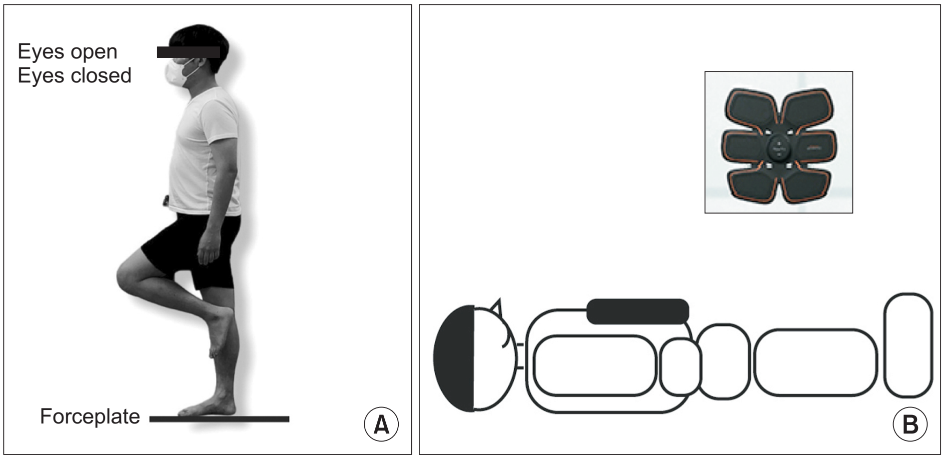

Figure 1. Participant performed (A) one-leg standing with arms at side, one-leg standing on a force plate (B) before and after NMES training of abdominal muscles.

Table 2. Average values of outcome variables

Measure	NMES				p-value		
	Eyes closed		Eyes open		Vision	Time	Interaction
	Pre	Post	Pre	Post			
MDIST (mm)	14.4 ± 2.7	15.2 ± 3.9	7.6 ± 1.6	8.3 ± 1.8	0.0005*	0.092	0.877
RDIST (mm)	15.9 ± 2.9	17.3 ± 5.4	8.5 ± 1.8	9.4 ± 2.1	0.0005*	0.075	0.639
TOTEX (mm)	764.5 ± 183.7	711.0 ± 182.7	364.1 ± 103.1	344.6 ± 104.7	0.0005*	0.051	0.350
MVELO (mm/s)	95.6 ± 23.0	88.9 ± 22.8	45.5 ± 12.9	43.1 ± 13.1	0.0005*	0.051	0.350
AREA (mm^2)	2145.3 ± 754.6	3448.7 ± 4526.1	650.3 ± 254.5	814.6 ± 352.9	0.0005*	0.196	0.313

Values are presented as mean ± standard deviation. MDIST, mean distance; RDIST, root mean square distance; TOTEX, total excursion; MVELO, mean velocity; AREA, 95% confidence circle area. *p < 0.05.

ing the first and last 1 second were used for COP data analysis. Outcome variables included mean distance (MDIST), root mean square distance (RDIST), total excursion (TOTEX), mean velocity (MVELO), and 95% confidence circle area (AREA) [23-25]. All outcome variables were calculated using Matlab routines (MATLAB R2019A; MathWorks, Natick, MA, USA).

Two-way repeated measures analysis of variance (ANOVA) was used to examine how the outcome variables were associated with time (pre and post) and vision (eyes closed and open) with a significance level $\alpha = 0.05$. All analyzes were performed using IBM SPSS software (ver. 21.0; IBM Co., Armonk, NY, USA).

RESULTS

All outcome variables were not associated with time ($p > 0.05$). However, all outcome variables were associated with vision ($p = 0.0001$), and MVELO and TOTEX were 52.4% (45.5 mm/s versus 95.6 mm/s) and 52.4% (364.1 mm versus 764.5 mm) smaller, respectively, in eyes open than eyes closed ($F = 55.8$, $p = 0.0005$; $F = 55.8$, $p = 0.0005$) (Table 2). Furthermore, there was no interaction between time and vision ($F = 0.024$, $p = 0.877$).

DISCUSSION

The purpose of this study was to examine effects on static balance of abdominal muscle strengthening with NMES. We found that the NMES-induced muscle strengthening did not improve static balance. This finding conflicts with a previous study, where Je and Choi [24] reported that static balance increased by 48.9% with application of NMES to tibialis anterior, gastrocnemius and soleus muscles. This discrepancy might be due, in part, to target muscles of strengthening. Amiridis et al. [26] have shown that static balance improves 49.4% with NMES training of the tibialis anterior muscle. And Acheche et al. [27] showed a 29.3% improvement in balance after applying NMES combined with VMC to the quadriceps and calf muscles. Furthermore, Bondi et al. [28] have reported that static balance improved by 30.3% after 8 weeks of application of NMES to the quadriceps and lumbar paraspinal muscles. Furthermore, In the study of Wakahara and Shiraogawa [29], NMES (low frequency 20 Hz) was used to evaluate muscle thickness using MRI and ultrasound images after 12 weeks of abdominal muscle training, but there was no significant difference. Therefore, 20 Hz appears to be an ineffective frequency for abdominal muscle training. Collectively, the effects of NMES-induced muscle training on static balance depend on the target muscle and electrical stimulation frequency.

Another purpose of this study was to examine how the effect of NMES on balance performance was affected by vision. Our ANOVA suggested no interaction between time and vision, indicating the time and vision affect balance independently. This result agrees with previous findings. Acheche et al. [27] in patients with chronic obstructive pulmonary disease, there was no vision interaction (group*vision) with the NMES, endurance-and-resistance-only group and the endurance-and-resistance-only group. And there was no interaction between the group to which visual and NMES were applied and the VMC group as in the Je and Choi [24]'s study. Furthermore, in the study of Kim et al. [25], there was no interaction between the independent variable and time as in the aforementioned studies. Collectively, there was no significant difference between pre and post the application of NMES, and it appears that there was no interaction between vision and time because more balance ability was required when eyes were closed than when eyes were opened.

Our results have limitations. First, we only focused on the non-muscle mass adaption caused by NMES. Another aspect of muscle strengthening (muscle mass adaptation), which may take several weeks, should also be considered. Second, we only included healthy young adults. Therefore, our results may not be applied to older adults since muscle functions (i.e., contraction, power, endurance) normally decline with age. Future studies addressing these limitations should be warranted.

CONCLUSIONS

In summary, The NMES-induced muscle training disrespects typical neurophysiology of VMC. Therefore, NMES-induced muscle training may change characteristics of muscle contraction, which may affect balance ability. However, the NMES training of the abdominal muscles did not affect balance.

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CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

AUTHOR CONTRIBUTIONS

Conceptualization: JJ, WJC. Data curation: JJ, WJC. Formal analysis: JJ, WJC. Funding acquisition: JJ, WJC. Investigation: JJ, WJC. Methodology: JJ, WJC. Project administration: JJ, WJC. Resources: JJ, WJC. Software: JJ, WJC. Supervision: JJ, WJC. Validation: JJ, WJC. Visualization: JJ, WJC. Writing - original draft: JJ, WJC. Writing - review & editing: JJ, WJC.

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