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Original Article

A comparative study of changes in H_{max}/M_{max} under spinning permanent magnet stimulation, repetitive peripheral magnetic stimulation, and transcutaneous electrical nerve stimulation in healthy individuals

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ABSTRACT

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Objective: We have developed a compact device using a spinning permanent magnet (SPM) that induces an electrical field by changing the magnetic flux. We hypothesized that SPM stimulation also reduced spasticity, comparable with repetitive peripheral magnetic stimulation (rPMS) and transcutaneous electrical nerve stimulation (TENS). This study evaluated the effect of a single session of SPM stimulation and compared it with those of rPMS and TENS in healthy individuals.

Methods: Eleven healthy adult men participated in this study. The active electrode was placed on the soleus muscle, and the reference electrode was placed at 5 cm distal from the active electrode on the medial side of the Achilles tendon. The stimulating electrodes were fixed on the popliteal fossa to stimulate the tibial nerve. The maximum H-reflex (H_{max}) and the maximum motor response (M_{max}) were measured, and H_{max}/M_{max} was calculated under the following conditions: a) 15 min SPM stimulation, b) 30 min SPM stimulation, c) 10,000 pulses rPMS, d) 15 min TENS, and e) 15 min rest (control). The devices for SPM, rPMS, and TENS were applied to the belly of the soleus muscle in the prone position.

Results: Compared with the control, H_{max}/M_{max} significantly decreased under SPM stimulation for 15 and 30 min, as well as under rPMS and TENS ($p < 0.005$). The changes in H_{max}/M_{max} under 15 min SPM stimulation were significantly smaller than those under 30 min SPM stimulation and rPMS ($p < 0.005$).

Conclusion: SPM stimulation reduced H_{max}/M_{max} in healthy individuals and is a potential new treatment for spasticity.

Key words: spinning permanent magnet, repetitive peripheral magnetic stimulation, transcutaneous electrical nerve stimulation, H_{max}/M_{max}

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Conflict of Interest: IFG Corporation has a pending patent and Drs. Mori and Kagaya are listed as inventors of the spinning permanent magnet (SPM) device. The SPM device was loaned free of charge from IFG Corporation. Dr. Mori is a stockholder with IFG Corporation. The remaining authors have no conflicts of interest.
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Introduction

Spasticity often interferes with rehabilitation. Transcutaneous electrical nerve stimulation (TENS) is one of the frequently used physical modalities to reduce spasticity [1]. TENS is a relatively safe intervention with an acceptable adverse event profile. Its short-term effectiveness has been previously demonstrated in the management of spasticity in various neurologic etiologies [2]. The electrodes for TENS were placed either on the agonist muscle belly,

the antagonist muscle belly, or along the course of the nerve. High-frequency TENS at 100 Hz seemed most beneficial [3]. Usually, the stimulation intensity is set above the sensory threshold but below the motor threshold, which causes a tingling sensation [2, 3].

Repetitive peripheral magnetic stimulation (rPMS) to the extremities is also effective in reducing spasticity. Even a single session of rPMS reduced spasticity, activating the nerves and muscles without stimulating the skin nociceptors [4−6]. In addition, rPMS does not need electrodes attached to the skin. Nevertheless, the current equipment for rPMS is bulky, and seems impractical to use for just reducing spasticity. The idea of using a spinning permanent magnet (SPM) for transcranial magnetic stimulation was first advocated by Helekar and Voss [7]. We have developed a compact SPM device for the extremities that induces an electrical field by changing the magnetic flux. Although the SPM stimulation intensity was lower than that of conventional rPMS, we hypothesized that SPM stimulation could nevertheless reduce spasticity as TENS that had a lower stimulus intensity than the motor threshold reduced spasticity [2, 3].

The effectiveness of TENS on spasticity is often evaluated with the Modified Ashworth Scale (MAS) [4, 6, 8−10], whereas the electrophysiological technique is used for objective measurement [11−13]. The ratio of maximum H-reflex (H_{max}) to maximum motor response (M_{max}), H_{max}/M_{max}, is a frequently used evaluation item compared with other parameters and is a high value in spastic muscle [13, 14]. A lower H_{max}/M_{max} means decreased spasticity, which decreases under TENS, even in healthy subjects [13, 14]. Therefore, this study evaluated H_{max}/M_{max} after a single session of SPM stimulation and compared it with those under rPMS and TENS in healthy individuals.

Methods

The participants were 11 healthy adult men with a mean (SD) age of 34 (9) years, mean (SD) height of 171.1 (6.2) cm, and mean (SD) body weight of 64.8 (7.8) kg. This study was approved by our Certified Clinical Research Review Board and was registered with the Japan Registry of Clinical Trials (Registration No. jRCTs042200013). Written informed consent was obtained from all participants.

The SPM device we have developed provides magnetic stimulation by spinning a disk-shaped permanent magnet with a motor. The magnet spins around a disk-shaped central axis. Four magnetic poles are arranged around the axis on the circumference of the flat surface of the magnet, and their polarity is reversed every 90 degrees. The direction of the magnetic flux from the magnet is perpendicular to the plane of the disk shape. The magnet is covered by a cylindrical plastic case, and an alternating current magnetic field with a frequency of 130 Hz and a maximum magnetic flux density of 0.23 T can be generated from the bottom of the case. The stimulus intensity of this device was set below both the sensory and motor thresholds based on the results of a preliminary study. The dimensions of the device were a diameter of 7.8 cm, height of 2.1 cm, and weight of only 108 g (Figure 1). It can be attached easily to the extremities. The device was under development and is not commercially available.

The participants lay in a prone position with the knees slightly flexed. They were then asked to relax their muscles as much as possible during the study. Ag/AgCl surface electrodes (NM-31, Nihon Kohden Corp., Tokyo, Japan) were used as recording electrodes. The active electrode was placed on the soleus muscle at the gastrocnemius–soleus muscle junction. The gastrocnemius and the soleus muscles were identified by ultrasound (Noblus, Hitachi, Ltd., Tokyo, Japan). The reference electrode was placed at 5 cm distal from the active electrode on the medial side of the Achilles tendon. A ground electrode was placed between the active and stimulating electrodes. The stimulating electrodes were fixed on the popliteal fossa to stimulate the tibial nerve using a Neuropack X1 (Nihon Kohden Corp., Tokyo Japan). The duration of the rectangular stimulus was 1 ms. The stimulation intensity was gradually increased to record H_{max} values and, subsequently, M_{max} values, with the location of the stimulating electrodes remaining unchanged. The peak-to-peak amplitudes of the H and M responses of the soleus muscle were recorded. These protocols were developed with reference to the previous study [13]. The H_{max}/M_{max} amplitude was calculated for each participant by dividing the maximum amplitude of the H-reflex by that of the M responses. H_{max}/M_{max} was evaluated twice to ensure the values obtained were stable, because it varies widely among individuals,

Figure 1. The spinning permanent magnet (SPM) device.
The dimensions of this device were a diameter of 7.8 cm, height of 2.1 cm, and weight of only 108 g.

even in healthy subjects. After confirming that the two H_{max}/M_{max} values were similar, the second value instead of the average and the H_{max}/M_{max} value after stimulation were used for further analyses.

The H_{max}/M_{max} was measured under the following conditions for each subject: a) SPM stimulation for 15 min, b) SPM stimulation for 30 min, c) rPMS for 10,000 pulses, d) TENS for 15 min, and e) 15 min rest without any stimulation (control). The devices for SPM, rPMS, and TENS were applied to the belly of the soleus muscle (Figure 2). The experiment was conducted under each condition on different days. A commercially available PMS stimulator (Pathleader; IFG Corp., Sendai, Japan) was used for rPMS with on- and off-times of 2 s each. The stimulation frequency was set at 50 Hz, which was the maximum for this machine. The stimulus condition for rPMS was described using the number of pulses rather than stimulus time; hence, it was difficult to match the stimulus condition of rPMS with SPM or TENS. Therefore, we adopted the stimulus condition for rPMS that seemed to be effective in reducing spasticity. TENS was applied at a pulse duration of 70 μs and a frequency of 100 Hz using a commercially available stimulator (Rehab; NIPPON SIGMAX Co., Ltd., Tokyo, Japan). For rPMS and TENS, the sensory and motor thresholds were determined by gradually increasing the stimulation intensity. The sensory threshold was the minimum stimulation intensity at which the subject reported feeling a tingling sensation, whereas the motor threshold was defined as the minimum stimulation intensity at which a visible twitch of the soleus muscle was observed. The stimulation intensity for both rPMS and TENS was set at the level above the sensory threshold but just below the motor threshold. Thus, rPMS has a stronger stimulus intensity than SPM. The mean (SD) intensity of rPMS applied was 0.33 (0.03) T.

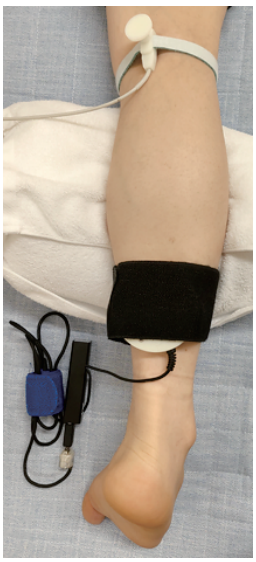

Figure 2. The spinning permanent magnet (SPM) device on the belly of the soleus muscle.
The device was connected to a small battery. The stimulating electrodes were fixed on the popliteal fossa to stimulate the tibial nerve. H_{max}/M_{max} was evaluated before and after stimulation.

Statistical analysis

The differences in the H_{max}/M_{max} values before and after stimulation or 15 min rest (control) were calculated as follows:
Changes in H_{max}/M_{max} = (H_{max}/M_{max} values just after stimulation) − (H_{max}/M_{max} values just before stimulation)
However, the control group used H_{max}/M_{max} values after 15 min of rest instead of just after stimulation.

The normality of the changes in H_{max}/M_{max} was evaluated using the Shapiro-Wilk test with a significance level of 5%. Each H_{max}/M_{max} change was compared using one-way analysis of variance (ANOVA) followed by the Wilcoxon signed-rank test with Bonferroni correction with a significance level of $5\%/{}_5C_2 = 0.5\%$. We used % changes and one-way ANOVA, because H_{max}/M_{max} is known to differ considerably from person to person even in healthy subjects [14, 15]. All statistical analyses were conducted using JMP version 12 (SAS Institute Japan Inc., Tokyo, Japan).

Results

No adverse events were observed in this study. As mentioned before, the H_{max}/M_{max} values evaluated twice were similar. The changes in H_{max}/M_{max} under the different conditions were normally distributed except those under TENS ($p = 0.023$). The median changes for 15 min SPM stimulation, 30 min SPM stimulation, rPMS, TENS, and control were −3.0%, −6.6%, −6.7%, −4.7%, and 0.2%, respectively. There were significant differences between groups by ANOVA ($F = 11.153$, $p < 0.001$). Compared with the control, H_{max}/M_{max} significantly decreased under SPM stimulation for 15 min ($p = 0.0020$), SPM for 30 min ($p = 0.0010$), rPMS ($p = 0.0010$), and TENS ($p = 0.0010$). The changes in H_{max}/M_{max} under 15 min SPM stimulation were significantly smaller than those under 30 min SPM stimulation ($p = 0.0020$) and rPMS ($p = 0.0049$) (Figure 3).

Discussion

Our study revealed that the changes in H_{max}/M_{max} values under SPM stimulation, rPMS, and TENS were lower than those of the control. SPM stimulation for 15 min was less effective than SPM stimulation for 30 min and rPMS but was comparable to TENS. A study in healthy individuals found that H_{max}/M_{max} and the latencies of the soleus H-reflex measured from the soleus H-reflexes whose sizes were 10% of the M_{max}

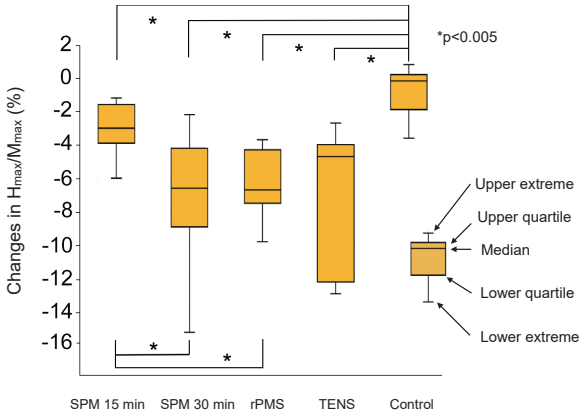

Figure 3. Changes in H_{max}/M_{max}.
Compared with the control, H_{max}/M_{max} significantly decreased under SPM stimulation for 15 min, SPM for 30 min, rPMS, and TENS. The changes in H_{max}/M_{max} under 15 min SPM stimulation were significantly smaller than those under 30 min SPM stimulation and rPMS.
SPM, spinning permanent magnet; rPMS, repetitive peripheral magnetic stimulation; TENS, transcutaneous electrical nerve stimulation.

were reduced significantly under 15 min TENS [14]. Another study found that H_{max}/M_{max}, H_{max}, M_{max}, and M slope ratio significantly decreased under 30 min TENS even in healthy participants [13]. Similarly, an H-reflex with an amplitude of approximately 30% of M_{max} decreased under 15–40 min TENS [16]. In the present study, a significant reduction of H_{max}/M_{max} under SPM stimulation indicates that this method can decrease spasticity as effectively as TENS. As the H_{max}/M_{max} values evaluated twice were similar, the second value was used for analyses in this study. If future studies show differences in these values, alternative methods can be considered.

Due to current technology limitations, the maximum magnetic flux density of the SPM device could only be 0.23 T, whereas rPMS applied to just below the motor threshold in this study was 0.33 T on average. Accordingly, a longer stimulation duration with the SPM device was needed to obtain the same efficacy as rPMS. Nevertheless, 15 min SPM stimulation was as effective as 15 min TENS. The reported effective duration of TENS varied from 15 min [17] to 60 min [18, 19]. TENS applied for 15 min on the agonist muscle at an intensity below the motor threshold for 5 days a week for 2 weeks significantly reduced MAS [17]. Even TENS with an intensity under the sensory threshold also decreased MAS [10]. The intensity of the SPM stimulation applied in this study was below both the sensory and motor thresholds; however, magnetic stimulation activates the nerve and muscles without stimulating the skin nociceptors. Therefore, the sensory threshold intensity of magnetic stimulation is possibly higher than that of electrical stimulation. Further studies are needed in the future.

The mechanisms by which TENS could be affecting spasticity and movement control remain unclear [2]. Agonist muscle stimulation can be used to enhance the recurrent inhibition as an inhibitory pathway for the agonist muscle. This is thought to be caused by the Renshaw cell, which has a negative feedback loop to the α-motoneuron [20, 21]. Antagonistic muscle stimulation may conveniently enhance the reciprocal Ia inhibition [20, 21]. In the present study, we measured H_{max}/M_{max} by agonist muscle stimulation. Antagonist muscle stimulation by SPM may lead to different results.

This study has several limitations. First, the stimulus intensities for SPM, rPMS, and TENS were not the same; different stimulus intensities may produce different results. The subjects recruited in this study were healthy individuals. Studies investigating SPM stimulation in patients with spasticity are thus warranted. Assessments of variables other than H_{max}/M_{max} using the electrophysiological technique will also be valuable. Standards on TENS conditions, such as electrode placement, pulse width, frequency, and intensity, have not been established [2]. The maximum magnetic flux density in the SPM device used in the present study is fixed at 0.23 T, but device placement (on the agonist muscle belly, the antagonist muscle belly, or along the course of the nerve) and stimulation duration can be adjusted.

Conclusion

We demonstrated that SPM stimulation reduced H_{max}/M_{max} as well as rPMS and TENS in healthy individuals. The SPM device is much smaller than an rPMS machine and does not result in a tingling sensation, because its stimulation intensity is below both the sensory and motor thresholds. TENS is used for clinical practice in reducing spasticity and for task-related training [9, 18]. Although the effect of SPM for patients is still unclear, this new device has potential as a new treatment method for spasticity.

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