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Original Article

Influence of Motor Imagery of Isometric Opponens Pollicis Activity on the Excitability of Spinal Motor Neurons: A Comparison Using Different Muscle Contraction Strengths

Yoshibumi Bunno, PT, MA[1)*], Yuko Yurugi, PT, MA[1)], Chieko Onigata, PT, MA[2)], Toshiaki Suzuki, PT, DMSc[2)], Hiroyasu Iwatsuki, PT, PhD[1)]

[1)] *Graduate School of Health Sciences, Graduate School of Aomori University of Health and Welfare: 58-1 Mase, Hamadate, Aomori 030-8505, Japan*
[2)] *Clinical Physical Therapy Laboratory, Faculty of Health Sciences, Kansai University of Health Sciences, Japan*

Abstract. [Purpose] This study aimed to determine the differences in the excitability of spinal motor neurons during motor imagery of a muscle contraction at different contraction strengths. [Methods] We recorded the F-wave in 15 healthy subjects. First, in a trial at rest, the muscle was relaxed during F-wave recording. Next, during motor imagery, subjects were instructed to imagine maximum voluntary contractions of 10%, 30%, and 50% while holding the sensor of a pinch meter, and F-waves were recorded for each contraction. F-waves were recorded immediately and at 5, 10, and 15 min after motor imagery. [Results] Both persistence and F/M amplitude ratios during motor imagery under maximum voluntary contractions of 10%, 30%, and 50% were significantly higher than that at rest. In addition, persistence, F/M amplitude ratio, and latency were similar during motor imagery under the three muscle contraction strengths. [Conclusion] Motor imagery under maximum voluntary contractions of 10%, 30%, and 50% can increase the excitability of spinal motor neurons. The results indicated that differences in muscle contraction strengths during motor imagery are not involved in changes in the excitability of spinal motor neurons.
Key words: Motor imagery, F-wave, Muscle contraction strength

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INTRODUCTION

Recently, the effectiveness of motor imagery (MI) has gained importance in rehabilitation. In many neurophysiological studies, the effects of MI assessed by positron emission tomography (PET), functional magnetic resonance imaging (fMRI), motor evoked potentials (MEPs), Hoffmann's reflex (H-reflex), and F-wave have been discussed. One study used PET to demonstrate activation of the supplementary motor area (SMA), premotor area (PM), somatosensory association area, and cingulate area (Cg) during motor imagery[1)]. Similarly, an fMRI study showed activation of the primary motor area (M1), SMA, PM, Cg, and cerebellum (Cb) during MI[2)]; furthermore, the primary somatosensory area (S1) and basal ganglia (BG) showed activation during MI[3, 4)]. Corticospinal excitability during MI may result from an increase in the MEP amplitude as measured by transcranial magnetic stimulation (TMS)[5)].

However, these studies could not determine the H-reflex and F-wave measurements as indices of the excitability of spinal motor neurons during MI[5–8)]. In our previous study, the excitability of spinal motor neurons during MI under maximum voluntary contractions (MVC) of 50% was higher than that at rest. Furthermore, the excitability of spinal motor neurons during MI under an MVC of 50%, determined by holding the sensor of a pinch meter between the thumb and index finger, was higher than that during MI without holding the sensor. During MI, maintaining a posture similar to the actual motion is important[9)]. In this study, using the F-wave, we examined changes in the excitability of spinal motor neurons during motor imagery of a muscle contraction at MVC strengths of 10%, 30%, and 50%.

An F-wave is a compound action potential obtained as a result of re-excitation ("backfiring") of an antidromic impulse following distal electrical stimulation of motor nerve fibers at the anterior horn cell[10–12)].

SUBJECTS AND METHODS

Subjects

In this study, we included 15 healthy subjects (males, 9; females, 6; mean age, 25.4±4.7 years). All subjects provided informed consent prior to the study's commencement. This

*Corresponding author. Yoshibumi Bunno (E-mail: 1392001@ym.auhw.ac.jp)

study was approved by the Research Ethics Committee at Kansai University of Health Sciences. The experiments were conducted in accordance with the Declaration of Helsinki.

Methods

Subjects were instructed to fix one eye on the pinch meter display (Unipulse, Digital indicator F304A) throughout the test while in the supine position. To maintain the skin impedance below 5 kΩ, an abrasive gel was applied. The room temperature was maintained at 25°C. F-waves were recorded by electromyography [VIASYS; Viking Quest electromyography machine (Nicolet)]. After stimulating the left median nerve at the wrist, we recorded the F-wave of the left thenar muscles with a pair of round disks attached to the skin with a collodion. The disks were placed over the muscle belly and on the thumb metacarpophalangeal joint. The electrodes comprised of a cathode placed over the left median nerve 3 cm proximal to the palmar crease and an anode placed 2 cm further proximally. The maximal stimulus was determined by delivering 0.2-ms square-wave pulses of increasing intensity to elicit the largest compound muscle action potentials. Supramaximal shocks (adjusted up to the value 20% higher than the maximum stimulus) were delivered at 0.5 Hz for acquisition of F-waves. The bandwidth filter ranged from 2 Hz to 3 KHz.

First, in a trial at rest (rest), the F-wave was recorded while the muscle was relaxed. Next, we measured the MVC; that is, the subjects held the sensor of the pinch meter while exerting their maximum effort for 10 s. Subsequently, the subjects learned the isometric opponens pollicis activity under an MVC of 10% for 1 min as a motor task. They performed the activity using visual feedback while watching the digital display of the pinch meter. They were then instructed to imagine the activity under an MVC of 10% by holding the sensor between the thumb and index finger. F-waves were recorded during the MI (10% MI). During trials of MI at rest, F-waves were recorded immediately at 5, 10, and 15 min after MI (post 0, post 5, post 10, and post 15). We defined the above process as the 10% MVC MI condition (10% MI condition). With regard to the 30% and 50% MVC MI conditions, F-waves were recorded using the same process. These conditions were randomly performed on different days.

F-waves were analyzed with respect to persistence, F/M amplitude ratio, and latency using 30 stimuli. In our study, persistence was defined as the number of measurable F-wave responses divided by 30 supramaximal stimuli. The F/M amplitude ratio was defined as the mean amplitude of all responses divided by the amplitude of the M-wave. Latency was defined as the mean latency from the time of stimulation to onset of a measurable F-wave. Persistence reflects the number of backfiring anterior horn cells. The F/M amplitude ratio reflects the number of backfiring anterior horn cells and the excitability of individual anterior horn cells[10, 11]. Therefore, persistence and the F/M amplitude ratio are considered indices of the excitability of spinal motor neurons.

We performed the following two statistical analyses: (1) To evaluate changes in the excitability of spinal motor neurons under each MVC MI condition, persistence, F/M amplitude ratio, and latency during MI at post 0, post 5, post 10, and post 15, respectively, were compared with those at rest using Dunnett's test. (2) We also evaluated the relative values obtained under the three MVC MI conditions by dividing the values of persistence, F/M amplitude ratio, and latency at rest with those obtained during MI at post 0, post 5, post 10, and post 15. The Kolmogorov-mirnov and Shapiro-ilk tests were used to evaluate normality of F-waves. The Friedman test was used to evaluate the difference between the relative values among the three MVC MI conditions. The significance level was set at $p < 0.05$. We used SPSS ver.19 for statistical analyses.

RESULTS

Regarding the changes in the F-wave, persistence under the three MVC MI conditions of 10%, 30%, and 50% was significantly increased (54.5±37.6%, 59.7±64.4%, and 120.2±138.2%, respectively) compared with at rest (Dunnett's test; $^{**}p < 0.01$; Tables 1–3). Persistence at post 0, post 5, post 10, and post 15 under the three MVC MI conditions of 10%, 30%, and 50% did not exhibit significant differences compared with at rest (Tables 1–3). No significant differences were observed between the relative values of persistence obtained under three MVC MI conditions of 10%, 30%, and 50% (Table 4).

The F/M amplitude ratio under the three MVC MI conditions of 10%, 30%, and 50% was significantly increased (97.8±128.0%, 156.8±215.6%, and 110.6±176.8%, respectively) compared with at rest (Dunnett's test; $^{**}p < 0.01$; Tables 1–3). The F/M amplitude ratio at post 0, post 5, post 10, and post 15 under the three MVC MI conditions of 10%, 30%, and 50% did not exhibit significant differences compared with at rest (Tables 1–3). No significant differences were observed between the relative values of F/M amplitude ratio obtained under three MVC MI conditions of 10%, 30%, and 50% (Table 5).

There were no significant differences in latency among the three MVC MI conditions (Tables 1–3). No significant differences were observed between the relative values of latency obtained under the three MVC MI conditions of 10%, 30%, and 50% (Table 6).

DISCUSSION

The excitability of spinal motor neurons under the MVC MI conditions of 10%, 30%, and 50% was higher than that of the spinal motor neurons at rest; this was considered to be the influence of the descending pathways corresponding to the thenar muscle. Excitatory input travels through the corticospinal pathway and reticulospinal tract and from the upper motor neurons to anterior horn cells. In contrast, inhibitory input travels through the extrapyramidal tract from upper motor neurons to anterior horn cells via interneurons. Previous research has demonstrated the activation of the cerebral cortex, M1, S1, SMA, pM, Cb, and BG during MI[1–4]. The SMA, pM, Cb, and BG have roles in planning and preparing movement and have connections to the M1.

Table 1. Changes in the F-wave during MVC MI of 10%

	Rest	10% MI	Post 0	Post 5	Post 10	Post 15
Persistence (%)	60.8 ± 16.0	89.3 ± 12.1**	65.4 ± 19.6	61.9 ± 14.5	59.5 ± 16.4	63.2 ± 15.2
F/M amplitude ratio (%)	1.17 ± 0.72	2.34 ± 2.27**	1.22 ± 0.80	1.16 ± 0.62	1.16 ± 0.87	1.12 ± 0.88
Latency (ms)	25.2 ± 1.7	25.0 ± 1.6	25.3 ± 1.6	25.3 ± 1.7	25.4 ± 1.7	25.4 ± 1.6

Mean ± SD. **p < 0.01 vs. at rest. Persistence and F/M amplitude ratio during the MVC MI of 10% were significantly higher than those at rest. Latency was not significantly different among all trials.
MVC, maximum voluntary contraction; MI, motor imagery

Table 2. Changes in the F-wave during MVC MI of 30%

	Rest	10% MI	Post 0	Post 5	Post 10	Post 15
Persistence (%)	59.5±20.4	86.5±18.0**	55.7±19.3	57.5±19.4	61.7±18.6	57.4±22.3
F/M amplitude ratio (%)	1.11±0.80	2.44±2.49**	1.03±0.49	1.16±0.92	1.18±1.03	0.98±0.78
Latency (ms)	25.0±1.8	24.7±1.5	24.6±1.6	25.0±1.7	25.0±1.8	25.1±1.8

Mean ± SD. **p < 0.01 vs. at rest. Persistence and F/M amplitude ratio during the MVC MI of 30% were significantly higher than those at rest. Latency was not significantly different among all trials.
MVC, maximum voluntary contraction; MI, motor imagery

Table 3. Changes in the F-wave during the MVC MI of 50%

	Rest	50% MI	Post 0	Post 5	Post 10	Post 15
Persistence (%)	52.2 ± 21.7	91.8 ± 13.9**	51.7 ± 24.5	56.9 ± 22.5	48.9 ± 19.5	56.0 ± 21.3
F/M amplitude ratio (%)	1.42 ± 0.76	2.49 ± 1.92**	1.41 ± 1.05	1.55 ± 1.14	1.30 ± 0.79	1.44 ± 0.80
Latency (ms)	24.9 ± 1.7	24.8 ± 1.9	24.8 ± 2.1	24.8 ± 1.9	25.3 ± 1.7	25.0 ± 1.6

Mean ± SD. **p < 0.01 vs. at rest. Persistence and F/M amplitude ratio during the MVC MI of 50% were significantly higher than those at rest. Latency was not significantly different among all trials.
MVC, maximum voluntary contraction; MI, motor imagery

Table 4. Comparison between relative values of persistence under the MVC MI conditions of 10%, 30%, and 50%

	MI	Post 0	Post 5	Post 10	Post 15
Relative values of persistence (10% MI condition)	1.54 ± 0.38	1.11 ± 0.34	1.06 ± 0.28	1.03 ± 0.36	1.09 ± 0.36
Relative values of persistence (30% MI condition)	1.60 ± 0.65	0.96 ± 0.22	0.99 ± 0.22	1.07 ± 0.23	0.99 ± 0.35
Relative values of persistence (50% MI condition)	2.20 ± 1.38	1.02 ± 0.30	1.17 ± 0.52	0.98 ± 0.28	1.11 ± 0.25

Mean ± SD. Relative values of persistence were not significantly different among the three MI conditions.
MVC, maximum voluntary contraction; MI, motor imagery

Table 5. Comparison between relative values of F/M amplitude ratio under the MVC MI conditions of 10%, 30%, and 50%

	MI	Post 0	Post 5	Post 10	Post 15
Relative values of F/M amplitude ratio (10% MI condition)	1.98 ± 1.28	0.84 ± 0.43	1.03 ± 0.56	0.95 ± 0.36	1.02±0.41
Relative values of F/M amplitude ratio (30% MI condition)	2.57 ± 2.12	0.76 ± 0.52	0.87 ± 0.42	1.05 ± 0.45	0.89 ± 0.31
Relative values of F/M amplitude ratio (50% MI condition)	2.11 ± 1.78	0.73 ± 0.42	0.86 ± 0.46	0.86 ± 0.27	1.01 ± 0.35

Mean ± SD. Relative values of F/M amplitude ratio were not significantly different among the three MI conditions.
MVC, maximum voluntary contraction MI, motor imagery

Table 6. Comparison between relative values of latency under the MVC MI conditions of 10%, 30%, and 50%

	MI	Post 0	Post 5	Post 10	Post 15
Relative values of latency (10% MI condition)	0.99 ± 0.02	1.01 ± 0.02	1.01 ± 0.02	1.00 ± 0.02	1.01 ± 0.01
Relative values of latency (30% MI condition)	0.99 ± 0.02	0.99 ± 0.05	1.00 ± 0.02	1.00 ± 0.02	1.00 ± 0.02
Relative values of latency (50% MI condition)	1.00 ± 0.03	1.01 ± 0.06	1.00 ± 0.05	1.02 ± 0.04	1.00 ± 0.03

Mean ± SD. Relative values of latency were not significantly different among the three MI conditions.
MVC, maximum voluntary contraction MI, motor imagery

The bulbar reticular formation (BRF), red nucleus (RN), Cb, and caudate nucleus have connections to anterior horn cells. The BRF has connections to the M1, SMA, pM, and Cb, and the RN has connections to the Cb. Activation of the cerebral cortex under MVC MI conditions of 10%, 30%, and 50% presumably increased the excitability of spinal motor neurons via the corticospinal pathway and extrapyramidal tract.

In addition, subjects performed MI while holding the sensor of a pinch meter; therefore, the influence of tactile and proprioceptive inputs should be considered. Mizuguchi et al.[13, 14] reported that the responsiveness of afferent pathways to the S1 during MI utilizing an object was modulated by a combination of tactile and proprioceptive inputs while touching the object. Somatosensory inputs from the periphery are projected to the S1. The S1 consists of Brodmann areas 1, 2, and 3 (BA1, BA2, and BA3), and BA3 consists of areas 3a and 3b (BA3a, BA3b). Proprioceptive inputs from the joint and muscle project to BA3a, and tactile inputs from the skin project to BA3b. There are no direct connections from BA3a and BA3b to the M1. Tactile and proprioceptive inputs from the periphery are integrated after they are hierarchically processed (i.e., BA3, BA1, and BA2) and then projected to the M1. Proprioceptive inputs project to the cerebellar nucleus via the spinocerebellar pathway and to the M1 via the RN and thalamic nucleus. It is considered that tactile and proprioceptive inputs while holding the sensor of a pinch meter increase the excitability of spinal motor neurons as part of the synergistic effect.

Differences in the muscle contractions strengths during MI are not involved in changes in the excitability of spinal motor neurons. With regard to the actual movement, Suzuki et al.[15] reported that persistence and F/M amplitude ratio increased linearly with the strength of muscle contraction during the isometric opponens pollicis activity under MVCs of 25%, 50%, 75%, and 100%. Hara et al.[16] showed that persistence and F-wave amplitude were significantly facilitated, compared with at rest, during stepwise increments of 3% to 30% in MVC. However, these metrics remained unchanged during stepwise increments of 3% to 30% in MVC. These results suggest that the excitability of spinal motor neurons may increase with the strength of muscle contraction; however, a greater voluntary effort may fail to induce additional enhancements at a very mild muscle contraction strength.

Various studies have reported about changes in the excitability of spinal motor neurons during MI of a muscle contraction at different muscle contraction strengths.

Hale et al.[17] reported that the soleus H-reflex amplitude during plantar flexion MVC MI of 40%, 60%, 80%, and 100% increased linearly throughout the test. However, there were no differences in the changes in the H-reflex amplitude during MI under all contraction strengths. This result suggests that the H-reflex amplitude was modulated by the practice of imagery rather than the intensity of imagery. Bonnet et al.[18] reported that the soleus H-reflex and stretch reflex amplitudes during plantar flexion MVC MI of 2% and 10% significantly increased compared with at rest. In addition, there was no difference in the H-reflex amplitude during plantar flexion between MVC MI of 2% and 10%. In contrast, the stretch reflex amplitude during the MVC MI of 10% was significantly higher than that during the MVC MI of 2%. Aoyama et al.[19] reported that there was no difference in the H-reflex amplitude during plantar flexion MVC MI of 50% and 100%. However, the stretch reflex amplitude during the MVC MI of 100% was significantly higher compared with that during the MVC MI of 50%.

On the basis of the results of previous studies as well as those of the present study, differences in the muscle contraction strengths during MI are not involved in the changes in the F-wave and H-reflex amplitudes; recurrent inhibition via Renshaw cells was considered to have an influence. The activity of Renshaw cells is modulated via the extrapyramidal tract. Hultborn et al.[20] reported that recurrent inhibition progressively increased with muscle contraction strength. Thus, it is considered that differences in muscle contraction strength during MI are not involved in changes in the excitability of spinal motor neurons. However, differences in muscle contraction strength during MI may be involved in changes in stretch reflex. The difference between the F-wave and H-reflex and the stretch reflex is that the stretch reflex contains muscle spindles within the spinal reflex pathways, whereas the F-wave and H-reflex do not. Gamma motor neurons regulate the sensitivity of muscle spindles. The extrapyramidal tract has a connection with the gamma motor neurons; an increase in the stretch reflex amplitude results from modulation of the stretch reflex gain by MI. Furthermore, as Hara et al.[16] mentioned, if a greater voluntary effort failed to induce additional enhancement of the excitability of spinal motor neurons at a very mild muscle contraction strength, then persistence and F/M amplitude ratio may be similar for MVC MI of 10% and 30%.

Park et al.[21] reported that the MEP amplitude during finger flexion or extension MVC MI of 10%, 20%, 30%, 40%, 50%, and 60% was significantly higher than that at rest. However, there were no differences in the changes in the MEP amplitude during MI under all contraction strengths. In an event-related potentials study, Romero et al.[22] reported that the M1 activity during MI does not correlate with the contraction strength but that the SMA and pM activity during MI do correlate with it. The SMA and pM are known to have the functions of motor planning and inhibition in the GO/NO-GO task[23, 24]. The result of SMA- and pM-inhibited muscle activity depended on muscle contraction strength with motor planning, and it is considered that differences in muscle contraction strength during MI are not involved in changes in the M1 activity. Because there was no change in the M1 activity, it was considered that differences in muscle contraction strength during MI are not involved in changes in the excitability of spinal motor neurons.

MI ability is a factor that affects the excitability of spinal motor neurons. Lorey et al.[25] studied the relationship between activation of the cerebral cortex during MI and the vividness of MI by fMRI. The M1, pM, S1, inferior parietal lobe (IPL) and superior parietal lobe (SPL), putamen, and Cb showed activation during MI. In particular, activation of the pM, IPL, SPL, and Cb was associated with increased vividness of MI, suggesting a correlation between the ac-

tivation of the cerebral cortex and vividness of the MI. Therefore, it is possible that motor imagery ability affects the excitability of spinal motor neurons.

A limitation of this study is that differences in the activation of the cerebral cortex during MVC MI of 10%, 30%, and 50% were not evaluated. Further study is required to evaluate the activation of the cerebral cortex during MI under different muscle contraction strengths.

The present study revealed that MVC MIs of 10%, 30%, and 50% can increase the excitability of spinal motor neurons. It is suggested that differences in muscle contraction strength during MI are not involved in changes in the excitability of spinal motor neurons.

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